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2022 DOE SSL Manufacturing Status & Opportunities

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List of Acronyms

Abbreviation	Definition
$/klm	U.S. dollar per kilolumen of light
$\$/m^2$	dollars per square meter
3D	three-dimensional
Al_2O_3	alumina
ALD	atomic layer deposition
AlGaInP	aluminum gallium indium phosphide
AlN	aluminum nitride
ANSI	American National Standards Institute
AuSn	gold-tin
AVI	automatic visual inspection
BOM	bill of materials
C_6H_3	phenyl
CAD	computer-aided design
Cd	cadmium
cd/m^2	candelas per square meter
CdSe	cadmium selenide
CES	Consumer Electronics Show
CGL	charge generation layers
CH_3	methyl
CIE	*Commission international de l'éclairage*
CMOS	complementary metal-oxide semiconductor
CO_2	carbon dioxide
COB	chip-on-board
COC	cyclo-olefin copolymers
COO	cost of ownership
Cp_2Mg	bis-(cyclopentadienyl)-magnesium
Cpk	process capability
DALI	Digital Addressable Lighting Interface
DFM	design for manufacturing
DLC	DesignLights Consortium
DOE	Department of Energy
DPSS	diode pumped solid state
DRAM	distributed recycling and additive manufacturing
DUT	device under test
EBL	electron blocking layer
EIL	electron injection layer
EMC	epoxy molding compound
EML	emissive layers
EOL	end of life

EQE	external quantum efficiency
ETL	electron transport layer
EU	European Union
FPD	flat panel display
Fraunhofer FEP	Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology
Fraunhofer IWS	Fraunhofer Institute for Material and Beam Technology
FWHM	full width at half maximum
GaAs	gallium arsenide
GaN	gallium nitride
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulfide
HBL	hole blocking layer
HDPE	high density polyethylene
HIL	hole injection layer
HTL	hole transport layer
HVPE	hydride vapor phase epitaxy
HVPE	hydride vapor-phase epitaxy
IES	Illuminating Engineering Society
IJP	ink-jet printing
InGaN	indium gallium nitride
InP	indium phosphide
IQE	internal quantum efficiency
IR	infrared
ITO	indium tin oxide
K	Kelvin
LED	light emitting diodes
LES	light-emitting surface
LLO	laser liftoff
lm/W	lumens per watt
L_p	rated flux maintenance life
m^2	square meters
MBE	molecular beam epitaxy
MCC	Mitsubishi Chemical Corp
MC-PCB	metal-core printed circuit board
MES	manufacturing execution systems
MLS	Mulinsen
mm	millimeter
mm^2	square millimeters
Mm^2	million square meters
Mn	manganese
MOCVD	metal organic chemical vapor deposition

MQW	multi-quantum well
n-doped	n-type doped semiconductor
N_2	nitrogen
NGS	Next Generation Source
NH_3	ammonia
nm	nanometer
NPB	N,N′-Di(1-naphthyl)-N,N′-diphenyl-(1,1′-biphenyl)-4,4′-diamine
O_2	oxygen
OLED	organic light emitting diodes
OVJP	organic vapor jet printing
OVPD	organic vapor phase deposition
p-doped	p-type doped semiconductor
PC	polycarbonate
PCB	printed circuit board
PC-LED	phosphor converted light emitting diode
PCT	Polycyclohexylene-dimethylene Terephthalates
PEC	photoelectrochemically
PECVD	plasma enhanced chemical vapor deposition
PET	polyethylene terephthalate
PF	power factor
PLCC	plastic leaded chip carrier
PMMA	polymethylmethacrylate
PPA	polyphthalamide
ppb	parts per billion
ppm	parts per million
PSS	Patterned Sapphire Substrates
PVD	physical vapor deposition
QCM	quartz crystal microbalances
QD	quantum dot
QDEL	quantum dot electroluminescence
QFN	quad flat no-lead
R&D	research and development
R2R	roll-to-roll
RGBA	red, green, blue, amber
RoHS	Restriction of Hazardous Substances
SAC	tin silver copper
SDS	sorted die sheets
SEI	Sumitomo Electric Industries
Si	silicon
SiC	silicon carbide
SiH_4	silane
SKU	stock keeping unit
SMC	silicone molding compound

SMT	surface mount technology
SPC	statistical process control
SSL	solid-state lighting
TADF	thermally activated delayed fluorescence
TEC	thermal expansion coefficient
TFFC	thin film flip chip
TiO_2	titanium oxide
TIR	total internal reflection
TMAl	trimethylaluminum
TMG	trimethylgallium
TMIn	trimethylindium
UL	Underwriters Laboratories Inc.
USTR	United States Trade Representative
UTG	ultra-thin glass
UV	ultraviolet
VCSELs	vertical cavity surface emitting lasers
VOC	volatile organic compound
VTE	vaccuum thermal evaporation
W/mK	watts per meter · Kelvin
YAG	yttrium aluminium garnet
$YAG:Ce^{3+}$	cerium-doped yttrium aluminum garnet
ZrO_2	zirconium oxide
µm	micron (micrometer)
µm/hr	micrometers per hour
Ω cm	ohm centimeters
Ω/□	ohms per square

1 Executive Summary

Solid state lighting (SSL) has grown to be a prominent lighting technology with its continually rising efficacy and long lifetimes, as well as its unique features that can enable new functionality and form factors. The maturation of light emitting diodes (LEDs), organic light emitting diodes (OLEDs), and SSL-based luminaire products over the past decade has led to an evolution of manufacturing approaches and a shift of the overall lighting supply chain makeup. The manufacturing processes for LEDs and LED-based lighting products have quickly moved into large-scale production processes with ever increasing performance and decreasing prices. The relative breakdown of subsystem costs has shifted significantly during this period, as LED packages were once the highest cost in the lighting system and are now among the lowest-cost subsystem. Despite the success to date, the changing features, requirements, and expectations for LED lighting products requires continued efforts to reduce manufacturing costs, accelerate adoption, and ensure products meet the levels of quality and reliability necessary for general illumination.

With the ongoing innovation of SSL technology, there is still an opportunity to rethink how products and components are manufactured across the product value chain and to embed sustainable manufacturing processes and materials into the manufacturing supply chain. For continued progress, manufacturing processes and technologies must adjust to further improve lighting product quality, reduce cost, and enable a wider variety of form factors and features as the technologies evolve. The unique technology features available with SSL present the opportunity to establish new manufacturing approaches and foster domestic manufacturing for portions of the supply chain. As SSL technology advances to employ more dynamic control, there is increasing synergy with LED display technology; new advances in micro-LED displays can be leveraged for new lighting concepts that can improve lighting application efficiency. SSL manufacturing processes should be developed to improve automation, create flexible manufacturing processes, and allow for a manufacturing-on-demand infrastructure. New manufacturing technologies can also influence where, when, and how products are made, possibly enabling more localized production close to the end use market.

LED, lamp, and luminaire manufacturing are global enterprises with a global supply chain. The vast majority of LED die and package manufacturing is centered in Asia, whereas LED luminaire manufacturing is distributed worldwide. Though luminaires are often manufactured across the globe nearer the end customer, there is a heavy concentration in Asia for the manufacture of commodity level LED lighting fixtures and LED lamps. External macroeconomic factors play a role in the location of manufacturing hubs for SSL, though ultimately, the geographical distribution of the manufacturing operation will depend on many factors, including supply chain infrastructure, manufacturing technology, control of intellectual property, product design, tax environment, regulation, shipping and distribution costs, and labor costs.

OLEDs may still present a potential counterpart to LED technology, providing a soft, diffuse light source that can provide low-glare illumination and be located close to the lighted task. While OLED source efficiency has improved, it has not realized the cost, lifetime and efficiency of LEDs. Advancements in OLED manufacturing technologies are crucial for reducing the cost of OLED lighting to gain broader market acceptance and impact energy savings. Today, the manufacturing baseline for OLED lighting products is limited due to a nascent market and limited commercialization of OLED lighting products. Some advances in the OLED displays manufacturing supply chain, such as the lower cost of OLED emitter materials realized from high volume displays manufacturing, can be leveraged to improve the state of OLED lighting manufacturing.

A consistent focus of the Department of Energy's (DOE) Solid-State Lighting Program has been to save energy through SSL technology development and advanced manufacturing support to allow for mass affordable deployment of the technology. An additional aim for DOE is that the economic benefit derived from such work benefits the U.S. economy to the greatest extent possible. Specifically, for the SSL Program, that objective translates into advancing a manufacturing role for the United States in the global lighting market. New technology advancements, increased automation, and additive manufacturing are promising vectors for innovation, with the potential to maintain and grow the U.S. manufacturing base and add domestic manufacturing jobs. The objective of this report is to highlight opportunities to develop manufacturing technologies that will benefit energy-saving SSL and support an increased role for U.S. manufacturing of highly efficient lighting products. There are many important manufacturing R&D opportunities that can advance SSL manufacturing and enable improved productivity, reduced cost, and new manufacturing technologies that can impact domestic manufacturing in lighting. The highest priority SSL manufacturing opportunities were selected based on several factors including the leverage of the technology improvement across the breadth of the supply chain, increased domestic manufacturing opportunities that can compete in the global SSL market, improved sustainable manufacturing, and manufacturing innovations that enable new form factors and improved lighting application efficiency.

As of the time of the data collection in 2020 and writing through early 2021, the highest priority SSL manufacturing R&D opportunities have been identified below.

LED Chip & Package Manufacturing

- **LED Wafer Wavelength Uniformity:** Development of improved metalorganic chemical vapor deposition (MOCVD) hardware platforms to allow an entire LED wafer to yield into a single performance bin.
- **LED Wafer Fabrication Automation:** Creating improved automation and integration within 100 mm and 150 mm wafer fabrication plants (fabs) by developing turn-key manufacturing execution systems (MES), tool-to-tool wafer movement, communication platforms, and statistical process control (SPC) systems not readily available for the compound semiconductor fabs.
- **LED Device Testing Productivity:** Development of unique schemes to test sections of the LED wafer instead of individual die one at a time to improve LED device testing productivity. This will require careful process uniformity understanding of upstream processes.
- **Measurement Innovation for Micro-LEDs:** Implementing micro-LEDs for lighting involves major changes to fabrication and measurement infrastructure used in mass production for LEDs. New measurement techniques need to be developed to identify good performing die at the micro-scale with high throughput.
- **Micro-LED Mass Transfer Processes:** Designing economical mass transfer methods with extremely high yields to make the use of numerous micro-LEDs in luminaire products.
- **Chip-Level Optical & Electrical Integration:** Integrating increasing amounts of functionality (optical control or drivers) at the wafer level can lead to cost savings on the luminaire assembly stage taking advantage of the more automated surface mount technology processes or semiconductor fabrication equipment over current luminaire assembly schemes.

LED Luminaire Manufacturing

- **Universal Voltage Drivers:** Creating universal voltage power supplies cost-effectively for luminaires can simplify the manufacturing supply chains allowing manufacturers to better leverage economies of scale.
- **Luminaire Assembly Automation:** Developing new luminaire designs that are easier for automated assembly by designing around the more manual and difficult to automate assembly processes.
- **Additive Manufacturing of Luminaires:** While proof-of-concept demonstrations exist for the use of additive manufacturing in many areas of the SSL value chain, R&D is required to develop printable materials with the sufficient properties to replace existing manufacturing approaches in electrical, thermal, and optical components for luminaires.

- **Sustainable Materials Supply Chain for Lighting:** There is an opportunity to jump start sustainable supply chains by developing and integrating sustainable materials, and to make every component of a lighting system recyclable, reusable, and free of harmful chemicals.

OLED Manufacturing

- **Customizable Manufacturing of Patterned Substrates for OLEDs:** The development of patterned substrates is required so that multiple panels can be fabricated with edges that are sealed to improve reliability of OLED devices.

- **Rapid Deposition of Organic Materials:** Reducing the deposition time for OLED panels require alternative deposition techniques to increase throughput and lower manufacturing cost.

- **Affordable OLED Encapsulation Techniques:** A simpler, less costly encapsulation technique is required for OLED stability.

Table of Contents

1 Executive Summary x

2 Overview of SSL Manufacturing 1

2.1 Current U.S. and Global Production 3

2.2 LED Manufacturing Supply Chain 4

2.2.1 LED-Based Manufacturing 4

2.2.2 LED Supply Chain Status 5

2.2.3 Macroeconomic Impacts to the Supply Chain 9

2.2.4 LED Pricing 11

2.2.5 LED Cost Breakdown 13

2.2.6 LED Luminaire/Lamp Cost Breakdown 17

2.3 OLED Manufacturing Supply Chain 19

2.3.1 OLED Supply Chain Status 21

2.3.2 OLED Cost Breakdown 23

3 LED Package and Luminaire Manufacturing Process, Equipment & Materials 25

3.1 LED Wafer Manufacturing 25

3.1.1 Epitaxial Growth 26

3.1.2 MOVCD Equipment Manufacturers 29

3.1.3 Substrate Materials 30

3.1.4 Chemical Reagents 33

3.2 LED Die Manufacturing 34

3.2.1 LED Die Design 35

3.2.2 Wafer Processing 36

3.2.3 Back-end Wafer Processing (Die Singulation and Testing) 41

3.3 LED Package Manufacturing 43

3.3.1 LED Package Platforms and Form Factors 43

3.3.2 LED Packaging Equipment 46

3.3.3 Packaging Materials 49

3.3.4 Down-Converter Application 53

3.3.5 Down-Converter Materials 57

3.3.6 Encapsulation and Lensing 60

3.3.7 Test and Inspection Equipment 64

3.4 LED Luminaire Manufacturing 68

3.4.1 LED Light Engines (Modules) Assembly 69

3.4.2 Remote Phosphors 70

3.4.3 Optical Component Manufacturing 71

3.4.4 LED Driver Manufacturing 75

3.4.5 Lamp/Luminaire Housing Manufacturing and Assembly 76

3.4.6 Test and Inspection 80

3.4.7 Design for Manufacturing 81

3.5 Advanced Manufacturing Technologies 83

3.5.1 Additive Manufacturing 83

3.5.2 Micro-LED Manufacturing 85

3.5.3 Sustainability 89

4 OLED Panel and Luminaire Manufacturing Process, Equipment & Materials 94

4.1 OLED Process Flow 94

4.2 Integrated Substrates 95

4.2.1 Substrate Choice 96

4.2.2 Barriers for Plastic Substrates 96

4.2.3 Extraction Enhancement Layers 97

4.2.4 Transparent Electrodes 98

4.3 Light Generation 99

4.3.1 Organic Materials 100

4.3.2 Cathode Deposition 102

4.3.3 Encapsulation 102

4.4 Substrate Patterning and Panel Separation 103

4.5 Roll-to-Roll Manufacturing 104

4.5.1 Roll-to-Roll Integrated Substrate 105

4.5.2 Roll-to-Roll Deposition of Organic Layers and Cathode 106

4.5.3 Roll-to-Roll Encapsulation and Panel Separation 107

4.5.4 Roll-to-Roll In-line Testing 107

4.6 Roll-to-Roll Back-End Processing 108

4.6.1 Testing and Inspection 108

4.7 OLED Panel Costs 109

4.7.1 Organic materials 109

4.7.2 Integrated Substrates 110

4.7.3 Back End Processing 110

5 References 111

List of Figures

Figure 2-1 Global installed base of luminaires, 2019 to 2024, with the predicted growth in installed LED-based luminaires increasing from 11% in 2019 to 29% by 2024. [2] 1

Figure 2-2 LED luminaire unit sales by region for 2019 shows the diverse sales across global regions with China leading the way in terms of units purchased. [3] 3

Figure 2-3 Replacement lamp sales revenues, 2019 to 2024, by lighting source technology. LED replacement lamps market share will continue to grow though overall lamps revenue will decline due to longer lifetimes associated with LED replacement lamps. [2] 4

Figure 2-4 LED-Based SSL Manufacturing Supply Chain..... 5

Figure 2-5 Price for high-power and mid-power warm-white and cool-white LED packages over time. The prices have dropped rapidly over the past decade with new technology innovation and a more robust supply chain. 12

Figure 2-6 Representative examples of LED packages from the four main platforms, including (from left) high-power ceramic-based LEDs, mid-power polymer-based LEDs, CSP LED packages, and COB LEDs..... 14

Figure 2-7 Typical cost breakdowns for high-power and mid-power LED packages. The LED die represents the biggest cost contribution of the LED package..... 14

Figure 2-8 High-power LED cost breakdowns over time show the packaging contribution decreased the most early on and then further cost reductions were attributed to decreasing the cost of the chip..... 15

Figure 2-9 Typical cost breakdowns for COB LED packages. The assembly cost is a significant contribution of the COB cost due to the large number of chips that need to be attached compared to high-power and mid-power LED packages. 16

Figure 2-10 Comparison of cost breakdown for different lighting applications in 2019. The categories of LED lighting products include a troffer, a downlight, an outdoor area light, and an A-lamp. Each product has a different balance of cost in the major elements, though housing is the biggest contributor in each product type..... 17

Figure 2-11 Comparison of cost breakdown for a 6" downlight from 2014 to 2019. The relative cost of the LEDs has dropped dramatically while other elements such as the driver retained similar relative cost breakdown even as cost has gone down. 18

Figure 2-12 OLED-based SSL Manufacturing Supply Chain. 20

Figure 3-1 Evolution of MOCVD technology for GaN LED growth. [9]..... 26

Figure 3-2 Cost of ownership of blue LED wafers as a function of 1 nm bin yield for the Veeco EPIK 700 and 868 MOCVD systems. The EPIK 868 system enables cost per wafer savings of more than 20% compared to previous generations. [10] 27

Figure 3-3 Schematic illustration of factors that impact key MOCVD process and cost including yield, throughput and equipment costs. [11] 27

Figure 3-4 Wafer to wafer wavelength uniformity a MOCVD run for blue LEDs using a Veeco EPIK 868 reactor. Ten 150 mm wafers were inserted as shown in the bottom right image. The entire run of wafers had average wafer wavelength fall in a 2.5 nm bin (upper and lower left). The wavelength distribution across each wafer is shown in the bottom right image. The gas/precursor injection flange (upper right) is designed for laminar flow to create uniform deposition profiles across the wafer carrier. [10] 28

Figure 3-5 MOCVD market share for the GaN LED market in 2017. Veeco had the dominant market share in the GaN LED market since 2010 but AMEC's emergence in 2016 has reduced Veeco's dominance in the GaN LED market. [14] 30

Figure 3-6 The patterned sapphire substrate scatters more photons at the textured surface compared to the planar sapphire substrates (left images), which allows more light to be emitted outside of the escape cone of TIR. [21] 32

Figure 3-7 The MOCVD process results in metalorganic precursors decomposing under from the heat at the substrate and incorporate with the other atoms in the growing semiconductor thin film. 34

Figure 3-8 Common LED die designs for various architectures including: (a) an early lateral chip structure with semi-transparent p-contact, (b) the more current lateral chip structure with transparent p-contact and patterned sapphire substrate, (c) an earlier design of the vertical thin film chip structure, (d) a more recent vertical thin film structure with via n-contacts, (e) an earlier thin film flip chip (TFFC) structure, and (f) the more current sapphire flip chip structure with patterned sapphire substrate. 36

Figure 3-9 General LED device fabrication step flow diagram. 37

Figure 3-10 Reduction in relative manufacturing cost when transitioning from 3" to 150 mm diameter LED wafers. [25]...38

Figure 3-11 Improved process control is seen with 150 mm wafer annealing equipment. Larger LED wafer sizes allows the use of advanced equipment with better process uniformity resulting in a die yield improvement. [25] 38

Figure 3-12 Images of batch wafer loading for plasma enhanced chemical vapor deposition (PECVD) of dielectric layers on 150 mm LED wafers. The process productivity and defect density for the dielectric deposition was an order of magnitude lower due to reduced manual handling. [25] 39

Figure 3-13 Loading 150 mm wafers into a holder for an e-beam evaporator. [26] 39

Figure 3-14 Ultratech Sapphire 100 Stepper tool for LED wafer processing. [29] 40

Figure 3-15 An image of laser scribing of an LED sapphire wafer showing a kerf width of 2.5 μm. [30] 42

Figure 3-16 Schematic of the LLO separation process for sapphire wafers. [32] 42

Figure 3-17 Supporting equipment such as film frame mounters and matrix die expanders are needed to support the backend processing. [33] 43

Figure 3-18 LED package revenue by geographic region for 2019. [34] 44

Figure 3-19 CSP LEDs with (a) a phosphor coating all 5 sidewalls (volume emitter) and (b) with white reflective sidewalls to reflect the side emission allowing light to come only from the surface (surface emitter). A conventional COB array (c) is compared to a CSP array (d). CSP arrays can provide a more compact source size for color tuning by using different color CSPs in the array. [35] [36] [37] 46

Figure 3-20 General LED packaging step flow diagram. 47

Figure 3-21 Typical high-power LED in-line packaging equipment for the different process steps. 48

Figure 3-22 Typical mid-power LED in-line packaging equipment for the different process steps. 48

Figure 3-23 Cross section schematic and images of a high-power ceramic-based LED package (left) and mid-power plastic-based package (right). [38] [39] [40] 49

Figure 3-24 Silver-plated LED lead frames with transparent encapsulation before (A) and after (B) silver sulfide formation at the surfaces and phosphor-containing encapsulation before (C) and after (D) silver sulfide formation. The silver plating turns darker due to sulfur-based contamination and results in a lower reflectivity surface and light loss. [41] 50

Figure 3-25 Comparison of the cost/performance balance for the four main die attach platforms used in LED packaging. The best solution varies between the different LED package platforms (high-power, mid-power, COB and CSP). [43] 52

Figure 3-26 Three common phosphor application methods for the major LED architectures are illustrated along with some product examples using that technique. Mid-power LEDs and COBs use a dispense application and high power LEDs can be a mixture of conformal coating/molding or chip coating/platelets. [44] 53

Figure 3-27 Image of a jetting nozzle for phosphor dispensing (left). Schematic of the phosphor settling process (a) before and (b) during settling (right). [45] 54

Figure 3-28 Comparison of the color point control for high-power white LED manufacturing using a phosphor slurry and a ceramic platelet. The blue area represents the typical color point distribution of using a phosphor slurry, whereas the red represents the distribution of LED using a ceramic platelet. LED device image and illustration of a TFFC LED with "Lumiramic" ceramic phosphor platelet. [46] [47] [48] 55

Figure 3-29 Comparison of the color point control for manufacturing using a molded versus conformal phosphor coatings. The conformal phosphor provides a tighter color point distribution than the molded phosphor. [44] 55

Figure 3-30 Schematic of the phosphor settling process (a) before (b) during and (c) after settling. [49] 56

Figure 3-31 Schematic of the phosphor application step for the CSP form factor. [50] 57

Figure 3-32 QE improvements can be seen in KSF phosphor from improvements in synthesis and materials processing innovations when comparing improvements by GE in their TriGain KSF phosphor to the typical KSF phosphor. [51] 58

Figure 3-33 Emission wavelength of CdSe QDs as a function of dot diameter. [61] As the diameter increases, the emission wavelength of the QD increases. 60

Figure 3-34 Schematic of LED-grade silicone molecules. The siloxane chain functional hydrocarbon group affect the resulting encapsulant properties. The most common function groups are methyl and phenyl groups. [62] 61

Figure 3-35 Illustrations of three common silicone application techniques (with or without phosphor) including dispensing, compression molding, and transfer molding. [63] 62

Figure 3-36 Lumen maintenance of a high-power LED with a methyl siloxane (blue line) and a phenyl siloxane (red line) encapsulant. While the phenyl-based silicone provides better refractive index, the methyl-silicone provides better photothermal stability resulting in a higher retained lumen flux over operation. [62] 63

Figure 3-37 The temperature of the phosphor layer as a function of thermal conductivity and the impact to the relative brightness of LED phosphors and (b) the temperature of the phosphor layer decreases with increasing thermal conductivity of the encapsulant. [65] 63

Figure 3-38 The chromaticity specification from ANSI C78.377-2015 of SSL products on the CIE 1976 (u',v') diagram. The black quadrangles represent the chromaticity tolerance size for a target CCT. The blue 4-step MacAdam circles are an alternate way of specifying chromaticity tolerances. [67] 66

Figure 3-39 CIE 1931 (x, y) diagram with various chromaticity sub-bins. The blue area represents a typical LED chromaticity distribution in the production of white LEDs. To reach the target chromaticity bin, represented by the yellow star, LED manufacturers can match LED multiple white LEDs from a variety of bins to achieve the target color point. For example, LEDs from the four green bins can be mixed to generate the target color point. [68] 66

Figure 3-40 Reliability test equipment for LM-80 measurements. The LM-80 systems combine LED drive electronics with fully integrated thermal control systems and automated light measurement. [70] 67

Figure 3-41 Examples of remote phosphor implementation into lighting products. [72] [73] 70

Figure 3-42 An image of a filament-style LED A-lamp (left) and a schematic of the assembly of a LED based filament (right). LED chips are mounted onto a glass substrate and then coated with phosphor in silicone. [74] 71

Figure 3-43 Illustrations of various secondary optics designs including: (a) a TIR lens which refracts the light to create a tight beam, (b) a reflector lens which reflects the incident light that hits the sidewall, and (c) a diffuser lens which scatters and diffuses the light that passes through the optic. [75] [76] 71

Figure 3-44 Schematic of a typical injection mold and its key features is illustrated (upper left), and images highlighting features inside the two mold plates are shown (upper right). An illustration of the main features of an injection molding system shows its key units (lower). [77] 72

Figure 3-45 (a) An illustration of how a diffuse reflector scatters the incident light ray to improve diffusion. Examples of how diffuse reflection can be implemented in different fixture geometries including (b) indirect lighting where the LEDs face away from the room, and (c) direct-view lighting where the light is scattered by the diffuser and additional reflection is provided by coating the inside of the fixture with a diffuse reflector. [79] 74

Figure 3-46 A TIR lens, optic holder and LED on a star board are assembled together to create the light enginge with optic for a directional lamp (top). A multi-lens structure allows for the integration of support pins to align with the PCB and can eliminate the need for an optic holder (bottom). [80] 74

Figure 3-47 Example process flow for the automated assembly of an LED lamp. Note: HS refers to heat sink. [81] 77

Figure 3-48 Example of automated assembly lines for LED A-lamp. [81] 78

Figure 3-49 An example of a luminaire assembly cell (top) and a straight conveyer assembly line (bottom). [82] [83] 79

Figure 3-50 Examples of integrating sphere (left) and goniophotometer (right) systems used to test LED lighting fixtures. [85] [86] 80

Figure 3-51 Images of 3-D-printed lighting fixtures. [87] [88] Custom optical distribution features of decorative luminaires can be achieved through additive manufacturing approaches that would not otherwise be practical or possible to achieve. 84

Figure 3-52 Illustration showing the deposition of droplets by UV print head onto substrate material (left-top). The droplets of polymer are allowed to “flow” under surface tension before curing with UV light, giving the smooth surfaces needed for optics (left-bottom). An array of micro-optic lenses is pictured (right). [89] 84

Figure 3-53 Images of integrated roadway luminaires with fully printed, integrated circuitry with LED, driver, sensors, and antennas. [91] 85

Figure 3-54 Wavelength distribution of a 6” blue LED wafer grown in a Veeco Epik 14x6” MOCVD reactor. The wafer shows ~4 nm distribution across the majority of the wafer area. [95] 86

Figure 3-55 Illustrations of new lighting schemes (a) and (b) using color tunable pixelated light sources to create different spectral power distributions and optical profiles. [96] [97] Illustrations of micro-LED display with (c) red, green and blue micro-LEDs applied to a TFT backplane and (d) blue micro-LEDs on a TFT backplane with a red and green color conversion materials (e.g., quantum dots) applied. [98] 87

Figure 3-56 Illustrations of three key types of micro-LED assembly and transfer techniques being investigated today (top). [98] Schematic of a novel digital printer approach the illustrates the features of a self-assembly scheme with the use of die-containing inks being applied and assembled onto a sheet in a roll-to-roll format (bottom). [99] 88

Figure 3-57 Comparison of the linear economy and circular economy schemes. The circular economy is based on the principles of designing out waste and pollution, whereas the linear economy is predicated on using materials and then disposing of them. [100] 90

Figure 3-58 Bamboo Pendant designed by Koerner Designs won the DOE Sustainable Manufacturing of Luminaires Prize in 2020. The key features of design include a biodegradable bamboo luminaire body and flaxseed printed circuit board along with an easy end of life (EOL) deconstruction design. [101] 92

Figure 3-59 A sample Declare label certified from the Living Building Challenge for a LED luminaire made by Finelite. The image highlights key features of the label disclosure including embodied carbon, end of life options, and ingredients. [102] 93

Figure 4-1 Layout of the OLEDWorks production line. After the integrated substrates are cleaned and surface treated, they enter two chains of vacuum deposition tools, arranged in loops to allow return of the masks. The substrates are then encapsulated to prevent damage to the fragile electronics before separation into panels. [106] 95

Figure 4-2 Process flow for the manufacture of an OLED luminaire. If required, the fabrication can be divided into three or four separate stages. [107] 95

Figure 4-3 Integrated Substrate with a Sub-Electrode Micro Lens Array. [114] 97

Figure 4-4 Schematic of organic layers in high-performance OLED stacks for lighting with six emitter units, each of which has multiple layers (left), and for display applications with only three emitter stacks (right). [117] 99

Figure 4-5 OLED panel with films added after singulation. [132] 103

Figure 4-6 Deposition of organic materials through a shadow mask. [106] 104

Figure 4-7 Process flow for R2R fabrication of OLED panels on thin glass. [132] 105

Figure 4-8 Applications of R2R vacuum coaters on ultrathin glass. [138] 106

Figure 4-9 Roll-to-roll fabrication equipment at the Fraunhofer FEP in Dresden with evaporators and a DC magnetron arranged around a cooling drum. [139] 106

Figure 4-10 R&D equipment at the University of Michigan used to test the roll-to-roll deposition of organic materials using both VTE and OVPD. [140] 107

Figure 4-11 Integration of an OLED panel into a luminaire, providing extra physical protection and electrical connections to the power source through a printed circuit board [145] 108

List of Tables

Table 2-1 The ranking of the top 10 global LED package companies by LED revenue. [3] 6

Table 2-2 The LED Supply Chain: LED Die, LED Package, and Luminaire Manufacturers 8

Table 2-3 The LED Supply Chain: Equipment Suppliers 8

Table 2-4 The LED Supply Chain: Materials Suppliers 9

Table 2-5 Summary of current LED package price and future performance projections. The LED performance projections are taken from the DOE 2019 Lighting R&D Opportunities report for LED packages at 35 A/cm^2. The price projections, taken from Figure 2-5, represent the lowest prices available with mid-power LEDs. 12

Table 2-6 The LED Supply Chain: Key Cost Drivers 19

Table 2-7 Suppliers of OLED Lighting Panels and Luminaires 21

Table 2-8 Suppliers of Materials for OLED Lighting Panels 22

Table 2-9 Suppliers of Manufacturing Equipment for OLED Lighting Panels 23

Table 2-10 Current status and cost targets for OLED panels 24

Table 3-1 Summary of the major LED package platforms in terms of package size, performance factors, and cost. 45

Table 3-2 Different properties of a methyl-based and phenyl-based LED grade silicone. The methyl-silicone has better stability while the phenyl-silicone has better light extraction and gas permeability. [63] 61

Table 4-1 Estimates of the cost of organic materials for each square meter of OLED panel area [125] 110

2 Overview of SSL Manufacturing

Solid state lighting (SSL) has become a leading lighting technology across the globe with its ever increasing efficacy, reliability, and tunability. The development pace of SSL technology has been meteoric over the past twenty years and the performance, features, and form factors of SSL continue to improve. SSL is characterized by light sources that are either light emitting diodes (LEDs) or organic light emitting diodes (OLEDs), which are then integrated into luminaire products for general illumination. The maturation of LEDs, OLEDs, and SSL-based luminaire products and systems has led to changes in manufacturing approaches and the makeup of the overall lighting supply chain over the past decade. The relative breakdown of subsystem costs has shifted significantly during this period, with LED packages beginning as the highest-cost component of the lighting system, but now constituting the lowest subsystem cost. Despite the technology and cost-reduction successes to date, the changing features, requirements, and expectations for LED lighting products requires continued efforts to reduce manufacturing costs and ensure products meet the levels of quality and reliability necessary for lighting. The unique technology features available with SSL present the opportunity to develop new manufacturing technologies and foster domestic manufacturing for portions of the supply chain.

SSL adoption continues to grow and has reached significant market penetration in most lighting applications, particularly in outdoor lighting. According to an adoption analysis conducted by Guidehouse, Inc. the installations of LED products in the United States have increased in all applications between 2016 and 2018, roughly doubling in unit sales and increasing LED penetration to 30% of all general illumination lighting. [1] LED lighting has an even higher penetration in U.S. outdoor applications, at 51.4%, compared to indoor applications with a penetration of 29.8%. The global installed base of luminaires lags U.S. adoption with 11% of the installed base being LED lighting, though it is expected to nearly triple by 2024, as seen in Figure 2-1. [2] As the SSL market has grown, the supply chain and manufacturing processes have shifted and evolved. Previous market participants have phased out of the industry while others have maintained or strengthened their position in the market, and new entrants with innovative technology or significant cost structure advantage have made their presence felt. The manufacturing processes for LEDs and LED-based lighting products have quickly evolved into large-scale production processes with increasing performance and decreasing prices.

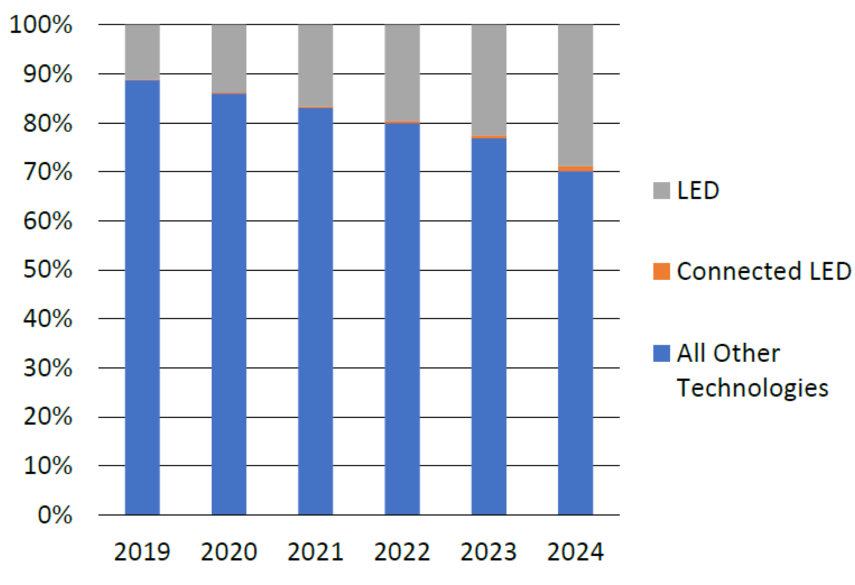


Figure 2-1 Global installed base of luminaires, 2019 to 2024, with the predicted growth in installed LED-based luminaires increasing from 11% in 2019 to 29% by 2024. [2]

With the ongoing advancements in SSL technology, there is still an opportunity for innovation in the manufacturing of products and components across the supply chain. Manufacturing processes and technologies must adjust to improve lighting product quality, reduce cost, and enable a wider variety of form factors and features as the technologies evolve. LED lighting manufacturing processes should be developed to improve automation, create flexible manufacturing processes, and allow for a manufacturing-on-demand infrastructure. New manufacturing technologies can also influence where, when, and how products are manufactured, possibly enabling more localized production close to the end-use market.

A consistent focus of the Department of Energy (DOE) Solid-State Lighting Program has been to save energy through SSL technology development and advanced manufacturing support to allow for mass deployment of the technology. An additional aim for DOE is that the economic benefit derived from such work benefits the U.S. economy to the greatest extent possible. Specifically, for the SSL Program, that objective translates into advancing a manufacturing role for the United States in the global lighting market. New technology advancements, increased automation, and additive manufacturing are promising catalysts for such U.S. economic benefits, with the potential to maintain and grow the U.S. manufacturing base and add domestic manufacturing jobs. Beyond these technical developments and manufacturing advancements, other external macroeconomic factors, such as tariffs, play a role in the location of manufacturing hubs for SSL. Recent policy decisions by the U.S. government have implemented tariffs on many Chinese-made LED and lighting products, which has resulted in a global diversification of the supply chain to establish country of origin factories outside of China. The 301-China tariffs have also accelerated the growth of LED lighting manufacturing facilities in Mexico to help create a product transformation that can avoid the tariffs once importing to the United States. Ultimately, the geographical distribution of the manufacturing operation will depend on many factors, including supply chain infrastructure, control of intellectual property, product design, tax environment, regulation, shipping and distribution costs, and labor costs. Many of these factors are the subjects of other published such as DOE's recently published 2020 LED Manufacturing Supply Chain report or forthcoming analyses on macroeconomic impacts on lighting and are outside the scope of this document.[1] The objective of this report is to highlight opportunities to develop technologies that will benefit energy-saving SSL and support an increased role for U.S. manufacturing of lighting products.

OLED-based lighting technology represents an area of SSL technology that can create diffuse light sources with direct emitters that are thin profile and, in some cases, bendable. OLEDs are fundamentally large-area, low-brightness, thin-form factor light sources which may make them desirable for proximal, low glare applications such as task lighting. These features of OLED lighting complement the high-brightness, small-area LED light sources in general illumination applications. Though OLED technology currently lags LED-based technology in both performance (efficacy and reliability) and pricing structure, it offers intriguing potential benefits and is steadily improving with commercial products now available. The greatest impediment to market acceptance of OLED lighting is the high cost of the currently available panels. There may be potential for OLEDs to improve their cost structure by shifting from batch level processes to roll-to-roll (R2R) production. The development of OLED lighting technology and manufacturing may be accelerated by the increasing adoption of OLED displays, with mobile devices currently the largest market, as well as other segments such as television displays. The high-volume OLED displays market has led to decreased costs for OLED materials that has been leveraged by the lighting industry. While important differences in the technology and performance requirements could limit the applicability of OLED display developments to lighting production (e.g. narrow emitters are needed for high color gamut displays but not for lighting), advancements in OLED production technology can nevertheless greatly impact the performance and cost of OLED products and influence the geography and structure of the OLED supply chain. Though the foundational OLED technology was developed in the United States, OLED displays are almost entirely produced in Asia today.

[1] The DOE SSL Program is currently developing a vector-autoregression model to analyze how various macroeconomic events and lighting specific supply chain elements impact LED product prices at the end-consumer level.

2.1 Current U.S. and Global Production

SSL involves a truly global supply chain and customer base. Meeting the market demand for lighting systems often means establishing manufacturing presence in local regions to have rapid delivery times with customizable lighting specifications (e.g. lumen level, color quality, color temperature, etc.) to the customer. For example, many of the large manufacturers have manufacturing activity in Asia in order to access the market growth in that region. In 2019, the global luminaire market revenue was $87.9 billion, of which LED-based luminaires accounted for 57.7% of the market, or $50.7 billion. [2] Figure 2-2 shows the unit sales distribution for LED luminaires by geographical region; Asia accounts for 42% of the unit sales, Europe 31% of unit sales, and North America 18% of unit sales. The compound annual growth rate (CAGR) in unit sales from 2019 to 2024 is approximately 10% and for revenues it is expected to be 13%. All other lighting technologies are expected to face steady declines during the 2019 to 2024 period, with fluorescent and incandescent luminaires declining the fastest at -22% and -15% per annum, respectively.

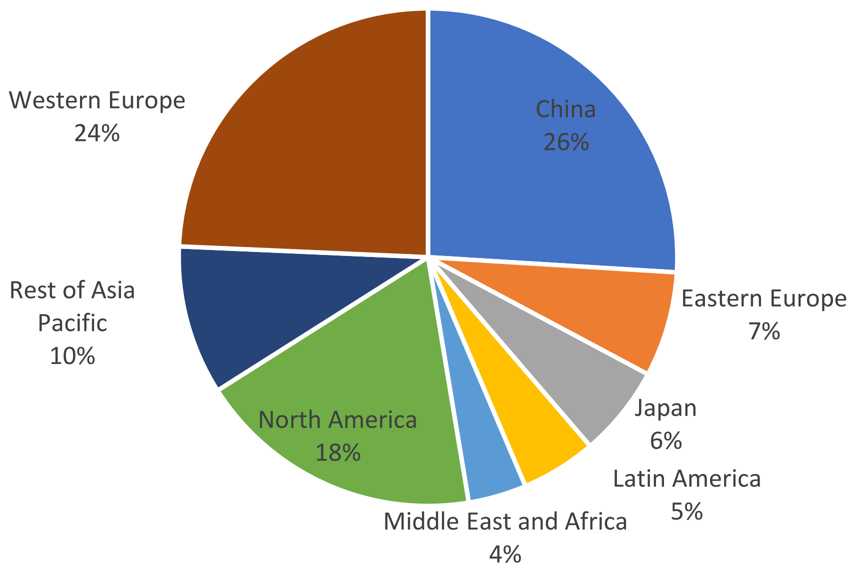


Figure 2-2 LED luminaire unit sales by region for 2019 shows the diverse sales across global regions with China leading the way in terms of units purchased. [3]

The global lamp (bulb) market revenue for 2019 totaled $16.3 billion, with 65% or $10.3 billion from LED replacement lamps. [2] The overall lamp market revenues are expected to decline over five years due to the longer lifetimes of LED replacement lamps, as seen in Figure 2-3, though the relative market share will continue to grow for LED technology.

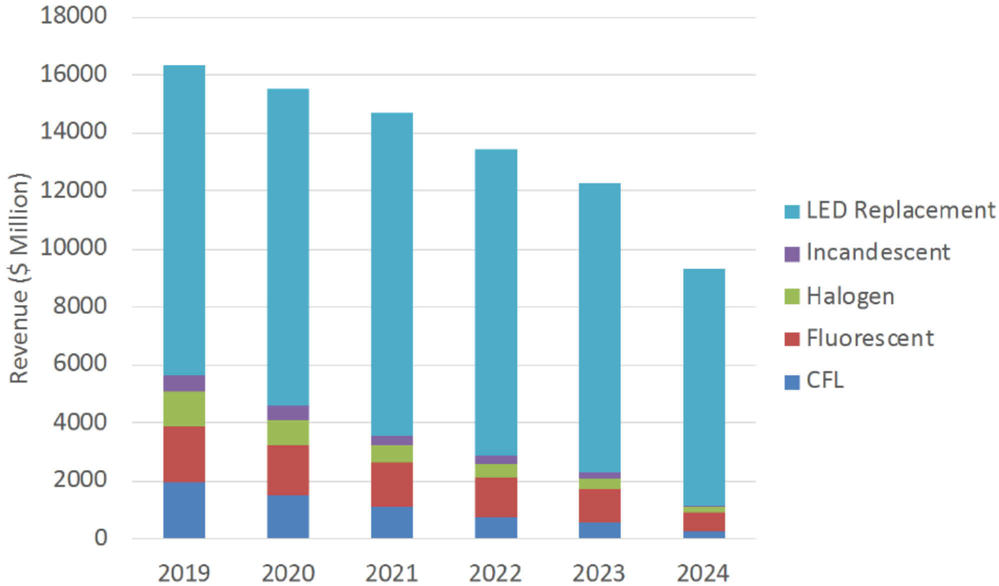


Figure 2-3 Replacement lamp sales revenues, 2019 to 2024, by lighting source technology. LED replacement lamps market share will continue to grow though overall lamps revenue will decline due to longer lifetimes associated with LED replacement lamps. [2]

2.2 LED Manufacturing Supply Chain

LED lighting manufacturing processes can be generally defined by a sequence of reasonably independent manufacturing steps. These manufacturing steps are supported by the supply of manufacturing equipment, materials, and testing equipment. The combination of the manufacturing processes, equipment, materials, and testing constitute the manufacturing supply chain. The manufacturing processes and supply chain will be discussed briefly in the remainder of Section 2 and will be detailed in depth in Section 3.

2.2.1 LED-Based Manufacturing

The manufacturing process for LED-based luminaires begins with LED die manufacturing, consisting of growth of the LED wafer by metal organic chemical vapor deposition (MOCVD), processing of the LED wafer by mostly conventional semiconductor processes, and separation of the LED wafer into individual LED chips (or die). The next step is typically to mount the LED die into an LED package, including the deposition of phosphor material to convert the blue LED emission to white light. Finally, LED packages are integrated into the end luminaire or lamp product. An alternative approach might involve skipping the intermediate LED package stage and mounting the die directly onto a circuit board or heat sink. The LED luminaire also requires the integration of a driver, heat sink, optical components, and a mechanical housing.

Figure 2-4 shows a schematic representation of the LED-based SSL manufacturing supply chain. The blue-shaded boxes and blue arrows describe the main manufacturing flow. The supporting elements of the supply chain are broken down into manufacturing equipment, materials, and test and measurement equipment. These supporting elements feed into the main manufacturing flow as indicated by the relevant arrows.

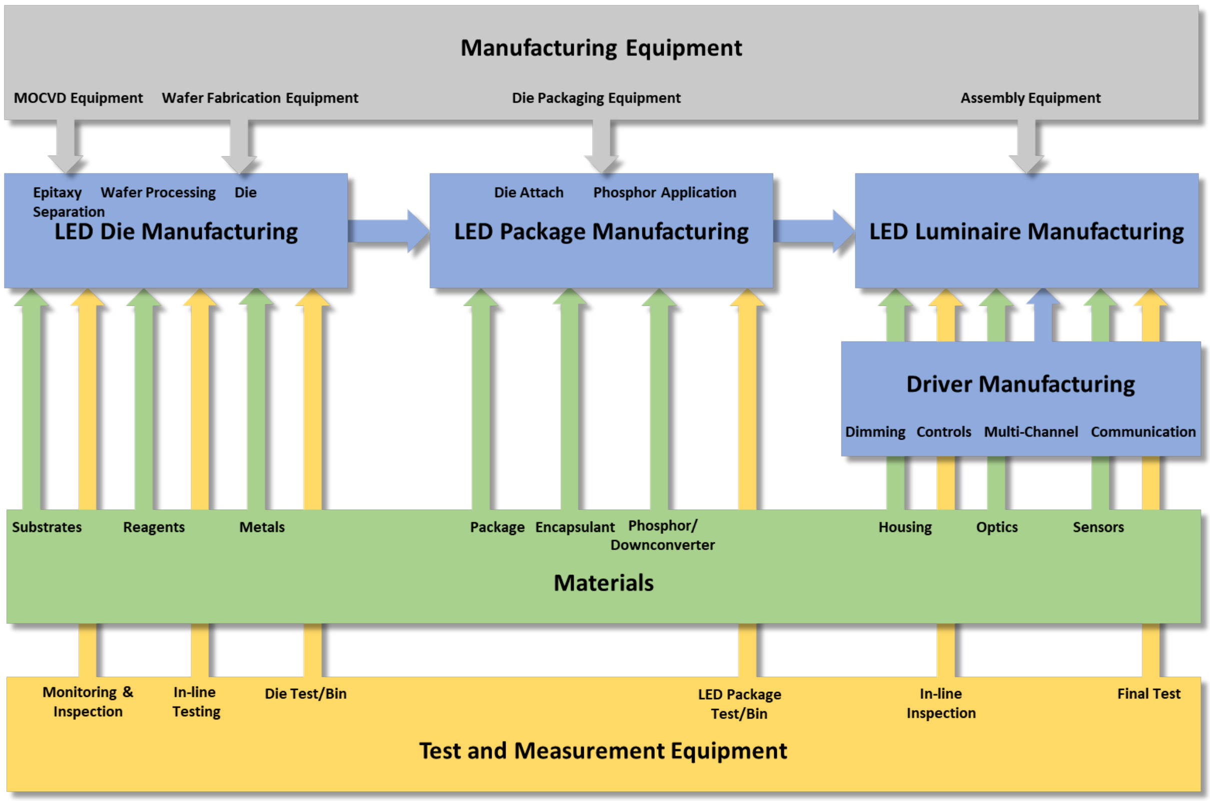


Figure 2-4 LED-Based SSL Manufacturing Supply Chain.

2.2.2 LED Supply Chain Status

The SSL supply chain has evolved as the industry has matured. A decade ago, vertically integrated manufacturers were more common and handled most production processes internally to obtain the combined performance and cost structure required for their business success. Over the past 6-8 years the supply chains have begun to consolidate in certain global regions for components like LED packages. As the LED die and package manufacturing has become commoditized, the advantage of being vertically integrated has lessened, allowing for more entities to compete. The availability of a wide variety of LED packages and light engines (also called modules – containing LED packages mounted onto a printed circuit board) has allowed many new manufacturers to participate since the technical know-how required to develop high performance LED lighting fixtures has eased with the proliferation of light engines. The availability of LED light engines reduces the manufacturing burden for lighting system manufacturers by eliminating the need for specialized electronics surface mounting and handling equipment. This availability along with dropping prices has moved the LED light source from the high-end item on the bill of materials (BOM) for an LED lighting fixture to the lowest cost in terms of major subsystems. Together, these absolute and relative decreases in cost for LED sources have resulted in a more disaggregated supply chain for LED lighting products and has allowed for improved manufacturing efficiency.

The vast majority of LED die and package manufacturing is centered in Asia. The manufacture of LED epitaxial wafers is less concentrated in a single global region compared to LED die and packages since involves more sensitive intellectual property and is often performed at the headquarters of a number of the Tier 1 LED manufacturers, such as Lumileds and Cree in the United States, Osram Opto Semiconductors in Europe, Seoul Semiconductor and Samsung in Korea, and Nichia in Japan. Though LED wafer production has been a technology differentiator for many years, it is evolving to be a commoditized part of the market for conventional die configurations and performance levels. With the improvement of the MOCVD equipment used to produce the LED wafers, the average LED epitaxial wafer performance has also advanced, enabling many manufacturers to reach a reasonable level of LED performance without specialized alterations of

MOCVD equipment or extensive process development work, somewhat equalizing the range of LED performance between first tier and next tier manufacturers. This has led to the commoditization of LED die and packages in Asia, especially in China by companies such as Sanan Optoelectronics and Mulinsen (MLS).

Some of the LED wafer processing is also handled locally but increasingly has been transferred to wafer fabrication facilities located in Asia. Packaging of the LED die is often performed in China or Malaysia, usually in factories owned and operated by the parent company (for Tier 1 manufacturers) rather than by independent contract manufacturers. Currently, a significant portion of the packaging activity in Asia is not directly related to general illumination. According to Strategies Unlimited, LED packaging for general illumination comprised 36% of global LED packaging revenues in 2019 ($15.7 billion) and is expected to grow at a CAGR of 2.3% between 2019 to 2024. [3] Signs and automotive are the next largest segments of the LED package market with 17% and 18% of the total revenue, respectively. These two segments are driving the strongest growth in the LED package market, while general illumination is posting modest growth.

In North America, LED package manufacturers Lumileds and Cree are both within the top ten worldwide by revenue and remain in the top tier with Nichia, OSRAM Opto, and Seoul Semiconductor when considering LED packages for general illumination applications. [2] Both companies manufacture their MOCVD epitaxial wafers in the United States but many of the other manufacturing processes take place through factories located in Asia.

Lumileds has established a 150 millimeter (mm) LED wafer fabrication facility in Singapore with back-end processes performed in Penang, Malaysia. Cree has a 150 mm wafer fab in North Carolina; however, they have established package and test facilities in Huizhou, China. OSRAM, a German manufacturer, continues to invest in its factories in Asia with the opening of a new 150 mm epitaxial growth wafer fabrication facility in Kulim, Malaysia. While two companies are still manufacturing in the United States, most of the package suppliers are centered in Asia. Table 2-1 shows the top LED manufacturers for 2019 with their estimated revenues.

Table 2-1 The ranking of the top 10 global LED package companies by LED revenue. [3]

Rank	Company	Location	Revenues ($M)	% Share
1	Nichia	Japan	$2,132	13%
2	OSRAM Opto	Germany	$1,411	9%
3	Lumileds	USA	$1,202	8%
4	Seoul Semiconductor	South Korea	$867	5%
5	Mulinsen (MLS)	China	$860	5%
6	Samsung	South Korea	$749	5%
7	LG Innotek	South Korea	$572	4%
8	Cree	USA	$502	3%
9	Everlight	Taiwan	$441	3%
10	Nationstar	China	$353	2%

The beginning of the commoditization in LEDs for lighting was spurred by two factors in the 2010-2011 era: Chinese government subsidies for MOCVD equipment and the oversupply of LED packages aimed at TV backlighting demand. The excess capacity generated by an overestimated demand of TV backlighting led manufacturers to pivot and try to integrate the LED packages made for display backlighting into the LED lighting market at low costs to release their inventory. [4] This led to pricing pressure for the LED manufacturers focused on the general lighting market and pushed the mid-power polymer-based LED package architecture into lighting products (which was a departure from the traditional high-power ceramic-based LED package). Simultaneously, the growth of SSL manufacturing in China was accelerated by government support (at the national, provincial, and municipal levels) for the acquisition of MOCVD systems with subsidies that could exceed 50% of the cost of MOCVD equipment. [5] The subsidies given to some of the leading manufacturers of LED chips and packages have played a major role in enabling them to gain a dominant position in Chinese domestic LED markets and the global markets for many products, such LED packages, light engines, and replacement lamps. Over the past decade, subsidies have provided substantial portions of the operating profits (over 35% of profits for some companies), enabling the companies to raise further capital from public equity markets. Most of the leading SSL companies in China are now publicly owned and have gained access to private funding. This would not have been possible if operating losses had not been reduced substantially or converted into profits through the large subsidies they received.

The production of tools and equipment for LED manufacturing and testing has been a traditional strength for U.S. manufacturers; however, this strength has eroded over the past 5-6 years as Asian suppliers have grown their offerings and by leveraging a large domestic manufacturing base. The MOCVD epitaxial growth tool is the cornerstone of the entire LED manufacturing process. The world-wide market for MOCVD tools is dominated by three manufacturers: Veeco in the United States, Aixtron in Europe, and Advanced Micro-Fabrication Equipment (AMEC) in Asia. These companies have benefitted from the growth of the LED market and continue to provide the vast majority of all MOCVD equipment used for LED production, though AMEC is gaining market share with much of the new MOCVD equipment sales into the lighting market over the past several of years. U.S. tool manufacturers also provide a meaningful portion of the specialty wafer processing, packaging, and test and inspection tools required for LED production. Companies such as Plasma-Therm, Veeco, and KLA-Tencor provide equipment to LED manufacturers all over the world.

LED luminaire manufacturing is distributed worldwide, though there is a heavy concentration in Asia for the commodity level lighting fixtures such as downlights and flat panel lighting. LED lamp manufacturing had originally sprouted up in North America, Europe, and Asia around 2010. Cree, Lighting Science Group, and Philips Lighting (now Signify) had developed LED lamp (bulb) manufacturing capabilities in North America a decade ago; however, the mass production of the LED replacement lamps has transitioned primarily to Asia (almost entirely to China) and is heavily entrenched there. [6] LED lamp manufacturing involves high volume product categories with limited configurations and complexity, which has resulted, when combined with price pressure, in the transition away from local manufacturing hubs. For luminaires systems (other than lamps, downlights, and flat panels), the manufacturers still maintained their regional production facilities since LED luminaires can be bulky leading to high shipping costs and long lead times, and luminaires may be designed for regional building types and lighting design preferences. Additionally, the high configurability of some LED luminaire systems complicates the delivery logistics to the end customer, which can be minimized through local production. The expectation of one-week delivery or less for products classes that have tens of thousands of stock keeping units (SKUs) makes a six-week shipping time for freight from Asia impractical. It would require massive inventory investments from the manufacturers to keep the right products in stock for their customer. Instead, a lean manufacturing approach near the customer has been the dominant manufacturing model for LED luminaires. Many of the large U.S. lighting companies such as Acuity Brands, Signify, Hubbell Lighting, and GE Current have manufacturing locations both in Mexico and the United States to serve the North American market.

While LED, lamp, and luminaire manufacturing are global enterprises with a global supply chain, some geographical production trends can be identified; however, many of the input materials and semiconductor processing tools are produced worldwide. Table 2-2,

Table 2-3, and Table 2-4 highlight the global nature of SSL manufacturing by listing some of the key companies in each major geographical region involved in the manufacturing of LED-based SSL products and in the supply of equipment and materials to that market. These tables categorize geographical location based on company headquarter location and may not entirely reflect the geographical balance of manufacturing activity.

Table 2-2 The LED Supply Chain: LED Die, LED Package, and Luminaire Manufacturers

Supply Chain	North America		Europe	Asia	
LED Die & Package	· Lumileds · Cree (Smart Global Holdings)		· OSRAM Opto Semiconductors	· Nichia · Seoul Semiconductor · Mulinsen (MLS) · Sanan · Samsung · LG Innotek · Everlight · Epistar · Lextar · Bridgelux · Lumens · Citizen · Stanley · Toyoda Gosei · Bridgelux · Luminus Devices	· HC Semitek · Nationstar · Lite-On · Kingbright · Edison Opto · Unity Opto · Refond · Hongli · Aucksun · Jufei · ChangFang · Changelight · Harvatek · Elec-Tech · Mason
Luminaire	· Acuity Brands · GE Current · Hubbell Lighting · Cree Lighting · Eaton · Finelite · Ecosense Lighting · Lighting Science Group	· Maxlite · Energy Focus · Green Creative · Feit Electric · ETC · Fluence · E-conolight · Soltech	· Signify · Zumtobel · TCP · Coelux · Regent Lighting · Trilux · Halla · Siteco	· LEDVance · Leedarson · LG · Sharp · Panasonic · NVC International · HPWinner · Opple Ligthing	· Kingsun · Yankon Lighting · MatrixLED · Foshan Electrical Lighting · Xiamen Topstar Lighting · PAK Corp · Sengled Optoelectronics · MinebeaMitsumi

Table 2-3 The LED Supply Chain: Equipment Suppliers

Supply Chain	North America		Europe	Asia	
Epitaxial growth	· Veeco	· Agnitron Technology	· Aixtron	· AMEC · Taiyo Nippon Sanso	· Taiyo Nippon Sanso
Wafer Processing	· Plasma-Therm · Lam Research · Veeco · Semicore	· IPG Photonics · Temescal · CHA Industries · Ultron Systems	· Oxford Instruments · EV Group · SUSS MicroTec · Logitech	· Nikon Corp · Canon · Ushio · Disco · SMEE	
LED Packaging	· Nordson ASYMTEK · Heller · BTU	· Ultron Systems · Palomar Technologies	· Besi · Mühlbauer	· ASM Pacific Tech. · TOWA · Shinwa	·Thinky · MPI · Kulicke & Soffa (K&S)
Luminaire Assembly	· Speedline Tech · Heller · Promation	· BTU	· ASM Siplace	· Panasonic · ASM SMT Solutions · Juki	· Nutek · ETA Technology · Zvision
Test and Inspection	· KLA-Tencor · Vektrex · Labsphere · Bruker	· Cyberoptics · Gamma Scientific · Radiant · Nordson DAGE	· Laytec · GL Optic · MKS Instruments - Ophir · Gigahertz-Optik · Malvern Panalytical	· Everfine · FitTech · Nikon · Konica Minolta · Shibuya Corp.	

Table 2-4 The LED Supply Chain: Materials Suppliers

Supply Chain	North America	Europe	Asia	
Substrates	· Rubicon · Kyma	· Monocrystal · Soitec	· Crystalwise · Crystal Applied Tech · Procrystal · Kyocera · Mitsubishi Chemical · Namiki · TeraXtal	· Ridgetech · Fujian Jingan Optoelectronic · Crystaland Co · Crystal-Optech · Cryscore · Tiantong
Chemical Reagents	· SAES Pure Gas · Air Products · Pall Corporation · Dow Chemical (Rohm & Haas)	· AkzoNobel · Dockweiler Chemicals · Air Liquide	· Showa Denko · Matheson Tri Gas · Nouryon · Nata Optoelectronic	
Packaging Materials	· Bergquist Company · Alpha Assembly Solutions · Indium Corp.	· Heraeus	· Tong Hsing · Ecocera · Tatsuta	
Phosphors/ Down-converters	· Intematix · PhosphorTech · Nanosys · Philips Lumileds (internal) · GE Current (internal)	· Merck/EMD · Osram Opto (internal)	· Nichia (internal) · Mitsubishi Chemical Corp · Denka · Chi Mei Corp · Nemoto · Luming Technology	
Encapsulation	· Dow Chemical · Momentive Performance	· Wacker	· Shin-Etsu	

2.2.3 Macroeconomic Impacts to the Supply Chain

As the LED lighting supply chain has become a globalized disaggregated network, it has become more vulnerable to macroeconomic impacts due to cross-border trade flows. Two large macroeconomic events, the Section 301-China tariffs and the COVID-19 pandemic, were recently analyzed to better understand the vulnerabilities and to offer directions for improving supply chain resiliency. [6]

The United States Trade Representative (USTR) initiated an investigation under Section 301 of the Trade Act of 1974 into the government of China's acts, policies, and practices related to technology transfer, intellectual property, and innovation. As a result, the Office of the USTR announced a 25% tariff on a list of goods originating in China including LED packages, that began on July 6, 2018. USTR subsequently announced another 10% tariff on certain traded goods, including LED luminaires, effective on September 24, 2018, which later underwent a tariff increase from 10% to 25% in May of 2019. Another 25% tariff on LED lamps that was scheduled for late 2019 never went into effect.

The Section 301-China tariffs had a significant effect on many companies in the LED lighting industry, but the level of impact varied by company, depending on the geographical manufacturing location, the stage in the supply chain in which the company operates, and the location of its customer base. A large percentage of LED manufacturers have part or all of their packaging operations in China. While some manufacturers are heavily invested in China, partly to access the Chinese market for their products and partly due to low labor costs and existing infrastructure, many others were more diversified with locations across Asia. The threat of the impending tariffs led some manufacturers to diversify their supply chains outside of China, while for others it accelerated the facility relocation that was already in progress. For some manufacturers, the cost of having a less fully-loaded factory in China while simultaneously establishing a second base elsewhere in Asia proved cost prohibitive.

Many of the global LED manufacturers indicated that the United States is only one portion of their global customer base and correspondingly the tariffs did not impact their sales to their customers in Europe, Asia, and the rest of the world. For LED manufacturers who sold into the U.S. market, those with country of origin products outside of China gained market share while others struggled with the choice of how much of the tariff to pass on to their customers and how much to lower their margins by not passing the tariff on. Following implementation of the tariffs in 2018, U.S. customers for LED packages from China generally faced a price increase between 5-25%. In some cases, manufacturers indicated that the full value of the tariff was passed on to their U.S. customers as a 25% price increase.

Downstream luminaire manufacturers also faced similar concerns with several manufacturers indicating that nearly all of their luminaires were manufactured in China. The tariffs placed on these goods led to a significant shift in their production (in some cases up to 40%) from China to other countries in South East Asia, such as Vietnam and Malaysia. Many manufacturers stated that there were already plans to move out of China prior to the implementation of the tariffs due to increasing labor costs within China and the uncertainty that impending tariffs caused for their business planning. While the tariffs between China and the United States accelerated this migration into other South East Asian countries, a large portion of manufacturing continues to take place in China.

Another major economic event was the COVID-19 pandemic which wreaked havoc on many global supply chains across numerous sectors. Over the first six to nine months of the pandemic, LED lighting manufacturers reported substantial impacts to their supply chain including supply shortages and delays, which began with the early factory shutdowns in China. Many manufacturing plants in China were shut down or forced to reduce staff and operations significantly. As the Chinese factories resumed operations, other countries (e.g., Malaysia and Mexico) started shutting down as the pandemic's effects spread locally. The factory shutdowns in the various global regions caused shortages in LED packages, driver components, and materials, which had a ripple effect throughout the LED industry, impacting plants in other countries and exposing vulnerabilities in the global LED supply chain.

These supplier shutdowns and decreased manufacturing capacity in China occurred at a time while lighting demand in other global regions was unaffected (first half of 2020), and in some cases, accelerated to complete lighting projects before the pandemic increased in severity and geographic breadth. As a result, lighting customers accelerated orders, often large size and rushed, to complete lighting projects before COVID-19 impacted the United States significantly. At the same time, manufacturers struggled to keep their supply chains together – seeking remaining components from suppliers, delivering on rush orders in the United States via expedited shipping for parts from Asia, and paying overtime to assembly workers in North America. Together, these events and responses to them, led to both inventory surpluses and shortages depending on the product line and manufacturer. As a result, manufacturers saw product manufacturing delays from four to eight weeks or more, as well as significant backorders. First came the "feast" in orders and then came the "famine" – i.e., the drying up of the demand as the pandemic increasingly affected the United States. Such dynamic behavior, due to variations of COVID-19 severity in different global regions, led to major challenges managing supply chain and demand.

Many manufacturers cited the decreased demand of lighting products as a result of the pandemic as the greatest challenge they faced in 2020. Quarterly earnings for publicly traded LED lighting manufacturers dropped substantially during the second and third quarter of the calendar year 2020, most seeing impacts of around 30% decreases with ranges from 10% to 50% earning losses which vary by region and market sector. With the shutdown of many commercial facilities and building construction delays, the commercial lighting industry saw the greatest declines in demand. Lighting manufacturers in the United States stated that many commercial retrofit projects were delayed or halted, reducing the immediate demand for their commercial luminaire products. In contrast, manufacturers indicated that other sectors, such as residential and outdoor lighting (street lighting and roadways), have remained flat or even seen slight increases. The residential increase was due to the masses now working from home. Outdoor lighting demand stemmed from municipalities working on roadway infrastructure improvement with the much lighter traffic due to much of the country working from home in the early part of the COVID-19 pandemic. In addition, some niche sectors such as home improvement retailers and public schools have continued to do lighting retrofits. Automotive lighting, on the other hand, did show declines that mirrored the slowdown of automobile sales.

Both of these macroeconomic events revealed vulnerabilities in the LED lighting supply chain for many industry stakeholders and proved to be major hurdles for LED and lighting companies, as well as their materials, component, and equipment suppliers, to overcome. Supply chain diversification is vital with the network of cross-border trade flows and unpredictable macroeconomic events, which are often outside the control of any one company or industry. Overall, single-source manufacturers (by either vendor or region) were hit hardest, while manufacturers with diversified suppliers by region and vendor were well-insulated against the impacts of COVID-19 supply shortages and impacts of tariffs on profitability. Some manufacturers had already diversified their supply chain before the pandemic to reduce overall business risk from major macroeconomic events and has benefitted greatly from those strategies during the COVID-19 pandemic. Others were able to anticipate the effect of the pandemic and move nimbly to adjust their supply chain to be more resilient. However, even manufacturers with multiple sourcing options reported difficulties as the pandemic severity increased. Moreover, manufacturers with greater supply chain dependencies faced more difficulties than others.

Lighting demand rebounded in 2021 as the nation adjusted to the challenges and constraints of the pandemic. The availability of the COVID-19 vaccine led to declining infections and reduced lockdowns, which allowed growth in industrial and commercial sectors. Construction is very strong in 2021, leading to robust lighting demand. While demand remains high, the global supply chains are extremely constricted leading to large gaps in supply and demand. Electronic component shortages are the biggest factor impacting production in many manufacturing sectors, including LED lighting. Components and parts that were readily available and easy to procure before the pandemic are experiencing unprecedented shortages in 2021. Additionally, new problems have risen in transportation. Freight remains slow, particularly for shipments into the US shipping, leading to further gaps in supply chains. More than ever before, flexible and nimble supply chain management is imperative to guiding production and fulfilling orders.

2.2.4 LED Pricing

Rapid price reductions of LED packages have occurred over the past decade with manufacturing process improvements and innovations, as well as prices pressures from the market dynamics discussed previously. The evolution of LED package prices is illustrated in Figure 2-5 for both warm white and cool white high-power and mid-power packages. The steep drop in prices over the past 10 years is associated with the introduction of mid-power LED packages that were originally developed for display backlighting but have matriculated into general illumination lighting. The mid-power architecture is now the largest volume sector of LED packages for lighting applications.

The price estimates in this section represent typical retail prices for LED packages purchased in quantities of 1,000 for high-power LEDs and 5,000 for mid-power LEDs from major commercial LED package distributors. Each LED manufacturer produces variants of each package design covering a range of correlated color temperature (CCT) expressed in Kelvin (K), color rendering index (CRI), and lumen output levels. Data are selected based on available datasheets and represent devices in the highest flux bins where this is reported (taking the average value within that bin) or typical flux values for the total available distribution. Chosen devices fall within specified ranges of CCT and CRI, as indicated in Figure 2-5. In all cases, the price is expressed in units of U.S. dollars per kilolumen of light ($/klm). The efficacy projections (detailed in the DOE 2019 Lighting R&D Opportunities report) and the price projections are summarized in Table 2-5. [7] The price projections in this table have been adjusted to account for the lower prices associated with mid-power package designs.

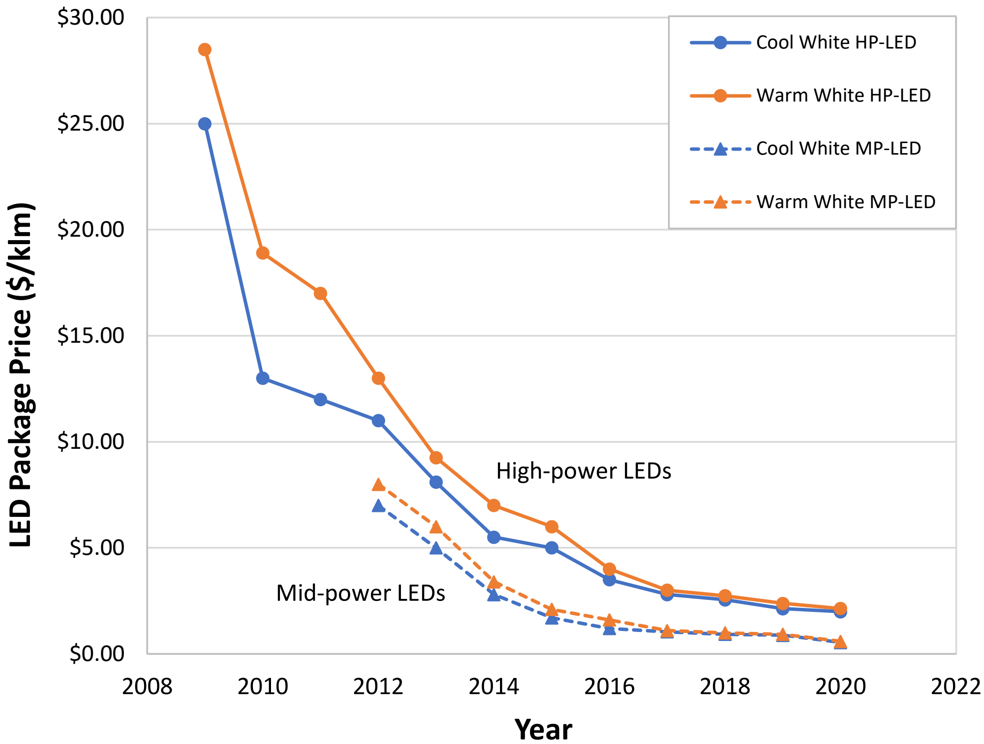


Figure 2-5 Price for high-power and mid-power warm-white and cool-white LED packages over time. The prices have dropped rapidly over the past decade with new technology innovation and a more robust supply chain.

Note: Cool-white LEDs assume CCT=5700 K and CRI=70; warm-white LEDs assume CCT=3000 K and CRI=80.

The LED package prices not only depend on the package architecture and color point, but also the efficacy. Mid-power LED packages with efficacies as high as 240 lumens per watt (lm/W) for cool white and 210 lm/W for warm white were available in production in 2020, though most product models tend to have lower efficacies. Prices for these LEDs with very high-end efficacies of over 200 lm/W are nearly four times those of LEDs in the 130 lm/W efficacy range. The low-end of the price range for the mid-power 3030 style packages is approximately $0.60/klm, but it reaches approximately $4.00/klm at the highest efficacy levels and color quality.

Table 2-5 Summary of current LED package price and future performance projections. The LED performance projections are taken from the DOE 2019 Lighting R&D Opportunities report for LED packages at 35 A/cm^2. The price projections, taken from Figure 2-5, represent the lowest prices available with mid-power LEDs.

Metric	2020	2022	2025	2035
Cool White Efficacy (lm/W)	185	228	246	249
Cool White Price ($/klm)	0.54	0.48	0.41	0.30
Warm White Efficacy (lm/W)	165	210	231	241
Warm White Price ($/klm)	0.59	0.52	0.45	0.30

High power packages have higher pricing due to the more expensive components to provide high light output and better optical and thermal control. Typically, the mid-power package costs will be 80-90% less than a high-power package (depending on die area), and the higher component cost is reflected in a similar price differential for packages. Again, as with mid-power LEDs, the efficacy and other performance metrics affect the price of high-power LED packages. High- power LED packages with efficacies as high as 185 lm/W for cool white and 165 lm/W for warm white were available in mass production in 2020.[2] Over the past several years, the price difference between warm white and cool white packages has decreased and can be almost negligible for a number of LED packages families.

In the near term, our analysis does not suggest any change in trend to high-power LED package price erosion, though mid-power package prices may remain more price stable while increasing performance levels at those prices. Market issues (e.g., oversupply) could impact these trends leading to further price reductions as more suppliers in China continue efforts to increase their market share, resulting in possible competitive price pressure. Where it is observed, a race to the bottom in pricing has impacted margins, and this prospect has led many LED package manufacturers to look towards other applications outside of general lighting, such as automotive and horticulture, to sustain their margins and provide alternate paths to revenue growth.

2.2.5 LED Cost Breakdown

For SSL manufacturing, reducing the cost of the final product involves an understanding of the source of costs at each key stage in the manufacturing process, and requires careful attention to the design of the product and of the manufacturing process. A diverse set of LED packages is available in the marketplace designed to tackle an array of different lighting applications. Because of the various LED package families available, there is a wide array of materials and methods of construction used to create these light sources. The various LED packages can be grouped into 4 major platforms, as illustrated in Figure 2-6:

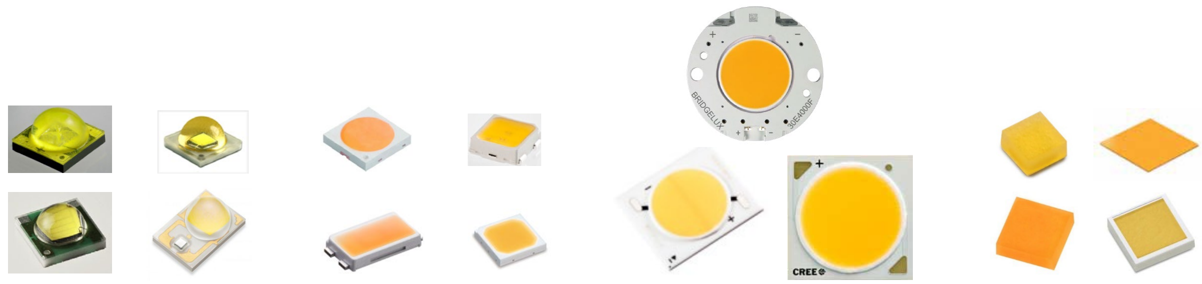
- High-power ceramic-based LEDs (1-5 W) consist of an LED die mounted onto a ceramic substrate with phosphor-silicone composite on top of the die and a molded silicone hemispherical lens. These are typically used for applications that require high power and high reliability or small source sizes such as directional lamps.

- Mid-power polymer-based LEDs (0.2-1 W) contain one or two small die mounted onto a metal lead frame embedded in a polymer cavity and filled with a phosphor containing encapsulant. These LED packages evolved from the plastic leaded chip carrier type of electronic packages. They are primarily used in omni-directional applications.

- Chip scale packages (CSPs, 1-3 W), also referred to as package-free LEDs, consist of a flip-chip LED die coated with phosphor to create a “white chip”; some styles contain white reflective sidewalls around the die to create a top side emitter. Since the package has a similar footprint to the LED die itself, they can be closely packed together in LED arrays with compact overall source size.

- Chip-on-board (COB, 10-80 W) vary largely in size and power level. They contain many small LED die mounted to a metal core printed circuit board (PCB) or ceramic substrate, which are then coated with a phosphor containing encapsulant. These are used when high luminance is required from small source size or high lumen density is needed.

[2] Note: these efficacies for high-power LEDs are listed at a current density of 35 A/cm^2.



High-power: ceramic substrates, molded lens | Mid-power: leadframe, polymer package | Chip on Board: metal-core PCB, ceramic PCB | Chip Scale Package: flip-chip with phosphor

Figure 2-6 Representative examples of LED packages from the four main platforms, including (from left) high-power ceramic-based LEDs, mid-power polymer-based LEDs, CSP LED packages, and COB LEDs.

The typical cost breakdowns for high-power and mid-power LED packages are shown in Figure 2-7. The breakdown for the high-power package assumes high-volume manufacturing of 2 square millimeters (mm^2) LED die produced on 150 mm diameter sapphire substrates, which are packaged on ceramic substrates (3.5 mm x 3.5 mm) with a molded lens to produce a warm white phosphor converted light emitting diode (PC-LED). The breakdown for the mid-power PC-LED package assumes a two-die (0.5 mm^2 die) plastic leaded chip carrier (PLCC) 3030 package (3.0 mm x 3.0 mm). As seen in the cost breakdown in Figure 2-7, the LED die (including epitaxy, wafer processing, and singulation) is the largest cost element accounting for just above half of the package cost. The relative contribution of the packaging costs and phosphor cost is where the mid-power and high-power packages diverge. The high-power package uses more expensive ceramic substrates and hemispherical over-molded lenses compared to the metal lead frame and plastic molded housing with a dispensed encapsulant. The lower packaging costs in the mid-power architecture makes the relative contribution of the phosphor cost element rise slightly in percentage of total cost as compared to the high-power package architecture.

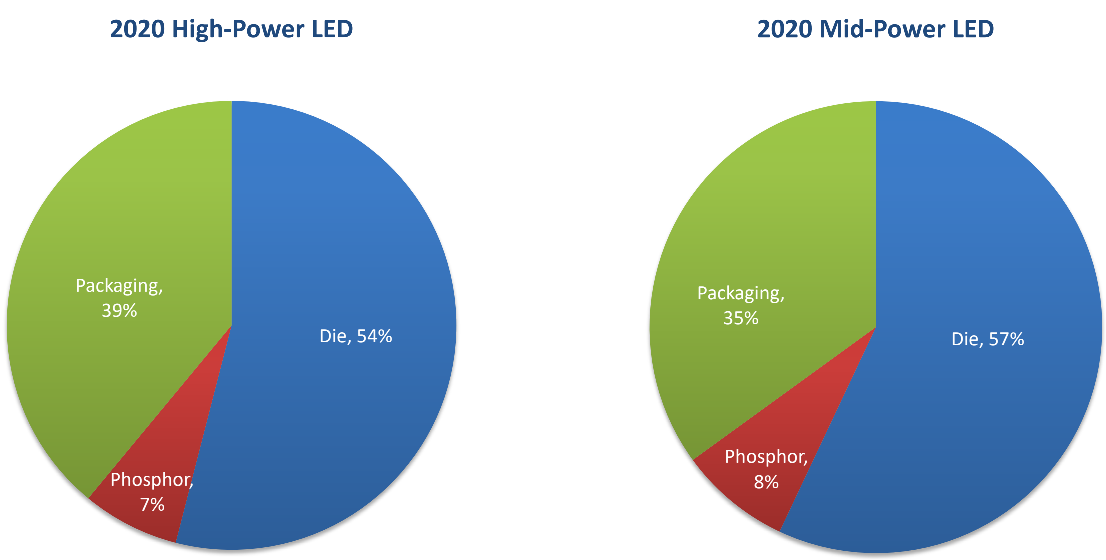


Figure 2-7 Typical cost breakdowns for high-power and mid-power LED packages. The LED die represents the biggest cost contribution of the LED package.

Note: High-power package assumes a 2 mm² LED die packaged on a ceramic substrate (3.5 mm x 3.5 mm) with a molded silicone lens. Mid-power LED package assumes a two die (0.5 mm² die) PLCC 3030 package (3.0 mm x 3.0 mm).

Source: Inputs from DOE SSL Roundtable and Workshop attendees

The relative cost elements of high-power LEDs have changed over time, with the LED die becoming the largest cost contribution to the BOM compared to the packaging contribution, as seen in Figure 2-8. Over the past 6-7 years, the overall high-power LED package cost has continued to decrease as volumes have increased, largely in line with expected learning relationships between cumulative production volume and marginal unit cost. The cost reduction during this period is due to general declines in materials costs, simplified chip designs, and a continuing erosion of gross margins. The relative contribution from epitaxy and wafer processing also decreased as LED production wafer sizes increased during this period; in addition, the chip design has changed to allow for lower cost manufacturing processes to be employed. The leverage of increasing wafer size on cost is not surprising since the final product is a packaged die and there are many thousands of such die on each wafer (e.g., around 15,000 1 mm^2 die on a 150 mm diameter substrate). The costs associated with die-level activities are not reduced in the same way as wafer level processes, so for manufacturers to realize further process cost reductions, they can either address die-level packaging process and/or material costs, or else move toward some different manufacturing approaches (e.g. perform more of the packaging activities at a wafer level).

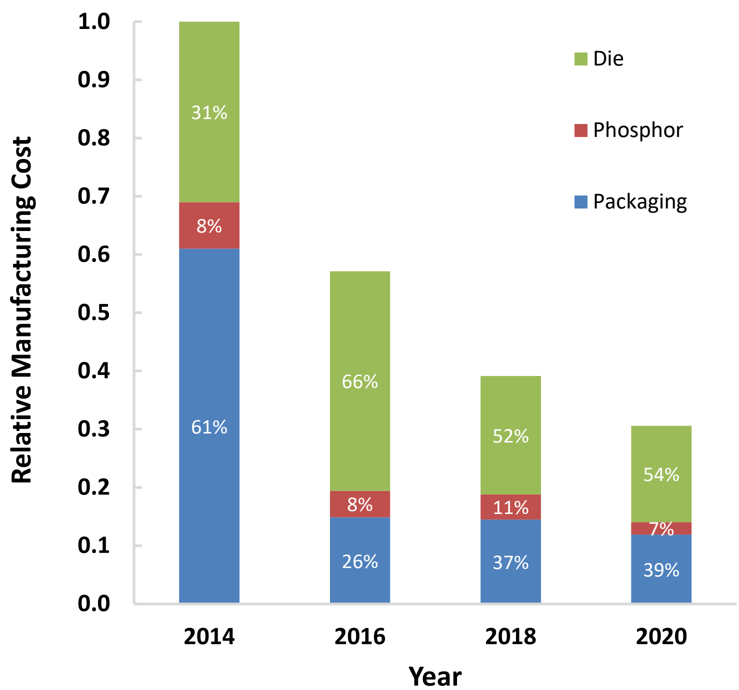


Figure 2-8 High-power LED cost breakdowns over time show the packaging contribution decreased the most early on and then further cost reductions were attributed to decreasing the cost of the chip.

Source: Inputs from DOE SSL Roundtable and Workshop attendees

Mid-power packages have reached prices that are close to the raw materials cost due to oversupply and intense competition, including from subsidized entities, in this market segment since 2014. The die cost and package cost are much lower for the mid-power package and the relative phosphor contribution is similar to that in high-power packages. The small LED die costs have decreased to such low levels that now many of the mid-power packages for lighting contain two die instead of only one die. The LED die cost is a key driving factor in the pricing of mid-power LED packages since the margins in packaging cost elements are minimal. While the die and phosphor costs are decreasing in these platforms, they still retain a very important role in the LED package performance.

A third prominent class of LED light sources is COB LEDs, which are used in products requiring high lumen output from small optical sources or extremely high-lumen density. COB LEDs typically use a large array of small die mounted onto a metal-core printed circuit board (MC-PCB) or a ceramic substrate. The LEDs are then covered with a phosphor mixed silicone. COB arrays provide high lumen output (up to 14,000 lumen) from a small optical source area and are often used in downlights, directional lighting, and high/low-bay lighting. The ease of COBs in luminaire manufacturing appeals to some smaller luminaire manufacturers who do not have the surface mounting equipment to assemble discrete packages onto MC-PCBs.

The cost breakdown for a COB LED is shown in Figure 2-9. The COB LED breakdown assumes a 20 W class product with a light-emitting surface (LES) size of 12-14 mm on an MC-PCB. One major difference for the COB LEDs compared to the high-power and mid-power LEDs discussed above is the number of die and subsequent assembly costs required to place anywhere from 15 to 100 or more LED die on the array substrate. For this reason, assembly cost and substrate costs have been broken out as separate cost elements instead of including them together as the packaging cost element (as was done for high-power and mid-power LEDs). As can be seen from Figure 2-9, the assembly cost is the most significant element for the COB LED, with LED die cost as the second highest element. As the LES size of the COB LED is increased, the LED die content proportion will increase relative to the COB substrate area.

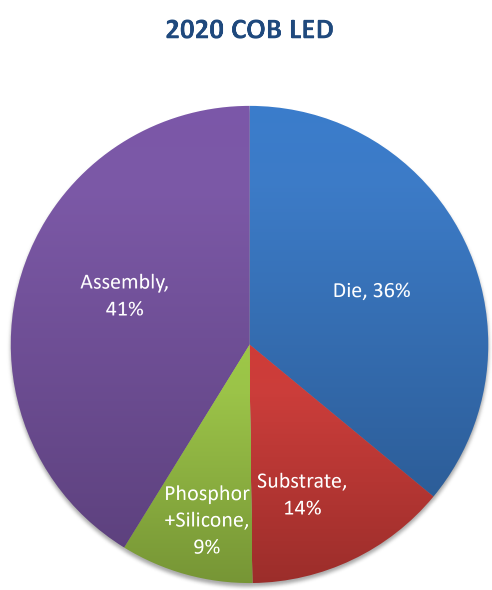


Figure 2-9 Typical cost breakdowns for COB LED packages. The assembly cost is a significant contribution of the COB cost due to the large number of chips that need to be attached compared to high-power and mid-power LED packages.

Note: The COB LED breakdown assumes a 20-Watt class product with a light-emitting surface (LES) size of 12-14 mm on a PCB substrate.

Source: DOE SSL Roundtable and Workshop attendees and industrial partners

While costs for LED packages have dropped by substantial amounts this past decade, there is still room for innovation in the area of LED packaging. Different approaches to cost reduction include technology improvements, new design concepts, and manufacturing innovations. Some key areas include:

- Optimized packages (e.g., simplified designs, lower cost materials, and multi-chips);
- Improved upstream process control[3] (yields);

[3] Wafer-level costs such as substrates, epitaxial growth, and wafer processing comprise a smaller percentage of the final device cost, but improvements here can have a significant impact on packaging costs and device performance (see Section 3.1 and 3.2).

- Improved equipment throughput (processing, testing, and inspection);
- Increased automation; and
- Chip-scale and wafer-scale packaging.

2.2.6 LED Luminaire/Lamp Cost Breakdown

The typical cost breakdown for a lamp or luminaire will vary depending on the lighting application and performance metrics of the luminaire. Figure 2-10 shows a comparison of the cost breakdown for an LED troffer, indoor residential downlight, outdoor area lamp, and A19 replacement lamp. This comparison reveals that relative costs for different form factors can vary considerably. A noticeable trend over the past 6-7 years is how fast relative LED package cost is dropping in both luminaires and lamps; it has fallen dramatically from approximately 33% of the cost of a 6” downlight in 2014 to 3% in 2020, as shown in Figure 2-11. Early in the development of LED lamps and luminaires, the cost of the LED packages dominated the total product cost, but this is no longer the case due to the lower prices and wide availability of lighting class LED packages with application specific designs. The cost of LED packages has continued to drop, even to commodity levels for some form factors, so future cost reduction must be achieved by focusing more on optimization of the complete system rather than focusing on any specific cost element. For most luminaire products, the dominant subsystem cost has become thermal, mechanical, and electrical components, which represents the housing, heat dissipating elements, electrical connectors, and mechanical fasteners. Overhead and assembly costs also represent a real cost element and should be included in the cost charts along with the bill of materials. The overhead included in the cost charts refers to manufacturing engineering, product development, documentation, in-line and compliance testing, shipping, and distribution. The retail price will include an additional channel margin of approximately 20% to 30%.

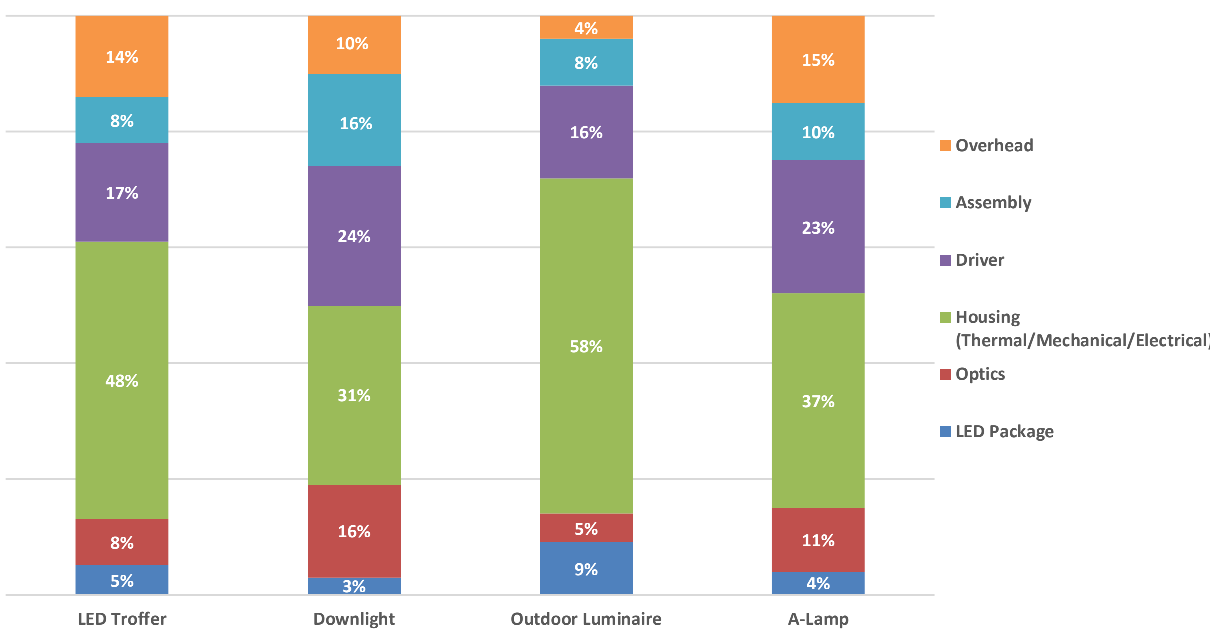


Figure 2-10 Comparison of cost breakdown for different lighting applications in 2019. The categories of LED lighting products include a troffer, a downlight, an outdoor area light, and an A-lamp. Each product has a different balance of cost in the major elements, though housing is the biggest contributor in each product type.

Note: This represents a typical manufacturing cost breakdown; though different luminaire manufacturers have varying cost breakdowns depending on their business models.

Source: DOE SSL Roundtable and Workshop attendees and industrial partners

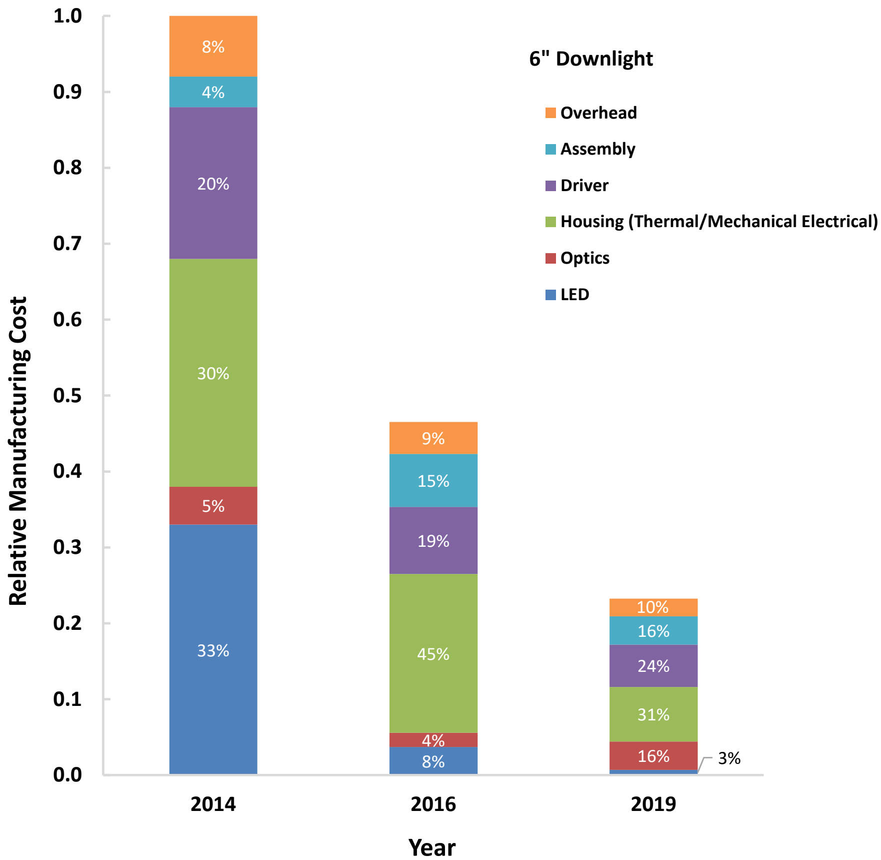


Figure 2-11 Comparison of cost breakdown for a 6" downlight from 2014 to 2019. The relative cost of the LEDs has dropped dramatically while other elements such as the driver retained similar relative cost breakdown even as cost has gone down.

Note: This represents a typical manufacturing cost breakdown; though different luminaire manufacturers have varying cost breakdowns depending on their business models.

Source: DOE SSL Roundtable and Workshop attendees and industrial partners

While a straight cost down process (i.e. reducing the cost of individual components to reduce system cost) is one approach to reducing luminaire cost, system redesigns are a more common way to make greater jumps in cost reduction by changing the amount and type of components in a system. This design for manufacturing (DFM) approach also affects the relative sub-system cost over time as different design approaches to achieving good optical, electrical, and thermal performance will affect the component costs, and therefore their ratios. Manufacturers continue to seek manufacturing approaches that can enable cost reduction without degrading system performance in terms of efficacy, lifetime, color quality, and other performance metrics. The key cost drivers for each major element of the LED supply chain are summarized in Table 2-6.

Table 2-6 The LED Supply Chain: Key Cost Drivers

Supply Chain		Cost Drivers		
Equipment Suppliers	Epitaxial growth	• Uniformity • Throughput	• Reagent usage efficiency	• In situ monitoring/ Process control
	Wafer processing	• Throughput	• Automation	• Yield
	LED packaging	• Throughput	• Flexibility (packaging materials and package types)	
	Luminaire assembly	• Throughput	• Automation	• Chip scale packaging
	Test and inspection	• Throughput	• Accuracy	• Reproducibility
Materials Suppliers	Substrates	• Diameter	• Quality	• Light Extraction
	Chemical reagents	• Quality/Purity	• Bulk delivery systems	• In-line purification
	Packaging	• Standardization	• Ceramics processing	• Plastic formulations
	Down-converters	• Quality/Efficiency • Consistency	• Stability (thermal and optical flux)	• Spectral width
	Encapsulation	• Quality	• Stability (thermal and optical flux)	• Processability
Die Manufacturing		• In-line inspection/ Process Control	• Yield • Testing	• Throughput • Capital costs
Package Manufacturing		• In-line inspection/ Process control • Labor content	• Testing • Down-converter application	• Yield • Throughput
Luminaire Manufacturing		• Automation/Labor content • Configurability	• Testing (performance and compliance)	• Modularization • Throughput

2.3 OLED Manufacturing Supply Chain

OLED lighting uses different materials, devices, and manufacturing processes compared to LED lighting, and thus has a different manufacturing supply chain. Portions of the OLED device, panel, and lighting materials, as well as the manufacturing platform, can also apply to new diffuse light emitter technologies such as quantum dot electroluminescence (QDEL). QDEL sources for lighting are much less mature than OLED technologies, so this section will focus on OLED manufacturing. OLED lighting manufacturing processes can also be generally defined by a sequence of reasonably independent manufacturing steps supported by the supply of manufacturing equipment, materials, and testing equipment. The manufacturing processes and supply chain will be discussed briefly in the remainder of the section and will be detailed in depth in Section 4.

Although most of the companies making OLED displays panels are in Asia, the leading supplier of panels for general lighting is OLEDWorks, which has two production lines, one in Rochester, New York, and the other in Aachen, Germany. The production of OLED lighting products involves four stages, each with its own set of equipment and material supply chains.

1. Formation of an integrated substrate onto which the organic materials will be deposited. Since the light is emitted through the substrate, the base material must be transparent and can be either plastic or glass. If plastic is used, a barrier against moisture and oxygen must be coated, either on the inside or outside of the substrate. Structures to facilitate light extraction are required for reasons that are explained below. Finally, a transparent electrode is deposited to supply current uniformly across the panel.

2. A multi-layer organic materials stack is formed to transport charge carriers between the electrodes and convert the electrical energy into photons. Up to 40 layers may be required to achieve high efficacy and long operational lifetimes. Individual layer thicknesses can be as thin as 5 nanometers (nm), so precise deposition control is vital. The total thickness of these layers is typically between 200 nm and 500 nm.

3. Deposition of the top electrode, encapsulation and then separation into individual lighting panels follows. The top layers are designed to ensure that electrical current and heat are spread evenly across the panels and to protect the organics against the ingress of moisture and oxygen. Patterning is necessary to make sure that current can flow uniformly into each panel and that the edges are sealed against water and oxygen which rapidly degrade the performance of the OLED device.

4. A mechanical structure is added and connections to the external electrical power system provided. Many luminaires will contain more than one panel. The most critical additional element in the luminaire is the power supply.

The manufacturing processes and required materials are shown schematically in Figure 2-12. The blue-shaded boxes and blue arrows describe the main manufacturing flow. The supporting elements of the supply chain are broken down into manufacturing equipment, materials, and test and measurement equipment. These supporting elements feed into the main manufacturing flow as indicated by the relevant arrows.

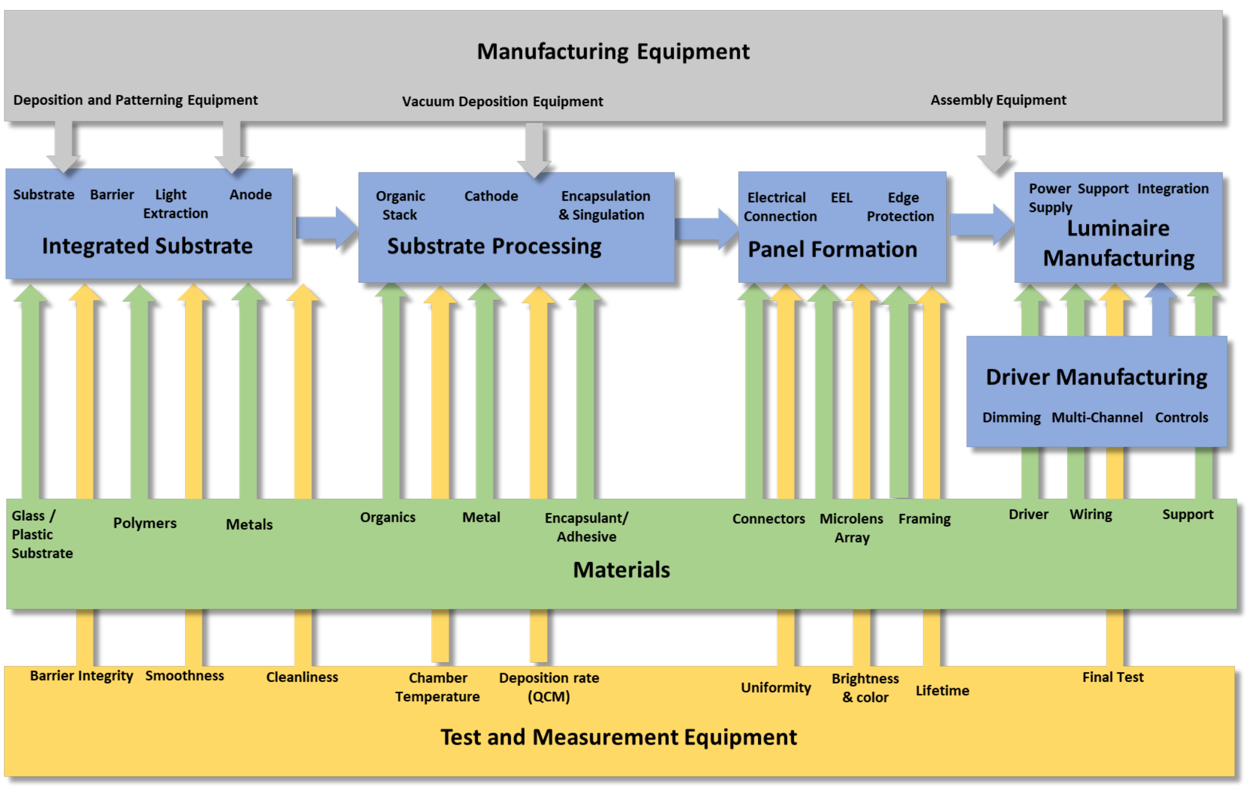


Figure 2-12 OLED-based SSL Manufacturing Supply Chain.

2.3.1 OLED Supply Chain Status

Due to intense cost pressures in general lighting, most manufacturers of OLED lighting panels are now focusing on niche applications. For example, Yeolight is suppling rear lights for automobile manufacturers in China. Konica Minolta in Japan and Inuru in Germany are focusing on signage, labels, and packaging. First O-Lite in China and Konica Minolta offer novelty products, such as toys and greeting cards incorporating OLED lights. Acuity Brands is the only major luminaire manufacturer incorporating OLED panels in general lighting, through its Peerless and Winona brands in the United States and Eureka Lighting in Canada. A selection of other suppliers are listed in Table 2-7.

Table 2-7 Suppliers of OLED Lighting Panels and Luminaires

Supply Chain	North America	Europe	Asia
OLED Panels	· OLEDWorks	· OLEDWorks · Inuru	· First O-Lite · Yeolite · Kaneka · Konica Minolta · Sumitomo Chemical · V-Technology · Lumtec · RITDisplay
Luminaires	· Aamsco · Acuity Brands · Arcio Lighting · Luxerus · Meyda · Nadarra · Visa Lighting	· Emde · Esyst · Peters Design · Tunto	· Jiangsu First-Light · Suzhou Light Matters Tech

Due to the small size of the OLED lighting market, it is essential to leverage suppliers in other industries; however, suppliers of the core organic materials already tailor their products to the needs of individual customers and the modifications required to optimize the materials for lighting applications are not too difficult. The required inorganic materials are also in demand for other applications. In some cases, such as ultra-thin glass (UTG), little modification is needed; for others, such as transparent conductors and moisture barriers, the demands of OLED lighting go well beyond those of other industries. A selection of material suppliers is shown in Table 2-8.

Table 2-8 Suppliers of Materials for OLED Lighting Panels

Supply Chain	North America	Europe	Asia
Substrates	· Ares Materials · Corning · DuPont Teijin	· St. Gobain · Schott	· Asahi · Nippon Electric Glass · NSG Pilkington · SKC Kolon
Barriers & Encapsulation	· 3M	· BASF · Ergis · SAES · TESA	· Ajinomoto · Dynic
Extraction Layers	· Corning · Luminit · Pixelligent	· Covestro · Rolic	
Conductors	· C3Nano · OTI Lumionics	· BASF · Heraeus · Sefar · TESA	· Cambrios · Duksan HiMetal · Huakei · Showa Denko
Organics	· Dow Chemical · DuPont · Molecular Glasses · PPG · R Display · UDC	· Avantama · Cynora · Heraeus · Merck · Novaled · Noctiluca	· Daejoo · Doosan · Duksan Hi-Metal · Heesung Material · Hodogaya · Idemitsu Kosan · Jilin Optoelectronic Materials · Kyulux · LG Chem · Lumtec · Material Science · Mitsui Chem · Nissan Chem · Sumitomo Chemical · Summer Sprout · Sun Fine Chem

There are many established vendors of manufacturing equipment for OLED display panels. Most of this equipment is too large, produces too much volume, and is too expensive for lighting applications at the current market scale. Small companies have played an important role in supplying tools for R&D and prototype production of OLED lighting panels. A selection of equipment suppliers for the OLED lighting industry is shown in Table 2-9.

Table 2-9 Suppliers of Manufacturing Equipment for OLED Lighting Panels

Supply Chain	North America	Europe	Asia
Vacuum Deposition	· Applied Materials · Intellivation · Kurt Lesker · Lotus Applied Tech · Sundew Technologies · Trovato	· APEVA · Beneq · Encapsulix · Manz · Von Ardenne	· AP Systems · Canon-Tokki · GJM · Jusung · SFA Engineering · SNU Precision · Sunic · YAS
Solution Depositon	· Kateeva · nTact · NovaCentrix	· Coatema · Meyer Burger · M-Solv · Notion Systems · REHAU	· Screen Holdings · Seiko Epson · ULVAC
Patterning	· Coherent	· 3D-Micromac · 4Jet Technologies	· Keyence
Automation, Test, & Inspection	· Ametek Mocon · Colnatec · Kurt J. Lesker · Radiant Zemax	· Inficon · Laytec · Manz · MBraun · Sempa Systems · Vinci	· Avaco · KPS · SFA Engineering

2.3.2 OLED Cost Breakdown

A big challenge for OLED lighting is reducing cost and enabling the production of lightweight, ultra-thin conformable panels that will lead to energy saving luminaires with distinctive lighting performance. Although the high sales volume of OLED displays has led to substantial cost reduction for OLED production, the cost of displays for OLED televisions is still around \$800 per square meter (\$/m^2), which is much higher than the long-term goal for OLED lighting. To enable high-volume sales in competition with LED luminaires, the manufacturing cost of OLED lighting panels needs to be reduced to about \$200/m^2. This corresponds to \$10/klm at a brightness of 7000 candelas per square meter (cd/m^2), allowing luminaires to be sold in the range of \$20/klm to \$50/klm. Current costs are much higher, due to the low manufacturing volume and limitations of tradition fabrication techniques. Paths to meeting the target cost with traditional fabrication techniques are shown below in Table 2-10. It is assumed that sheet-to-sheet processing will be used in a new generation of equipment in 2025, but that roll-to-roll fabrication will be used in 2035. Two manufacturing approaches are presented for 2030 (2030SS and 2030RR).

Table 2-10 Current status and cost targets for OLED panels

	2020	2025	2030SS	2030RR	2035RR
Substrate Area (m^2)	0.2	1.2	2.7	5*	15*
Capital Cost ($M)	50	125	150	150	200
Cycle Time (minutes)	3	2	1	0.2**	0.1**
Input Panel Area (1000 m^2/yr)	22.5	200	900	1,200	2,900
Depreciation ($/$m^2$)	450	125	33	25	14
Organic Materials ($/$m^2$)	150	75	40	40	30
Inorganic Materials ($/$m^2$)	450	200	80	80	60
Labor ($/$m^2$)	80	15	3	2	2
Other Costs ($/$m^2$)	50	15	10	10	10
Total (unyielded) ($/$m^2$)	1,180	430	166	157	116
Yield of Good Product (%)	70	80	85	80	90
Total Cost ($/$m^2$)	1,680	540	195	195	130

* Area processed per minute
** Time for web to travel 1m

The cost breakdown for an OLED panel is presented as cost per square meter of product, since the costs scale more closely with panel area, rather than with the light output. Because of the low level of OLED lighting production, estimation of future costs of materials and equipment is difficult. Meeting cost targets will depend on the willingness of vendors to attend to the special needs of OLED lighting and development of new production technologies. Increasing the utilization efficiency will be critical to meeting cost targets. For example, the fraction of the substrate area that is used to produce light in the manufactured panels is currently around 60%. Market demand may limit the time of use for particular manufacturing equipment and lines, which will negatively affect the factory utilization.

3 LED Package and Luminaire Manufacturing Process, Equipment & Materials

LED lighting manufacturing comprises several main process flows beginning with LED die manufacturing, followed by LED package manufacturing, and finally luminaire manufacturing. The LED luminaire manufacturing supply chain was shown schematically in Figure 2-4 in Section 2. Various inputs impact the manufacturing processes, ranging from LED manufacturing equipment to specialty materials to test and measurement equipment. Each element of the supply chain is described in more detail in the following sections, along with an indication of the major participants and their geographical distribution.

The manufacturing process begins with LED die manufacturing, consisting of epitaxial growth of the LED wafer via MOCVD equipment, device fabrication on the LED wafer by mostly conventional semiconductor processes, and separation of the LED wafer into individual LED die (chips). The next step is typically to mount the LED die into a package, including the deposition of phosphor material to convert the blue LED emission to white light. Finally, the LED packages are mounted onto a PCB to create the light engine and are combined with a driver, heat sink, optical components, and mechanical elements to form the end luminaire or lamp product. The manufacturing process is constantly evolving as individual elements are refined or removed, new elements are developed, or new process sequences are introduced. Ultimately the optimum process flow for a particular product will depend on a detailed system-level optimization.

The production of LED packages and luminaires involves the use of a wide range of specialized manufacturing equipment. The critical equipment requirements for each major manufacturing step are discussed in the following sections, along with some consideration of the worldwide equipment manufacturing base. The manufacturing equipment landscape is continually evolving to satisfy the ever-changing demands of the LED and luminaire manufacturers. Many manufacturers place a premium on low acquisition cost and have, in the past, tended to modify their own equipment. In recent years, the communication between equipment manufacturers and end users has improved. The market better understands the requirements of the LED manufacturing industry and has begun to offer a more complete range of manufacturing equipment specifically designed to meet those needs. Equipment is most often characterized by the cost of ownership (COO), which is the total cost of producing a good part from a piece of equipment, and can be used to drive manufacturing equipment evolution to reduce the cost of production. To achieve a low COO, the equipment must offer excellent repeatability and reproducibility leading to high process yields, low acquisition and operating costs, high throughput, high utilization, and a small factory footprint.

While there are many different designs of LED lighting systems and components that they consist of, this section will focus on the most common technology approaches used in the LED lighting industry.

3.1 LED Wafer Manufacturing

LED wafer manufacturing process comprises epitaxial growth of the LED device layers on a substrate using precursor molecules to create an atomic stack that comprise the III-V semiconductor device. This section will focus on the wafer manufacturing processes for blue indium gallium nitride (InGaN) LEDs since they comprise the core of the vast majority of LED lighting systems. Red LEDs are made from a different semiconductor material system, aluminum gallium indium phosphide (AlGaInP), with similar but distinctly different epitaxial process details. Since the used of red and amber AlGaInP LEDs in energy-saving general illumination application is limited today, the focus of the manufacturing discussion will be on the blue LED processes that are used for effectively all white LED production. Future R&D work on improving the efficiency of red, amber and green LED can lead to color-mixed LED illumination systems using four independent color channels – red, green, blue, amber (RGBA) – that can be more efficient than today's established white LED architecture using a blue LED and yellow phosphor.

3.1.1 Epitaxial Growth

Epitaxial growth is of fundamental importance in the LED manufacturing process and is currently accomplished using MOCVD equipment. The MOCVD systems or reactors are used to grow epitaxial thin film semiconductor layers upon a substrate using chemical precursors that ultimately comprise the LED device structure. MOCVD is the only technology available today that is capable of growing the entire LED device structure in a cost-effective manner, including (for blue LEDs) the complex low-temperature nucleation layer upon the substrate, the thick gallium nitride (GaN) buffer, the n-GaN electron injection layers, the multi-quantum well (MQW) active region, and p-GaN hole injection layers. Alternative growth methods such as molecular beam epitaxy (MBE) and hydride vapor phase epitaxy (HVPE) offer advantages over MOCVD in some limited areas of application, but have not proven out their advantages to gain traction in mass production of LED wafers. HVPE equipment can deposit thick GaN layers at high growth rate and low cost, and is mostly used to produce GaN templates to serve as substrates in some more specialized device applications. In the long term, new growth techniques that can move beyond the limitations of current growth equipment would be valuable. The ability to move past vacuum-based batch process growth techniques is highly desirable, though an significant investment in foundational semiconductor growth R&D is required to realize such a manufacturing technique.

Improving MOCVD growth equipment and processes is critical to improving the performance and yields of LED wafers. R&D into MOCVD systems was supported by the DOE SSL Program and led to platform improvements in the Veeco MaxBright MOCVD system in 2011. The equipment vendors have continued to advance MOCVD science steadily over the years with efforts to increase throughput, uniformity, and improve LED performance. Figure 3-1 illustrates the evolution of the Veeco MOCVD system design for GaN LED growth. Compared to previous generations, the current state of the art EPIK 868 MOCVD system claims cost per wafer savings of more than 20% compared to previous generations with a combined advantage of best operating uptime, low maintenance costs, and best-in-class wafer uniformity, as shown in Figure 3-2. [8] In addition, the system offers a four-reactor platform for the highest productivity in an efficient manufacturing footprint.

Figure 3-1 Evolution of MOCVD technology for GaN LED growth. [9]

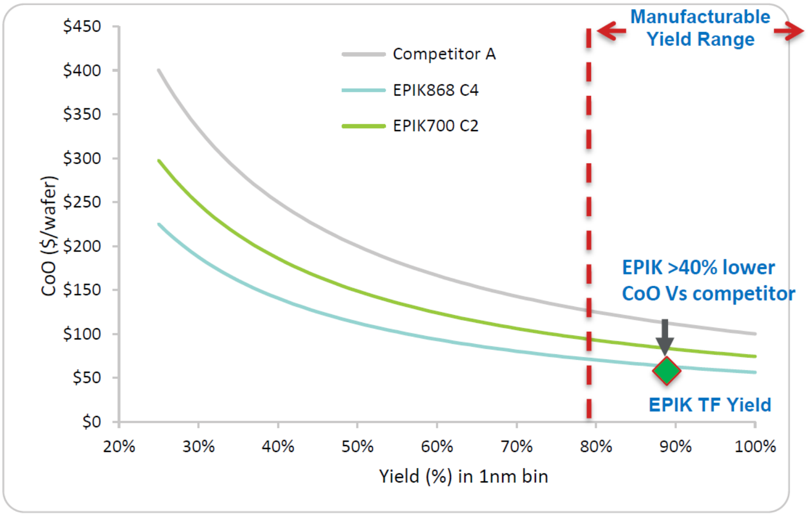


Figure 3-2 Cost of ownership of blue LED wafers as a function of 1 nm bin yield for the Veeco EPIK 700 and 868 MOCVD systems. The EPIK 868 system enables cost per wafer savings of more than 20% compared to previous generations. [10]

There are many factors that govern the performance, throughput, and costs of the LED epitaxial growth process. The complexity of the MOCVD process and equipment design is illustrated in Figure 3-3. Yields depend on process control including uniform gas flow and temperature in the reactor to achieve tight alloy and growth rate distributions, both inter-wafer and intra-wafer. Sophisticated in-situ monitoring (to measure wafer temperature and growth rates) and accurate process modeling can be leveraged to better meet the demanding reproducibility and uniformity requirements. Throughput is dependent on the reactor wafer capacity, equipment maintenance needs (uptime), loading/unloading speeds, and process speeds (growth rates, temperature ramping and stabilization). The equipment operating and depreciation costs involve the source utilization efficiency, factory footprint, energy consumption and labor rate. The main issues driving MOCVD epitaxial growth development can be summarized as in the diagram below.

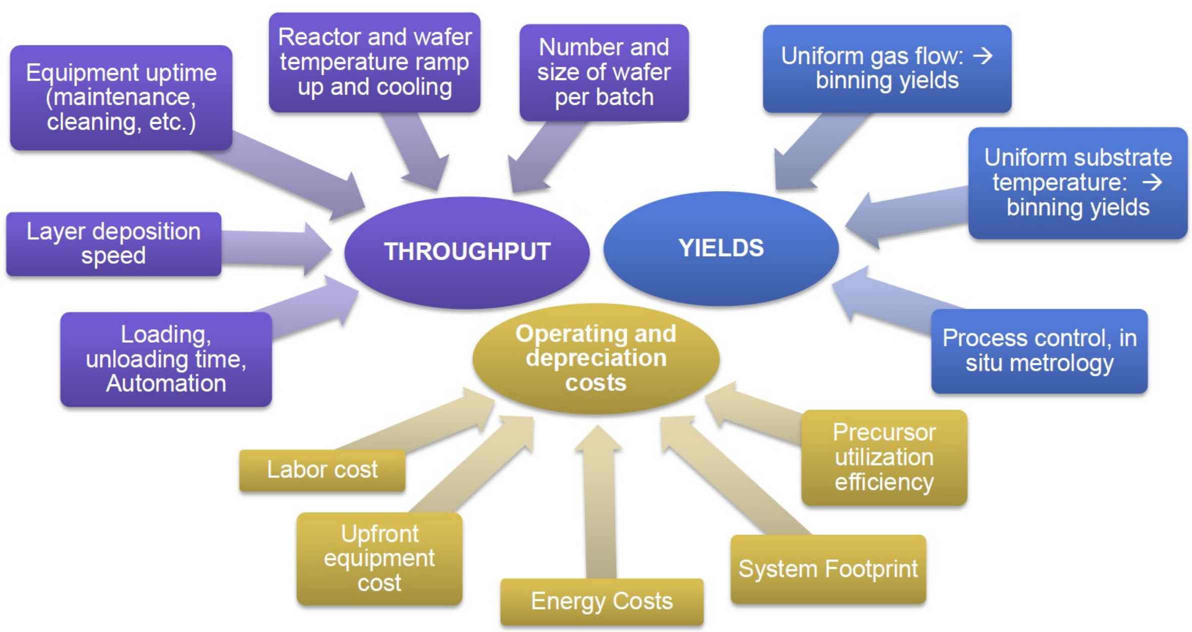


Figure 3-3 Schematic illustration of factors that impact key MOCVD process and cost including yield, throughput and equipment costs. [11]

Wavelength uniformity and reproducibility: Achieving tighter control over the wavelength uniformity and reproducibility of the LED light emission is critical to improve the white color point consistency in the final product, optimize product yields, eliminate the need for binning, and reduce product costs. Similarly, the equipment must enable continuous improvement in material quality and internal quantum efficiency (IQE) in order to achieve the target efficacy improvements. The challenge to controlling wavelength uniformity is the strong temperature dependency of the indium incorporation into the quantum well (InGaN composition largely determines wavelength of the LED). The temperature uniformity at the growth surface of the wafer must be carefully controlled across all the wafers in a large scale reactor. Bowing of the wafer/substrate that occurs from thermal stresses during growth creates non-uniform contact between the wafer and the wafer carrier resulting in non-uniform heating. In-situ monitoring to measure temperature and wafer bow is essential to help maintain wavelength uniformity across the wafers in a reactor run and from run to run. Active temperature control via pyrometry to measure temperatures at the wafer surface offers a more direct route to active control. Other in-situ tools, such as for detecting wafer bow, are routinely incorporated into most production reactors for monitoring the manufacturing process. Temperature uniformity can be improved by using contoured wafer carriers, where the shape of the pockets holding the wafers match the wafer bow at this critical stage of active region growth and provides uniform heating of the wafer. Additionally, having uniform gas injection profiles across the reactor is important to maintain uniform temperatures, alloy compositions, and growth rates. Today's wafer uniformity status is shown in Figure 3-4 for the growth of blue LED wafers in a Veeco Epik 868 tool. The entire run of ten 150 mm wafers had average wafer wavelength within in a 2.5 nm bin.

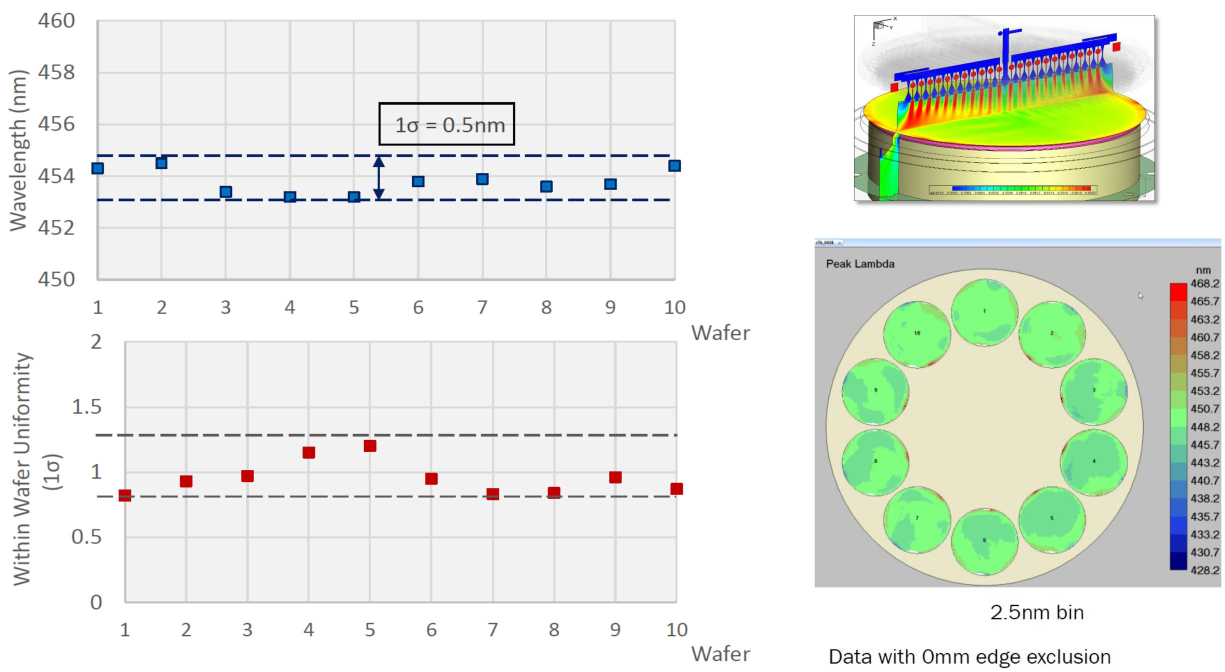


Figure 3-4 Wafer to wafer wavelength uniformity a MOCVD run for blue LEDs using a Veeco EPIK 868 reactor. Ten 150 mm wafers were inserted as shown in the bottom right image. The entire run of wafers had average wafer wavelength fall in a 2.5 nm bin (upper and lower left). The wavelength distribution across each wafer is shown in the bottom right image. The gas/precursor injection flange (upper right) is designed for laminar flow to create uniform deposition profiles across the wafer carrier. [10]

Cost of Ownership: A reduced COO might be achieved in a number of different ways, such as increased throughput (reduced cycle times and/or increased capacity), lower capital costs, improved materials usage efficiency, smaller tool footprint, or increased yields. A multiple chamber cluster tool with automated wafer transfer provides a compact system architecture (high footprint efficiency) and reductions in COO by not duplicating every MOCVD subsystem to gain increased capacity. The automated transfer process between multiple chambers also reduces the labor rate. Overall equipment efficiency improvements will also lower operating costs through improved preventive maintenance schedules and minimization of non-productive operations such as chamber cleaning to maximize process uptime.

Throughput of the MOCVD system is dependent on the reactor wafer capacity, loading/unloading speeds, and process speeds (growth rates, temperature ramping and stabilization). The reactor growth time and cycle times are critical to driving throughput. Large-capacity MOCVD cluster tools capable of producing high-quality material are commercially available with capacities up to 140 x 100 mm or 56 x 150 mm wafers (34 x 100 mm or 14 x 150 mm wafer capacity per growth chamber). The development of a four-chamber MOCVD cluster tool system by Veeco (supported in part by DOE R&D funding) offered a 300% improvement in combined throughput and capital efficiency over four single-reactor systems. [12] [13] Additionally, equipment design modifications and process improvements such as improving the precursor injection uniformity into the chamber to increase the area of stable operation and reducing the areas of recirculation and buoyancy phenomena has allowed increases in the GaN growth rate to reach 15-20 micrometers per hour (μm/hr), which essentially reduces growth times significantly for the thicker GaN layers. Heater technology is critical as well since it impacts more than just wavelength uniformity; it controls temperature ramp rates and temperature stabilization times, both of which impact the process times and resulting throughput. Additionally, improving heater lifetimes increases the reactor uptime due to less frequent maintenance events.

Process control improvements will increase yield, and equipment design changes can increase the efficiency of reagent usage – all leading to improved COO. High-purity metalorganic alkyl sources and hydride gases are expensive. One of the major costs for the epitaxially grown wafer is associated with trimethylgallium (TMG), since a large amount of the material is used to produce an LED epitaxial structure. Improved injection flange designs allow for lower alkyl precursor flows and overall carrier gas flows leading to reductions of source usage by approximately 40%. Further improvements in gas injection designs to maximize the reactant incorporation through laminar flow profiles into the thin films is required at the equipment design level to provide better the source utilization and reduce manufacturing costs.

3.1.2 MOVCD Equipment Manufacturers

The MOCVD equipment market is dominated by a few companies: Veeco Instruments in North America, Aixtron in Europe, and AMEC in China. These three companies provide around 90% of the MOCVD equipment used for the manufacturing of GaN-based LEDs. The only other significant MOCVD equipment manufacturer is Taiyo Nippon Sanso in Japan, who operates almost exclusively within their home market. While Veeco and Aixtron shared the dominant portion of the market for years, the onset of AMEC's market share growth occurred in 2016. The sales increase of AMEC tools was partly driven by the strong market demand in China and partly by the fact that 2017 was the year in which Chinese LED companies judged that AMEC tools had reached an acceptable level of performance. [14] Figure 3-5 shows the estimated market share of MOCVD sales into the GaN LED market as of 2017. The domestic manufacturing presence combined with the low pricing put the existing vendors Veeco and Aixtron under pressure to compete in China for an increasingly commoditized LED market. Aixtron choose to pivot from the GaN LED MOCVD market and put more emphasis on power semiconductors and AlGaInP LEDs (infrared/red/orange/yellow wavelengths) – markets with less pricing pressure. In late 2018, Veeco also shifted away from the commodity GaN LED market, moving to new market opportunities with vertical cavity surface emitting lasers (VCSELs), power electronics and micro-LEDs. Although Veeco and Aixtron have not completely exited the GaN LED MOCVD market, since they continue to supply existing customers, GaN LEDs are no longer a growth driver for either company. AMEC is estimated to have 50% of new MOCVD orders for GaN LEDs in 2020.

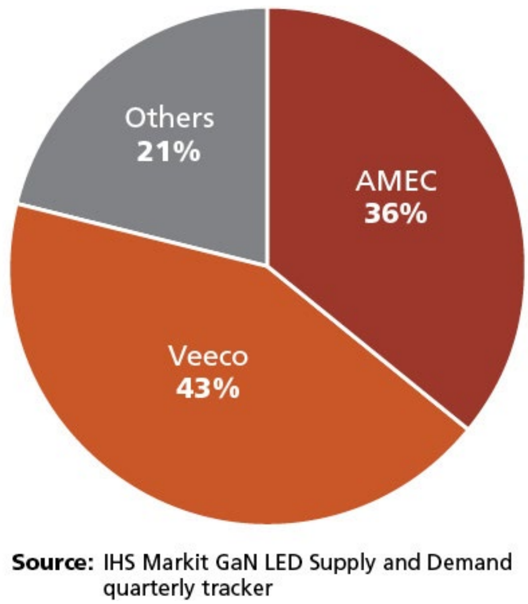


Figure 3-5 MOCVD market share for the GaN LED market in 2017. Veeco had the dominant market share in the GaN LED market since 2010 but AMEC's emergence in 2016 has reduced Veeco's dominance in the GaN LED market. [14]

Note: Although not yet recognized in the counting method (used in this image which is based on revenue recognition which can take 6 months or more after shipment), AMEC units ultimately surpassed former MOCVD market leader Veeco during 2017.

Less than a decade after the large scale MOCVD equipment subsidies in China led to huge excess capacity in 2010-2011 (as mentioned in Section 2.2.3), IHS Markit, Trendforce, and Yole Developpment noted that Chinese LED manufacturers have again taken advantage of another round of subsidies over the past few years, which has led to excessive LED capacity build-up. [15] [16] [17] IHS Markit projected that there was a GaN LED capacity surplus of 7.4% in 2017, which would grow to 15.8% in 2018, and 28.3% in 2019 (with an average capacity utilization of 78% in 2019). [15] The estimated capacity added in 2018 was similar to the peak year of 2010 (754 reactor chambers shipped) in terms of total LED production capacity. Based on analysis from market research firms, it is evident that there is a significant overcapacity in MOCVD for GaN LED production, i.e. low manufacturing capacity utilization. MOCVD investment is particularly challenging to forecast, even over horizons of the next few years, with large year to year changes possible. [18] The overcapacity has led MOCVD tool manufacturers to focus on growing markets such as micro-LEDs, power electronics and VCSELs to drive tool sales.

Many LED manufacturers from other countries have realized they cannot compete with the price pressures from subsidized Chinese manufacturers and their resulting low costs. Therefore, a number of LED manufacturers have shifted focus to other LED categories for further revenue growth and profitability, including automotive lighting, red LEDs for horticultural lighting, micro-LEDs for displays, and ultraviolet (UV) LEDs for germicidal UV applications. Another dynamic is that most LED companies (outside of China) have not expanded their capacity significantly in recent years. For example, some companies have not invested in MOCVD at all, and such capital-light strategies could result in capacity decreases over time as older machines go offline. Some of these LED manufacturers with reduced capital spending have instead shifted to buying commodity die from China to incorporate into packaged LED or light engines. In some cases, they outsource their entire production of packaged LEDs to China. [15]

3.1.3 Substrate Materials

A decade ago, there was debate about what is the best growth substrate material for LED manufacturing. While sapphire substrates were the most broadly used substrate type since the development of GaN LEDs in the

1990s, a handful of substrate options were still being explored for the manufacture of high-power GaN-based LEDs. A range of substrate materials have been developed, including sapphire, silicon carbide (SiC), silicon (Si), and bulk GaN. Today, sapphire is the dominant solution for volume LED manufacturing as the other substrate candidates have failed to gain market share in LED production for different reasons as described below.

SiC substrates have been used to produce GaN-based LEDs with state-of-the-art performance, primarily by Cree, a vertically integrated LED manufacturer that fabricated its own SiC substrates. Over the past 5 years, the SiC wafer supply has become dominated by the growing power electronics market, which requires low defect insulating SiC substrates. The value of SiC to the power electronics manufacturers, coupled with the dominance of sapphire and the dropping costs of LEDs, led Cree to phase out their reliance on SiC substrates for LED products. At this time, SiC is generally not used as a LED substrate.

GaN substrates for homoepitaxial growth also gained interest to help reduce defects and improve performance of LEDs. Soraa was a company that commercialized the growth of LEDs on GaN substrates for their lighting products. The advantages they listed for GaN-on-GaN growth were reductions in threading dislocations (defects which cause non-radiative recombination). The lower defect density, in turn, allows operation at a far higher current density (allowing more light out of the same die area) without as big of an efficiency droop penalty as LEDs grown on sapphire. Additionally, a GaN substrate improved the light extraction from a volume-emitting LED chip. The major issue impacting adoption of GaN substrates for LEDs was the extremely high substrate cost, inconsistent quality, limited supply, and the unavailability of larger diameters. Soraa is no longer employing the GaN substrates in their lighting products because the performance benefit provided by homoepitaxy did not justify the higher cost for the growing commoditization of LED chips. GaN substrates do remain a critical technology for other optoelectronic devices such as GaN laser diodes, but are not a key enabler for LED lighting. The GaN substrate market is heavily concentrated. More than 85% share is held by three Japanese firms: Sumitomo Electric Industries (SEI), Mitsubishi Chemical Corp (MCC), and Sciocs. [19] The commercial GaN substrates are generally produced by hydride vapor-phase epitaxy (HVPE) technology, but details of the growth process and separation techniques vary by company.

Silicon substrates for LEDs have been investigated for many years to leverage the many available or underutilized 200 mm silicon wafer fabrication facilities, but the mass production of LEDs on silicon to date has been limited due to technical challenges such as high lattice mismatch and high thermal expansion coefficient (TEC) mismatch with GaN. Additionally, the absorbing nature of the substrate led to optical losses or more complicated fabrication processes to remove the substrate or "hide" the absorbing substrate from interacting with the light emitted from the active region of the LED chip. While the technical challenges were a barrier for implementing silicon substrates, manufacturers such as LatticePower commenced volume production of GaN-on-Si die in June 2012 and Toshiba launched its first GaN-on-Si LED products in 2013, though their product availability was limited to only a few years. [21] OSRAM Opto Semiconductors began fabricating GaN-on-Si LEDs and continues to do so today for their high-power UX3 LED devices. [20] Silicon continues to be used for processes requiring larger wafer scaling and has gained traction in the developing micro-LED industry to allow for wafer size scaling to 200 and 300 mm.

Patterned Sapphire Substrates (PSS) have become widely used by LED chip manufacturers to improve the efficiency performance in LED chips compared to growth on planar sapphire substrates. Nano-scale patterning of the substrate surface improves light extraction out of the chip through increased scattering from the patterned features, thus reducing total internal reflection (TIR). This effect is illustrated in Figure 3-6 comparing an LED grown on a planar sapphire substrate to an LED on PSS. The sapphire wafers are patterned with small periodic features – typically conical, pyramidal or dome shaped – with a pitch spacing of 1 to 5 microns (μm). Photolithography equipment and plasma etchers are required to create the patterned features on the substrate, which are then used for the MOCVD growth of the LED heterostructure. Because of the variability of MOCVD growth processes in the LED industry, there is not one predefined feature size or shape, but instead varies depending on the specifications of the particular LED manufacturer.

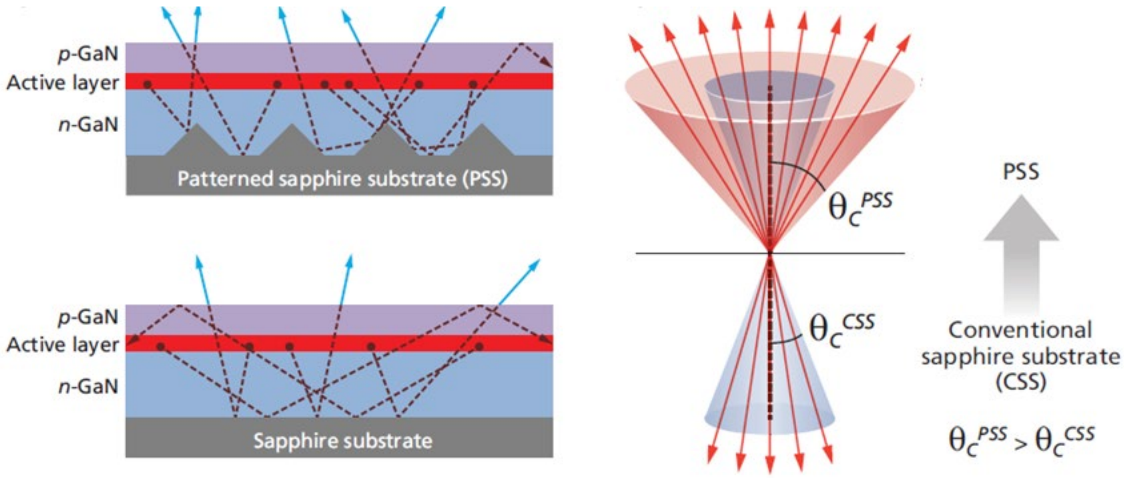


Figure 3-6 The patterned sapphire substrate scatters more photons at the textured surface compared to the planar sapphire substrates (left images), which allows more light to be emitted outside of the escape cone of TIR. [21]

The MOCVD process consists of nucleating the GaN film on the sapphire, and in the case of PSS, laterally growing the film over the pattern so it coalesces into a smooth surface. The benefit of the lateral growth required with the PSS is that it bends many threading dislocations (which causes non-radiative recombination) in the film, thereby stopping dislocations from propagating up through the heterostructure. The lower dislocation density from the epitaxial growth mechanisms induced by the patterned features improves the internal quantum efficiency of the LED structure. When PSS was first introduced, LED chip manufacturers either fabricated the PSS in-house or outsourced it to contract manufacturers because the critical nature of the epitaxial growth process required very careful processing to allow for the growth of a high-quality LED structure on the PSS. As the substrate patterning process has become more developed, the sapphire wafer manufacturers have begun patterning sapphire wafers in partnership with the LED chip manufacturers to ensure proper surface control for the subsequent MOCVD growth. [21]

Although the average size of PSS has increased over time, this trend has stagnated over the past 5-6 years. Previously, wafer size scale-up was a major focus for Tier 1 LED manufacturers, progressing from 2” and 3” (approximately 75 mm) substrates during the 2000s to 100 mm and 150 mm in this past decade. Philips Lumileds began manufacturing LEDs on 150 mm sapphire wafers at the end of 2010 and Osram Opto started moving its standard production of GaN-based LEDs to 150 mm diameter sapphire substrates early in 2012. [22] [23] Similarly, Cree established a 150-mm SiC manufacturing line at its facility in North Carolina in 2011. [24] Early in the scale-up effort, there was a cost premium at larger wafer sizes and developing a robust 150 mm sapphire substrate supply was a major challenge for many manufacturers. As the yields for substrate manufacturing improved this challenge has gradually diminished, though it remained a competitive advantage in certain contexts (e.g. for Cree, given its control over the internal development timeline of SiC substrates scale-up.)

As larger wafer sizes allow manufacturers to benefit from economies of scale (lower cost savings per device on larger wafers), the increase in availability of large-diameter sapphire substrates was a major development. This abundance was partly driven by Apple and other smartphone manufacturers, who developed sapphire covers for camera lenses and home buttons in 2012-2014. Demand for these applications prompted much R&D into wafer size scale-up and led to capacity expansion in the sapphire market creating the availability of 150 mm and 200 mm substrates and beyond. While many of the Tier 1 manufacturers transitioned their epitaxy and wafer fabrication lines to larger wafer sizes, much of the market in Asia still remains on 100 mm wafers today. The past few generations of MOCVD systems can interchange between 100 mm and 150 mm wafers carriers, allowing the LED manufacturer to scale up the substrate size when they are ready. The slack in LED production due to current excess MOCVD capacity and reactor design upgrades necessary for uniform processing of 200 mm LED wafers are the main barriers from moving beyond today's 100/150 mm operations. Additionally, the lack of scale-up of the existing 100 mm capacity is often due to the very low margins on LED chips and the cost of new wafer fabrication facilities (required for making the LED die). As observed in other capital-intensive industries, LED manufacturers are reluctant to allocate toward capital equipment upgrades in a market characterized by oversupply issues and eroding average sales prices, previously discussed in Section 2.2.2.

Early on, global sapphire manufacturing capacity was primarily located in North America, Russia, and Japan. These regions still continue to provide the high-quality material and led the transition to large substrate diameters. As the LED industry continued to grow, the rise of sapphire manufacturers in Taiwan and China increased rapidly. The demand driven by smartphone applications drove much of the sapphire market growth. Once Apple moved away from sapphire in its next generation phones, the sapphire industry witnessed a significant reduction in demand, leading to an oversupply situation. Further, the slowdown in global LED demand in 2015 further hurt upstream sapphire ingot and substrate suppliers, thus causing some sapphire suppliers to leave the industry in 2015 and led to a restructuring of the industry in 2016. Competitive sapphire manufacturers benefited by absorbing market share from shuttered competitors and grew their sales during this time. The challenging market conditions also led sapphire ingot manufacturers to focus on more profitable larger sizes, such as 100 mm and beyond, leaving behind the commodity 2" sapphire substrate products. In 2017, as the overall demand for LED sapphire substrates steadily grew, the sapphire market recovered to a healthy state. Some of the main substrate manufacturers of sapphire substrates and PSS include:

- Rubicon in North America, Monocrystal in Europe, Kyocera and Namiki in Japan
- Crystalwise Technology, Crystal Applied Technology, ProCrystal, Ridgetech, and TeraXtal in Taiwan
- Fujian Jingan Optoelectronic (Sanan), Crystal Optech, Crystaland (HC Semitek), Cryscore, and Tiantong in China

3.1.4 Chemical Reagents

The most important chemical reagents in terms of their impact on device performance and manufacturing cost are those used in the epitaxial growth of the semiconductor structure. These include the metalorganic sources such as trimethylgallium (TMG), trimethylindium (TMI), and trimethylaluminum (TMA), and the gaseous source ammonia (NH_3) for GaN LED growth. Carrier gasses of hydrogen (H_2) and nitrogen (N_2) are used to transport these precursor metalorganic molecules into the MOCVD chamber. When the precursors are flowed across the hot substrate, the desired metal atom (Ga, In, Al) is released from the molecule (which decomposes when exposed to heat) and incorporated at the substrate into the growing thin film layer, as illustrated in Figure 3-7. Similarly, the ammonia gas is injected into the reactor and undergoes pyrolysis to provide the nitrogen atom for the growing film. There are variations of the molecular makeup of the precursors, such as triethylgallium (TEG) instead of TMG, to reduce the amount of carbon byproducts that gets incorporated into the growing film. (Carbon leads to defect complexes that create undesired yellow luminescence peaks). Dopant precursors for GaN LEDs typically include of bis-(cyclopentadienyl)-magnesium (Cp_2Mg) for the p-type doping source and silane (SiH_4) gas for the n-type doping source. The process is similar for other compound semiconductor films such as AlGaInP LEDs, but the specific precursor sources may be different.

The purity of these chemical reagents is critical to the LED performance and only the very highest purity and most expensive sources can be used. In addition, it is common to include point-of-use purification to achieve the highest levels of purity for best quality and consistency. If water (H_2O) or oxygen (O_2) molecules are present in these gases, even in trace concentrations above a few parts per billion (ppb), then oxygen atoms can become incorporated into the crystalline structure of the LED and degrade the device performance.

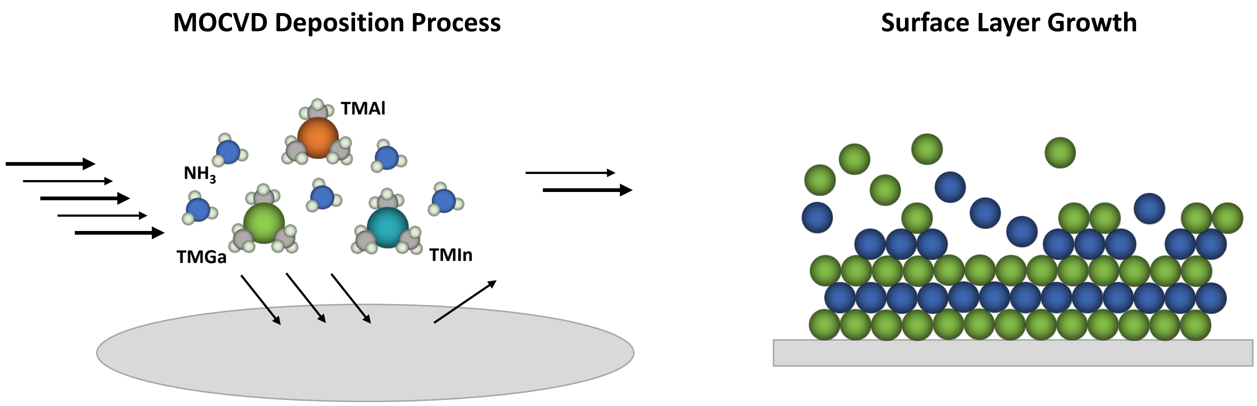


Figure 3-7 The MOCVD process results in metalorganic precursors decomposing under from the heat at the substrate and incorporate with the other atoms in the growing semiconductor thin film.

From a cost perspective, the most critical reagents are TMG and NH_3, because the majority of the LED structure comprises GaN material, and a very high V/III ratio is required for optimum material quality, requiring large flow rates for the NH_3 gas.

The main metal organic reagent suppliers include the following:

- Dow Chemical (Rohm & Haas) and SAFC Hitech in North America
- AkzoNobel, EMD Performance Materials and Lanxess in Europe
- Nouryon and Nata Optoelectronic in Asia

The main hydride gas suppliers include:

- Air Products in North America
- Linde and Air Liquide in Europe
- Showa Denko and Matheson Tri Gas in Japan

Point-of-use gas purifiers are provided by companies including the following:

- SAES Pure Gas and Pall Corporation in North America
- Linde in Europe
- Matheson Tri Gas in Japan

3.2 LED Die Manufacturing

The LED die manufacturing involves processing of the LED epitaxial wafer to define individual devices and singulation of the wafer to produce individual die (chips). The principal manufacturers of LED die for general illumination applications include the following:

- Lumileds and Cree in North America
- Osram Opto in Europe
- Nichia and Toyoda Gosei in Japan

- Epistar, Lextar, and Kingbright in Taiwan
- Seoul Semiconductor, Samsung, LG Innotek, and Lumens in South Korea
- Sanan, HC SemiTek, Aucksun, and Changelight in China

Most LED die suppliers have process lines located in Asia, even those with headquarters and other manufacturing in North America or Europe. For example, U.S. manufacturer Lumileds has located its 150 mm wafer processing facility in Singapore and German manufacturer OSRAM has its 150 mm wafer processing facility in Malaysia.

3.2.1 LED Die Design

After the LED wafer is epitaxially grown, the next stage is the fabrication of individual LED die (chips). The epitaxial wafer is delivered to the wafer processing line, which may be co-located in the same facility or may be in a different geographical location. Wafer processing involves patterning of the semiconductor layers to create the individual devices and expose different surfaces. Metal layers are deposited to form the n- and p-contacts. In certain die designs the n- and p-contacts are formed on the upper surface (lateral die); in other designs they might be formed on separate upper and lower surfaces (vertical die); or might involve the use of vias to form both contacts on the lower surface (flip chip die). Dielectric layers are used to passivate the structures and provide electrical isolation. Surface texturing of the n-GaN layer is often implemented to improve the light extraction out of the chip structure. Figure 3-8 shows the evolution of GaN-based chip designs over time.

Early LED designs were lateral chip structures, with a semi-transparent thin p-contact deposited across the p-GaN layer to promote current spreading in a more resistive p-type semiconductor thin film layer (Figure 3-8a). The semi-transparent contact provided the current spreading while also allowing the generated light in the active region to pass through the top side of the chip. Contacts were created on the top of the die with wire bond connections to the package. Current lateral chip designs (Figure 3-8b) have implemented a transparent conductive oxide contact to provide the current spreading while allowing more light pass through the top side of the chip compared to the thin metal semi-transparent contact. Additionally, the use of PSS substrate provides the light extraction features at the GaN/sapphire interface (see Section 3.1.3) to improve the light extraction efficiency of the chip over planar sapphire.

Vertical power chip designs (Figure 3-8c) were implemented in the 2005-2006 time frame to provide high light output level necessary to create illumination class light fixtures compared to the conventional small lateral chip prevalent at the time (Figure 3-8a). This chip architecture, also known by tradenames such as ThinGaN from OSRAM and EZBright from Cree, removed the epitaxial growth substrate and flipped the thin film semiconductor layers over, applying a p-mirror contact to the p-GaN (to reflect all the downward light back out the top of the chip) and bonding it to a conductive substrate (silicon). The exposed n-GaN on the top of the chip was photoelectrochemically (PEC) etched to create a pyramidal texture that helped improve light extraction (similar to the concept of PSS in Section 3.1.3). Improvements to these vertical chip architectures include implementing vias for the n-contact to create a flip-chip architecture (Figure 3-8d) and removing the wire bond for better reliability and more compact packages.

Another die design implemented in 2007 was the thin film flip chip (TFFC) architecture introduced by Lumileds (Figure 3-8e). This design was intended to achieve the same high optical power and improved light extraction as the vertical LED structure in Figure 3-8c, but instead was designed to be a flip chip structure when removing the epitaxial semiconductor layers from the growth substrate. The chip was mounted onto a ceramic submount for mechanical support. While this structure was efficient, the manufacturing costs were high due to the number of process steps, so this type of die design eventually transitioned to a sapphire flip chip architecture (Figure 3-8f) where PSS substrate was used to create the texture for light extraction, thus skipping the difficult substrate removal process of the TFFC architecture.

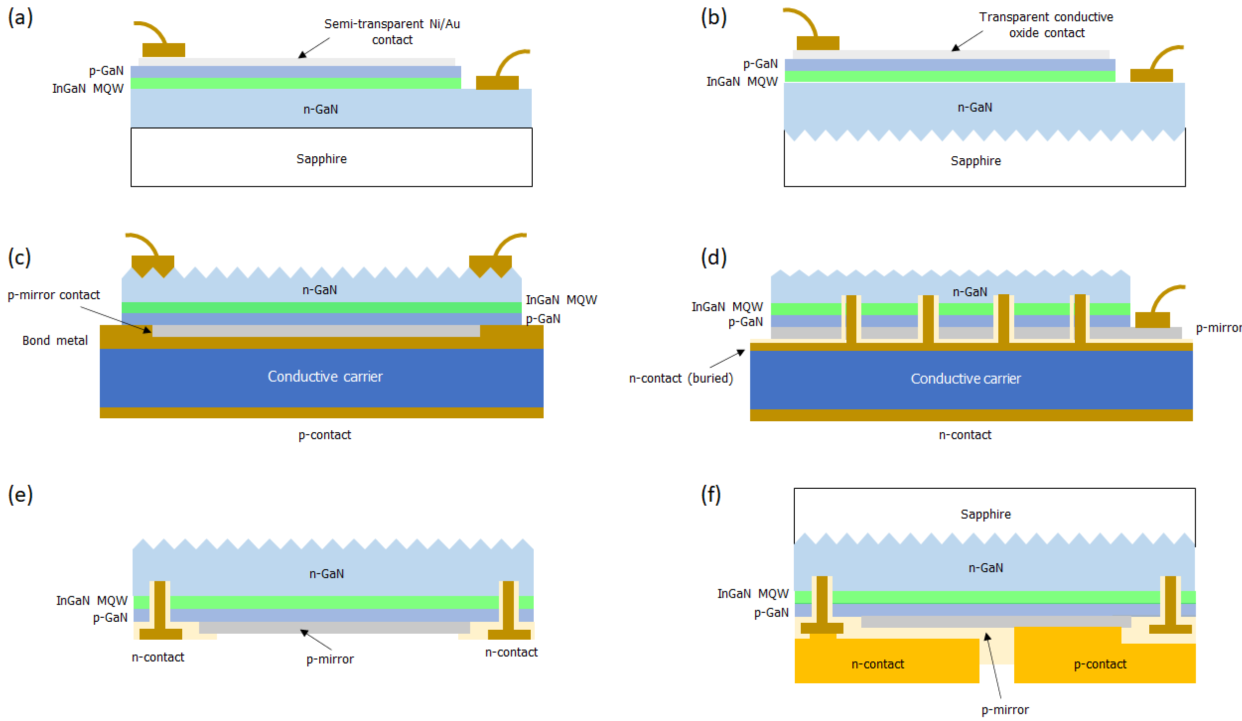


Figure 3-8 Common LED die designs for various architectures including: (a) an early lateral chip structure with semi-transparent p-contact, (b) the more current lateral chip structure with transparent p-contact and patterned sapphire substrate, (c) an earlier design of the vertical thin film chip structure, (d) a more recent vertical thin film structure with via n-contacts, (e) an earlier thin film flip chip (TFFC) structure, and (f) the more current sapphire flip chip structure with patterned sapphire substrate.

Over the past decade the lateral chip, vertical chip, and flip chip designs have evolved to optimize performance, reliability, and manufacturing cost (number of process steps & yields). Die designs will continue to adapt over time to optimize different features for the different package and luminaire designs. New innovations such as tunnel junctions have potential to improve the performance of LEDs by allowing a cascaded LED structure that can circumvent current density efficiency droop that limits efficiency of conventional GaN LEDs at high drive currents. Additionally, newer classes of LEDs – micro-LEDs and mini-LEDs – are being developed for display applications but can also be leveraged to enable new lighting architectures. More about tunnel junctions and micro-LEDs can be found in the DOE SSL Program's 2019 Lighting R&D Opportunities document. [7] While new chip architectures enable new functionality, they also require new considerations for manufacturing processes, some of which will be described in Section 3.5.2.

3.2.2 Wafer Processing

The wafer processing equipment used to fabricate blue LED devices on the MOCVD-grown semiconductor wafers is largely derived from equipment originally developed for the silicon and gallium arsenide (GaAs) wafer processing industry. Many of the lithographic, etching, deposition, and metallization processes employed in the fabrication of GaN-based LEDs are similar to those used successfully for other semiconductor materials such as AlGaInP (used for red and amber LEDs). Major differences revolve around the etchant chemicals, etchant gases, and contact metals employed for the GaN-based materials system, and the need in some cases to completely remove the insulating substrate to facilitate electrical contracting and efficient light extraction (by removing the refractive index step between epitaxial layer and sapphire that inhibits light passage). Substrate removal can be achieved by mechanical grinding to remove most of the material, followed by a final separation, which may be achieved by laser lift-off (for sapphire), by mechanical grinding followed by chemo-mechanical polishing (for sapphire, SiC or silicon), or by purely chemical means (for silicon substrates). The resulting thinned wafer is normally bonded to a carrier to provide mechanical support during subsequent process steps.

The device fabrication process typically starts with the formation of the p-contact layer because of the sensitive nature of the p-GaN surface. In most cases the p-GaN surface is passivated prior to undergoing the lithography process steps for extra protection. Following the p-contact process, a mesa etch occurs to expose the surface of the n-GaN layers. The n-type contact process follows and can be a top-side contact deposition for lateral chip configurations or can be through vias for a flip chip process. Following the two metallization steps for the p- and n-contacts, the thicker pad metal is applied to both contact to support the connection to the package (via wire bond or die attach). The substrate may be removed as the last fabrication step. After the devices are formed, the wafer is probed to measure the LEDs for light output, wavelength, forward voltage, and leakage currents and then sort into performance bins. Some manufacturers also test the die for electrostatic discharge (ESD) resistance. The general LED device process flow schematic is shown in Figure 3-9.

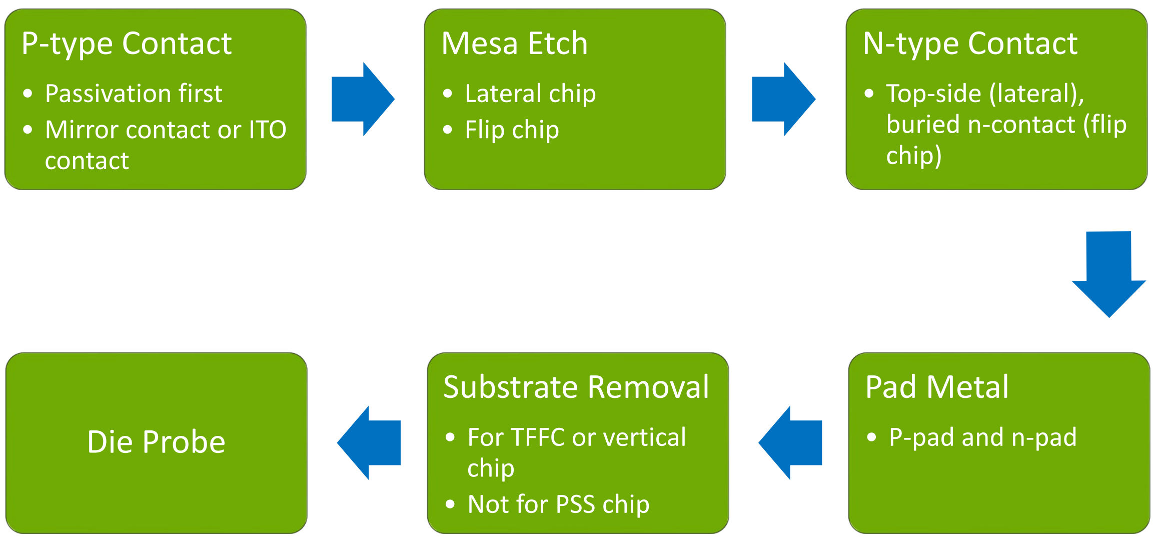


Figure 3-9 General LED device fabrication step flow diagram.

Most Tier 1 LED manufacturers have transitioned to 150 mm substrates; in 2010-2014 much of the LED industry had fabricated LEDs on 100 mm wafers. The trend toward scaling to larger diameter wafers was focused on reducing manufacturing costs in the wafer fabrication stage. Scaling up wafer size allowed capacity growth in the LED factories since a 150 mm wafer contains approximately four times more die in a single wafer compared to a 75 mm (~ 3”) wafer, thus increasing the device production for each batch of wafers. Significant cost reductions were achieved when implementing the transition from 75 mm to 150 mm diameter wafers in 2012, as shown in Figure 3-10 for Lumileds wafer size conversion. The cost reductions associated with increasing wafer sizes for MOCVD growth process is not as significant as in the wafer processing stages.

Beyond scaling die count per wafer, new equipment with advanced capabilities for 150 mm wafers led to process improvements and better process control. A decade ago, the most widely available compound semiconductor process tools tended to be manual or semi-automatic tools that do not lend themselves to an automated production line. Manual wafer loading and manual tool operation slow the throughput, reduce yields, and increase costs. Beyond wafer sizing scaling, the newer and larger process tools have enhanced tool capabilities, which results in process yield improvements through reduced defects and results in tighter die performance characteristic distributions (optical and electrical parameters). Moving from 75 mm to 150 mm wafers allows for the use of a vertical furnace and a larger flat zone for LED wafer annealing (which activates the p-type carriers in the as-grown MOCVD wafer). Leveraging the larger flat zone of the furnace led to a factor of two improvement in the process capability (Cpk), as shown in Figure 3-11. [25]

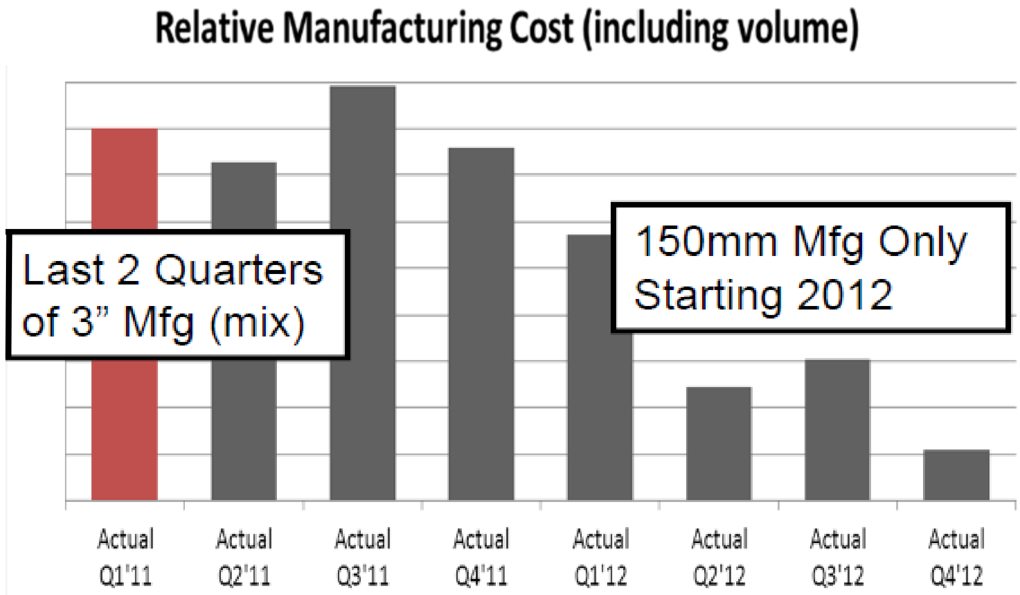
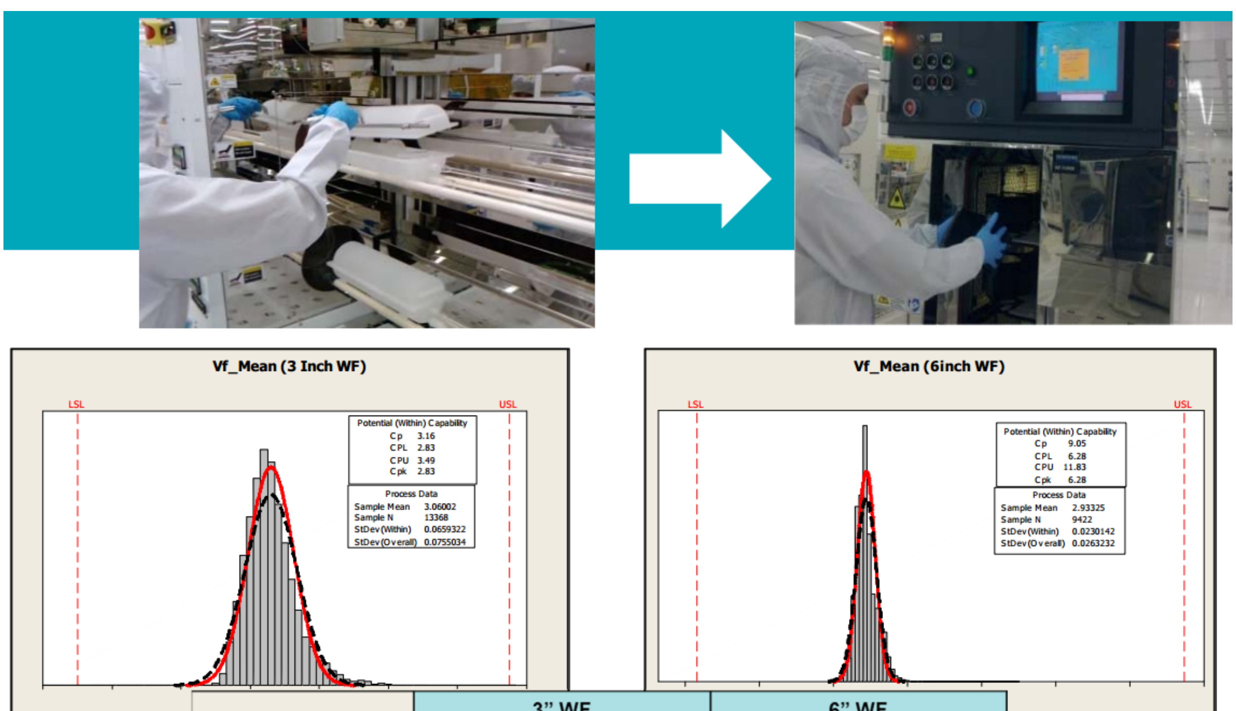
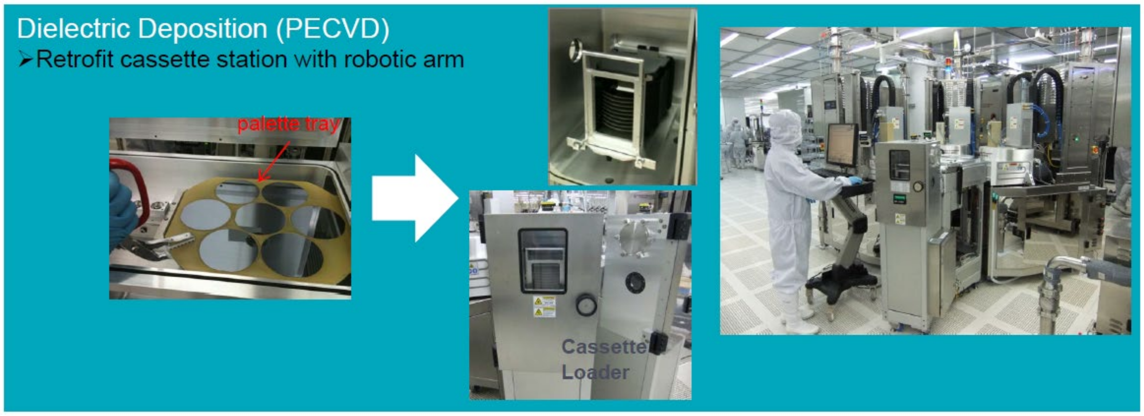


Figure 3-10 Reduction in relative manufacturing cost when transitioning from 3” to 150 mm diameter LED wafers. [25]



	3” WF		6” WF	
Parameters	Average	Stdev	Average	Stdev
Vf_Mean (350mA)	3.06	0.075	2.93	0.026

Figure 3-11 Improved process control is seen with 150 mm wafer annealing equipment. Larger LED wafer sizes allows the use of advanced equipment with better process uniformity resulting in a die yield improvement. [25]



	3" WF		6" WF	
Parameters	**Average**	**Stdev**	**Average**	**Stdev**
Defect Density (count/cm2)	0.194	0.200	0.017	0.029

Figure 3-12 Images of batch wafer loading for plasma enhanced chemical vapor deposition (PECVD) of dielectric layers on 150 mm LED wafers. The process productivity and defect density for the dielectric deposition was an order of magnitude lower due to reduced manual handling. [25]

Typical wafer handling for the LED industry involved batch processing and manual wafer loading for smaller substrate sizes (2" and 3"). The individual handling as part of a batch process is time consuming and can lead to increased wafer breakage and non-conforming materials (increased particles on the wafer, scratches from tweezers, etc.). Cassette-to-cassette wafer loading eliminates single wafer handling by operators, which reduces the occurrence of wafer breakage and provides significantly fewer opportunities for misprocessing. Figure 3-12 illustrates cassette-to-cassette equipment for a plasma enhanced chemical vapor deposition (PECVD) tool and the reduction in defect count with this automated loading. While wafer handling has improved for batch processing in some equipment, other process tools such as metal deposition can still involve manual wafer loads as pictured in Figure 3-13.

Figure 3-13 Loading 150 mm wafers into a holder for an e-beam evaporator. [26]

Improved alignment between equipment capabilities and the unique properties of sapphire-based LED wafers was critical to improving yields and throughput. Previously, the most widespread LED compound semiconductor tools were originally developed for conventional silicon processing and had challenges handling the transparent sapphire wafers. Such process tools verify the proper placement of wafers in and out of the process chambers using laser sensors. These sensors are specifically designed for detecting presence/absence and improper positioning of semiconductor wafers by using a reflected laser beam to detect the edge of the wafer. Sapphire wafers are transparent at common laser wavelengths, they reflect far less light than silicon wafers making their edge detection more difficult. To address these challenges, tool manufacturers increased the sensitivity of wafer-handling sensors, often with algorithmic adjustments for the detectors, allowing the tools to detect weaker reflected signals associated with transparent wafers. The insulating nature of the sapphire wafers also resulted in further challenges in wafer handling, as electrostatic chucks commonly used to hold silicon wafers are not as effective. The insulating substrate requires a much higher clamping voltages and much higher charge dissipation on unclamping compared to conductive silicon wafers making this method more challenging. Mechanical clamping is often implemented to hold the insulating sapphire wafers, though it leads to a loss of processable wafer area and may lead to particle generation. Some tool manufacturers have developed proprietary designs to improve the electrostatic clamping of sapphire wafers to avoid yield losses with mechanical clamping. [27]

Improved lithography tools such as projection steppers can increase the device yield on the LED wafer by improving print accuracy without introducing defects. Traditional contact aligners (initially used for LED device production) image the wafer by using a full wafer-sized mask to create a shadow of the mask that defines the feature on the exposed wafer. The mask is in contact or close proximity to the wafer where the optimum exposure condition is a compromise between near contact for best image quality and a large gap space to minimize mask and photoresist damage (defects) due to mask-to-wafer contact. The bowed nature of the LED wafers (from thermal strain during MOCVD growth) make it challenging to achieve uniform image quality across the wafer with the contact alignment method since the wafer will not be in consistent contact with the mask because of height variations from the bowing. Projection lithography tools (also called steppers) do not need to be in contact with the wafer and can compensate for wafer height variations since they use projection optics to image the mask onto the substrate. Unlike with the contact aligner, the mask and wafer are separated by the projection optics and never come into contact. The stepper "steps" across the wafer exposing partial regions (fields) until it has traversed the entire wafer, each step re-focusing from field to field. The re-focusing mitigates the uniformity challenges with the wafer bow variations. Steppers result in better device yields since defects from wafer-to-mask contact are not generated during the lithography process. Additionally, the mask is not degraded due to contact damage and reduces the costs associated with replacing masks more frequently. Projection lithography tools also allow for finer critical dimensions, which is attractive as die designs are miniaturized. Research and development into projection lithography systems was supported by the DOE SSL Program and led to platform improvements in the Ultratech Sapphire 100 stepper system designed for LED manufacturing (pictured in Figure 3-14). [28] With the yield improvements and wafer handling automation available with projection lithography tools, they have become the choice for high volume LED manufacturing.

Figure 3-14 Ultratech Sapphire 100 Stepper tool for LED wafer processing. [29]

Manufacturing Opportunity: LED Wafer Fabrication Automation. An opportunity lies in improving wafer fabrication automation for compound semiconductor fabs. Most of the 100 mm to 150 mm GaN wafer fabs require labor to run the equipment since manual loading or moving cassettes is still required. Manufacturing execution systems (MES), tool-to-tool wafer movement, communication platforms, statistical process control (SPC) systems are not readily available as turn-key solution for the smaller 150 mm wafer fabs. These process control solutions must be cobbled together independently by those creating the process lines. With LED operating margins so very low, the labor of running tools is too expensive for U.S. manufacturing. There is an opportunity to leverage the automation know-how from advanced silicon fabs to create more automated 150 mm to 200 mm compound semiconductor wafer fabs. Increased automation will reduce the operating cost of wafer fabrication facilities and create better opportunities to operate domestically.

While the majority of LED fabs are in Asia, improved automation can lead to opportunities to perform LED fabrication for new or complex device designs domestically. Newer power electronics device fabs are growing in the United States and share a similar need to leverage automation while providing opportunities to domestic manufacturing job growth. Improved fab automation can be leveraged to strengthen U.S. manufacturing for multiple industries.

Beyond the technological development, economic considerations have driven the decision of many manufacturers to limit scaling the factory beyond 100 or 150 mm. Though scaling up to 200 mm wafers will continue to improve the cost structure in wafer fabrication, there are still challenges in upgrading MOCVD tools and growth process the larger wafer sizes. The price pressure in LEDs for general illumination has led to low margins and a hesitation to upgrade capital equipment to larger wafer sizes unless the manufacturer is undergoing a factory expansion. Additionally, it is vital to keep the factory utilization high to maintain profitability, so unless the manufacturer is consistently running a full factory, the equipment upgrades are not a priority. The drive of the display industry to develop micro-LED technology has resulted in manufacturers scaling up MOCVD processes for growth of GaN on silicon. Development effort in micro-LED devices could help drive the upgrade of wafer sizes for conventional LED production.

3.2.3 Back-end Wafer Processing (Die Singulation and Testing)

The processed LED wafer comprises a large number of LED devices in a regular repeating pattern. Once the device processing (also called “front-end” processing) has been completed, the wafer must be prepared for device separation. The singulation of the wafer into individual die starts the “back-end” assembly. The LED wafers can be separated into die by conventional singulation techniques used in semiconductor wafer fabrication such as sawing, cleaving, or laser scribing. As described in the previous section, the substrate may be removed completely from the active layers during wafer processing. If this is not the case, then the wafer is commonly thinned before singulation, by grinding or chemo-mechanical polishing, to better facilitate the singulation processes. Prior to singulation, the wafer is normally mounted on a flexible adhesive film to hold the die together in a wafer-like format after the singulation is completed. The flexible film is subsequently expanded after the singulation process to separate the die and allow individual die to be pick-and-placed onto a tile, sub-mount, or package.

Laser scribing has become the main method of singulation since it increases the number of LED die on a wafer by creating a much narrower kerf width compared to traditional mechanical scribing or sawing. Smaller kerf widths increase the LED capacity on a single wafer since the die can be much more closely spaced. Figure 3-15 shows a cross-sectional image of laser scribing for LED singulation with a kerf width of 2.5 µm. Since laser scribing is a non-contact process, it also can reduce micro-cracking and damage to the sapphire substrate (very hard material that can tend to crack), thus improving singulation yield. In the laser scribing process, the laser is tightly focused on the sapphire substrate ablating the material to create a narrow scribe line between the devices. The speed of laser scribing is also much faster than mechanical singulation. Additionally, the wider process tolerance of lasers and the elimination of blade wear and breakage result in a more robust, lower cost manufacturing process.

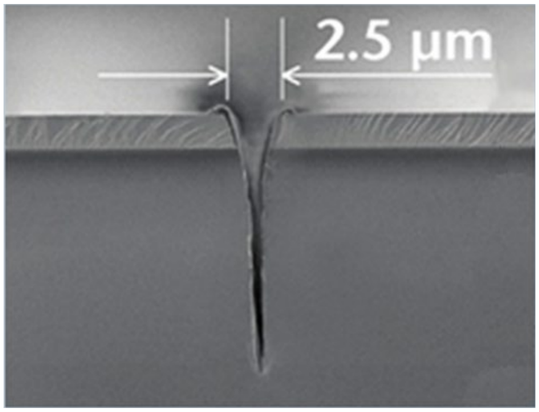


Figure 3-15 An image of laser scribing of an LED sapphire wafer showing a kerf width of 2.5 µm. [30]

Laser liftoff (LLO) is the most common sapphire substrate removal technique used for volume manufacturing of thin film architectures. To separate the sapphire wafer from the GaN film, a UV laser selectively irradiates the GaN buffer layer near the sapphire interface. This process typically uses a UV-C laser at a wavelength of approximately 250 nm, where sapphire is virtually transmissive and the defective GaN buffer layer strongly absorbs the laser radiation. The absorbed laser energy leads to thermal decomposition of the GaN buffer into metallic gallium, which become liquid at 30°C, and nitrogen gas. The metallic gallium at the interface allows the sapphire wafer to be easily removed from the adjacent GaN thin film layers. To remove the entire wafer via LLO, the laser rasters across the wafer utilizing a beam homogenizing optical system to deliver flat beam profiles. The spatial beam uniformity and fluence stability of the laser source is critical to prevent side-effects such as crack formation or chipping during the process. Delamination of the sapphire substrate can be accomplished with a single laser pulse per area so a 150 mm wafer will require only a few thousand laser pulses stepped across the wafer to achieve full removal. [31] Although krypton fluoride (KrF) excimer lasers were commonly used for LLO separation tools, diode pumped solid state (DPSS) lasers have been adopted in recent years since they are cheaper, easier to maintain, and provide a more stable process quality. The LLO process is illustrated in Figure 3-16.

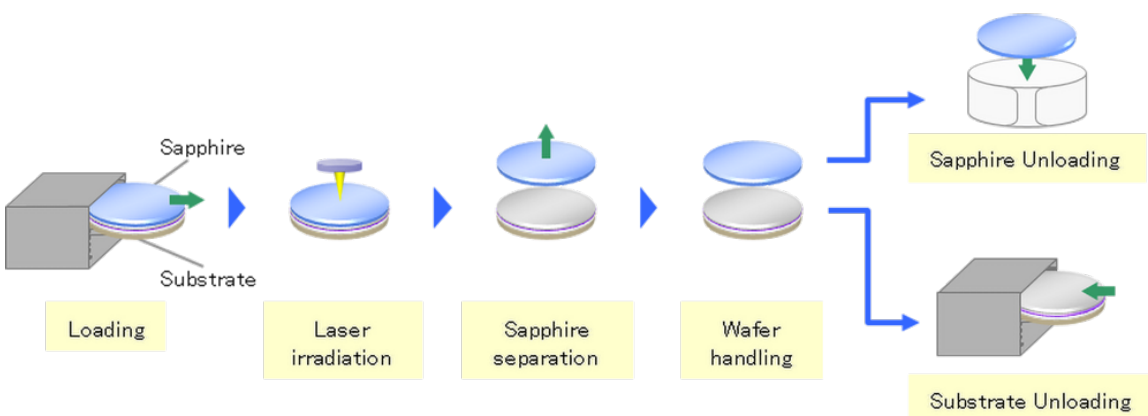


Figure 3-16 Schematic of the LLO separation process for sapphire wafers. [32]

Manufacturers of singulation equipment include:

- Disco, AP Systems, HGLaser, and Philoptics in Asia,
- IPG Photonics and Coherent in North America,

- InnoLas Solutions in Europe.

Beyond the singulation equipment discussed previously, other types of process equipment are required to support back-end assembly processes die separation (i.e., preparing wafers for singulation or handling wafers with singulated die). A couple key pieces of back-end equipment are film frame mounters and die expanders; examples of these back-end tools are shown in Figure 3-17. Film frame mounters affix the LED wafer onto an adhesive plastic film in preparation for singulation. The adhesive film holds the die together in the form of the wafer during singulation for handling in the subsequent process steps. Once the LED wafer is singulated, the die is then stretched apart to allow for testing and LED die transfer. The singulated wafer on the adhesive film is inserted into the matrix die expanders to stretch the singulated wafer into die arrays for pick and place machines to move and sort the individual die in preparation for packaging.

Film Frame Mounter

Die Expander

Figure 3-17 Supporting equipment such as film frame mounters and matrix die expanders are needed to support the backend processing. [33]

3.3 LED Package Manufacturing

The LED package serves many functions during operation. The package electrically, mechanically, and thermally connects the LED die to the board or module that is coupled to the electrical power and heat dissipation in the luminaire systems. The package architecture often provides the mechanism for integrating the phosphor material that converts the blue emissions of the LED chip into white light, and also for the encapsulation that protects the LED die from environmental contamination. The package imparts a robust structure that can be rapidly assembled onto PCBs, lighting arrays, or modules with reduced risk of mechanical damage. An outline of the LED package manufacturing process and critical materials is provided in the following sections.

3.3.1 LED Package Platforms and Form Factors

Although a decreasing portion of a luminaire BOM, the LED package remains the key component within the luminaire. Intense competition by the many LED manufacturers, especially in Asia, have led to pricing pressures and resulted in commoditization of many LED package form factors, as discussed in Section 2.2.2. Most of the companies that manufacture LED die also manufacture LED packages, and these packaging operations are also mostly located in Asia. Beyond these manufacturers listed in Section 3.2 there are a number of companies that rely entirely on other manufacturers for their LED die supply. These include MLS, Lite-On, Unity Opto, Nationstar, Jufei, Honlitronic, and Refond, among others. The overall global distribution of LED package revenue in 2019 is shown in Figure 3-18, with Asian companies accounting for 75% of overall LED package revenue. Approximately 36% of all LED packages are sold into general illumination applications, with Nichia, Lumileds, Seoul Semiconductor, MLS, and Cree as the top five LED manufacturers who sell products for general illumination. [34]

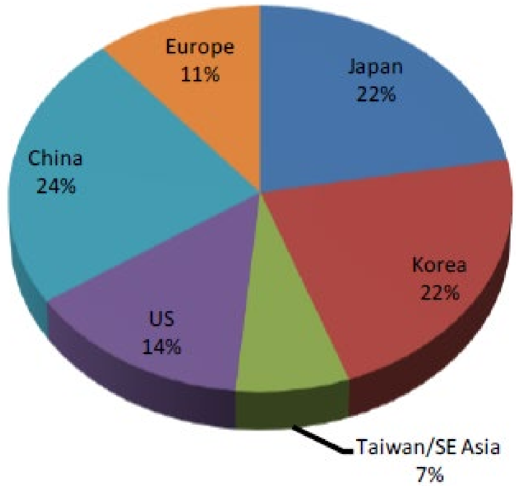


Figure 3-18 LED package revenue by geographic region for 2019. [34]

The variety of LED packages for general illumination has grown rapidly between 2010-2020, from a few types of 1 W class packages to numerous of form factors, lumen levels, voltages, optical patterns, and physical dimensions. An LED manufacturer may have 50 different package families, and each family has multiple variants based on lumen output, forward voltage, CCT, CRI, bin tolerances, package size, luminance, and optical distribution. Ultimately, the package design reflects the requirements of the target application, and with the variety of lighting applications, there is also a wide range of package types in terms of physical dimensions and light output characteristics.

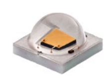
Currently, there are well-understood LED package performance trade-offs, which include the typical trade-offs between luminance, optical distribution, efficacy, color qualities, size, and cost. Reducing these trade-offs to improve system level lighting performance is requires manufacturing improvements as well as innovations in materials and product designs. LED package families may be designed to offer higher lumen output, higher efficacy, lower cost, improved color quality, tighter color control, or some optimal combination of these attributes. Offering a broad product mix ensures that an optimal design exists for each lighting application, whether it is for an omnidirectional large-area source or a high center-beam intensity directional source. This package diversity has given luminaire manufacturers the freedom and flexibility to use LEDs best suited for the targeted lighting application and market. In general, packages can be grouped into 4 major platforms, as illustrated in Figure 2-6 and described in Section 2.2.2:

- High-power ceramic-based LEDs (1-5 W) – includes dome lens and flat lens
- Mid-power polymer-based LEDs (0.2-1 W) – includes PLCC and quad flat no-lead (QFN) packages
- Chip scale packages (1-3 W) – includes CSPs with/without reflective sidewalls and with/without submount
- COBs (10-80 W) – size range varies with an LES between 6 and 35 mm.

The general form factors, performance features, and costs for the different platforms is summarized in Table 3-1. Because the LED package interacts with light emitted by the LED, the choice of package platform impacts the overall performance of the lighting system.

Table 3-1 Summary of the major LED package platforms in terms of package size, performance factors, and cost.

Power Increasing

Type	PLCC / QFN	QFN	CSP	Ceramic	COB
Package Material	PPA/PCT	EMC/SMC	Phosphor/EMC	AIN	Ceramic, metal
Package Size	5630, 2835, 3014	3030, 5050	3030	3535	Varies
Chip Type	Low/mid power	Low-high power	Mid-high power	High-power	Mid-power
Reliability	Ok	Good	Good	Excellent	Good
T_j max	115°C	125°C	125°C	150°C	125°C
Cost (high volume)	\$0.015-0.035	\$0.04-0.06	\$0.20-0.35	\$0.25-0.45	\$1.50-11.00
Example					

From 2004 to 2012, the LED industry focused on the manufacture of high-power 1 W packages for lighting applications. These lighting class packages generally contained a single 1 mm^2 die and produced around 80-100 lumens of white light. High-power packages provide high efficacy, high luminous flux, and good reliability based on their thermal management and optical design. The package design typically consists of a large die (1 to 4 mm^2), or even multiple die for a high-power array, mounted onto a ceramic substrate for thermal management. The phosphor is applied to the chip and then a hemispherical silicone lens or flat lens is over-molded onto the package. In addition to the large die, some high-power package designs use numerous small die in series (which can even be combined monolithically) to create a high voltage package architecture that, when grouped with a boost driver topology, can yield system efficiency improvements.

Mid-power packages originated in display and backlighting applications but found their way into general lighting applications in 2012 as chip performance improvements led to viable lumen levels for lighting applications. Mid-power LEDs consist of a plastic molded lead frame package that typically contains one to three small LED die. The die are mounted on a silver-coated metal lead frame surrounded by a plastic cavity, which is filled with phosphor mixed in silicone to act as the down-converter and encapsulant. Such products use inexpensive plastic packaging materials, resulting in very low-cost packages. While the lumen output per package is much lower than a high-power LED, it is possible to use many more packages to achieve similar overall light output levels at relatively low cost. Mid-power LEDs have gained favor over high-power LEDs in many applications due to their low cost and high efficacy, which improves the lumens per dollar (lm/$) metric of the lighting system. Mid-power plastic packages are well suited to the production of diffuse lighting, while compact, high-power packages are well suited to the production of high-intensity point sources. Improved resin materials have led to newer LED product models with mid-power package form factors that operate at levels more typical of high-power packages (~ 1 W) with good reliability.

COB arrays typically use a large array of small die mounted onto a MC-PCB or a ceramic substrate. The LEDs are then covered with a phosphor mixed silicone. COB arrays provide high lumen output (up to 14,000 lumens) from a small optical source area and are used in applications such as high-bay lighting and low-bay lighting. With a good thermal substrate, these COB arrays can have the same color and lumen stability associated with high power packages as long as the operating temperature is kept within specification. The easy assembly of COBs in luminaires often appeals to smaller luminaire manufacturers who do not have the surface mounting equipment to assemble discrete packages onto PCBs. LED manufacturers have continued to innovate and add new functionality in COBs, such as using different phosphor mixes to achieve dim-to-warm or warm-to-cool white CCT tuning.

CSP LEDs have gained prominence recently due to their lower cost by removing many packaging materials and manufacturing steps. Additionally, the small footprint of CSPs allow tighter packing in a luminaire to create higher lumen densities. The number of CSP product offerings continues to grow, as does the number of manufacturers offering this LED product type. Many CSP products use flip-chip die as a base, onto which the phosphor and encapsulant is applied, while other CSPs have added reflective side walls to create a surface emitter (light coming only from the top face of the package) instead of a volume emitter (where phosphor is on the top and all four sidewalls of the chip), as shown in Figure 3-19. Eliminating wire bonding and removing the need for package cavities or ceramic substrates allows for a more compact size and reduced cost. While CSPs use less packaging materials than their LED package counterparts, they still utilize a larger die, and therefore are more expensive than the mid-power packages. CSPs are often used where a small optical source size is required for a light source that has white tuning or color tuning to give more functionality than a conventional COB source due to their tight array packing (see Figure 3-19d).

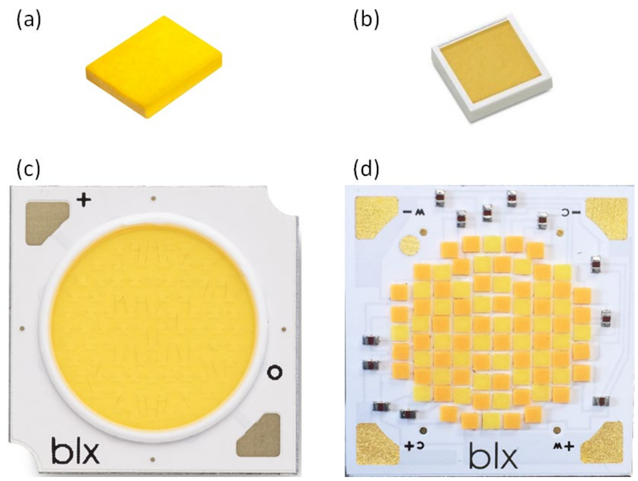


Figure 3-19 CSP LEDs with (a) a phosphor coating all 5 sidewalls (volume emitter) and (b) with white reflective sidewalls to reflect the side emission allowing light to come only from the surface (surface emitter). A conventional COB array (c) is compared to a CSP array (d). CSP arrays can provide a more compact source size for color tuning by using different color CSPs in the array. [35] [36] [37]

Die packaging remains a sizeable cost component for the packaged LED, as seen in Figure 2-7 and discussed in Section 2.2.5; the challenge to reduce packaging costs still remains. Generating more light output per package or implementing more efficient use of raw materials (either using less material or finding more affordable alternatives) can enable lower cost LED packages without compromising on performance. The move to low power plastic packages for lighting class LEDs has provided a major cost savings to the industry. Such packages use smaller, inexpensive die, and as they operate at low power, they do not require expensive thermal solutions such as ceramic materials. As the resin material used in the plastic package body has improved over the past 5-6 years, the lumen maintenance behavior has also improved to approach lifetimes seen from high-power ceramic packages. The low cost, high efficacy, and reasonable reliability performance has made mid-power packages the dominant form factor sold by volume for use in omni-directional lighting applications where fixture form factors have the space to accommodate the required number of packages. High-power packages, COBs, and CSPs are more common when higher lumen density and tighter beam sizes are required for the lighting applications.

3.3.2 LED Packaging Equipment

Die packaging is heavily based on equipment and processes developed for the general semiconductor die packaging industry. Certain customization has been required for improved COO, but to a large extent existing equipment was already suitable. There is a high degree of commonality with packaging materials such as ceramic packages and sub-mounts, and surface mount technology (SMT) to conventional semiconductor die packaging. Similarly, the industry has been able to employ many of the existing processes and equipment for die-attach, wire bonding, flip-chip, encapsulation, and lens attach. Probably the most critical difference from conventional die packaging occurs in the controlled application of a phosphor or other down-conversion material to the die to create a phosphor-converted white LED.

LED die are generally mounted in a package to provide an effective interface between the small semiconductor die and the rest of the system. The package provides good thermal conductivity, control over the light distribution, and electrical connectivity. Various types of packaging equipment will be employed depending on the die configuration (top or bottom emitting) and design of package. For example, die attach equipment might be required to perform flip-chip processing and eutectic bonding onto ceramic carriers or silicon sub-mounts. Electrical connections between the semiconductor die and the sub-mount or package can be made using wire-bonding equipment or solder bump technology equipment. Encapsulation and/or phosphor material is often conformally coated over the surface of the die once it is mounted on the sub-mount or ceramic substrate. Finally, a lens is generally molded or attached above the LED die to provide the required light distribution pattern. Once the manufacture of the package is complete, the packages are tested and sorted into performance bins. The binned packages are then mounted in tape and reel packaging for use in pick-and-place SMT equipment to place onto PCBs for the light engine. This general sequence is illustrated as a package manufacturing flow diagram in Figure 3-20.

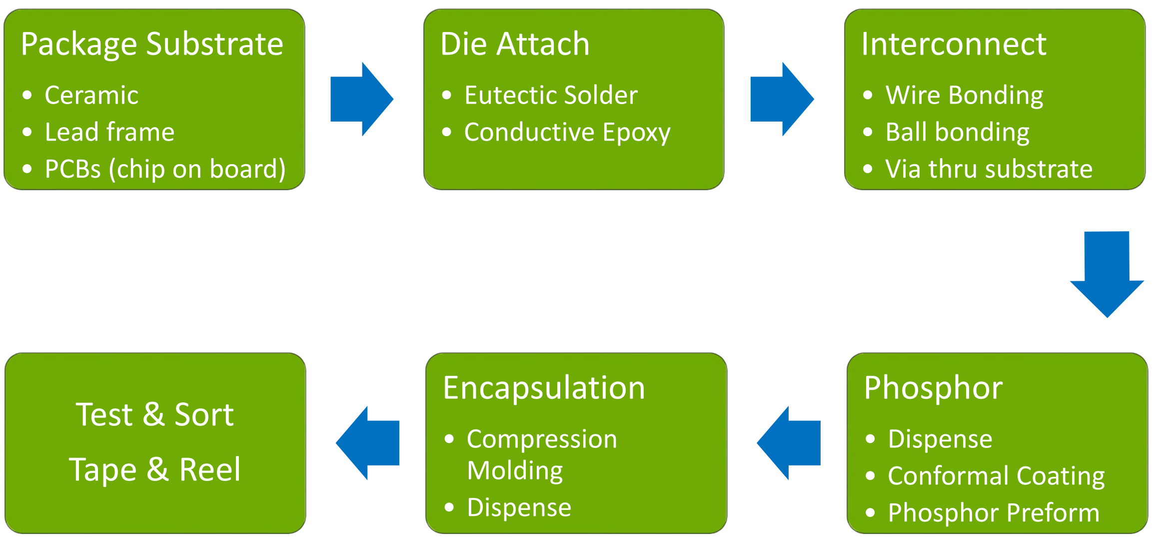


Figure 3-20 General LED packaging step flow diagram.

One consequence of an increasingly diverse range of package designs is the need to achieve a high degree of flexibility in the manufacturing line to handle the different options. For example, the packaging line may need to accommodate different package shapes and materials, die sizes, die attach methods, phosphor application approaches, and primary optics. Various methodologies exist to set up a production line and balance the equipment throughput and flexibility for different product starts. One-to-one tools for each production step can limit throughput, whereas complete balancing of tool throughput (different process steps have inherently different throughput speeds) to give minimum number of tools for the factory limits the range of products and the flexibility switch product types through the line. The typical installation lies somewhere in the middle since establishing separate packaging lines for each different design is not always practical; hence, the ability to reconfigure the production line for runs of different packages is essential. However, while flexibility is important, some specialized manufacturing equipment will be needed for specific package platforms that will not be applicable to all platforms. For example, singulation of ceramic substrates is different than trimming and forming lead frames; compression molding hemispherical lenses requires different equipment than dispensing encapsulant into a package cavity. Typical process equipment for high-power LED packaging is shown in Figure 3-21 and typical process equipment for mid-power LED packaging is shown in Figure 3-22.

Figure 3-21 Typical high-power LED in-line packaging equipment for the different process steps.

Figure 3-22 Typical mid-power LED in-line packaging equipment for the different process steps.

In general, the packaging of electronic and optoelectronic components is a well-established technology. Conventional semiconductor packaging equipment already exists and is well suited to the task with limited requirements for customization. Companies such as ASM Pacific Technologies in Asia, Besi in Europe, and Palomar Technologies in North America provide die attach, wire bonding, and flip-chip bonding equipment. Companies such as Nordson ASYMTEK in North America and ASM Pacific Technologies in Asia provide dispensing equipment (e.g., phosphor coating, silicone encapsulation, epoxy dispensing, lens attachment, and flip-chip). Additionally, compression molding equipment is produced by TOWA in Asia.

While a certain amount of automation is employed, certain processes like visual inspection or the need for a high degree of process flexibility and the ability to handle a wide range of product types on the same production line means that LED die packaging remains a more labor-intensive activity than other areas of the LED supply chain. Consequently, much of the packaging activity takes place in regions with lower labor and tooling costs such as Asia. Shipping costs for small and lightweight LED packages are insignificant, also contributing to the decision to manufacture such products at offshore facilities.

3.3.3 Packaging Materials

As discussed previously, the LED package provides mechanical support and protection for the die, creates external contact pads for electrical and thermal connection to the die, and optimizes light extraction. Typical examples of a high-power ceramic-based and mid-power plastic-based package are illustrated in Figure 3-23. Packaging materials include the substrate type, the interconnection materials, package body materials, and encapsulation. Detailed discussion of phosphor materials can be found in Section 3.3.5.

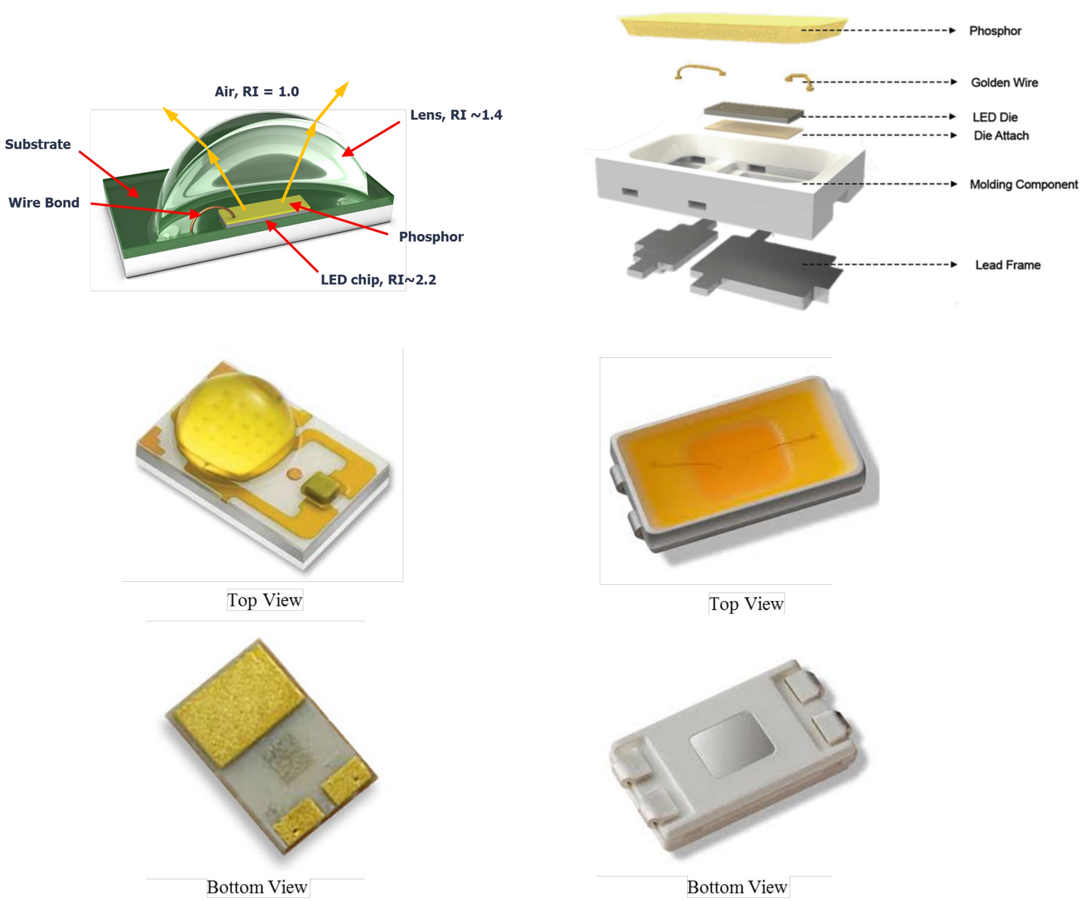


Figure 3-23 Cross section schematic and images of a high-power ceramic-based LED package (left) and mid-power plastic-based package (right). [38] [39] [40]

Package Substrates: The packaging of high-power LED die is currently based around the use of a ceramic substrate due to its heat dissipation and chemical stability. Two types of ceramics make up the vast majority of high-power LED package substrates: alumina (Al_2O_3) and aluminum nitride (AlN). Copper is used to create the traces and contact patterns on the front and rear of the substrate, and copper filled via holes provide interconnection between the front and rear patterns of the substrate, making the packages compatible with SMT assembly processes. Alumina is the more affordable substrate option with a thermal conductivity of 20 watts per meter-Kelvin (W/mK). AlN has an excellent thermal conductivity of 140-180 W/mK, but requires a more expensive high temperature synthesis process. AlN substrates are used for the more thermally demanding, high performance packages due to its improved thermal properties compared to alumina; alumina, however, is the lower cost substrate and is used in the commodity, cost-conscious high-power LED package models.

Mid-power plastic packages are based on a metal lead frame construction with an over molded plastic resin cavity that houses the LED chips and supports encapsulation. One to three small LED chips are placed on the lead frame and then the phosphor and silicone encapsulant is dispensed into cavity. The angled package sidewalls behave as a reflector to direct the light out of the package. Mid-power LEDs follow the standard nomenclature for SMT packages such as 5630, 2835, and 3030. The package name reflects the physical dimensions (e.g., a 5630 package has 5.6 x 3.0 mm dimensions). There are two major configurations of LED plastic packages: the older-style PLCC having two or four leads wrapped around to the base of the package for surface mounting and the newer and more prevalent QFN packages, which shares a lot in common with the PLCC package, but instead of leads, it has pads located on the base of the package.

The lead frame for the plastic-based package is plated to enhance its reflectivity and chemical stability. Silver-plated copper lead frames are commonly used because of silver's high reflectivity across a large portion of the visible spectrum and especially at the blue wavelength range of the LED die. The silver-plated lead frame requires a high-quality electrolytic finish to achieve the reliable wire bonding and high reflectivity. While desirable for its high reflectivity, silver does have a high reactivity to sulfur compounds such as hydrogen sulfide (H_2S), which corrodes the lead frame plating and causes discoloration, as seen in Figure 3-24. Barrier coatings can be applied as a post-treatment for silver plated lead frames to improve corrosion resistance. Gold plating is an alternative that can provide a lead frame with higher chemical stability, especially against sulfur, but has a lower reflectivity than silver. For reliability critical applications like automotive lighting, gold-plated lead frames are commonly used despite the lower brightness.

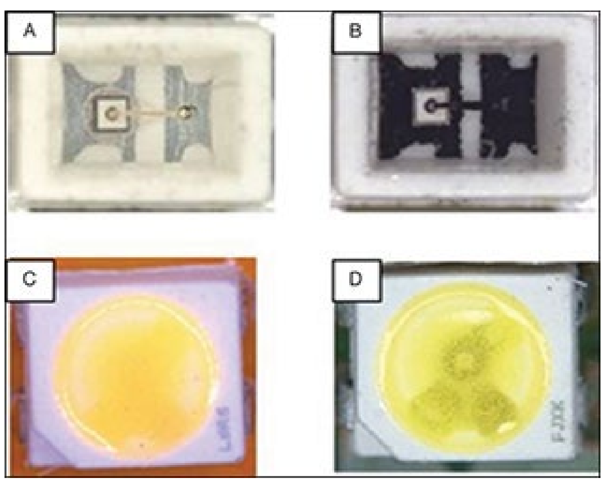


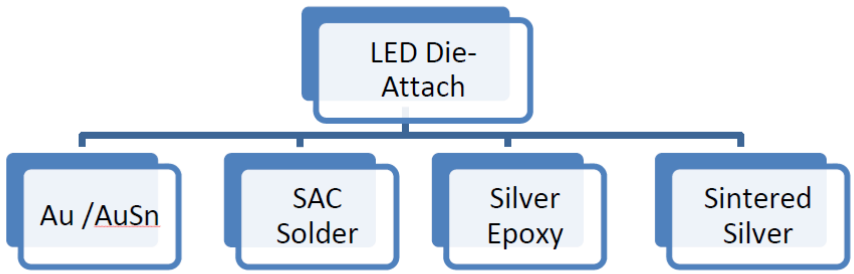
Figure 3-24 Silver-plated LED lead frames with transparent encapsulation before (A) and after (B) silver sulfide formation at the surfaces and phosphor-containing encapsulation before (C) and after (D) silver sulfide formation. The silver plating turns darker due to sulfur-based contamination and results in a lower reflectivity surface and light loss. [41]

The resin material used to form the plastic cavity is critical to the reliability and performance of the LED package. The higher the temperature and more blue flux density the resin can resist, the longer the lifetime of the package. Early on, most mid-power packages were made using polyphthalamide (PPA), a thermoplastic material, since it had good moldability, high sidewall reflectivity (95%), and was low-cost. Unfortunately, PPA has poor resistance to heat and blue flux, which limited the LED operating power to less than 0.5 W and impacted the lumen and chromaticity maintenance performance due to degradation of the plastic sidewall reflectivity (typically discoloring which caused lumen drops and chromaticity shifts). Polycyclohexylene-dimethyleneTerephthalates (PCT) is a thermoplastic that rivaled PPA because of its better resistance to heat and light which improved the lumen maintenance behavior; however, PCT had a slightly lower sidewall reflectivity (93%) and was more expensive than PPA. While PPA and PCT were acceptable for lower power applications, the need for higher light output required new resins with better thermal and photostability to allow the package to be operated at higher currents without rapid degradation in lumen and chromaticity maintenance.

In 2013, LED package manufacturers began implementing epoxy molding compound (EMC), a thermosetting resin that has a much-improved resistance to heat and blue flux, which provides lumen and chromaticity maintenance behavior that approaches the levels obtained in the high-power ceramic-based packages. [42] Additionally, the reflectivity of the EMC resin is suitable at 95%. EMC's improved photothermal stability has allowed plastic packages to reach operating powers of 1 W, which is generally the power range of ceramic high-power LEDs. The drawback is that EMC is more costly than its PPA and PCT predecessors, though it has been the primary resin choice for many package form factors of late. Lastly, silicone molding compound (SMC), a thermoset resin, has also been explored alongside EMC. While used more sparingly than EMC due to its higher cost, it maintains excellent photothermal stability for long lifetime lumen and chromaticity maintenance and has a reflectivity of 97%, which increases the brightness of the LED package. Like EMC, SMC package performance approaches operating powers and reliability expected from ceramic-based high-power packages. Despite the improvement in thermal stability, a plastic housing (rather than a ceramic substrate) will still struggle to dissipate very high heat flux densities when the LED is driven at very high currents.

A COB LED provides an integrated array of LED die in a form factor that is directly attached to the heat sink of the luminaire as opposed to discrete high-power, mid-power, or CSP LED packages mounted on a PCB to create the light engine. COB LED arrays use a thermally conductive substrate, such as a MC-PCB or ceramic, to ensure an efficient thermal path between the LED die and the heat sink. The MC-PCB incorporates a base of metal material (normally aluminum), which acts as the heat spreader, a dielectric polymer layer with high thermal conductivity as a thermal interface layer, and an upper metal circuit layer (normally copper). Ceramic substrates are used for high lumen density COB sources since they can better dissipate the heat from a high-density die packing designed to create maximum light output from the same LES size. Compared with ceramic substrates, MC-PCBs have advantages of lower costs and better mechanical strength, though they have inferior thermal dissipation.

Die Attach: The electrical connection between the LED die and the various package substrate types is made via wire bonding or with the die attached directly to the substrate with a conductive material. Die attach materials are used to bond the chip to the package substrate while making an electrical connection. The selection of the die attach material involves a number of considerations for performance (thermal dissipation and light output), manufacturing (throughput and yield), and reliability (lumen maintenance and thermal cycling). LED die attach materials include conductive adhesives, eutectic gold-tin (AuSn) solder, and sintered materials. Figure 3-25 compares cost/performance balance of the main die attach platforms used in LED packaging.



	Au /AuSn	SAC Solder	Silver Epoxy	Sintered Silver
Secondary Reflow Possible	Yes	No	Yes	Yes
Thermal (W/mK)	~57	~60	2-50	>100
Cost of Ownership	High	Low	Medium	Pressure-less : Medium Pressure-Assisted: High

Figure 3-25 Comparison of the cost/performance balance for the four main die attach platforms used in LED packaging. The best solution varies between the different LED package platforms (high-power, mid-power, COB and CSP). [43]

Conductive adhesives, which are typically silver filled epoxies, are the most used thermal die attach materials in LED packages; this die attach class is the preferred material of choice for lateral die without back-side metallization and are extensively used in the high-volume mid-power LED packages, as well as most COBs. Conductive adhesives provide the lowest cost structure with reasonable performance (thermal conductivity up to 50 W/mK) and are compatible with secondary reflow processes used in SMT lines to attach the discrete LED package to the PCB. [43]

AuSn solder die attach is used in high power LED applications due to its excellent thermal conductivity (57 W/mK) and its reliability (high creep & fatigue resistance). AuSn solder uses a higher temperature reflow process since it must be compatible with the secondary solder reflow process used to attach the LED package to the PCB; the die attach solder must have a higher reflow temperature than the package solder, so the die does not detach from the package during SMT assembly for the light engine. Tin-silver-copper (SnAgCu or SAC) solders typically used in SMT process lines reflow at temperatures in the 240 to 260^{o}C range, whereas the AuSn solder is reflowed above 300^{o}C. A less-used alternative for high-power packages includes silver sintered materials, which consist of nano-scale silver particles that undergo atomic diffusion to fuse together at 180 to 300°C to form a nano-porous, yet pure, silver joint. [43] Silver sintered materials can be applied as a paste or a preformed film to sinter thermally with pressure during the thermal process or without pressure in a reflow oven. These silver materials have shown superior mechanical reliability and higher thermal performance than AuSn eutectic solder.

Bond wires are typically made of gold for semiconductor packaging due to its high resistance to surface corrosion and bonding stability and are principally used as an interconnection material in semiconductor packaging. With the high prices of gold, manufacturers have looked to other materials such as silver for their good electrical and thermal conductivity. Unfortunately, the challenge in using silver bonding wires is poor reliability due to silver migration. While some low-cost products use silver wire bonds, gold is the predominant choice. This has made the interconnect a sizeable portion of the packaging bill of materials, especially for COBs which can contain many die.

There are many manufacturers of ceramic substrates and MC-PCB materials. Many ceramic substrates manufacturers are based in Taiwan, and China has many PCB manufacturers. Some representative LED substrate manufacturers include the following:

- Bergquist Company (Henkel), Cambridge America, and Coorstek in North America
- Tong Hsing, Chin-Poon, Ecocera, Viking Tech, Gia Tzoong, HolyStone, and Leatec in Taiwan
- Zhuhai Totking, Mascera Technology, 3X Ceramic Parts, HuanYu, and Hunan Ketao in China
- Denka, Kyocera, and Maruwa in Japan

Manufacturers of die attach and bond wires include:

- Alpha Assembly Solutions and Indium Corporation in North America
- Heraeus in Europe and Tatsuta in Asia

3.3.4 Down-Converter Application

The application of phosphors or other down-converter materials to achieve high-quality white light at the specified chromaticity point and color quality requires careful control of material composition and layer thickness. A manufacturer has several options available to control the white LED color point, including the choice of blue LED pump wavelength, phosphor conversion strength (phosphor loading and thickness), phosphor color point, and choice of phosphor composition (further described in Section 3.3.5).

There are several different methods available to apply a phosphor to the blue die including: the relatively simple dispense method (fill the cavity), the use of a conformal coating such as depositing a silicone/phosphor mixture, the use of a molded phosphor loaded film, the use of phosphor-loaded ceramic platelet, or the use of a remote phosphor. The phosphor application method affects many characteristics of the final package and must be carefully chosen for each package family and its required performance. The dispense method is largely utilized with plastic package mid-power LEDs and COB packages, while the conformal methods are more commonly used for high-power LEDs or CSPs (volume emitting die). Three common application methods are illustrated in Figure 3-26. Remote phosphors are generally applied in light engines and modules and will be discussed in Section 3.4.2.

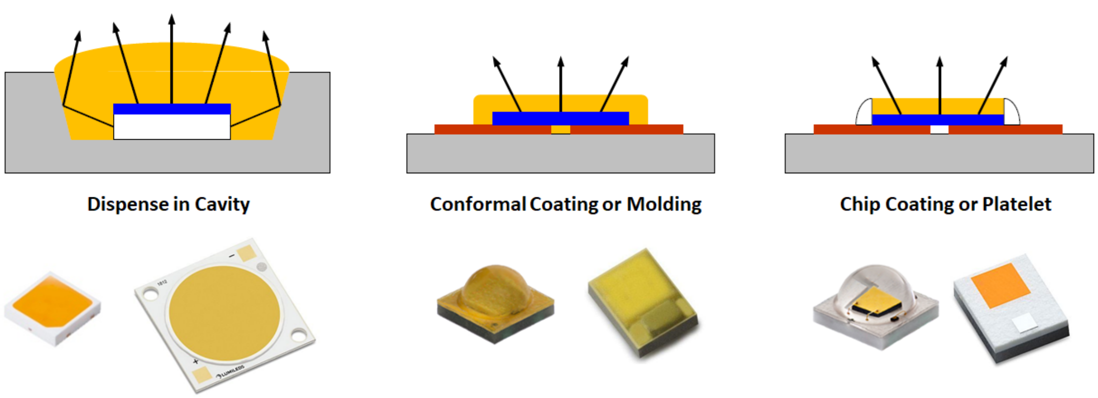


Figure 3-26 Three common phosphor application methods for the major LED architectures are illustrated along with some product examples using that technique. Mid-power LEDs and COBs use a dispense application and high power LEDs can be a mixture of conformal coating/molding or chip coating/platelets. [44]

Manufacturing processes play a large role in color consistency of production parts. The amount of phosphor conversion from sample to sample must be carefully regulated to yield a reproducible chromaticity point. The resulting white LED chromaticity point is dependent on three major parameters that are challenging to tightly control in high volume with the inherent parameter variation in some of the production processes. For example, the blue LED wafer has a wavelength distribution across the 150 mm wafer (which can have 100,000s of die) with a wavelength variation of +/- 5 nm (or less for extremely optimized MOCVD process tools). The exact wavelength combined with the phosphor particle loading into the silicone matrix and the layer thickness is what defines the white point. If two of these three main parameters remain fixed, but the other one changes, so does the resulting white color point. The tolerances of the production processes impact the resulting distribution of LED white points in the LED package production line.

Carefully controlling the distribution of phosphor particles in the silicone matrix is critical to create reproducible white chromaticity points in production. Typically, a slurry is created by mixing the phosphor powder into the silicone binder using a centrifugal vacuum mixer and then is placed into the syringe of the dispense system as shown in Figure 3-27. Phosphor particles are very dense and will tend to settle out of the slurry which can lead to non-uniform deposition from part to part over time in a production line. Uniform mixing and dispersion of the phosphor particles in the silicone is critical, so the same particle loading can be achieved part after part. The pot life of the phosphor/silicone mixture, or the time before the silicone viscosity changes and the dispersed particles can settle out in faster, is ideally 8 to 12 hours (the length of a manufacturing shift). A thixotropic agent such as fumed silica can be added to the phosphor slurry to help keep the phosphor particles from settling down to the bottom of the syringe. Syringe agitation by the dispense system is another method to prevent particle settling. The phosphor particle settling becomes more problematic as phosphor blends with multiple different phosphors are used to create different spectral power distributions.

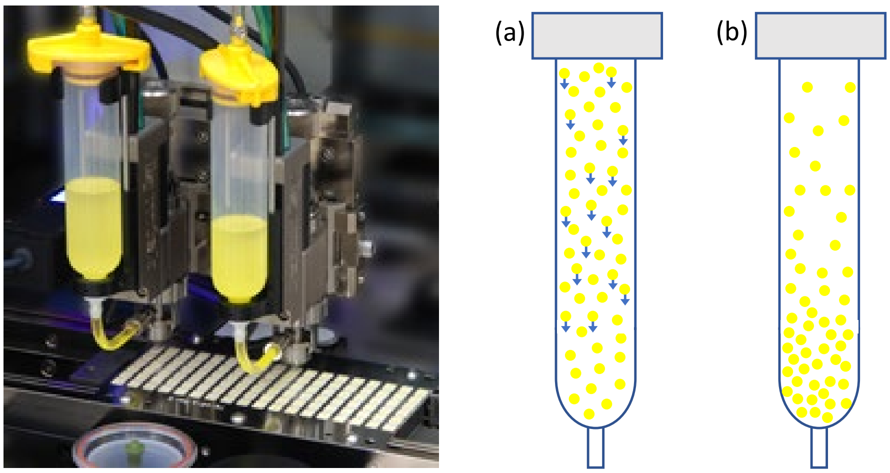


Figure 3-27 Image of a jetting nozzle for phosphor dispensing (left). Schematic of the phosphor settling process (a) before and (b) during settling (right). [45]

In a high-mix manufacturing line offering a full-range product platform, there might be 6 to 8 CCTs and 2 to 4 CRIs, creating 24 or more phosphor solutions per LED package product family. In addition, a high-mix production environment can lead to material inefficiency due to the need for a finite stabilization period when switching between mixtures for different product models (the pot life of the phosphor mixture expires typically in 8 to 12 hours). A manufacturing process must quickly dial-in and stabilize a new phosphor/silicone mixture to target a given chromaticity point to keep a high line throughput and manufacturing efficiency.

Despite ongoing development work by manufacturers to uniformly coat a phosphor/silicone mixture, a wide distribution of LED chromaticity is still found in production processes due to the inherent distribution in the various components that control the final chromaticity point, as seen in the blue points in Figure 3-28 . Lumileds developed another approach to provide phosphor color conversion by using pre-characterized phosphor ceramic sheets, which are cut into LED chip-sized platelets, called Lumiramic technology. [46] These platelets were binned for their phosphor color point and then matched to the measured wavelength of the LED chip. Once the matching pair of phosphor platelets and die were identified, the platelet was attached to the die with a transparent polymer adhesive. This approach strongly reduces the white chromaticity point spread, as seen with the red points in Figure 3-28, compared to the use of phosphor particles deposited in a resin (blue points).

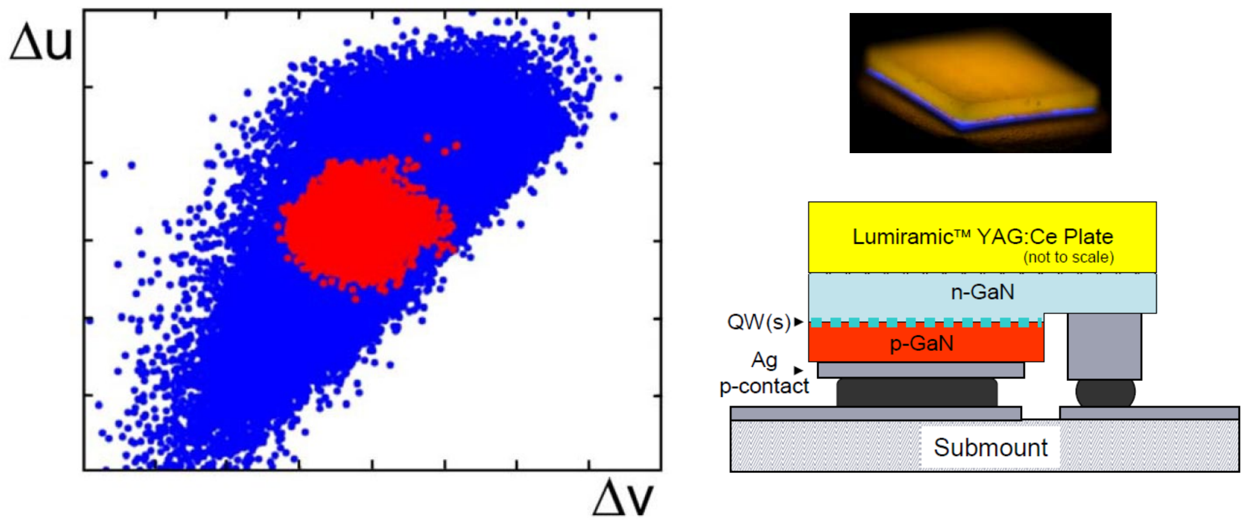


Figure 3-28 Comparison of the color point control for high-power white LED manufacturing using a phosphor slurry and a ceramic platelet. The blue area represents the typical color point distribution of using a phosphor slurry, whereas the red represents the distribution of LED using a ceramic platelet. LED device image and illustration of a TFFC LED with "Lumiramic" ceramic phosphor platelet. [46] [47] [48]

While matching ceramic platelets to exact LED die wavelengths yields the tightest wavelength distribution in production, it is very costly and time consuming to measure the phosphor platelets and then mix and match platelets and die. More cost effective approaches include coating solutions, such as over-molding phosphor in a silicone matrix over the die or applying a conformal coating on the die. A conformal coating is often preferred over a molded film to achieve improved chromaticity point consistency, as shown in Figure 3-29.

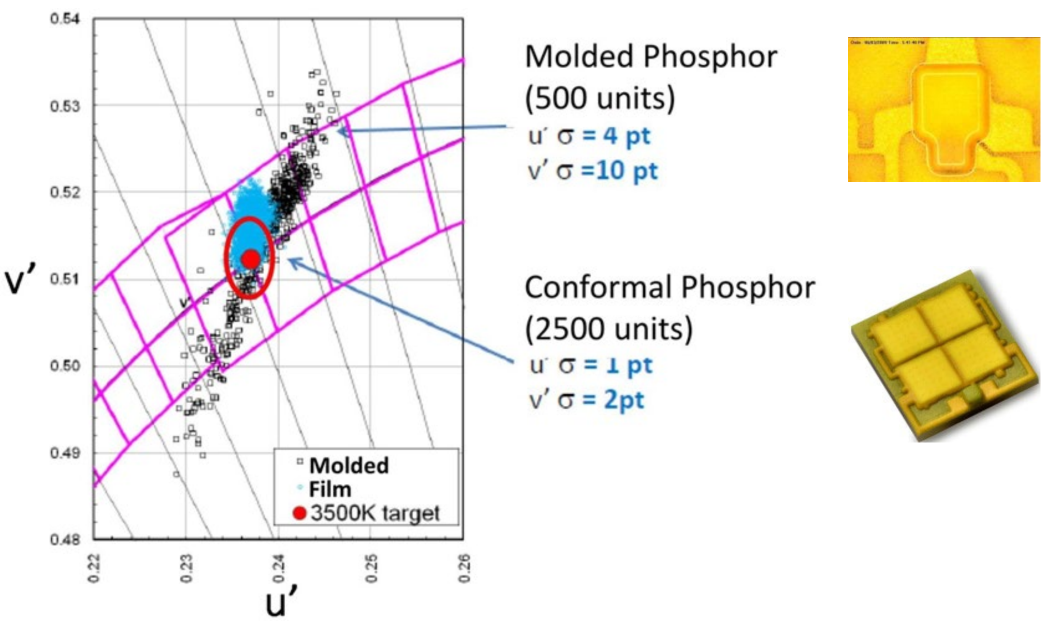


Figure 3-29 Comparison of the color point control for manufacturing using a molded versus conformal phosphor coatings. The conformal phosphor provides a tighter color point distribution than the molded phosphor. [44]

Conformal phosphor coatings can be applied with different methods such as electrophoretic deposition or settling the phosphor particles on the chip. As described above, the phosphor particles can settle from the silicone matrix since they are dense relative to the silicone. While settling is undesirable when in the dispense tool syringe, settling phosphor particles onto the chip will provide a conformal coating in the package, as illustrated in Figure 3-30. Settling of the phosphor particles from the dispensed silicone matrix can be accelerated by using a heated substrate chuck since the silicone viscosity decreases at first when it undergoes the thermal cure cycle. A number of warm white package manufacturers use the settling process for the red oxynitride phosphor since it is more thermally sensitive than the yellow yttrium aluminum garnet (YAG) phosphor. The LED chip and the package substrate will act as a heat sink to help remove the heat generated in the settled red phosphor particles more efficiently (than through the silicone with poor thermal conductivity), thus limiting the thermal efficiency quenching. While the red phosphor is being settled, the yellow phosphor can be settled as well, or instead, remain dispersed in the silicone encapsulant.

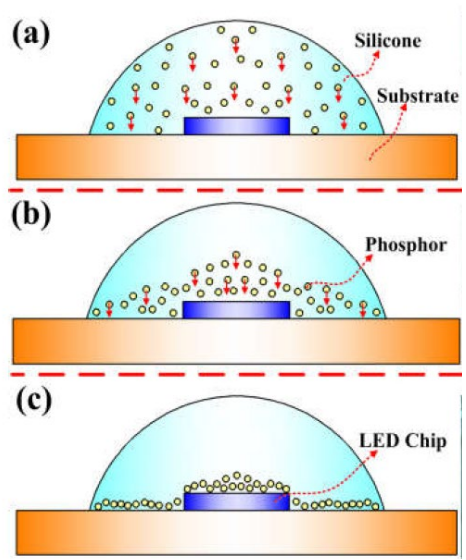


Figure 3-30 Schematic of the phosphor settling process (a) before (b) during and (c) after settling. [49]

The phosphor application for the CSP LED differs from the other package platforms described above. The processed LED wafer is singulated and measured, then die are transferred onto a thermal tape for phosphor dispensing, as illustrated in Figure 3-31. The phosphor is dispensed and planarized to coat the sidewalls with phosphor and the CSP is subsequently singulated to create the finished LED. Alternatively, a roll-to-roll film coating process using hot-melt adhesives can be used to integrate the phosphor layer to the CSP LEDs.

To further tighten the chromaticity point tolerance, a tunable phosphor application process could be employed. One form would be to test the die in the package prior to phosphor application and to adjust the phosphor recipe to apply the correct concentration and thickness of phosphor to achieve the target chromaticity point. Alternatively, the phosphor could first be dispensed and then the white point is measured. If the LED meets the chromaticity target, no further processing is required; if it does not meet the target, then an additional amount of phosphor could be applied in a second step. For this secondary application methodology, the first deposition needs to err under the desired white point so as not to exceed the target within the dispense tool volume dispense tolerance. To date, the tunable phosphor application process is not common due to the extremely cost-sensitive LED packaging sectors with lower profitability. Alternatively, if the blue LED epitaxial wafers could be produced with a 1 nm wavelength distribution across the entire 150 mm wafer, then creating a wafer of white LEDs with tight chromaticity point tolerance would be much more straightforward.

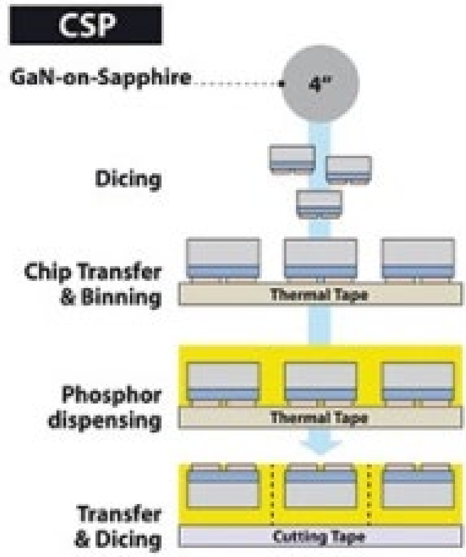


Figure 3-31 Schematic of the phosphor application step for the CSP form factor. [50]

3.3.5 Down-Converter Materials

Phosphors and other down-converter materials are expensive materials, especially when considering their associated matrix materials (e.g., silicones). While part of the cost is linked with the raw materials themselves, especially for the more specialized red phosphors and quantum dot materials for warm-white LED packages, the other cost contributer is the processing of the materials. The cost of the cerium-doped YAG phosphor has come down dramatically over the past decade from \$2000/kg to < \$600/kg. Cool white LEDs have a very low portion of the packaging BOM associated with the phosphor powder itself. The silicones, interconnects, and package substrate are bigger contributors than the phosphor powder itself. Red oxynitride $(Sr,Ca)AlSiN_3:Eu^{2+}$ (SCASN) phosphors and the narrow-band potassium fluorosilicates $K_2SiF_6:Mn^{4+}$ (KSF or PFS) phosphors are still more expensive, running 2 to 3 times the cost of the YAG yellow phosphor.

Improvements are required in the manufacturing of the phosphor or down-conversion materials to lower costs and manufacture more efficient, uniform, and reproducible materials characteristics. Areas for materials improvement include the realization of more uniform particle sizes, better controlled morphology, improved chemical and thermal stability, and more consistent excitation characteristics. Impurities can decrease optical property performance much more rapidly than mechanical properties. These impurities may be introduced in one of the reactants, a solvent, or by the equipment used during the manufacturing of the phosphor. It is not uncommon to find that 10 parts per million (ppm) or less of a metal impurity can significantly decrease phosphor brightness. For example, large improvements in phosphor quantum efficiency (QE) may result in shifting from a 99.5% pure precursor to a 99.99% pure precursor, so manufacturers often must balance a large increase in precursor cost with the resulting material performance.

While significant improvements have been made to narrow-band KSF red phosphors over the past several years, opportunities still exist to improve material synthesis and composition to result in fewer materials defects and allow for higher activator manganese (Mn) concentrations that can reduce the amount of phosphor materials needed on the LED. Innovations in phosphor synthesis and materials processing has led to improved QE in KSF phosphors, as seen in Figure 3-32, which can lead to lower phosphor volumes at the same chromaticity point currently in a comparable LED.

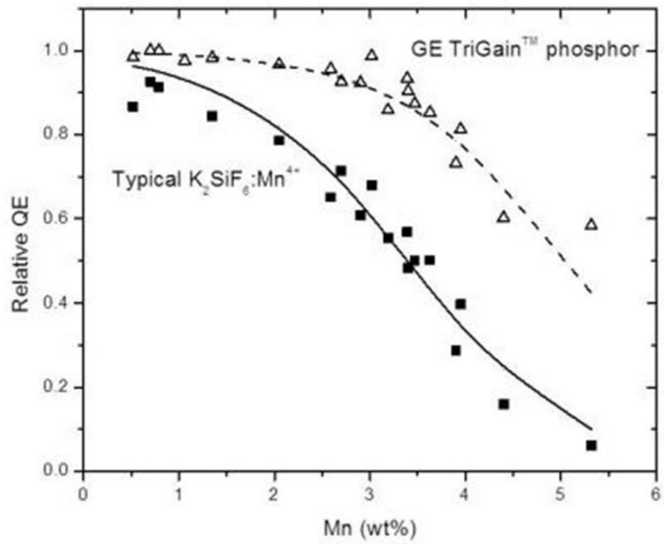


Figure 3-32 QE improvements can be seen in KSF phosphor from improvements in synthesis and materials processing innovations when comparing improvements by GE in their TriGain KSF phosphor to the typical KSF phosphor. [51]

Batch-to-batch variations in phosphor powder (e.g., particle size and chromaticity point) can lead to a significant amount of waste stream of expensive materials since new batches must be qualified prior to use in the LED manufacturing line. This qualification generally involves a trial batch approach to establish the transfer functions, which diverts effort and uses up material. Part of the reason for a trial-and-error approach is the current limitation in accurately characterizing phosphor powders and their interaction with matrix materials. Powder-level measurements include the determination of excitation, absorption, and emission characteristics, decay lifetime, quantum efficiency, particle size distribution, and reliability with respect to high temperatures, humidity, and incident flux. While these powder properties are well understood and measured, the complex interaction between the phosphor powder and the silicone matrix material creates the necessity to test for compatibility in application and assembly.

Scaling up phosphor production from R&D to pilot-scale production and eventually to full-scale production often takes a significant investment in both time and resources. Challenges can be encountered during the scale up of the blending, precipitation, or annealing steps, including variation in dopant concentration, changes in phosphor particle size, and varying sintering properties of the annealed phosphor. In terms of manufacturing improvements, the introduction of continuous processing methods (as opposed to batch-processing methods) has the potential to significantly reduce phosphor manufacturing costs, though other issues can be encountered when phosphors are scaled by annealing in a large furnace. For example, when annealing in a large furnace, a boat or crucible (of phosphor) located in the middle of the furnace hot zone may experience a longer time at a higher temperature than a boat on the edge of the hot zone resulting in a performance variation. Additionally, as larger size crucibles are used, sometimes a "striation" appearance of the sintered phosphor occurs where powder at the bottom is more sintered than powder at the top of the boat. This can often happen when precursors of very different particle sizes and or densities are used, or when fluxes are employed. Finally, the development of materials compatible with manufacturing at lower temperatures and pressures would help simplify the manufacturing process. Much of the manufacturing technology for garnet, aluminate, and silicate-based phosphors (yellow/green emission) is well established; however, an improved low-cost batch manufacturing process for nitride-based red phosphors is required to efficiently handle the higher temperatures and pressures involved.

Another consideration in the manufacturing of phosphors is their supply chain. Phosphor materials contain rare earth elements, which are a set of seventeen chemical elements in the periodic table (specifically the fifteen lanthanides, as well as scandium and yttrium), that are also used in other sectors of clean energy technology such as electric vehicles and wind turbines. Contrary to their name, most rare earth elements are relatively plentiful in Earth's crust, with cerium being more abundant than copper. While still abundant, their risk of supply disruption due to heavy concentration in a few countries, along with their importance to the clean energy economy, make them a critical material for the United States. [52] Today, China largely dominates rare earth production and controls large portions of the supply chain and pricing for these materials, as China's production is approximately double that of the next three leading countries combined (United States, Australia, and Myanmar). Outside the leading producers, significant reserves are found in other countries such as Canada, Vietnam, Brazil, India and Russia, although these locations only contribute marginally to this market today. [53] The geographical concentration of rare earths poses a risk for the supply of phosphors, a crucial component for LED lighting. Fortunately, on the basis of lumens per rare earth ounce, the consumption in LED lighting is orders of magnitude less than used in fluorescent sources. [54] [55]

Quantum dots (QDs) have long been targeted for use as down-converters in LEDs due to their combination of two unique emission characteristics: tunability of wavelength and narrow emission linewidths. These quantum-confined semiconducting nanocrystals are made of inorganic semiconductor material and commonly "grown" using colloidal synthetic chemistry, with electron and hole confinement, that results in unique optical properties. Colloidal QDs feature a tunable bandgap that can span the entire visible spectrum with nanometer scale resolution by adjusting the particle size and a narrow full width at half maximum (FWHM) owing to the direct transition from the band gap edge. Until recently, QDs have not gained much traction as a drop-in solution into the LED package because the LED operating temperature and blue flux intensities result in strong thermal quenching and fast photo-degradation. R&D progress in this area has led to the commercialization of a mid-power LED package using red QD down-converters (combined with phosphors). [56] LEDs with on-chip application of down-converter material can operate where the QD temperature exceeds 100°C and the blue flux intensity reaches 0.2 W/mm^2 in mid-power packages. Red QDs used in combination with a conventional phosphor material can improve LED conversion efficiency by 5% to 15% over commercial PC-LEDs between CCTs of 2700 K to 5000 K through reduction of the amount of longer wavelength red light where there is limited eye response. [57]

While cadmium selenide (CdSe) QDs provide the best performance to date, there is still the need to develop alternative cadmium (Cd)-free QDs due to the regulatory requirements on Cd use regulated by the European Union (EU) under the Restriction of Hazardous Substances (RoHS) Directive. The most advanced Cd-free QD technology is currently indium phosphide (InP)-based QDs, which is the dominant QD system for display applications. Currently, InP QDs emission spectral widths (FWHM) and environmental stability does not meet the level of their Cd-containing counterparts. The FWHM has improved the past few years and is now approximately 34 nm for green and 37 nm for red, nearing the target of 30 nm FWHM. The progress in the last few years has come from better materials design, but stability is still a large hurdle that requires further research and development. The DOE SSL Program is funding R&D to improve performance and stability of InP QDs. [58] [59] Other potential Cd-free QD systems include perovskites, which are still in the early stages of development and require more work to assess the performance levels and stability.

Beyond creating QDs with the required performance properties and reliability behavior for incorporation in LED packages, the ability to manufacture large-scale batches of QD material is critical for use in SSL. One significant hurdle in QD synthesis is controlling the size of the QD ensemble. Slight diameter changes will result in wavelength changes in the down-converter, as illustrated in Figure 3-33. When the ensemble of QDs with slightly varying diameters is applied in an LED package, the emission FWHM can broaden. New synthesis techniques can help improve the layer-by-layer synthesis, which is difficult to consistently control. One effort to potentially significantly improve the scalable synthesis of high-performance QDs employs a convergent (rather than linear) approach that uses a single-step heterostructure synthesis. This creates graded alloy QD architectures using tunable reaction kinetics of a set of precursors. Reliably dictating QD size, concentration, and monodispersity requires well-controlled precursor conversion. The DOE SSL Program is funding research to prove out the synthesis reproducibility, QD performance, and reliability using new colloidal synthesis. [60] In addition, further development of QDs that do not contain heavy metals (such as Cd or Pb) or scarce materials is needed for the changing regulatory requirements on these materials. Once the performance properties and stability challenges with QDs have been largely met, then development work to scale-up QD synthesis for mass production is required.

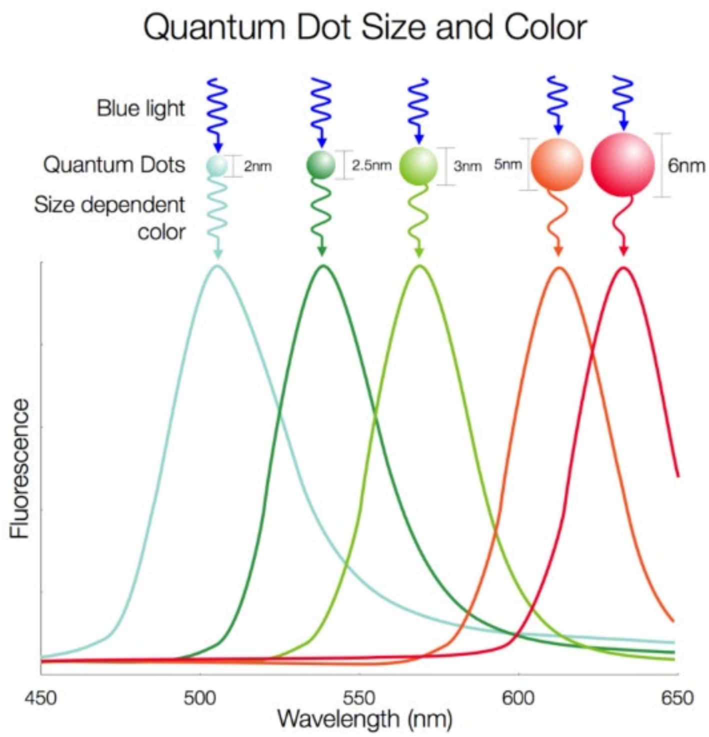


Figure 3-33 Emission wavelength of CdSe QDs as a function of dot diameter. [61] As the diameter increases, the emission wavelength of the QD increases.

Major suppliers of phosphors and quantum dot down-converter materials to the industry include the following:

- Intematix, Lumileds (internal)[4], GE, PhosphorTech, and Nanosys in North America
- Merck/EMD and Osram Opto (internal) in Europe
- Nichia (internal), Mitsubishi Chemical Corp, Denka, and Luming Technology in Asia

3.3.6 Encapsulation and Lensing

The LED die is encapsulated to provide environmental protection and improve light extraction from the LED chip and phosphor. Encapsulation is generally accomplished through the application of a silicone-based layer since other encapsulants, such as epoxy, degrade more rapidly with the high energy blue flux. Only certain grades of silicone material are suitable for LED applications to withstand the elevated operating temperatures and high blue optical flux densities while providing high transparency and high permeability (for oxygen and water). In high-power LEDs, the encapsulation is often in the form of a molded lens over the LED. The lens assists with the efficient extraction of light from the LED die and controls the directional emission characteristics. It is common for the silicone material to also act as a matrix for the phosphor or down-converter material. In this case, the phosphor/down-converter material is dispersed within the silicone matrix prior to being deposited over the LED die such as with mid-power LEDs and COBs.

[4] "Internal" refers to manufacturers that produce phosphors and quantum dot down-converter materials, but only use these materials internally within the company rather than selling it externally.

Silicones consist of an inorganic silicon-oxygen backbone (siloxane chain) with organic hydrocarbon groups covalently bonded to the silicon atoms. Methyl (CH_3) siloxanes use a methyl functional group on the siloxane chain, whereas phenyl (C_6H_3) siloxanes use the phenyl group off the siloxane chain. The different functional groups are illustrated in Figure 3-34. The properties of the encapsulant and which functional groups are used impacts the resulting properties of the LED package.

Table 3-2 shows some of the key difference in properties for the methyl and phenyl- silicones; phenyl silicones have a higher refractive index, but methyl silicones have a better stability under blue optical flux.

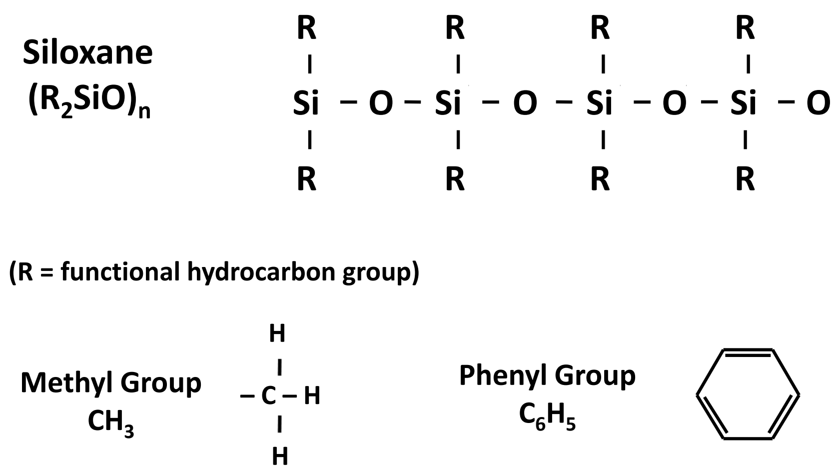


Figure 3-34 Schematic of LED-grade silicone molecules. The siloxane chain functional hydrocarbon group affect the resulting encapsulant properties. The most common function groups are methyl and phenyl groups. [62]

Table 3-2 Different properties of a methyl-based and phenyl-based LED grade silicone. The methyl-silicone has better stability while the phenyl-silicone has better light extraction and gas permeability. [63]

	Methyl	Phenyl
Refractive Index (np)	1.41	1.53-1.54
Transmittance	Excellent	Excellent
Light Stability	Excellent	Very Good
Gas Barrier	Fair	Very Good

Most optical silicones consist of a two-part solution (A:B) that can be combined with the down-converter. The two-part silicone compound is mixed in a centrifugal vacuum mixer to degas, thereby preventing the formation of bubbles which cause light scattering. After mixing the silicone encapsulant (which may have phosphor loaded in it), it is applied to the LED package by dispensing or over-molding processes, as illustrated in Figure 3-35. After being applied to the package, the silicone must undergo a thermal cure cycle. While a one-step thermal cure is possible, it can lead to poor surface wetting and result in silicone shrinkage and pulling from the surface. A multi-step cure where the temperature is stepped up can lead to a nice flat surface through well-promoted wetting. Additionally, the multi-step cure allows any bubbles to escape the surface better than in the one-step cure.

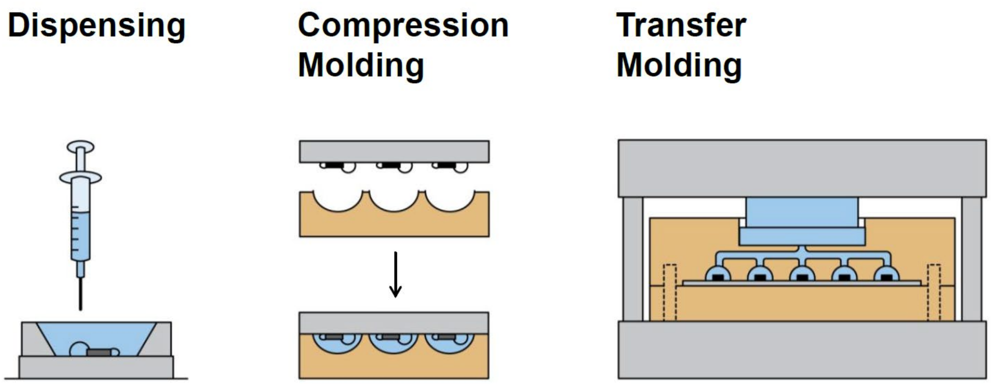


Figure 3-35 Illustrations of three common silicone application techniques (with or without phosphor) including dispensing, compression molding, and transfer molding. [63]

The appropriate silicone formulation for a specific package type will depend on its required rheological and mechanical properties. The rheological properties are critical for the manufacturing processes, whereas the mechanical properties must be selected to provide the right hardness level for the final package. Dispensed silicone formulations typically have a lower viscosity than those used in transfer molding process, which tend to have higher viscosity and elongation percentage. A silicone with higher hardness (in the Shore D range) is preferable for high power packages to provide a strong hemispherical lens that is not tacky (to avoid collecting dust and contamination particles). Mid-power and COB packages utilize a silicone with Shore A hardness to provide stress relief for the many wire bonds providing electrical connection to the LED die.

Increasing the refractive index of LED encapsulants can improve the light extraction out of the package, thereby leading to higher efficiencies. The higher the refractive index, the more light that can be coupled from the chip. Methods to increase the refractive index involve adding more phenyl end groups to the siloxane backbone chain (phenyl-based silicones) compared to the methyl-based silicones. The methyl siloxanes commonly used in blue LED packages have a refractive index of ~1.41, whereas the phenyl siloxanes commonly used in white pc-LED packages have a refractive index of ~1.55. There is a practical limit to adding phenyl end groups to the siloxane chain; when too much phenyl content is added the stability of the silicone decreases under LED optical flux densities and temperatures, essentially creating an upper limit at the 1.55 refractive index available today. [64] Phenyl silicones have a better gas barrier and are more resistant to silver corrosion, which helps maintain high light output from the package. [63] Often methyl silicones are used for blue LED packages since they can better withstand the high energy blue photon flux and provide better reliability than their phenyl counterparts.

The silicone matrix materials are being pushed to their limits by the high photon fluxes and high thermal loads being generated by high-performance LEDs. The phosphor within the silicone is typically the hottest part of the LED package due to the light conversion process and Stokes loss energy being dissipated as heat. These materials are also subject to issues including volatile organic compound (VOC) induced transient browning, thermally induced permanent browning, and silicone cracking. Only certain grades of silicones can avoid degradation as a function of this exposure and show good long-term stability. Even within the "LED grade" silicones, there are trade-offs on their performance and stability behavior. The long-term lumen maintenance during LM-80 testing shows that higher index phenyl siloxanes have lower stability than the lower index methyl siloxanes, as illustrated in Figure 3-36.

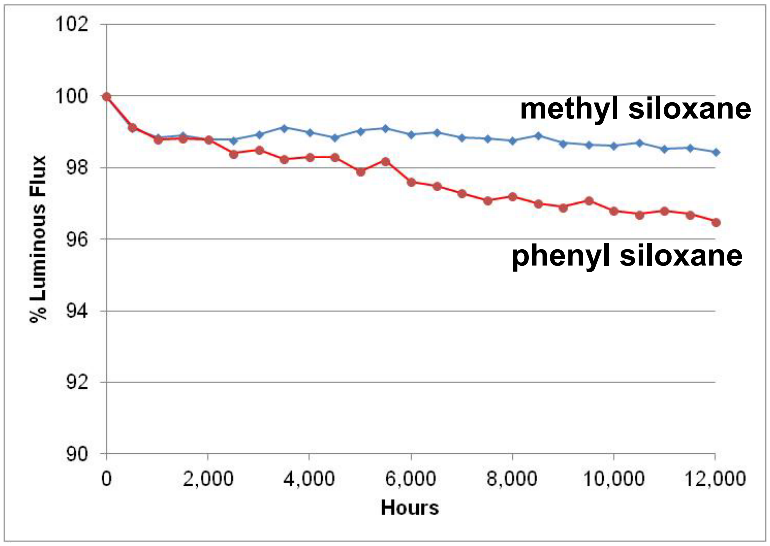


Figure 3-36 Lumen maintenance of a high-power LED with a methyl siloxane (blue line) and a phenyl siloxane (red line) encapsulant. While the phenyl-based silicone provides better refractive index, the methyl-silicone provides better photothermal stability resulting in a higher retained lumen flux over operation. [62]

The low thermal conductivity of current silicone encapsulants (~ 0.2 W/mK) can lead to heating of phosphor particles and rapid degradation of conversion efficiency when the LED is driven under high current operation. The Stokes losses from the conversion of blue to white light result in 20% to 30% of the absorbed pump energy to be lost as heat, which causes the phosphor particle to have lower efficiency if the heat cannot be conducted away by the surrounding encapsulant. Increasing the thermal conductivity of the encapsulant to 1 W/mK can lower the phosphor layer temperature by 50°C or more, which can lead to phosphor efficiency improvements of 10% or more during standard operating conductions of the LED package, as seen in Figure 3-37. While improving the thermal conductivity of encapsulants would be of great benefit, progress in this area has been slow. Thermal transport properties of hybrid materials (e.g., high thermal conductivity additives in a silicone resin) present an opportunity for improvement through engineering the thermal conductance of the polymer/particle matrix. Reducing the scattering cross-section of particle fillers can enable higher optical transparency at higher inorganic loading. Moving this concept to the extreme by using inorganic encapsulants, such as low melting point glasses, is another potential path towards improving refractive index and thermal stability.

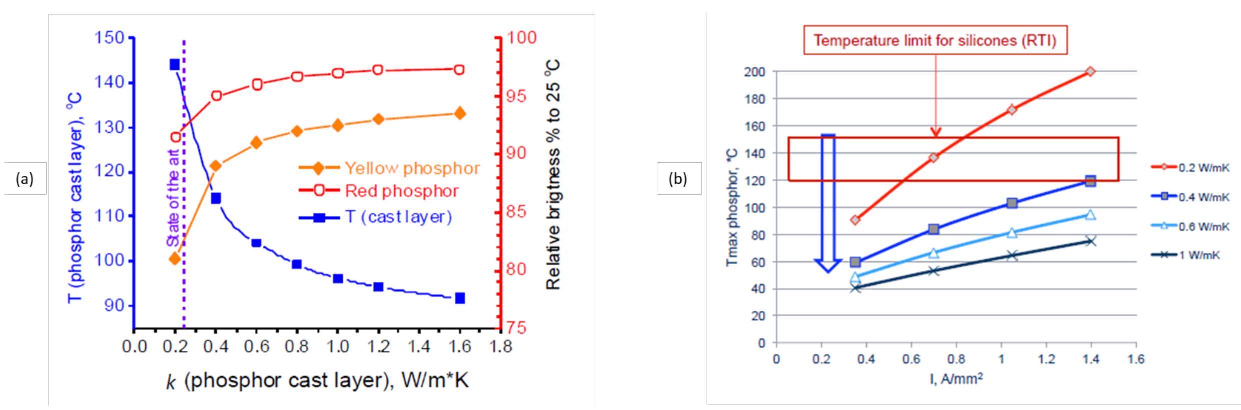


Figure 3-37 The temperature of the phosphor layer as a function of thermal conductivity and the impact to the relative brightness of LED phosphors and (b) the temperature of the phosphor layer decreases with increasing thermal conductivity of the encapsulant. [65]

Unfortunately, the premium-grade silicone materials required are very expensive and a significant cost factor in LED manufacturing. Lower cost alternatives with the requisite optical stability are required. Some representative "LED-grade" silicone manufacturers include the following:

- Dupont Specialty Materials (formerly Dow) and Momentive Performance Materials in the United States
- Wacker in Germany
- Shin-etsu in Japan

3.3.7 Test and Inspection Equipment

Test and inspection equipment are required throughout the LED package manufacturing process, from the inspection and qualification of incoming materials, through process monitoring and control, to end-of-line product testing. Test and inspection equipment for LED die manufacturing starts with qualification of manufacturing materials. This involves non-destructive optical inspection of substrates using tools like the KLA-Tencor Candela 8720 Inspection System, whose platform was developed in part with R&D funds from the DOE SSL Program [66]. Such inspection tools are also used throughout the wafer manufacturing process to detect killer defects at an early stage and optimize process yields.

Automatic visual inspection (AVI) tools perform much of the visual inspection, from incoming wafer inspection to fully processed die, including the inspection of the LED die after singulation. The AVI machines look for non-conforming defects such as improper cuts during singulation, metal contacts that are peeling or missing, large scratches or particles across the LED device, and more. This typically takes on the order of 10-15 minutes for a 100 mm wafer with 100,000 die. In addition, a manual microscope inspection is also employed by some manufacturers to look for large level defects that cross many devices and can confuse the AVI tools. These larger defects include large sections of scratches or peeling metal contacts. After the devices have undergone measurements via probing, they are then sorted into performance bins. Some manufacturers employ another manual visual inspection to check for probe damage (deep scratches) or other sorting defects on sorted die sheets (SDS).

A critical area for LED manufacturing is high-speed testing of the LED die, and later, the final LED package. The ability to rapidly characterize and bin LED die and packages is an important requirement for the manufacturing lines. LED die are typically characterized for light output, wavelength, forward voltage, reverse leakage voltage, and electrostatic discharge. The fabricated LED wafers are typically probed before singulation and the resulting wafer performance map can then be used to measure performance bins for wavelength, light output power, and forward voltage. The die is then sorted from the wafer level into SDS with other die in the same performance bin. While probing and sorting of the LED device wafer is quite advanced and manufacturers are able to measure every die and package, it is a time-consuming process in the manufacturing line. Testing is typically be performed under pulsed current conditions in order to determine the peak or dominant emission wavelength and the radiometric output power. Typical die probing speeds are 150 ms and sorting speeds are 190 ms per die. Considering a 100 mm wafer with 70,000 or more die, this constitutes a measurement time of several hours per wafer. For a 150 mm wafer with small LED die this can increase to 8 hours per wafer.

Manufacturing Opportunity: LED Device Testing Productivity. There is an opportunity to improve device testing productivity and LED package manufacturing efficiency. While improvements in upstream processes such as MOVCD growth and device fabrication can lead to processed LED wafers with less variation in wavelength, light output and electrical characteristics, the challenge is determining when the LED wafers are uniform enough to not require the probing and sorting of every die. This is the dilemma facing the micro/mini-LED development sector. Unique schemes to test sections of the wafer instead of individual die one at a time can help improve throughput but will require careful process uniformity understanding of upstream processes.

Testing of the final LED package is also performed to measure the lumen output, chromaticity coordinates, CCT, CRI, and forward voltage. LED manufacturers must manage the variations in LED properties during mass production to provide repeatable device performance to their customers. The packaged LEDs are sorted based on several key properties such as luminous flux and chromaticity. The result of this sorting is to create “bins” in which LEDs are sold to the luminaire customer. For most LED lighting professionals, the type of binning that comes to mind involves chromaticity variations. Color consistency in lighting is crucial since the human eye can detect minor color variations (tolerance regions described in MacAdam ellipse steps); therefore, tight color control is important for those producing LED luminaires. As described in Section 3.3.4, the source of color point variation in white LEDs results from variation in the underlying blue LED chip wavelength and the thickness and concentration of phosphor applied to the chip.

SDS provide a single bin of LED die for incorporation into packages to reduce the final white color point distribution (assuming a given phosphor application recipe). SDS are more typically employed for high power LED die (1 mm^2 or larger) since the resulting white color point distribution for single die packages with a conformal phosphor coating will be much more sensitive to the starting blue wavelength variability of die in the production line. Much of the difficulty and concern with binning is that most luminaire manufacturers want a certain chromaticity range around several defined CCTs near the black body curve, as shown in the International Commission on Illumination (*Commission international de l'éclairage* [CIE]) diagram in Figure 3-38. Unfortunately, the bin distribution of LED production covers much larger area of bins and not all of the bins are desired by the luminaire manufacturers. This binning problem can be largely reduced at the LED package level for multi-chip LED packages. LED manufacturers have sophisticated systems to mix and match LED chips and phosphor conditions to produce multi-chip LED packages that result in very tight color control within a 2-step MacAdam ellipse, which is comparable with that of incandescent bulbs (the highest bulb standard for color consistency). This mixing approach is illustrated graphically in the CIE diagram shown in Figure 3-39.

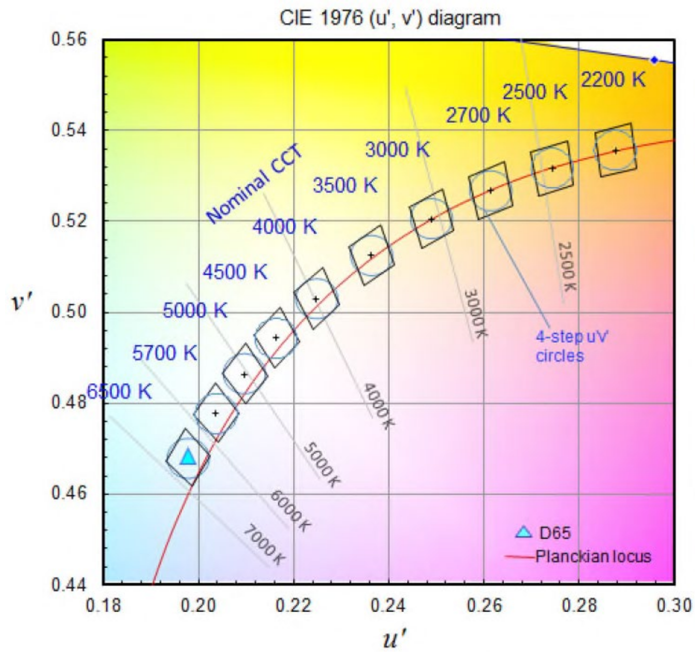


Figure 3-38 The chromaticity specification from ANSI C78.377-2015 of SSL products on the CIE 1976 (u’,v’) diagram. The black quadrangles represent the chromaticity tolerance size for a target CCT. The blue 4-step MacAdam circles are an alternate way of specifying chromaticity tolerances. [67]

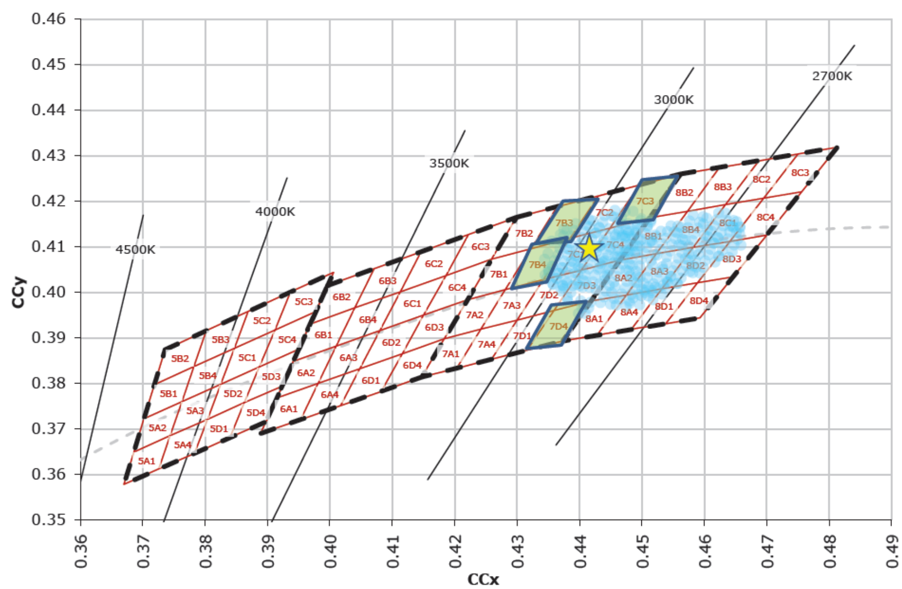


Figure 3-39 CIE 1931 (x, y) diagram with various chromaticity sub-bins. The blue area represents a typical LED chromaticity distribution in the production of white LEDs. To reach the target chromaticity bin, represented by the yellow star, LED manufacturers can match LED multiple white LEDs from a variety of bins to achieve the target color point. For example, LEDs from the four green bins can be mixed to generate the target color point. [68]

While this mixing and matching system is very effective for manufacturers to use the full distribution of white points to tighten the multi-chip package chromaticity distribution, other form factors, such as the cost-sensitive mid-power LED models can accept a little more die variation since the extra cost associated with sorted die sheets would reduce already thin profit margins. COBs with a large die array can handle a wider blue wavelength distribution since the photons from the different chips will reflect within the cavity and mix together to balance out some of the individual chip wavelength variations. These types of LED packages lessen the degree of chromaticity binning required, thus enabling luminaire and bulb manufacturers to deliver the consistent color with more ease. Some experienced LED luminaire manufacturers choose to do this mixing and matching themselves with individual LED components, but many luminaire makers can rely on the LED manufacturer's expertise in producing color consistent LED packages for ease of luminaire manufacturing. These tightly binned LED components can remove the issue of chromaticity binning, though it still comes at a manufacturing productivity cost, requiring algorithms to pour through die maps and mixing and matching the SDS in the pick and place systems to create the right mixtures of arrays.

In the past, testing of the final LED package was performed at room temperature (25°C), but most manufacturers are now measuring at a more realistic operating temperature of 85°C to help the luminaire manufacturer better understand what their expected performance of the package will be at the steady-state operating temperature of the luminaire. While the 85°C test point helps define the package performance at that specific temperature, not all luminaire manufacturers run the LEDs at the same temperature and operating current that the LED manufacturer uses for testing. Many performance parameter shifts occur with temperature; therefore, measuring closer to the final operating temperature improves the accuracy of the extrapolation of device characteristics. The luminaire manufacturer still needs to scale the LED package performance for their fixture design. LED manufacturers publish data for LED light output and color point shifts with increasing temperature and drive currents in the LED package data sheets to help luminaire manufacturers determine the performance of the LED package at their given luminaire operating conditions (temperature and drive current). Furthermore, many LED manufacturers have created design tools to help customers estimate the output of the LED at their operating conditions to help eliminate the guesswork.

Test equipment for LED reliability measurements is also necessary to perform burn-in testing, and complete long-term reliability testing to identify potential failure mechanisms and certify package lifetimes. While it is not an in-line test in the manufacturing line, it is critical equipment to certify package reliability for LED luminaires. Reliability equipment includes environmental chambers, an integrating sphere, and the necessary control electronics to perform package measurements of lighting output, chromaticity point, and forward voltage. To perform the reliability tests, LED packages must be assembled onto reliability test boards (PCBs) using the SMT process. The testing method for LED packages and arrays is well established and described in detail by the American National Standards Institute (ANSI) and Illuminating Engineering Society (IES) in ANSI/IES LM-80-20 standard: *Measuring Luminous Flux And Color Maintenance Of LED Packages, Arrays, And Modules.* [69] An example of an LM-80 complete test system is shown in Figure 3-40.

Figure 3-40 Reliability test equipment for LM-80 measurements. The LM-80 systems combine LED drive electronics with fully integrated thermal control systems and automated light measurement. [70]

In the LM-80 testing, three sets of LED samples of the LED make and model being evaluated must be tested at a specific temperature; one set at 55ºC, the second set at 85ºC, and the third set at one other temperature that the LED manufacturer may select. The standardized temperatures allows LED data sets to be easily compared. The third temperature, selected by the manufacturer, is available so that the performance of the LED can be highlighted if it has been designed for a particular application environment. The duration of the LM-80 test must be no less than 6,000 hours. The six reporting requirements in LM-80 for each working device under test (DUT) at each test interval are as follows: [42]

- Initial and subsequent flux values (e.g., luminous flux, radiant flux, photon flux)
- Initial and subsequent chromaticity coordinates, dominant wavelength, peak wavelength, or centroid wavelength. Chromaticity is required to be expressed in CIE u' and v' chromaticity coordinates
- Statistical information for all of the DUTs at each measurement interval
- Electrical drive level for photometric and electrical measurements
- Measurement point temperature and location for photometric and electrical measurements
- Description of the photometric measurement method

LM-80 data sets can be fit with an exponential decay model by using the methodology established in IES TM-21-19. [71] To avoid projections that exceed the statistical significance of the data, TM-21 mandates that rated flux maintenance life (L_p) times cannot be greater than 6 times the actual LM-80 test duration, and only when specific test conditions, such as the number of samples, have been met. For example, if L_{70} is the time required to reach 70% luminous flux maintenance and an LM-80 test was conducted for a total of 10,000 hours, then the maximum value of L_{70} is 60,000 hours, although the L_{70} time could be less. [42] Together, LM-80 and TM-21 have become the accepted methods for reporting the luminous flux maintenance performance of LEDs used in lighting applications, especially for white LEDs.

Other test equipment commonly utilized in a LED production plan includes tools to test LED package reliability. Examples of other reliability tools include thermal shock chambers to check the reliability of the package interconnects, and multipurpose bond testers to measure interconnect strengths (e.g., die shear, ball shear, and wire pull strengths). Furthermore, a probe station, pulse source and thermal electric stage are needed to perform thermal resistance measurements.

Manufacturers of test and inspection equipment for LED die and package manufacturing include the following:

- KLA-Tencor, Cascade Microtech, Labsphere, Nordson Yestech, Dage, and Vektrex in North America
- Instrument Systems (Konica Minolta), Gigahertz-Optik, and SUSS MicroTec in Europe
- MPI, FitTech, ASM Pacific Technology, Mirtec, and Nikon in Asia

3.4 LED Luminaire Manufacturing

Manufacturing an LED luminaire involves combining the LEDs with mechanical and thermal components (e.g., the heat sink), optical components to tailor the light distribution, and driver electronics to provide power to the LEDs. LED packages are a critical component of LED-based luminaires, and luminaire manufacturing revolves around integrating the LED source with the other luminaire components to achieve the required form factor and the optimum balance between cost, performance, product consistency, and reliability. The balance of these features and necessary trade-offs depends on the lighting application needs, the customer profile, and cost. For example, a 6-inch downlight for the residential market can provide 70 lm/W, whereas a higher end commercial downlight from the same manufacturer can reach 100 lm/W at the same CCT and CRI. The difference in these two models is a factor of design choices for the product requirements for those applications. A lower cost downlight will have fewer LEDs, which in turn are driven at higher currents to achieve the lumen output required, thus pushing the efficacy lower due to current density droop at higher drive currents. Additionally, lower cost power supplies or optics can have lower efficiencies.

Reducing the number of LEDs can lower costs at the expense of efficacy, but there are further consequences to consider: higher drive currents lead to higher temperatures in the package, which in turn leads to earlier lumen degradation and chromaticity shift, thus affecting the luminaire's reliability performance and warranty life. This describes just one tradeoff with the LED source design. Further subsystem design choices such as heatsink, driver, and optics designs lead to additional trade-offs. Understanding all the nuanced performance trade-offs and impacts on product design and manufacturing costs determines the efficacy, CCT, CRI, warranty life, and cost points at which different luminaire products are brought to market. Lighting quality features such as high CRI, color tuning, dimmability, and longer L_{70} lifetimes come at a higher cost. Lamps that have lower first cost generally do not have dimmability, longer lifetimes, or high CRI metrics. This illustrates why there is no "one size fits all" lighting product. The value of efficiency, color quality, or lifetime vary for different applications and affect what customers are willing to spend for those benefits. The fact that some form factors have lower efficacy than others does not necessarily indicate that certain LED lighting product classes cannot be made as efficient or reliable as other LED lighting products. Instead, this often reflects a specific tradeoff the manufacturer selected for the end-use case. There are certain cases, such as etendue limited lighting designs required for narrow spot lights, that can have efficacy limitations compared to large area light sources such as troffers (due to the small source size required to achieve small spot sizes), but these efficacy limitations are not fundamental in most designs.

Manufacturing of LED-based lighting products shares little in common with conventional lighting products because conventional lighting technologies tend to be based around the fixture-plus-lamp paradigm, with the manufacturing of each part handled completely separately, and often by separate companies. LED-based replacement lamps and LED luminaires have a similar level of integration, though lamps use a standard electrical interface and body size to allow use within conventional lighting fixtures. The integrated nature of an LED-based lighting product, where fixture, light engine, and driver electronics are typically combined in a single unit, significantly complicates the manufacturing process. Luminaire manufacturers have successfully addressed the challenge by introducing manufacturing technologies more commonly seen in the consumer electronics industry, simplifying the materials and manufacturing processes, introducing system-level design optimization methodologies (including design for manufacturing and design for assembly), and developing improved testing capabilities. Various sub-assemblies such as the light engine, the driver, the thermal and mechanical components, and the optics are often manufactured separately and then combined during luminaire assembly. Currently, the final assembly is more labor intensive than the manufacturing processes for the individual sub-assemblies. The main subsystems are discussed separately in the following sections before considering the complete luminaire.

3.4.1 LED Light Engines (Modules) Assembly

LED packages are a critical component of all LED-based luminaires, and luminaire manufacturing revolves around integrating the LED source with the other luminaire components to achieve the required form factor and the optimum balance between cost performance, product consistency, and reliability. While advances in LED component performance continue to be made, luminaire manufacturers continue to adjust their product designs and manufacturing processes to use the most appropriate LED packages that are available.

A key element of the LED-based luminaire and module assembly process is the use of SMT manufacturing processes to mount the LED packages onto the PCB to create the light engine. This light engine assembly typically entails using a stencil printer to pattern the solder paste die attach onto the PCB, then moving the LED package onto the solder pad via a pick and place tool. The PCB with the LED packages is then run through a reflow oven, where the solder paste melts to create permanent solder joints, to finish creating the light engine module. Suppliers of SMT manufacturing equipment include the following:

- Illinois Tool Works (Speedline) and Heller in North America;
- ASM SMT Solutions, Kulicke & Soffa (K&S), Panasonic, Juki, and Fuji Machines in Asia.

3.4.2 Remote Phosphors

Phosphor or down-converter material is normally applied at the package level; however, it can also be applied at the module or luminaire level. Phosphor conversion at the module/luminaire level is achieved by integrating phosphor-coated optical material placed some distance above blue-emitting LEDs. This method is referred to as a remote phosphor. The main advantage of using a remote phosphor is that the flux density of the blue light reaching the phosphor is reduced so temperature rise in the phosphor is also reduced, although thermal management of the phosphor material must still be considered. Lowering the temperature rise in the phosphor converter reduces thermal quenching within the phosphor particle, thus maintaining the phosphor efficiency level and enabling a more consistent chromaticity point. Another advantage is the higher tolerance of the blue emission variation from the pump LEDs since the various LED wavelengths can be averaged in the light mixing chamber before it reaches the remote phosphor, thereby providing more consistent color points. The main disadvantages are that much larger volumes of phosphor material must be used (which is expensive), deposition uniformity must be maintained over larger areas, and the optical system between the LED and remote phosphor may be more complex and less efficient. Some examples of remote phosphor configurations are shown in Figure 3-41. Companies such as Intematix and PhoshorTech in North America are able to supply sheets, or custom-molded shapes, of remote phosphor material with well-defined performance characteristics when combined with blue LEDs.

Figure 3-41 Examples of remote phosphor implementation into lighting products. [72] [73]

A newer class of LED lamps involve the use of filament LED sources which use a quasi-remote phosphor configuration. To create an LED filament, the LED die are typically mounted onto a glass substrate (or sometimes sapphire) that is optically clear to allow light to escape from the full circumference of the filament. Electrodes are plated on the substrate to connect the LEDs to the power supply. The LED filament is then overcoated with a phosphor/silicone coating, as illustrated in Figure 3-42. Using a high-grade silicone is important to maintain the long lifetime of the LED lamps. Some manufacturers use lower quality silicones to cut costs, but over time, the silicone can become brittle and can cause the filament structure to fracture and break the electrical connection of the string of LEDs. To enhance the performance of the filament source, the glass lamps are typically filled with a high thermal conductivity gas, such as helium, to help facilitate heat transfer from the LED filament to the glass surface.

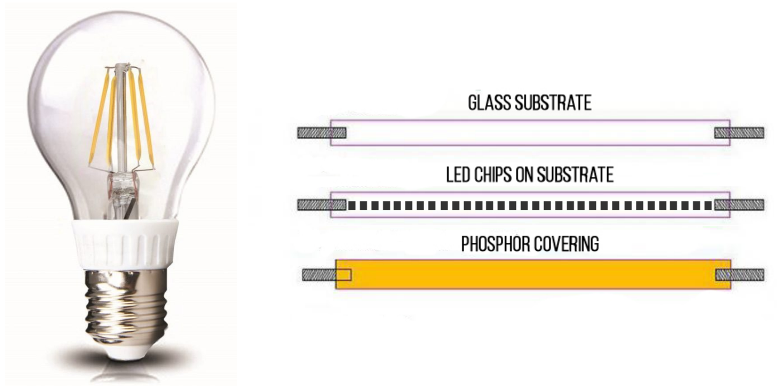


Figure 3-42 An image of a filament-style LED A-lamp (left) and a schematic of the assembly of a LED based filament (right). LED chips are mounted onto a glass substrate and then coated with phosphor in silicone. [74]

3.4.3 Optical Component Manufacturing

Luminaires incorporate a variety of optical elements to increase light extraction and tailor the light distribution. LED optics come in a variety of shapes and sizes; there are also a variety of optical materials to choose from and ways of attaching the optic to the luminaire housing. All of these considerations, as well as the luminaire form factor and lighting application, impact the optics design choice and manufacturing process. These optical elements might be refractive, reflective or diffusive in nature, depending on the application. Figure 3-43 illustrates some common secondary optics schemes in LED lighting, which all alter the path of the light, but create different effects. Total internal reflection (TIR) lens designs provide precise control over the light emitted and can create various beam angles and optical distributions used in directional lighting or area lighting applications. TIR lens designs can be both rotationally symmetric optics or freeform asymmetric lenses with different light distributions along X and Y directions. Reflectors redirect the light that is incident on the sidewalls, but they do not control the portion of the center beam which does not hit the reflector; therefore, reflectors do not have the same sharp a cutoff of the beam spread as TIR lenses. Diffusers are used to scatter the light and give a more uniform light output from the fixture and hide the multiple source images (hot spots) when arrays of LEDs are used.

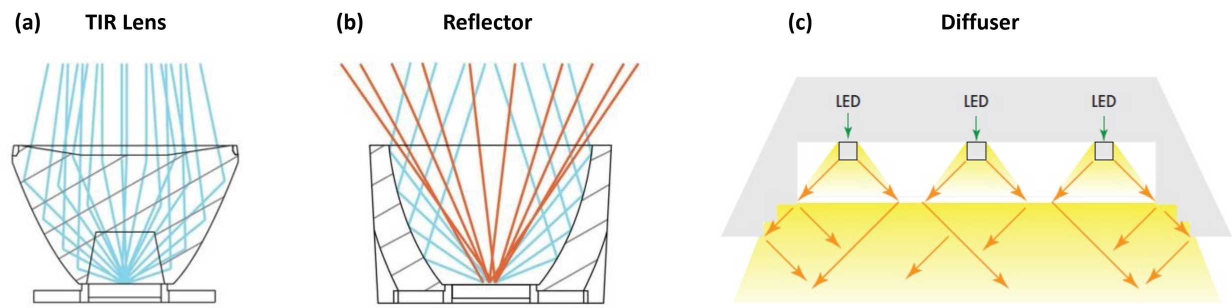


Figure 3-43 Illustrations of various secondary optics designs including: (a) a TIR lens which refracts the light to create a tight beam, (b) a reflector lens which reflects the incident light that hits the sidewall, and (c) a diffuser lens which scatters and diffuses the light that passes through the optic. [75] [76]

Common materials choices for LED optics include polymethylmethacrylate (PMMA), polycarbonate (PC), cyclo-olefin copolymers (COC), and silicones. When selecting the material for the secondary optics, factors such as refractive index, thermal and impact resistance, aging properties, and cost must be considered. PMMA is a widely used optic due to its low cost, ease of molding, high UV stability, high light transmission (93%) and a refractive index of 1.49. PC is also another widely used optic which is also easily molded and has a higher refractive index than PMMA (1.58), but a lower light transmission of ~88%. PC has lower water absorption and a higher softening temperature than PMMA, allowing for better heat resistance. PC has a low UV stability and yellows under prolonged UV exposure, which then contributes to chromaticity stability challenges in lighting products, PMMA is much more stable under UV exposure. COC provides high molding precision, high light transmission, a refractive index of 1.53, and high thermal and UV stability; and compared to PMMA and PC, COC has lower water absorption. Though the optical and mechanical properties are excellent, the higher cost of COC limits its use. Silicones also have benefits over PMMA and PC including higher temperature stability and UV stability, high impact resistance, and a low viscosity allowing easier molding and more complex lens shapes. Drawbacks for silicones include a lower refractive index of 1.42 and higher costs, though in some applications the cost premium is justified with improved optical performance.

Typical thermoplastic and thermosetting resin materials (e.g. PC, PMMA, COC, silicone) can be formed quickly and cost-effectively using injection molding techniques to produce optics with a high degree of repeatability and accuracy. The precision of the final optic depends on the molding press as well as the precision built into the mold itself. The mold requires a tighter set of tolerances than those required of the optic it produces, making it expensive to fabricate. Though creating the mold is a significant cost of the process, the investment is then justified when producing high volumes of optical lenses. If the volume of the production run is not high, then the cost per optic may become prohibitive for a specific custom design. Thermoplastic materials shrink as they cool, so the amount of shrinkage must be accounted for when designing the mold dimensions. A schematic of the key features of a mold is shown in Figure 3-44.

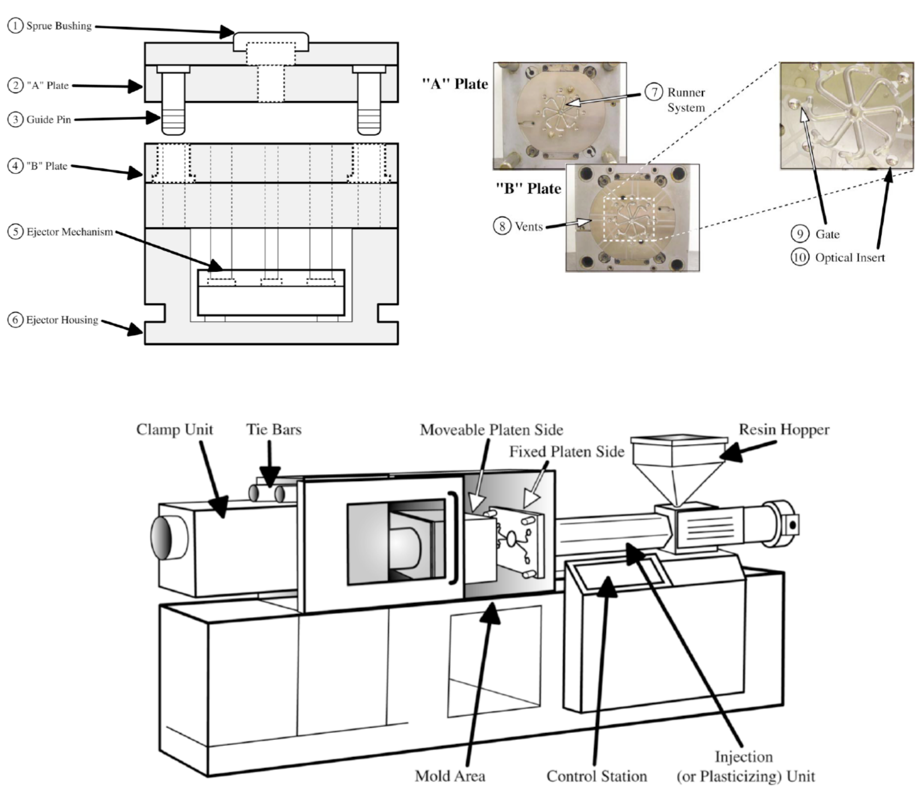


Figure 3-44 Schematic of a typical injection mold and its key features is illustrated (upper left), and images highlighting features inside the two mold plates are shown (upper right). An illustration of the main features of an injection molding system shows its key units (lower). [77]

The mold is mounted into the injection molding machine where the thermoplastic is melted and injected into the mold. Figure 3-44 illustrates the key features of an injection molding machine. The process begins with two halves of the mold coming together and clamping shut as molten material is injected into the mold at the optimum speed and pressure to flow into the mold and fill the cavities. After the necessary cooling time for the thermoplastic has passed, the mold opens to remove the optic. Then the cycle begins again for the next set of parts. Once the optical parts are removed from the mold, they still are connected through the runners (the paths that the molten plastic flows to fill the cavity shown in Figure 3-44). The optical parts must be “degated," or removed from the runner system.

Unlike the injection molding for the thermoplastic materials discussed above, the use of a silicone liquid rubber resin allows injection at room temperature with low clamping forces and at relatively low pressure through small gates and runners with good flow lengths due to the low viscosity. Furthermore, the low room temperature viscosity combined with the drop-in viscosity during mold filling (at higher temperature) allows the replication of micro-sized features with small radii of curvature, such as Fresnel lens patterns. [78] Silicones also can enable new design features that are not seen in the conventional thermoplastic optics such as PMMA and PC; since silicone remains slightly flexible, molding optical designs with features such as undercuts is possible. The optic can be designed with new shapes to improve light output in the fixture and improve durability over time or can be multifunctional behaving both as an optic and a gasket in the luminaire configuration.

Innovations to injection molding can improve manufacturing productivity. The conventional single-layer molding process for optical lens manufacturing can lead to long cycle times of up to 15 minutes due to the cooling times required for the lens thickness. Innovations such as multi-layer injection molding can allow the molding of thicker lenses with shorter cycle times by splitting up lenses into several layers which are then molded in parallel. Such novel practices are being used more in the development of automotive optics.

In addition to secondary lenses and diffusers, diffuse reflective layers are included in many luminaires to reduce the absorbing surfaces around the LED board or in the optical chamber to help improve light output from the system. White reflective materials made from spun polymer microfibers composites like high density polyethylene (HDPE) embedded with reflective particles or from microcellular polyethylene terephthalate (PET) have advantages for the luminaire including high total reflectivity across the visible spectrum, high diffuse reflectivity, and light weight. These diffuse reflective layers are a tool used in LED lighting designs to further mix the light to reduce hot spots and provide a more uniform light emission. Additionally, they can improve color mixing if multiple colors are used in the LED arrays. Some different orientations of optical designs using diffuse reflectors are shown in Figure 3-45. The indirect-view orientation hides the light source from view to provide a uniform light emission but requires a high-performance diffuse reflector. When the light ray is reflected by the diffuse reflector surface, a portion of the light will be absorbed so the diffuse reflector is implemented to minimize the absorbance from multiple bounces and maximize the usable exiting light. The direct-view orientation has the LED array shining down into the room with most of the light interacting with the diffuser lens directly; additional light that hits the sidewalls with the diffuse reflector can be recycled and improve the optical efficiency of the fixture.

Optics can be integrated into lamps and fixtures in a variety of way. Common attach techniques include tape, adhesives, press fit fixtures, screws, clips, and lens-holders. The process selected must consider mechanical stress, humidity, temperature fluctuation, vibration, and features on the PCB that can weaken the strength of the fastening and bonding. Figure 3-46 show a few schemes of attaching a TIR lens to an LED mounted on a small star board. Often with a single LED TIR optic, a lens holder is typically needed; for an optic with multiple lenses such as a triple optic, they can more easily be installed without a lens holder because legs can be formed to integrate with into holes in the PCB. White diffuse reflective layers can also be integrated in multiple ways, including as rolls or precut sheets that can be attached with tapes or adhesives. Alternatively, some can be coated directly onto the structural housings.

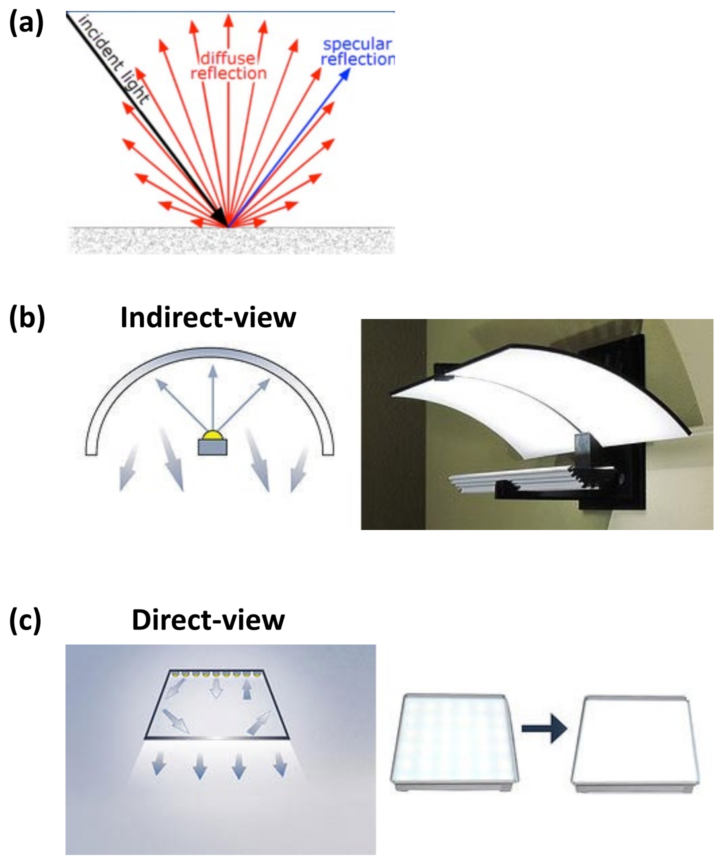


Figure 3-45 (a) An illustration of how a diffuse reflector scatters the incident light ray to improve diffusion. Examples of how diffuse reflection can be implemented in different fixture geometries including (b) indirect lighting where the LEDs face away from the room, and (c) direct-view lighting where the light is scattered by the diffuser and additional reflection is provided by coating the inside of the fixture with a diffuse reflector. [79]

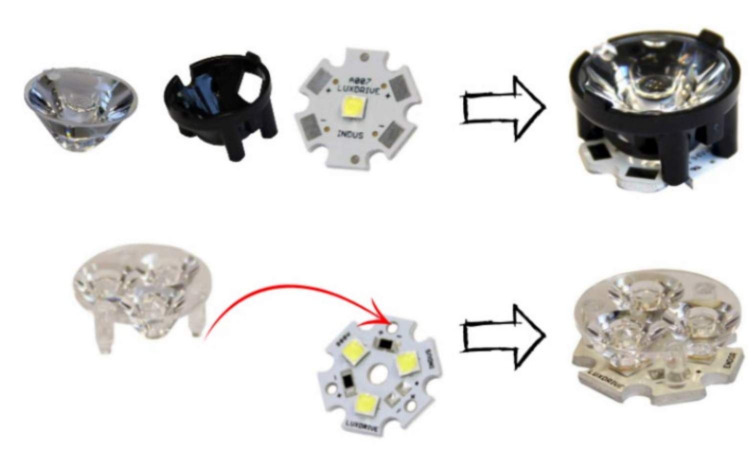


Figure 3-46 A TIR lens, optic holder and LED on a star board are assembled together to create the light enginge with optic for a directional lamp (top). A multi-lens structure allows for the integration of support pins to align with the PCB and can eliminate the need for an optic holder (bottom). [80]

Manufacturers of optical components include:

- Fraen, Dow Performance Silicones, White Optics (Acuity Brands), and Luminit in North America,
- Carclo, Khatod, Gaggione, and LEDiL in Europe,
- Bicom and LedLink in Asia.

3.4.4 LED Driver Manufacturing

Drivers (power supplies) remain a critical component in LED-based luminaires and can significantly impact luminaire performance and reliability. Features built into the driver, such as controls, can add value to LED lighting products. Most of the issues associated with drivers are more related to product performance and cost trade-offs than they are to manufacturing technology. The manufacturing of power supplies for consumer electronics is a mature field. Power supplies, fundamentally, can be manufactured at low cost if the product performance requirements are well understood.

While basic driver manufacturing technology may be well understood, the need for drivers with improved efficiency, reliability, flexibility, and form factors within the luminaire still remains. Challenges for LED driver technology includes improving the ease of multi-channel tunability, reducing size and weight, and improving performance (increasing efficiency and reducing flicker) over a broad operating range with high reliability. These factors result in design trade-offs of cost and performance unless new technology approaches can be leveraged. Wide bandgap semiconductors power devices can lead to driver architectures that address these problems by utilizing higher frequency and innovative circuit topologies. [7] Smaller more compact drivers can be designed using the high frequency available with wide bandgap components and coupling that with high frequency planar magnetics (low profile devices). Planar magnetics also allow for a more automated manufacturing process that can reduce labor costs (eliminate hand winding) and move more of the driver manufacturing to SMT assembly processes.

The manufacturing of drivers with some level of controllability and interoperability is also a concern for driver and luminaire manufacturers. Luminaires for varying lighting applications may require different types of control. Internal electronic control of various channels for color point tunability, compatibility with multiple dimming systems, or communication with various forms of wired or wireless controls may be required for the lighting application; this functionality is typically integrated into the power supply. The ability to integrate these controls into the luminaire can impact the assembly costs of the luminaire, as well as its reliability. Improvements to the design and manufacturing of drivers and the control systems can have a significant benefit for luminaire cost, performance, and reliability. For example, as new multiplexing-based circuit topologies become available, they can help address the performance of multi-channel drivers, with the potential of providing higher efficiency at dimmed operation, no flicker (no pulse width modulation), lower component count, and lower driver volume.

Standards for networked control of individual luminaires or groups of luminaires, such as the Digital Addressable Lighting Interface (DALI), can help reduce the complexity of the control design by allowing networked control of the luminaires, groups of luminaires, or all luminaires via a connected DALI bus. DALI-2 standardizes the interface for intra-luminaire communication and the newer D4i standardizes the feature set of the LED driver for intra-luminaire networks (expanding on DALI-2). D4i digital drivers can store and report data in a standardized manner, and supply external components, such as sensors and communication modules, with power. The standardized bidirectional intra-luminaire data communication makes it easier to determine the current luminaire status in real time – capturing data such as energy consumption, operating time, and temperature – and feeding it back to the building data analytics.

Manufacturing Opportunity: Universal Voltage Drivers. Developing universal voltage drivers is an opportunity to improve driver manufacturing by increasing the economies of scale. In general, the individual components for the driver are sourced globally and then imported to the regional driver manufacturing factory. LED driver manufacturing is typically carried out region for region to be close to the regional luminaire assembly factories and due to the region-specific voltage requirements. Universal power supplies are common in consumer electronics devices (e.g., laptops, mobile phones), but not yet seen in LED lighting. Creating power supplies for the different voltages used in various global regions requires multiple supply chains for the same lighting applications; thus, resulting in manufacturing more driver SKUs and managing inventory on more components since parts, like magnetics, are sized to the voltage range of the driver. The biggest barrier to achieving universal voltage drivers is the extreme cost pressure on LED driver manufacturers; the luminaire manufacturers resist incorporating a universal power supply unless it is cost neutral. Solving this feature-cost trade-off for LED drivers can simplify the supply chains with inventory management and improve the economy of scale.

Manufacturers of complete driver sub-assemblies include some luminaire manufacturers and specialist driver manufacturers Inventronics and Meanwell. Representative driver manufacturers include:

- GE Current, eldoLED (Acuity Brands), Cree, ERP Power, Fulham in North America
- OSRAM Digital Systems, Signify, Tridonic (Zumtobel), Dialog Semiconductor, and Harvard Power Systems in Europe
- Inventronics, Meanwell, Moso Power Supply, and Sosen in Asia

LED driver integrated circuit (IC) manufacturers include (listed alphabetically): Allegro Microsystems, Analog Devices, AMS, Diodes, Inc., Infineon Technologies, Macroblock, Maxim Integrated Products, Monolithic Power Systems, NXP Semiconductors, ON Semiconductor, O2 Micro, Power Integrations, Rohm Electronics, Semtech, Silicon Touch Technology, STMicroelectronics, Texas Instruments, and Toshiba.

3.4.5 Lamp/Luminaire Housing Manufacturing and Assembly

Early in SSL manufacturing, many companies were vertically integrated, controlling many parts of their own supply chain to provide the highest performance level and help control cost structures. As SSL technology has matured, more commoditization has led to disaggregation of the supply chain and has allowed more luminaire manufacturers able to compete without having a vertically integrated factory. LED packages and light engines are easily procured from manufacturers with reasonable costs. The availability of off-the-shelf drivers and optics has also allowed more new entrants to compete with the historical lighting manufacturers.

The integrated nature of an LED-based lighting product, where the mechanical housing, light engine, and driver electronics are typically combined in a single unit, is very different from conventional lighting technologies which revolve around the fixture-plus-bulb paradigm. Luminaire manufacturers have successfully addressed the challenge created with such an integrated semiconductor-based product by incorporating SMT manufacturing processes. What were previously factories full of metal working equipment to make luminaire housings and connect ballasts have turned into factories with SMT lines mounting electronic packages to PCBs to create the light engine of the luminaire. The luminaire manufacturers had to develop new manufacturing processes and bolster system-level design optimization methodologies, including DFM with the new complexity of SSL. Along with the manufacturing capabilities came the need to developing new testing capabilities for performance and reliability (discussed in more detail in Section 0).

Lamp and luminaire assembly involves the integration of many components, as described earlier. The complexity of the assembly depends on the exact form factors and features offered (i.e., color tuning, controls, sensors, etc.). Factory automation for assembly of LED lamps and some basic products such as small downlights has become common in Asia. The smaller variability in product designs and higher volumes for lamps compared to luminaires make automation more feasible. Additionally, lamps have more similar size scales of housings, drivers, and optics parts that makes handling and integrating the components easier than luminaires with larger variation in component size and shapes. Mechanics (e.g., screws, pressure sensitive adhesives, wiring), which can be difficult to automate, is also a smaller part of lamp assembly compared to luminaires. Figure 3-47 shows a representative process flow for the assembly of LED lamps. Automated assembly robots move the lamp bases along the assembly line where they have the driver inserted, screws to connect the light engine to the heat sink and adhesives applied to hold the outer lens. The lamps then run through a line-based light-up test. An example of some of these automated processes is shown in Figure 3-48.

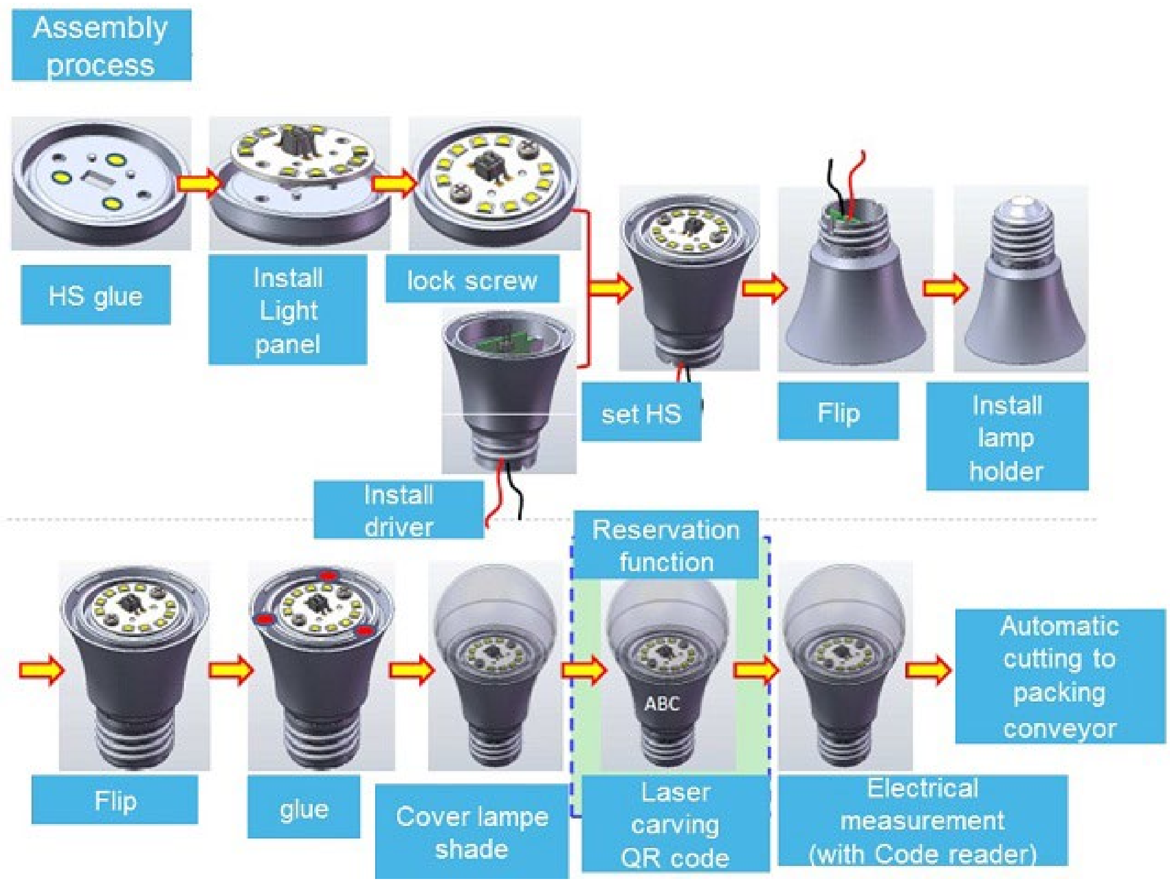


Figure 3-47 Example process flow for the automated assembly of an LED lamp. Note: HS refers to heat sink. [81]

Figure 3-48 Example of automated assembly lines for LED A-lamp. [81]

While LED lamp manufacturing has transitioned to automated assembly lines, assembly cells with manual labor are more standard for LED luminaire manufacturing. Some luminaire assembly plants still employ straight conveyer lines for assembly work, though most have moved away from linear assembly lines toward cellular workstations to employ lean manufacturing practices. Assembly cells are specialized for the specific product being built in it, which increases the operating efficiency by minimizing the movement of parts and reducing the restocking time of components. Examples of these assembly cells and lines are shown in Figure 3-49.

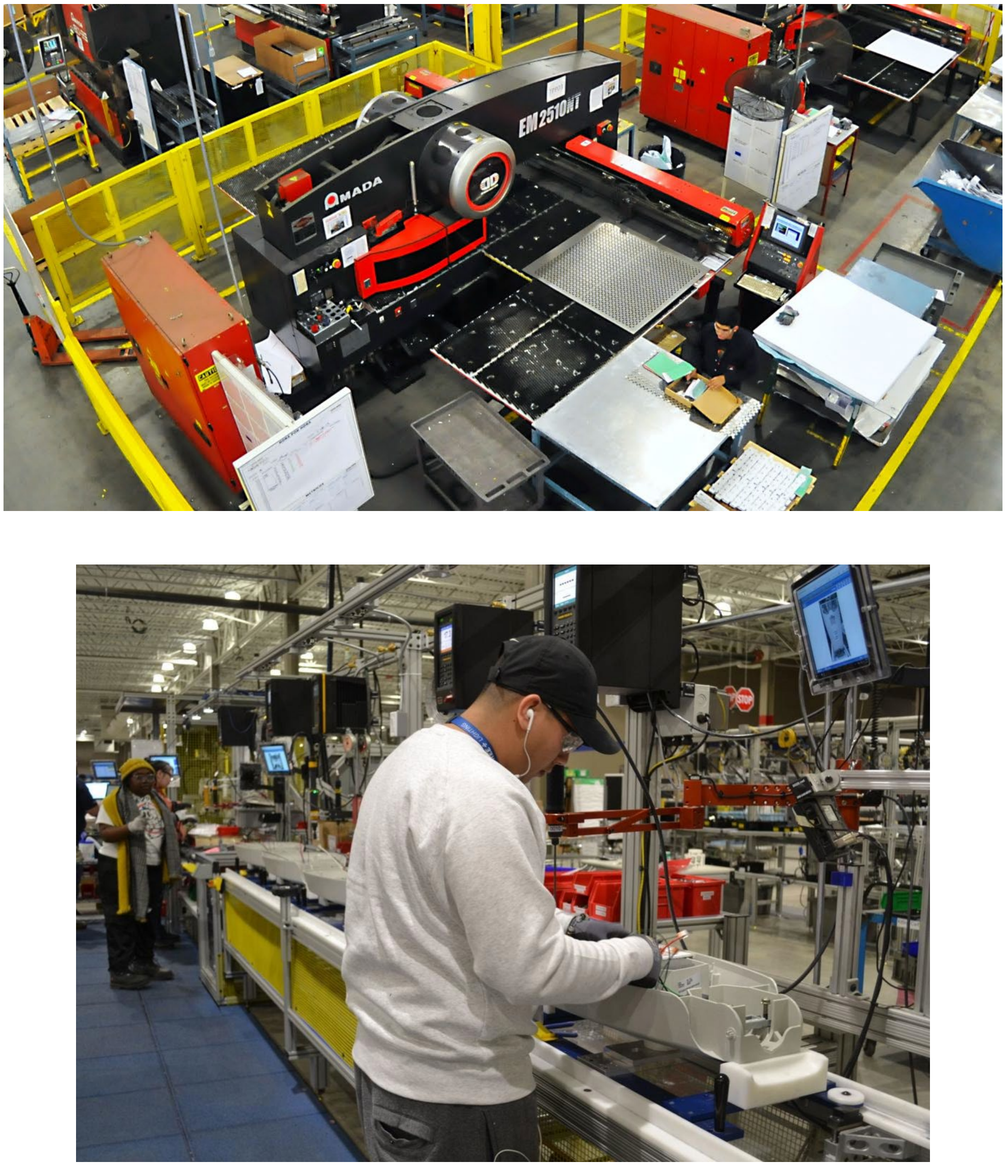


Figure 3-49 An example of a luminaire assembly cell (top) and a straight conveyer assembly line (bottom). [82] [83]

Manufacturing Opportunity: Luminaire Assembly Automation. There is an opportunity to improve automation in luminaire manufacturing by creating new luminaire designs that are easier for automated assembly. In luminaire manufacturing, more manual assembly on the production lines is required due to the difficulty of automating certain processes in addition to the varying size scale of components in many luminaire products. There have been moves to automate elements of the manufacturing operation to improve efficiency and reduce costs; however, the progress has been limited due to the large variety in luminaire product dimensions and performance SKUs (lumen packages, CCTs, CRIs, driver voltage, etc.). Moreover, assembly of mechanics such as screws, pressure sensitive adhesives, and wiring can be very difficult to automate. The DFM process should remove some of the pain points (i.e., change how things are assembled to reduce or entirely avoid steps that are difficult to automate).

Most lighting companies are manufacturing LED-based luminaires and modules. Historical lamp manufacturing companies such as Philips (Signify), Osram Sylvania (split into LEDVANCE & OSRAM Digital Systems), and GE (Current), as well as luminaire manufacturers such as Acuity Brands, Hubbell

Lighting, and Zumtobel, manufacture LED-based lighting products as their main product offerings. Also, many newer entrants to the lighting industry, including organizations such as Cree Lighting, Ecosense Lighting, Lighting Science Group, and many more, have joined the lighting industry as part of the rapid adoption of LED lighting technology. More LED lighting manufacturers can be found in Table 2-2 in Section 2.2.2

3.4.6 Test and Inspection

The introduction of LED-based lighting technology has significantly complicated the testing requirements of luminaires. Testing has become more significant due to the fact that each LED-based luminaire is a unique fixture comprising a number of subcomponents. Each LED-based lighting fixture has its own distinct electrical and photometric performance characteristics and must be separately tested (via absolute photometry). Previous lighting technologies tend to be based around the fixture-plus-bulb paradigm, which allowed for simple and rapid photometric testing with readily anticipated results.

Test and inspection equipment for luminaire and module manufacturing is required to validate incoming components, to perform in-line testing, to obtain photometric characteristics for completed products, to perform burn-in testing, and complete long-term reliability testing to identify potential failure mechanisms. Typically, the industry employs computer-controlled integrating spheres in conjunction with goniophotometers to test luminaires. Examples of equipment used for photometric testing of luminaires is shown in Figure 3-50. Such equipment is used to measure luminaire output, efficacy, intensity distribution, zonal lumen density, and colorimetric data. The testing method for SSL luminaires is well established and described in detail in IES LM-79 *Approved Method: Electrical and Photometric Measurements of Solid State Lighting Products.* [84] The content of a given LM-79 report depends in part on the apparatus used for measurement. Although LM-79 does not prescribe a report format or the minimum content, a substantial list of "typical items reported" is provided. Using an integrating sphere, the total lumen output of a tested source and its colorimetric data is captured in a single measurement. By contrast, using a goniophotometer, luminous intensity measurements are recorded at a series of locations surrounding the test sample and then total luminous flux is calculated. Some goniophotometers may have the capability, but most do not measure colorimetric performance. A variety of electrical measurements may be conducted as part of LM-79 testing, including but not limited to measuring input voltage, input current, input power, and power factor (PF).

Figure 3-50 Examples of integrating sphere (left) and goniophotometer (right) systems used to test LED lighting fixtures. [85] [86]

Test and inspection requirements associated with luminaire manufacturing includes sub-assembly testing which is often performed by the sub-assembly manufacturer. Incoming sub-assemblies such as the light engine or driver must be tested and inspected to ensure they meet specification. However, the most significant test and inspection activity is associated with the end-of-line testing of the completed luminaire to measure the light output and colorimetric data, sometimes after a burn-in period from 6-24 hours. Over the past several years, many luminaire manufacturers have moved away from 100% end-of-line testing due to the time and cost. Often, the key components such as the LED light engine and drivers are tested as incoming parts. So instead of full testing after luminaire assembly, a quick power check is performed to make sure the product lights up. Full functional testing and data collection after burn-in is no longer performed on every part for many manufacturers, though some still take the time to do rigorous testing on every product produced.

The impact of test and inspection on yield, cost, or performance of the final product will depend on the point in the manufacturing process that the measurement is made. Luminaire testing currently culminates in a number of specific compliance tests to demonstrate adherence with the requirements dictated by a number of agencies and certification bodies, including Underwriters Laboratories Inc. (UL)[5], DesignLights Consortium (DLC)[6], and ENERGY STAR[7]. The industry continues to work with these groups to understand how this testing burden might be minimized.

Manufacturers of test and inspection equipment for luminaire manufacturing include the following:

- Labsphere, Instrument Systems Inc. (Konica Minolta), Gamma Scientific, Radiant Vision Systems, Metrue, GL Optic, Everfine, and Gigahertz-Optik.

Many test laboratories have also been established to provide independent luminaire performance and compliance testing including (in the U.S.):

- Intertek, Gamma Scientific, ITL Boulder, CSA Group, LightLab International, Bay Area Compliance Labs Corp. (BACL), and Light Laboratory Inc.

3.4.7 Design for Manufacturing

Design for manufacturing can help remove some of the current challenges in manufacturing LED luminaires. Creating new designs with ease of manufacturing or automation in mind can help alleviate some of the existing pain points in current manufacturing or assembly processes. Improved DFM can entail removing labor intensive assembly process or changing the materials of construction and form factor of the fixture to allow for easier automation, lower cost, or higher performance levels. Some important manufacturing opportunities currently being discussed include the following:

Integration: One method to simplify the manufacturing process is to streamline the integration of the luminaire by simplifying or reducing the interfaces between the subcomponents of the luminaire. Within the LED luminaire product there are opportunities to better integrate the LED die, LED package, or LED module with the luminaire mechanical, electrical, and optical structures. Such advancements could simplify the design of the lamp or luminaire products, simplify the manufacturing of these products, and reduce product costs. The potential for high levels of component integration within LED-based luminaire products will have a significant impact on how such products will be manufactured. For example, the LED chip could be mounted directly to the luminaire heat sink by printing the circuit on the heatsink, thus removing several layers of material and thermal interfaces. This higher level of integration would blur the distinction between the LED package or light module and the luminaire. The thermal, mechanical, optical, and electrical interfaces could all be considered for enhanced integration as described in the manufacturing opportunity that follows.

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[5] https://www.ul.com/
[6] https://www.designlights.org/
[7] https://www.energystar.gov/

Manufacturing Opportunity: Chip-Level Optical & Electrical Integration. There is an opportunity to bring more integration of optical control or driver functionality down to the component or chip level, which can lead to cost savings on the luminaire assembly stage taking advantage of the more automated SMT or semiconductor fabrication equipment over the assembly schemes currently used in luminaire manufacturing. Combining semiconductor layers for different types of devices on the same wafer and using more sophisticated processing technology to monolithically integrate different functions on the same chip can allow the integration of optoelectronic, electronic, and microelectromechanical functions. Another example might be the use of wafer-level packaging techniques developed in other semiconductor technology areas such as in the production of complementary metal-oxide semiconductor (CMOS) cameras for cell phones. Such methods might allow a significant proportion of the packaging to be completed at the wafer level and could offer the prospect of highly automated optical and electrical testing prior to final assembly. Integrating increasing amounts of functionality at the wafer level is an excellent approach to cost reduction providing that the performance is not compromised. The more that can be achieved before the wafer is singulated, the less that will need to be accomplished at an individual die level where the cost per die will be much higher.

Novel Form Factors: Most LED-based lighting products replicate the form factors of conventional lamps or luminaire products. This enables easy replacement into existing fixtures and provides a sense of comfort for consumers who may be skeptical of new form factors. However, forcing LED lighting technology into legacy form factors reduces performance and increases cost of the lighting products. For example, with the common A19 lamp form factor, the screw-in Edison socket does not provide a thermal path to dissipate heat from the LEDs, and the required optical distribution is difficult for LEDs to match and frequently is not optimum for the lighting application. Developing new luminaire form factors can maximize LED lighting performance while reducing cost and delivering appropriate light levels. While there are some form factors embracing the unique features of LEDs, the majority of products resemble legacy form factors and building integration schemes. This reimagining of form factors can also feed into improved DFM in terms of assembly complexity and ease of automation, as discussed in Section 3.4.5. Novel form factor products will require rethinking of existing lighting systems and possible redesign of how lighting is integrated into buildings. The use of DC micro-grids in buildings can help reduce the power supply conversion losses today and allow more efficient use of renewable energy sources such as photovoltaics.

Novel Materials: Novel materials that can simplify manufacturing and reduce the complexity, cost, and weight of the luminaire should be considered. Luminaire manufacturing would benefit from lighter weight and lower cost heat sinks and thermal handling materials. Luminaires and LED modules could benefit from lower cost, but similarly robust, optical materials. New materials could even serve multiple purposes, such as optical materials that can dissipate heat as part of the thermal handling system or heat sinks that also serve as the "circuit board." There are numerous areas of the luminaire where advanced, novel materials could improve performance and/or reduce cost, including printable materials for optics or heatsinks, and new materials for a sustainable supply chain, as will be discussed further in Section 3.5.

Modularization: A modular approach to luminaire design and assembly, using standardized form factors and interfaces between subcomponents, can allow for a consistent integration process regardless of the supplier of a given subcomponent. Such an approach is similar to that supported by the Zhaga Consortium[8]. The components of the luminaire, such as the LED light engine, driver, thermal handling, optics, and housing, can be designed to readily fit together in a variety of configurations, which can enable rapid manufacturing of a broad range of products, reduce inventory demands, and simplify luminaire design. The modular approach can also benefit smaller scale and traditional luminaire manufacturers who could more easily and rapidly design and manufacture LED-based lighting products. Finally, the modular approach can help enable replacement or

[8] More information on the Zhaga Consortium can be found at: https://www.zhagastandard.org/about-us/vision-mission.html

upgrading of components within the luminaire, and also be amenable to deconstruction upon removal to allow for recycling of the luminaire materials. While the modularity offers many advantages, there are inevitable performance compromises since the general-purpose modules cannot be optimized for each specific lighting application. Often, modular assembly will contain more individual piece parts than with a holistic design; moreover, it is more challenging to remove interfaces to lower cost and improve performance (as discussed previously). The modular approach to the design and manufacturing of LED-based lighting products will likely exist in parallel with products that take the opposite approach of reducing interfaces and highly integrating sub-components. The likely benefit that may promote modularity beyond what exists today is the benefit to the circular economy by allowing upgrades/replacements of existing parts and easier deconstruction for recycling at end of life.

3.5 Advanced Manufacturing Technologies

As the technology for lighting has changed, there have necessarily been modifications in how lighting products are manufactured. Many of the desired features discussed in this document have required new manufacturing technologies to be developed. With SSL, there is still an opportunity to rethink how products and components are manufactured across the value chain and to embed sustainable manufacturing processes and materials into LED lighting products. Advanced manufacturing technologies can help eliminate pain points in conventional product designs and can allow new approaches to managing supply chains over traditional manufacturing approaches. New and improved manufacturing processes and technologies can enhance lighting product quality, reduce cost, and enable a wider variety of form factors and features. New manufacturing technologies can also influence where, when, and how products are manufactured, possibly enabling more localized production. A few promising advanced manufacturing technologies for LED lighting will be discussed in the sections below.

3.5.1 Additive Manufacturing

Over the past few years, additive manufacturing has been a growing area of interest for SSL product prototyping and manufacturing. Additive manufacturing is a fabrication process where a three-dimensional (3D) object is created by computer-controlled deposition of material (in a layer-by-layer approach) based on a computer-aided design (CAD) model. It can be more efficient than traditional "subtractive" manufacturing approaches, such as milling, grinding, and polishing, which involve removing material to achieve the desired form, either for product fabrication or for creating molds or tooling. Additive manufacturing offers fast, flexible, cost-effective prototyping and direct CAD to fabrication manufacturing without tooling or inventory. Additive manufacturing also enables more product performance options through high configurability, unique designs that are not possible with traditional manufacturing, lower parts counts (reduced assembly complexity and cost), and easier product lifecycle management (more changes and shorter cycles). In addition, reduced costs can be realized with a lower equipment investment (no tooling) and with a lower energy intensity that comes from eliminating production steps, using substantially less material, and producing lighter products.

Additive manufacturing can impact the LED lighting supply chain in multiple areas including fixture housings, secondary optics, and even electronic components and modules. For the most part, the primary use of additive manufacturing in SSL to date has been for rapid prototyping on new design concepts to iterate product variations or functional form-and-fit processes and testing. The tides have been shifting as more manufacturers are using or developing 3D printed luminaire parts for production; some recent examples of 3D printed commercially-available luminaires are shown in Figure 3-51. 3D printing enables the design of custom fixtures with improved visual appeal from unique designs and reduced costs.

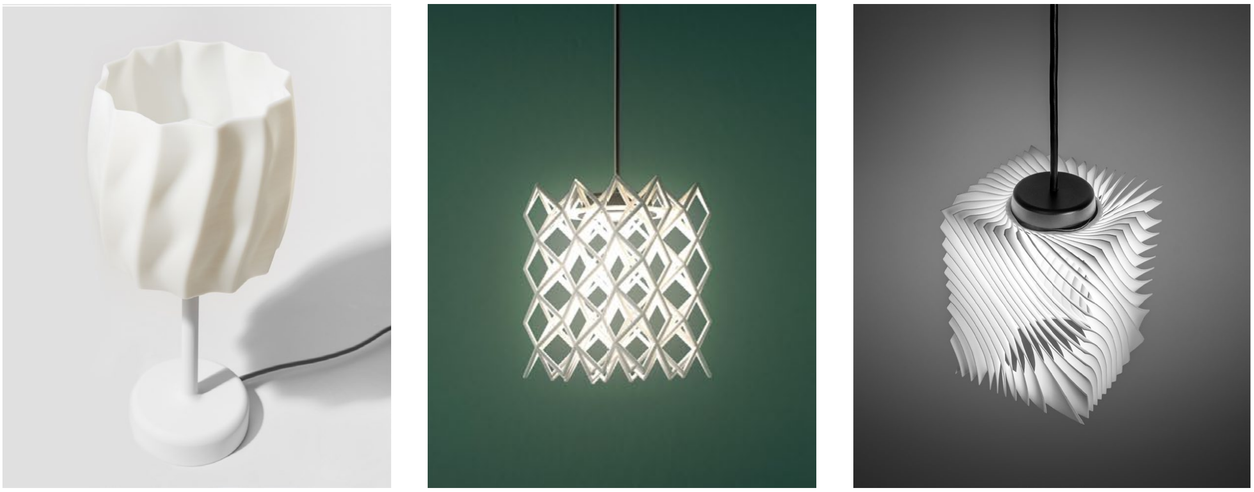

Figure 3-51 Images of 3-D-printed lighting fixtures. [87] [88] Custom optical distribution features of decorative luminaires can be achieved through additive manufacturing approaches that would not otherwise be practical or possible to achieve.

Beyond the use of additive manufacturing to make luminaire housings, this technique has been used to create the functional components of luminaires, such as optics. These optical structures are made from a UV-curable polymer ink and cured by UV lamps in the print head upon each pass of printed droplets, as illustrated in Figure 3-52. This method allows geometric and free form shapes to provide the desired optical control features, while it simultaneously eliminates the expense of molds and tooling and enables on demand manufacturing.

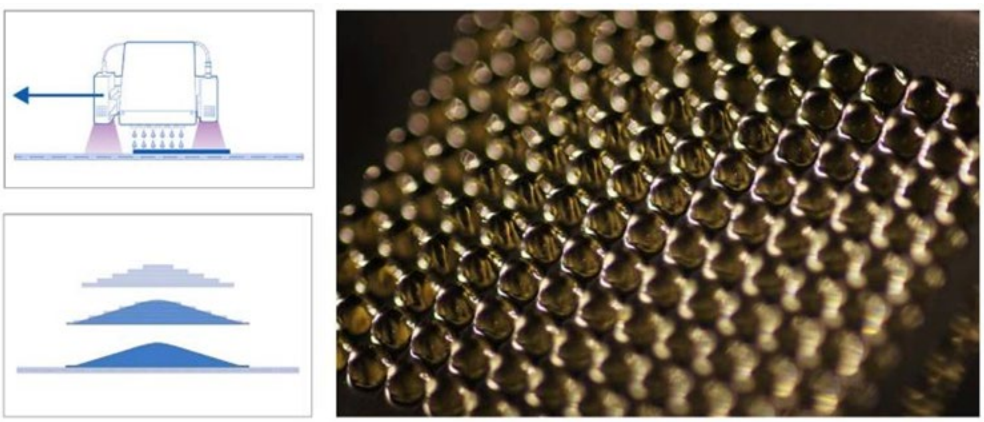

Figure 3-52 Illustration showing the deposition of droplets by UV print head onto substrate material (left-top). The droplets of polymer are allowed to “flow” under surface tension before curing with UV light, giving the smooth surfaces needed for optics (left-bottom). An array of micro-optic lenses is pictured (right). [89]

Another additive manufacturing technique being explored in LED luminaires is developing direct chip-to-system solder-attach geometry that will enable LED electrical integration into systems for improved performance at a simultaneously reduced fabrication cost. One manufacturer has focused on replacing the metal-core printed circuit board and thermal interface material with a printed circuit on the luminaire system (metal) to reduce the thermal interfaces, thus improving thermal resistance. [90] Adding an integrated driver circuit facilitates full automation of electronics component assembly, and this significantly reduces material costs. Fully printed, integrated circuitry with LED, driver, sensors, and antennas was demonstrated in a DOE SSL project shown in Figure 3-53.

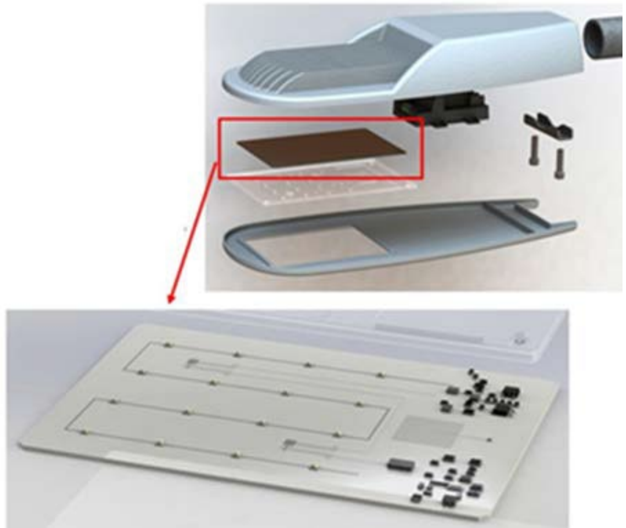

Figure 3-53 Images of integrated roadway luminaires with fully printed, integrated circuitry with LED, driver, sensors, and antennas. [91]

Manufacturing Opportunity: Additive Manufacturing of Luminaires. There are multiple technical challenges to enable more additive manufacturing production opportunities, including developing faster additive manufacturing processes by increasing print speeds and creating systems with larger beds and multiple print heads to generate more parts per run, thereby reducing cost. It is essential to develop new printable materials with improved optical properties and UV resistance for optics, polymer materials with higher thermal conductivities for heat sinks, and improved UV and infrared (IR) curing for electronic materials used to generate the circuit. Moreover, the developed materials must all be able to pass all safety ratings and standards. Another area requiring improvement is creating better "net shapes", so minimal post processing is required. Printing with better surface properties is critical, especially to prevent scattering centers in the optics or to prevent surface roughness on the heat sink from causing shorts in the printed electronic circuit. While proof-of-concept demonstrations exist for the use of additive manufacturing in many areas of the SSL value chain, more R&D is required to develop printable materials with the sufficient properties to replace existing manufacturing approaches in electrical, thermal, and optical components.

Another area of interest for additive manufacturing in the SSL value chain is to create tooling using 3D printing. The lead time for tooling for molding or stamping processes often takes 10 to 12 weeks to be created, whereas 3D printing has the potential to reduce the lead time significantly and create tooling in 2 to 4 weeks. [92] Such a shortening of the leadtime allows for a shorter product development cycle and quicker pilot line development. The use of additive manufacturing in creating tooling has the potential to create efficiency gains with SSL product manufacturing.

3.5.2 Micro-LED Manufacturing

Another area of advanced manufacturing involves high density LED assembly. The future use of high-density pixelated LED sources to create advanced lighting designs necessitates new methods to assemble large number of mini- or micro-LEDs at speeds and cost levels that can be supported in the lighting industry. The challenge with using these smaller micro-LED die (< 50 μm size) to create small pixel sizes is the conventional manufacturing technologies don't scale effectively – both from the device fabrication side, as well as the die transfer process (at the light engine level). Additionally, when moving to these small LED die dimensions, the efficiency of LEDs can drop rapidly with chip size.

The development of micro-LED chips is a growing area of R&D for displays and lighting technology. A few key areas will be highlighted below, particularly where they pertain to die manufacturing processes. While LED die for conventional packages are quite efficient with external quantum efficiencies (EQEs) passing 80% for blue InGaN LEDs, the efficiency drops rapidly as the die are scaled down from a few hundred µm to tens of µm in size. This efficiency drop with miniaturization is even more pronounced in the AlGaInP materials system used for red LEDs because of their higher recombination velocity allowing carriers to reach a defect in the mesa sidewall. [93] Further development work is necessary to understand how much of the efficiency decrease is driven by size effects, defects at the sidewalls, and the differences between epi quality in different research teams. IQE improvements for the devices are largely focused on keeping carriers away from defects. Another focus area is developing fabrication techniques to reduce sidewall damage during the mesa etching process and surface treatments to passivate the sidewalls and limit nonradiative recombination. [94] Other device fabrication improvements such as reflective contacts or surface texturing can be employed to enhance light extraction, and hence EQE performance in micro-LEDs.

Manufacturing Opportunity: LED Wafer Wavelength Uniformity. Micro-LED wafers require unprecedented levels of uniformity for optical and electrical properties since binning die is no longer practical. This necessitates investing in development of improved MOCVD hardware platforms to allow an entire wafer to yield into a single performance bin. The wavelength uniformity across a 6” wafer needs to be 1-2 nm. Furthermore, new methods of measuring micro-LED wafers are required to help ensure the devices shipped are conforming. This investment in MOCVD uniformity will also be leveraged into standard LED chip sizes for lighting packages as well.

Figure 3-54 shows the wavelength distribution across a 6” blue LED wafer grown in an MOCVD reactor, which still varies to be ~4 nm for the majority of the wafer area. MOCVD manufacturers (e.g., Veeco and Aixtron) both realize the potential of the micro-LED market and have been putting effort into this, though more development work is needed than the internal R&D budgets of individual companies are likely to support in order to overcome this barrier.

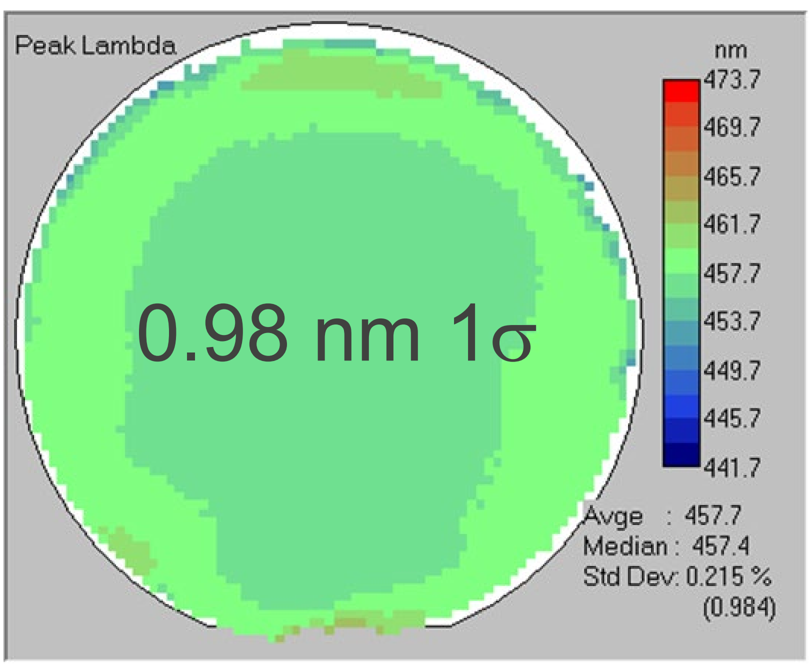

Figure 3-54 Wavelength distribution of a 6” blue LED wafer grown in a Veeco Epik 14x6” MOCVD reactor. The wafer shows ~4 nm distribution across the majority of the wafer area. [95]

Manufacturing Opportunity: Measurement Innovation for Micro-LEDs. While the performance of the micro-LEDs is one technical challenge, another key issue in implementing micro-LEDs is the major change to fabrication and measurement infrastructure used in mass production for LEDs. LED devices are fabricated at the wafer level and then each die is measured for its optical and electrical properties to properly categorize the LED die into its performance bins. The customer would then receive a sorted die sheet of LEDs from the performance bin they requested; failing die would be screened out and not sold to the customer. The major difference with micro-LEDs is that they are too small to be probed by conventional test methods, therefore each die cannot be shipped with known performance parameters; thus, the system manufacturers (making displays or lighting systems) cannot differentiate between conforming on non-conforming die (i.e. if the wavelength is out of range or there is a shorted device). This puts a burden on both the micro-LED manufacturer to create wafers with very little performance variation across millions of die or system manufacturers to handle a larger rework processes scale or place redundancy for failed die (i.e., put two die for every pixel in case of a failing die). New measurement techniques need to be developed to identify good performing die at the micro-scale with high throughput.

Until industry can solve the issues with outgoing micro-LED testing and die efficiency reductions, mini-LEDs have instead filled the gap (especially in display applications). Mini-LEDs are typically 100-200 μm in size and fall in the size range between conventional small LED die for lighting packages and micro-LEDs. The benefit of mini-LED die is that they utilize the existing supply chain in terms of die manufacturing, testing, and binning, but provide a better pixel density than using conventional LED packages. Mini-LEDs are leveraging new modified pick and place equipment designs that can place the LEDs more accurately and rapidly than conventional pick and place tools used in LED packaging today. Many leading display companies have shown demonstrations of mini-LED displays in the 2020 Consumer Electronics Show (CES) with improved performance in resolution, color gamut, and dynamic range. Lighting companies are looking at implementing mini-LEDs in new lighting schemes as illustrated in Figure 3-55. These new full color pixelated lighting sources can provide high-precision dynamic beam shaping and color projection, and will start to create lighting-display fusion by incorporating features such as wayfinding or information display.

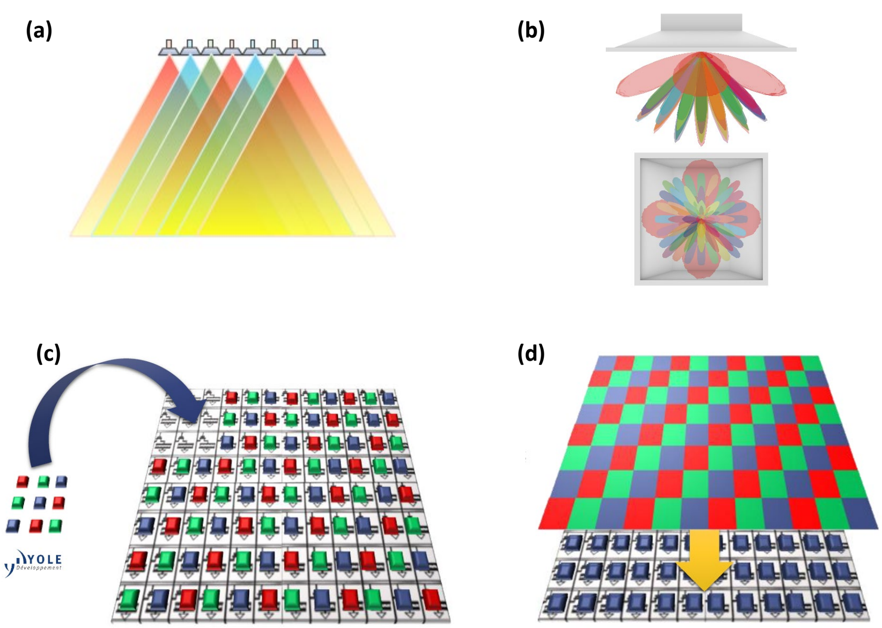

Figure 3-55 Illustrations of new lighting schemes (a) and (b) using color tunable pixelated light sources to create different spectral power distributions and optical profiles. [96] [97] Illustrations of micro-LED display with (c) red, green and blue micro-LEDs applied to a TFT backplane and (d) blue micro-LEDs on a TFT backplane with a red and green color conversion materials (e.g., quantum dots) applied. [98]

Currently, techniques such as massively parallel pick and place that use transfer stamps, sequential/semi-continuous placement, and self-assembly processes are being explored by dozens of companies and researchers. These types of transfer processes, illustrated in Figure 3-56, have different challenges and a clear winner has not yet emerged. Other approaches such as the use of digital printers for self-assembly offer new promising paths to perform self-aligning mass transfer of chips (both LEDs and control electronics). The display industry is putting considerable resources into innovations for micro-LED mass transfer, which the lighting industry can leverage while also considering new approaches such as digital self-aligning chip printers. Elements of the LED supply chain will require innovation to provide high performing mini/micro-LED die for lighting application requirements, as they will differ from the requirements of displays.

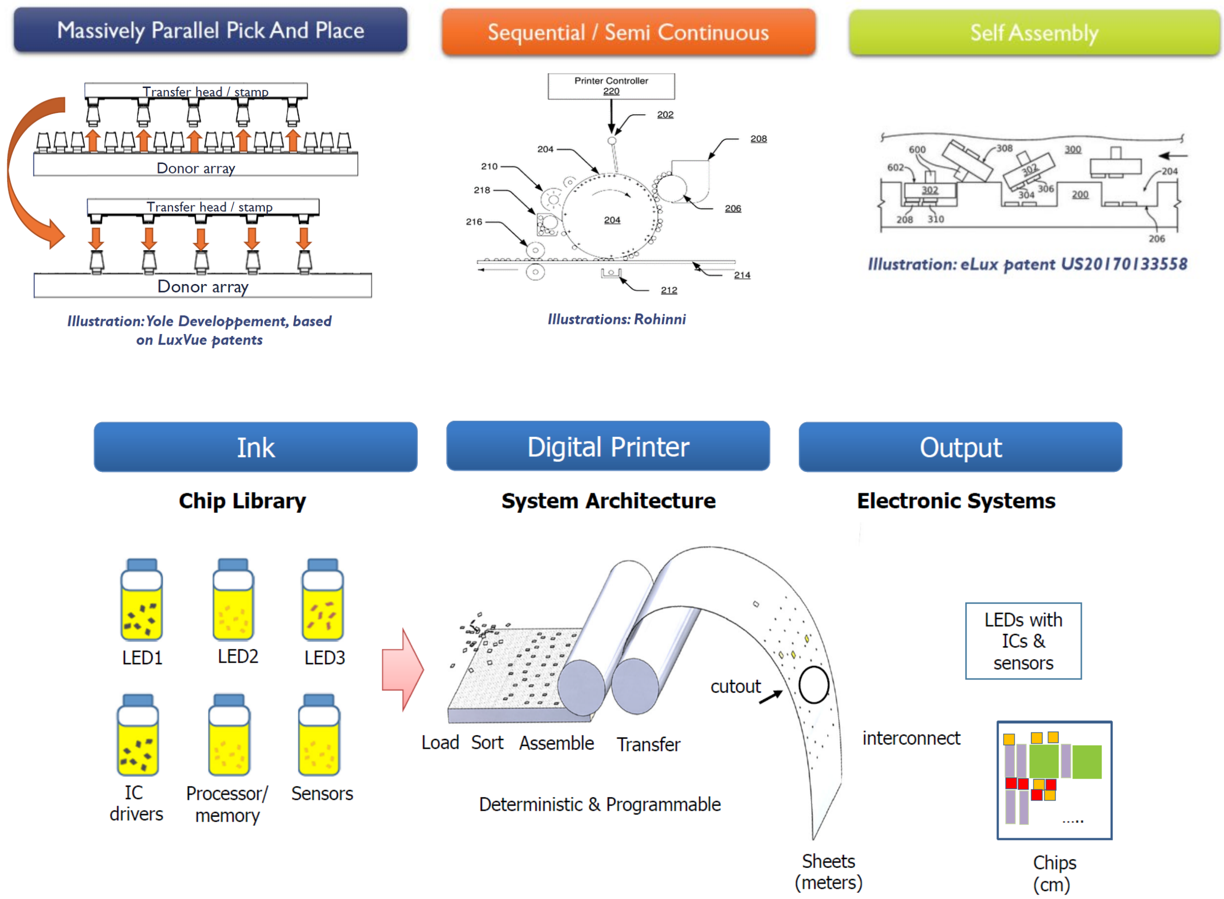

Figure 3-56 Illustrations of three key types of micro-LED assembly and transfer techniques being investigated today (top). [98] Schematic of a novel digital printer approach the illustrates the features of a self-assembly scheme with the use of die-containing inks being applied and assembled onto a sheet in a roll-to-roll format (bottom). [99]

The speed of transfer of massive numbers of LEDs is only one of the challenges. The transfer process must also provide extremely high yield (99.999% and above) to be viable for mass production. There is the possibility of repair of misplaced or non-functional LEDs, though it must be limited to only a few failures per display or lighting system to be viable. Automated rework processes and equipment is another focus of development for micro-LED mass production. There is less effort currently in the development of automated rework equipment, though it is no less essential to make micro-LEDs viable.

Manufacturing Opportunity: Micro-LED Mass Transfer Processes. Advances in the mini/micro-LED die placement processes is an area of research with a variety of approaches being pursued in display applications, including mass parallel transfer and rapid pick and place schemes. There is an opportunity to develop mass transfer processes to provide more efficient mass transfer of die (both LED and other semiconductor die like control ICs) to creating low-cost roll-to-roll lighting systems. To date, most of the development work in micro-LEDs has been focused on the mass transfer of large arrays of LEDs from the wafer onto a display substrate (as illustrated in Figure 3-55) and the fabrication of high performing micro-LEDs. Traditional pick and place equipment used to place LED packages on PCBs operates at a speed of 8 to 10 LEDs per second with a placement accuracy of 25 µm. Die bonding equipment that places LED die into packages are considerable slower at a rate of one LED per second but more accurate with a placement tolerance of 5 µm. To place the 100 million LEDs required for an 8K display at 10 LEDs per second would take nearly 4 months, making today's current methods impractical. There has been considerable effort in industry the past several years to develop economical mass transfer methods with extremely high yields to make the use of so many LEDs a possibility in a consumer electronics product. New lighting products can also leverage these pixelated light sources to create new or improved functionality.

3.5.3 Sustainability

As the manufacturing of LED lighting is considered, the environmental impact of today's system designs and production processes should be addressed. Developing a sustainable supply chain that feeds into the circular economy is an opportunity for lighting industry to model the transformation needed for a sustainable future. As illustrated in Figure 3-57, the circular economy is based on the principles of designing out waste and pollution, reusing materials and products, and recycling end-of-life products back into the cycle, unlike the linear economy, which is predicated on using materials and then disposing of them. A commitment from the lighting industry is needed to create a sustainable supply chain and prioritize the circular economy. Manufacturers must design differently by using more sustainable materials, and deconstruct differently by creating intentional designs for disassembly and recycling of luminaire materials. Designing products for the circular economy can also lead to new business models such as Lighting as a Service (LaaS).

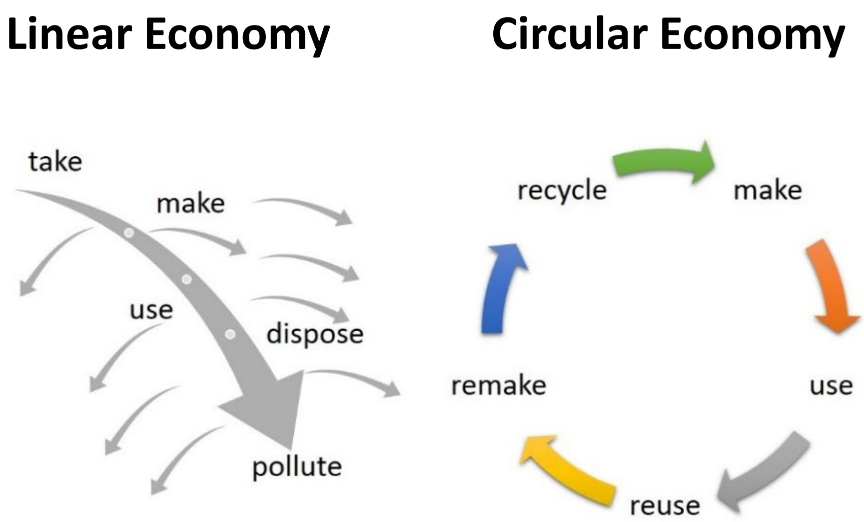

Figure 3-57 Comparison of the linear economy and circular economy schemes. The circular economy is based on the principles of designing out waste and pollution, whereas the linear economy is predicated on using materials and then disposing of them. [100]

Manufacturing Opportunity: Sustainable Materials Supply Chain for Lighting. A sustainable lighting future requires the creation of eco-friendly designs with minimized component count, and the use of low-embodied energy materials, recycled materials, or bioderived materials.[9] The majority of today's SSL luminaires use aluminum and other energy-dense structural and thermal materials in their designs and manufacturing processes. There is an opportunity to jump start sustainable supply chains by developing and integrating bioderived materials like bamboo or flax seed into the luminaire, producing lenses and other components out of ocean plastics, exploring repurposed "trash" for 3D printing source materials, and making every component of a lighting system recyclable, reusable, and free of harmful chemicals.

In late 2019, DOE announced the Sustainable Manufacturing of Luminaires Prize as part of the Manufacturing Innovator Challenge (which consists of six individual challenges across multiple technologies to find ideas that will enhance manufacturing in the United States). [10] The Bamboo Pendant designed by Koerner Designs won one of the prizes with elements that exemplified sustainable design: simple construction, fast disassembly, reduced toxicity, reduced lifecycle costs, and reduced environmental impact. Figure 3-58 shows some of the design elements of the Bamboo Pendant that illustrates sustainable supply chains (bamboo body and flax seed PCB), low embodied energy glass lenses, simple assembly processes with luminaire design, and ease of end of life (EOL) deconstruction and recycling. [101] This luminaire was designed to integrate a centralized power conversion and a DC grid to maximize electrical efficiency (less AC/DC losses throughout the building). The continuation of such manufacturing challenges could spark further creative innovation and problem solving in the sustainability domain.

The use of recycled materials can help save energy and repurpose items from the landfill. Extracting and processing raw resources to make usable materials requires a lot of energy, whereas recycling often requires

[9] A "bioderived" material refers to a material that is composed, in whole or in significant part, of biological products, including renewable domestic agriculture materials, renewable chemicals, and forestry materials; or an intermediate ingredient or feedstock.

[10] The prize criteria can be found at: https://www.energy.gov/eere/buildings/articles/energy-department-announces-winner-sustainable-manufacturing-luminaires

much less processing to turn previous products into usable materials. The potential energy savings estimates for recycling common materials is as follows: [102]

- Aluminum ~ 95% energy savings
- Steel ~ 67% energy savings
- Paper ~ 60% energy savings
- Plastics ~ 33% energy savings

Ocean plastics are currently being repurposed to make many different products from bottles to knit caps. These materials have potential for replacing some of the plastics used in luminaires. Similarly, creative use of existing "trash" can help drive the circular economy. Distributed recycling and additive manufacturing (DRAM) enables reusing materials by cleaning waste plastics, mechanically grinding them into pellets, and then turning those pellets into the feedstock used to create the filament sources for 3D printing. Filaments made with recycled waste material is very economical with costs around $0.05 per pound as compared to commercial filaments which can run about $10 per pound or more. [103]

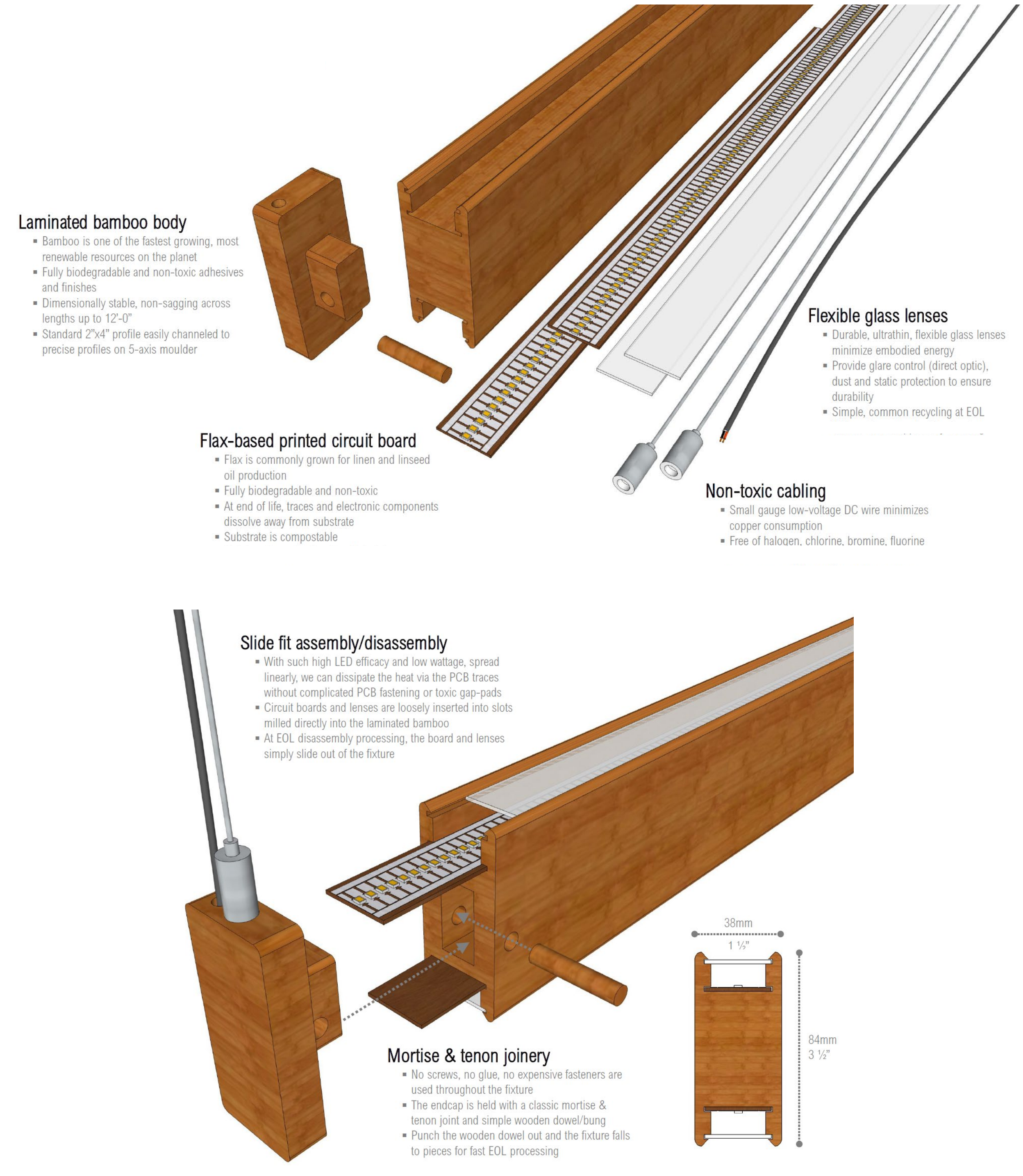

Figure 3-58 Bamboo Pendant designed by Koerner Designs won the DOE Sustainable Manufacturing of Luminaires Prize in 2020. The key features of design include a biodegradable bamboo luminaire body and flaxseed printed circuit board along with an easy end of life (EOL) deconstruction design. [101]

Beyond the use of sustainable materials, it is important to eliminate unsafe chemicals from every component and for manufacturers to provide materials transparency through certification bodies, such as the Living Building Challenge and their "Declare" label. The Declare label contains information on the life cycle impacts of the product and shows the Red List status, which has more than 800 chemicals listed as hazardous to the environment or human health. Figure 3-59 shows a sample declare letter from a Finelite LED luminaire.

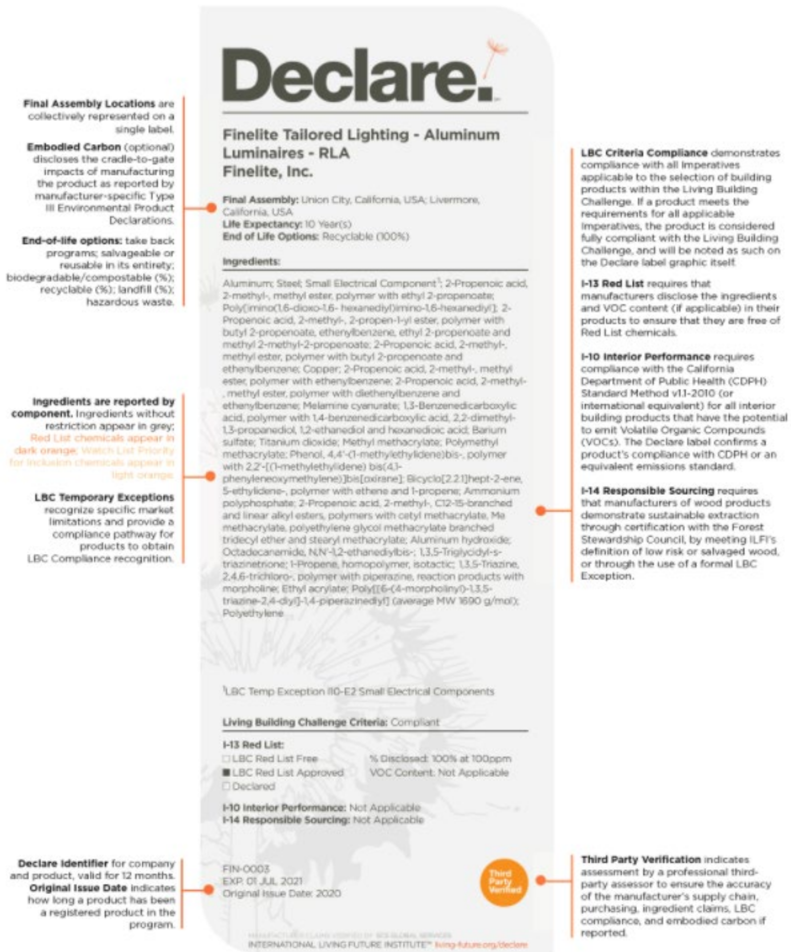

Figure 3-59 A sample Declare label certified from the Living Building Challenge for a LED luminaire made by Finelite. The image highlights key features of the label disclosure including embodied carbon, end of life options, and ingredients. [102]

The approach of sustainable supply chains and the circular economy has the potential to create a local economic advantage by embracing the concept of upgradeable or repairable fixtures and allowing for more maintenance and servicing local revenue streams. Additionally, maintaining more bio-friendly materials and an emphasis on reducing transportation waste can help improve the local supply chains. If a sustainable design rating was a competitive barrier, then categories such as reduction in transport waste, sustainable materials use, and efficient recycling could be differentiators in rating. It is not essential to wait for every component, luminaire, or supporting process to be sustainable to start on the path to sustainability. For established technologies and supply chains such as those relevant to lighting, moving forward one step at a time is an important process.

4 OLED Panel and Luminaire Manufacturing Process, Equipment & Materials

OLED light source technology was developed over the same time period as LED technology. OLED sources can be quite efficient but have not been able to match the cost and lifetime of LED technology. OLEDs still present a counterpart to LED technology, providing a soft, diffuse light source that can offer low-glare illumination and be located close to the lighted task. Advancements in OLED manufacturing technologies are required to reduce the cost of OLED lighting to levels comparable with LED lighting and make it competitive in the market. The manufacturing baseline for OLED lighting products is relatively immature since the commercialization of OLED lighting products has a limited market, thereby resulting in much more uncertainty in the pricing, supply chain, and prospects for OLED lighting technology. This is in stark contrast to the rapid growth in the manufacture of OLED panels for displays. OLED technology has gained a substantial portion of the market for high-end mobile phones and is gaining market share in large televisions. This has led to the investment of $40B in OLED manufacturing equipment over the 5 years between 2016 and 2020. [104] Much of this equipment is too large and too expensive for lighting manufacturers. However, the market for OLED materials has grown to over $1B per year, leading to substantial cost reductions that will help to promote lighting applications. [105] In general, OLED lighting sources are simpler than OLED displays, but they have much higher requirements for efficiency, lifetime, lighting performance, and lower cost than OLED displays.

The manufacturing steps, technologies, and materials that will be described for OLEDs could also be relevant for QDEL lighting which would likely use similar device and panel architecture but with a QDEL emissive material rather than an organic light generation layers.

4.1 OLED Process Flow

In 2014, three main production lines for OLED lighting panels were operating: the Philips line at Aachen, Germany, which processed 400 mm x 500 mm glass substrates, while LG Chem at Ochang, Korea and First O-Lite in Nanjing, China used 370 mm x 470 mm sheets. Since that time, the Philips OLED business was acquired by OLEDWorks and control of First O-Lite was assumed by Jiangsu First-Light, which also supplies OLED luminaires in China with panels from OLEDWorks. The OLED lighting business at LG was transferred from LG Chem to LG Display. In 2016 the company announced that it would build the world's first 5th generation (1000 mm x 1200 mm) OLED light panel manufacturing facility in Gumi, South Korea. The planned capacity was 15,000 substrates per month, implying a cycle time (takt time) of 3 minutes. Although the start of production was announced in December 2017, the company decided to withdraw from the OLED lighting market in 2019.

The acquisition of the Philips assets enabled OLEDWorks to use the Aachen line for the manufacture of standard products while focusing their two lines in Rochester to research and prototype or custom production. The performance of the panels produced at the Aachen line has improved substantially and markets have been established in automobile applications as well as in general lighting. OLEDWorks manufactures rigid panels with thickness of 1.4 mm and flexible panels on 0.1 mm Willow® Glass from Corning, with a panel thickness of 0.6 mm and a bending radius as low as 10 cm. The layout of the production line used by OLEDWorks for lighting panels is shown in Figure 4-1. The integrated substrate, received from an external vendor, is cleaned and primed in the equipment shown at the top of Figure 4-1. Deposition of the organic layers takes place in the upper loop. The masks are returned to the beginning of this loop, while the substrates are passed to the second loop. A new mask is attached for cathode deposition. The final stage of substrate processing involves encapsulation and singulation. The complete manufacturing process flow is shown in Figure 4-2, including the formation of the integrated substrate and the incorporation of panels into a luminaire.

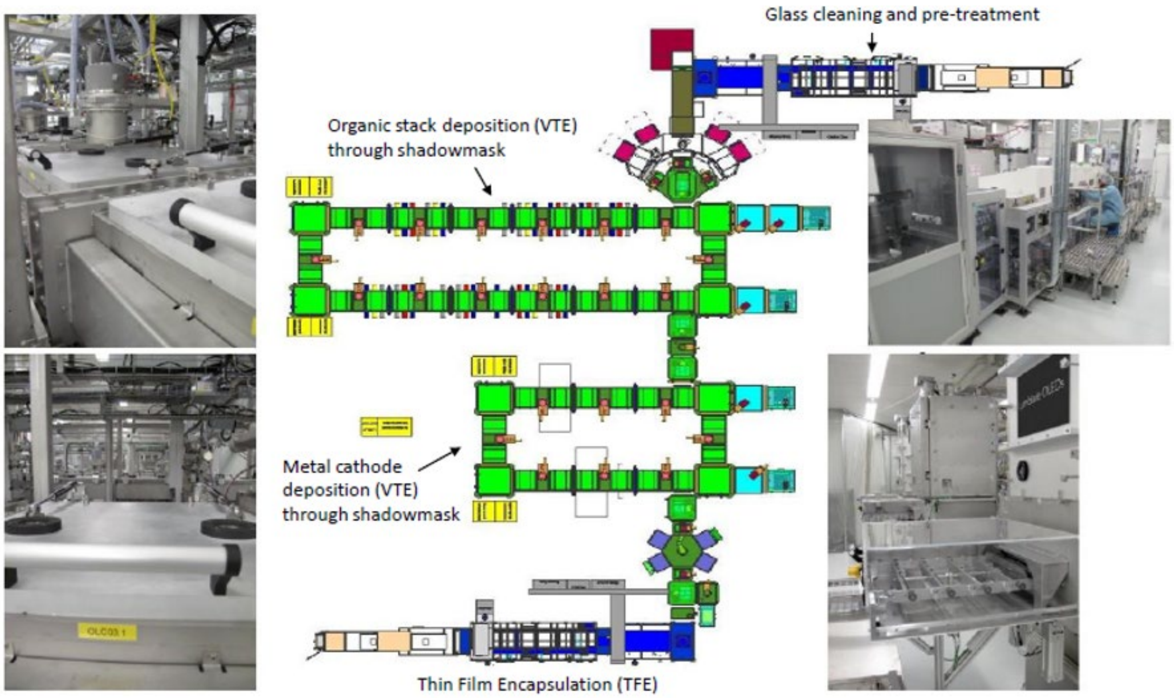

Figure 4-1 Layout of the OLEDWorks production line. After the integrated substrates are cleaned and surface treated, they enter two chains of vacuum deposition tools, arranged in loops to allow return of the masks. The substrates are then encapsulated to prevent damage to the fragile electronics before separation into panels. [106]

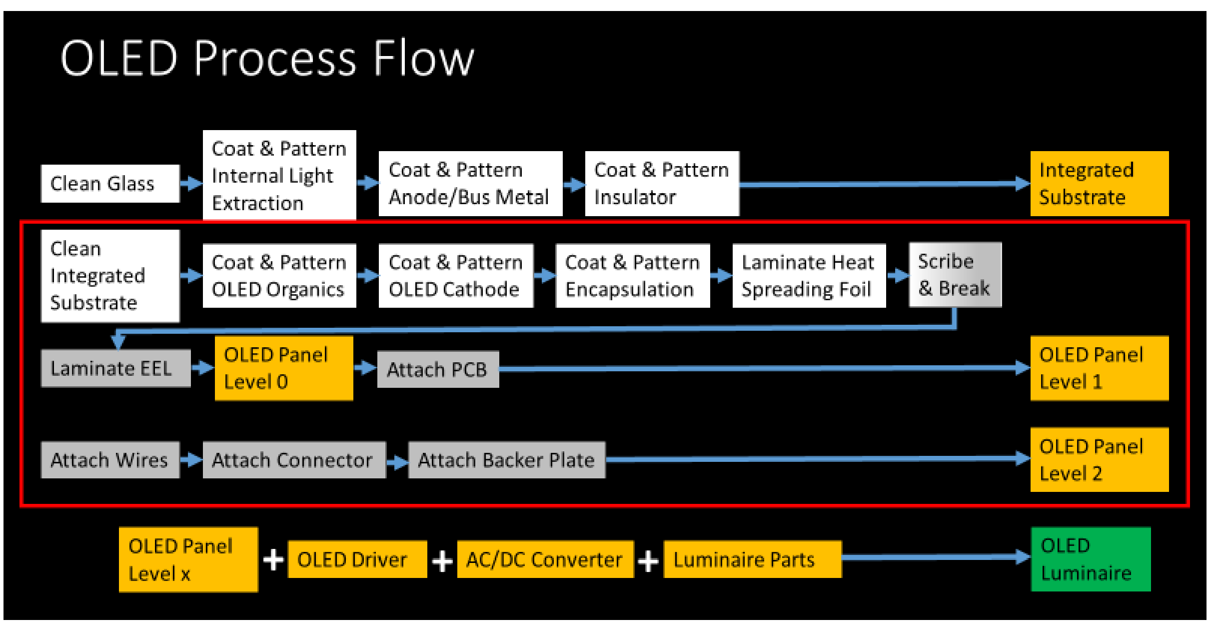

Figure 4-2 Process flow for the manufacture of an OLED luminaire. If required, the fabrication can be divided into three or four separate stages. [107]

4.2 Integrated Substrates

The essential function of the substrate is to form a smooth, clean surface onto which the organic materials can be deposited. Since the light is emitted through the substrate, the base material must be transparent and is typically either plastic or glass. Its dimensional stability must be sufficient that thermal expansion during processing is not enough to cause significant alignment errors. Several additional layers are usually required before the organics can be applied. If plastic is used, a barrier against moisture and oxygen must be coated, either on the inside or outside of the substrate. Structures to facilitate light extraction are also needed in high-performance panels and are located either above or below the substrate. Finally, a transparent electrode is deposited to supply current uniformly across the panel. OLED lighting panel manufacturers often purchases these integrated substrates from vendors.

4.2.1 Substrate Choice

The preferred substrate in current production is display glass, such as the alkali-free borosilicate glass from Corning, which provides a smooth surface and will tolerate high-temperature processing. The glass substrates have thicknesses between 0.1 mm and 0.9 mm. The high demand from the display industry has led to significant cost reductions for thicknesses of 0.5 mm and higher. For UTG the lower cost of procuring and heating the raw material is more than offset by the extra difficulty of finishing and handling, leading to a premium for thicknesses less than 0.2 mm.

The 0.1 mm Corning Willow® glass allows bending with radius of curvature down to 10 cm, which should be adequate for many lighting applications. Rolls of UTG with a width of 300 mm from several manufacturers have been used in the processing of prototype OLED lighting panels at the Fraunhofer Institute in Dresden and at the Industrial Technology Research Institute in Taiwan. Sheets of such glass are already used by OLEDWorks in the commercial production of conformable panels.

Plastic substrates can also be used for OLED panels; they are less susceptible to breakage but need to be attached temporarily to a rigid substrate for sheet-to-sheet processing. The prime choice for display applications is polyimide, which is deposited in-situ on the temporary substrate. Most polyimides have a yellow tint, but this is acceptable for displays, since the light is emitted upwards. Although clear forms of polyimide are available for lighting applications, their cost is currently too high for implementation.

The most common plastic for lighting applications is PET. It provides relatively high dimensional stability, with low coefficient of thermal expansion and little shrinkage under temperature cycling. When heat-stabilized, PET can sustain processing temperatures up to about 150^0C. It is resistant to solvents and has low water absorption, although water is transmitted easily and a barrier to moisture and oxygen is required. PET can be co-extruded with a peelable protective layer that absorbs damage in web transport and handling.

4.2.2 Barriers for Plastic Substrates

The organic materials used in OLED stacks are extremely sensitive to oxygen and water. When plastic films are used as substrates or encapsulants, a barrier layer must be added. The barrier for substrates is usually placed on the inside surface, to keep out any water that may be trapped in the plastic film. The upper limits for permeation through the barrier are typically ~10^{-6} g/m^2/day for water and 10^{-4} cm^3/m^2/day for oxygen. Measuring such low rates has been a cumbersome process until recently, and the availability of an in-line measurement technique would be a major advancement, especially when R2R processing is used.

The feasibility of reaching such targets has been demonstrated in display applications, through hybrid multi-layer films that combine inorganic and organic layers. The inorganic layers are usually deposited by PECVD and the organic layers by ink-jet printing. This equipment is expensive and can contribute significantly to the manufacturing cost, especially while production volume is still low. Most of the protection in these hybrid layers is provided by the inorganic layers, which are usually formed using oxides or nitrides of metals or silicon. While these are very dense films, they may contain pinholes or other defects. The organic layers are introduced to hinder migration of the water or oxygen between the defects in the inorganic layers.

There have been several attempts to reduce the cost of barriers by using only inorganic materials. Multiple layers with differing hardness and plasticity can be created by varying the deposition condition in sputtering machines or physical vapor deposition (PVD), as demonstrated by Vitriflex. [108] The soft layers replace the conventional organic layers but can be deposited in the same equipment. This approach could be even less expensive if an effective barrier can be formed with a single layer. Atomic layer deposition (ALD) produces extremely dense layers, but traditionally is a relatively slow deposition process, resulting in higher cost production. Research has been underway for several years to speed up the ALD process, for example by using spatial ALD. [109] Extreme care must be taken in speeding up ALD or any other process to form a barrier layer. Although ALD leads to very smooth layers in theory, implementation can lead to defects or contaminants. To date, multiple layers have been found necessary to mitigate this risk. [110] [111]

4.2.3 Extraction Enhancement Layers

Improving light extraction efficiency in OLED panels is critical for the advancement of OLED lighting. In OLEDs, the light is generated in layers with an effective refractive index of around 1.7. This limits light extraction to only those photons that are emitted in a small escape cone around the normal, which can emerge directly into air. Typically, only 25% of the light escapes unless corrective action is taken, such as implementing enhancement layers to increase the portion of light that is extracted. One approach is to introduce random scatterers and reduce absorption within the whole structure so that the photons can bounce many times between the transparent substrate and reflecting cathode until they escape. Another is to create 3D structures that preferentially refract the light towards the normal. Reducing absorption within the device is also critical and tailoring of the refractive index of neighboring layers can help to reduce Fresnel reflections.

Random scattering has been achieved by embedding metal oxide nanoparticles of size close to the wavelength of visible light into a polymer layer. The refractive index of the polymer is raised from its intrinsic value of approximately 1.55 to over 1.7 by the incorporation of smaller zirconium oxide (ZrO_2) or titanium oxide (TiO_2) nanocrystals with core sizes of 5 to 15 nm. [112] [113] The layer can be deposited by standard solution-processing techniques, such as slot-die coating or ink-jet printing.

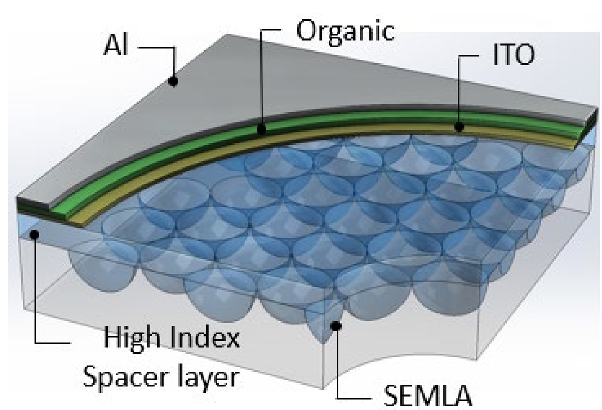

Figure 4-3 Integrated Substrate with a Sub-Electrode Micro Lens Array. [114]

Another approach to scattering is illustrated in Figure 4-3 with an integrated substrate developed at the University of Michigan using an etched glass substrate. Micron-sized structures can be created in glass by chemical or reactive-ion etching through resist that has been patterned by photolithography. Patterns can be formed in coated polymer layers by nanoimprinting or traditional stamping techniques before curing. Another approach can be to employ self-assembly of preformed microspheres. These techniques can be applied either in sheet-to-sheet or roll-to-roll mode.

While there have been advancements in light extraction technology for OLED panels, a critical challenge has been the ability to manufacture light extraction technologies at costs low enough to be suitable for general illumination lighting application. Light extraction technologies need to be developed with overall device compatibility and manufacturing in mind.

4.2.4 Transparent Electrodes

The main function of the anode is to distribute current uniformly over the panel with minimal loss of voltage while also allowing generated light to efficiently get out of the device structure. Achieving uniformity over 90% requires that the voltage drop across the panel should be limited to less than 0.1V. Indium tin oxide (ITO) is still the material of choice in commercial production, despite many years of R&D on the development of alternative transparent conductors. The resistivity of good ITO deposited at high temperature can be as low as 10^{-4} ohm centimeters (Ω cm), which means that a sheet resistance of 10 ohms per square (Ω/□) may be attained with a thickness of around 100 nm. The ITO layer can be made thicker to reduce the resistance to below 10 Ω/□; however, the optical transparency decreases leading to more absorption. The use of inexpensive plastic substrates reduces the temperature at which ITO can be deposited, leading to higher sheet resistance. For example, with PET it is difficult to achieve sheet resistance below 20 Ω/□ with acceptable levels of light transmission.

An attractive strategy for large substrates is to combine a grid of metal wires with a thin sheet of ITO. [115] Linewidths of the metal wires are typically kept below 100 µm, such that they are not visible from a viewing distance of around 1 meter. The pitch between metal lines is typically 1 to 2 mm, optimized to balance effective current spreading with minimal optical efficiency impact. The metal film thickness is typically in the range of 200 to 500 nm. Since the total organic stack thickness is usually in this same range, the metal traces must be planarized with an insulator material to ensure good step coverage and prevent shorting between the anode and cathode. An insulator material such as a positive photoresist around 1 µm thick provides an effective approach to the planarization of patterned metal and ITO edges.

With respect to alternatives to ITO, good results have been obtained in research laboratories using silver nanowires. In one project supported by the DOE SSL Program, anodes with sheet resistance of 10 Ω/□ and optical transmission of 84.5% were created on a PET substrate. Initial tests have confirmed that reliable OLEDs can be formed on such anodes. [116] These anodes were deposited and patterned in a research laboratory by printing techniques, thus avoiding the use of masks, but have not yet been tested in commercial production.

Preparation of the surface of the anode is essential to avoiding shorts and ensuring efficient hole injection. This is especially important if the integrated substrate is assembled under contract and shipped to the OLED manufacturer. The methods chosen to form the anode must result in a smooth surface with no spikes or sharp edges. Before deposition of the organic materials, the substrate undergoes several preparation processes such as cleaning, baking to remove moisture, and plasma or UV-ozone treatment to remove organic contaminants and increase the work function of the anode surface. The baking and surface preparation processes are typically done just prior to coating the organic layers, and precautions are taken to avoid exposure to moisture and oxygen.

Manufacturing Opportunity: Customizable Manufacturing of Patterned Substrates. OLED manufacturers need patterned substrates so that multiple panels can be fabricated with edges that are sealed to prevent shorting between the electrodes and to minimize the ingress of oxygen and water. The substrate should be conformable with a bending radius as low as 10 cm to support roll to roll manufacturing. The substrate should contain an electrode with effective sheet resistance below 10 ohms/□ and optical transmittance of over 85%. The top surface should be smooth enough to allow deposition of thin organic layers that will not be prone to shorting. Light extraction layers should be incorporated, giving an enhancement factor of at least 2.0. If the basic substrate consists of a polymer material, an effective barrier against water and oxygen should be formed between the substrate and electrode. The fabrication processes should support the production of customized patterns in modest quantities at an affordable cost, preferably below $50/m^2, and should be scalable to substrate areas of at least 2 m^2.

At the present time, the manufacturing of OLED panels for lighting is hampered by the absence of U.S. suppliers of customized integrated substrates. Reliance on Asian vendors leads to delays and additional cost of transportation. Although many solutions have been proposed for each component of the integrated substrates, the greatest need is for a set of manufacturing processes that might enable U.S. vendors to deliver products that meet the desired performance at an affordable cost.

4.3 Light Generation

A series of organic layers are deposited between the anode and cathode to convert electrical current into photons. The photons are created in emissive layers (EML), while the flow of electrons and holes is controlled by charge injection layers (electron injection layer, EIL, and hole injection layer, HIL), transport layers (electron transport layer, ETL, and hole transport layer, HTL) and blocking layers (electron blocking layer, EBL, and hole blocking layer, HBL). Maintaining a balance between electrons and holes is critical for efficiency and lifetime of the device. The blocking layers are introduced to make sure that the charges meet in the emission layers rather than crossing all the way between the electrodes. The requirements for lighting level brightness and lifetime are high so several emission layers are used, separated by charge generation layers (CGL) in which new electrons and holes are created. Figure 4-4 shows a typical structure with six stacks, as used by OLEDWorks. Three of the stacks contain red and green phosphorescent emitters, while the other three have fluorescent blue emitters. The thickness of each of the 40 to 50 layers varies between about 3 nm and 100 nm with an average of ~10 nm. The requirements for precise thickness deposition over a large area, different materials for multiple layers that must be compatible, and high yield result in a very challenging deposition process. Advancements to OLED performance need to consider these production factors, otherwise lab scale technical advancements cannot be transitioned to full scale manufacturing.

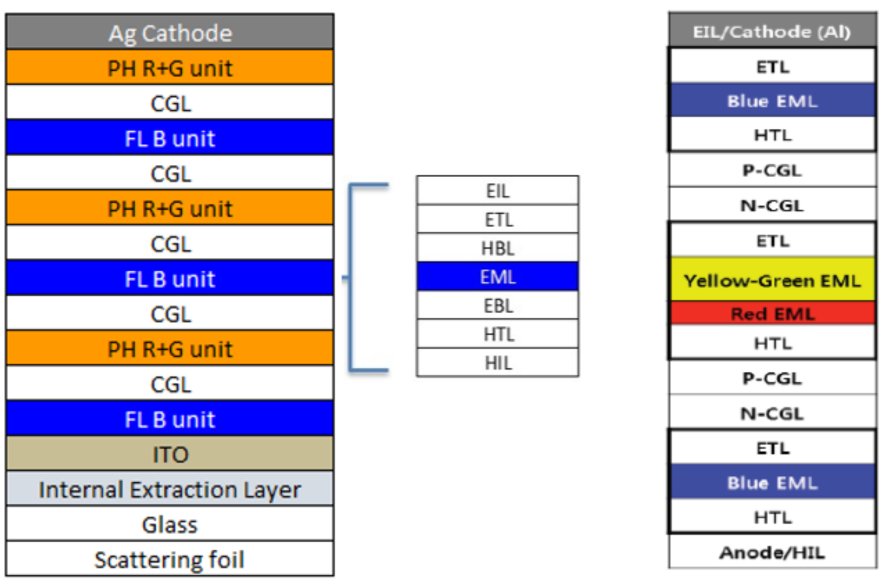

Figure 4-4 Schematic of organic layers in high-performance OLED stacks for lighting with six emitter units, each of which has multiple layers (left), and for display applications with only three emitter stacks (right). [117]

The similarity between the structures used for lighting and those used for television screens means that some of the benefits of high-volume production can be transferred from displays to lighting. However, the material sets used in both applications are tailored to each producer's preference and require, so that there will be some premium for small manufacturers or specialty products.

4.3.1 Organic Materials

The most critical and expensive materials are those in the emitter layer. To satisfy the requirements of efficient photon generation and charge transport, these layers usually contain a small percentage of fluorescent or phosphorescent emitting molecules in a host material, as described in the 2019 DOE R&D Opportunities document. [7] Data from a leading market research company suggests that the average cost of these organic materials in OLED TV applications is about $80/m^2$ of processed substrate. [118] The average price paid by all OLED display makers for dopants was about $325/g, whereas other organic materials were less than $20/g. [119] The dopants used in commercial production for both display and lighting applications are fluorescent for blue and phosphorescent for red and green. Although research has been underway for several years into hybrid systems, such as Hyper-fluorescence and thermally activated delayed fluorescence (TADF), these have not yet been deployed in high-volume manufacturing due to inadequate operating lifetimes.

Organic molecules are almost all deposited in vacuum and are relatively small in size. Solution processing has been promoted as a less expensive approach for large panels, and the development of appropriate molecules has been underway for two decades, using both "small" molecules and polymers; however, the performance has always lagged that of the vacuum-deposited materials. The deposition of solution-processible materials by ink-jet printing is being brought into production for displays by some Chinese and Japanese manufacturers but has not yet been used for lighting.

The standard method for the deposition of organic materials is vacuum thermal evaporation (VTE), in which the molecules are evaporated from crucibles in one chamber and then transported to the production line and injected from nozzles. The pressure in the deposition chamber is typically around 10^{-7} Torr. For most organic materials used in OLED devices, the dry powder material evaporates via sublimation, in which the desired vapor pressure is achieved before reaching the melting point. However, a few commonly used organic compounds are known to melt first, such as N,N′-Di(1-naphthyl)-N,N′-diphenyl-(1,1′-biphenyl)-4,4′-diamine (NPB). Most of the organic compounds have sufficiently high vapor pressures to be evaporated at temperatures below 400^0C.

The dispensing nozzles can be in a point, linear, or planar configuration. The linear configuration gives the most uniform distribution and is preferred for in-line or R2R operation. A mask is place between the nozzle and the substrate to prevent deposition between and around the several panels on the substrate. The substrate and mask move continuously above the source in a horizontal orientation or at the side if a vertical orientation is preferred. Many large tools are in operation by the major display manufacturers in Asia, coating substrates of up to 10 m^2 in area in 60 to 90 seconds. Separate tools are needed for each layer, although several different molecules can be evaporated simultaneously.

It seems unlikely that the large Asian companies that supply deposition equipment to the display industry will be willing to devote the resources necessary to design and manufacture custom tools suitable for lighting applications. It may be more attractive for OLED manufacturers to design special tools, in conjunction with the U.S. suppliers of research equipment. A recent project supported by the DOE SSL Program at OLEDWorks demonstrated that this approach could result in smaller size equipment that could meet targets for deposition rates and device performance. [120] The outcomes of this 'Next Generation Source' (NGS) development project included:

- Four material co-depositions
- Wide range of deposition rate between 0.005 nm/s and 6 nm/s
- Deposition uniformity of ±3%
- Material usage efficiencies up to 68%
- Efficient techniques to refill or change material sources.

The deposition rate is usually controlled by changing the temperature in the evaporation chamber. Accurate control is important, especially within the chambers that are used for dopants and hosts that are mixed before deposition. The deposition rates are monitored using quartz crystal microbalances (QCM). These are offset from the substrate and so must be calibrated carefully.

To minimize material wastage and the risk of contamination, deposition of the organics on the walls of the equipment must be kept low, so that all surfaces within the delivery system can be kept hot. Careful thermal management of the whole system is essential. The nozzles in the NGS were typically kept at a temperature of ~350^{0}C. Heating of the substrate itself must be limited, even for rigid glass substrates. Extra care must be taken when plastic substrates or ultra-thin glass are used without a thick rigid backing in R2R systems.

Maintenance of VTE equipment is critical to avoid contamination of the organic layers. Some of the organic material and metal does not reach the substrate in the active area, but is deposited onto the masks, frames, shields, shutters, and other parts of the machine. As the buildup of organics on the machine walls increases, the coating will begin to flake off, resulting in particles inside the vacuum chambers. Coatings that deposit on moving parts will also generate particles when the parts move, such as if rollers contact the coated surfaces. For these reasons it is necessary to stop the production operation periodically, cool down the sources, vent the vacuum chamber, and clean the surfaces that have organic or metal deposited on them. The frequency of this operation depends on the material usage efficiency and the design of the machine. At the same time, the organic and metal crucibles are refilled and new quartz crystals loaded in the QCM heads. The target limit for downtime due to this scheduled maintenance is less than 10% in most lines. [121]

The high temperatures required in evaporation chambers to achieve the target deposition rates can lead to dissociation of some of the more fragile molecules. An alternative deposition technique, known as organic vapor phase deposition (OVPD), was suggested by researchers at Princeton University in 1995. [122] The evaporation and transport of the organic molecules are accelerated by a flow of an inert gas. The improved transport allows target deposition rates to be achieved with lower temperature in the evaporation chamber, but also leads to greater material utilization. For example, for a typical hole transport material, Aixtron was able to achieve a decomposition rate of 4 nm/s with a source temperature of 200^{0}C, whereas an evaporation temperature of 320^{0}C was needed to deposit the same material at 0.1 nm/s in a conventional VTE tool. [123] Tests to qualify a small OPVD production tool for display manufacturing are underway. [124] An adaptation of OVPD appropriate for R2R processing of OLED lighting panels is being tested in a current DOE SSL project at the University of Michigan. [125] Another potential advantage of OVPD is that the vacuum requirements are less severe, with typical pressure around 1 Torr. However, H_2O and O_2 still must be kept out of the deposition chamber. The Michigan project is using both techniques in side-by-side chambers to check whether the web can be passed from one to the other without contamination or scratching of the active surface.

Another alternative approach to the deposition of organic materials is organic vapor jet printing (OVJP). [126] OVJP allows manufacturers to use a gas stream to “print” small-molecule OLED materials onto panels and to use the same type of commercially proven materials that are used in existing vacuum deposition systems. Although the technique was originally proposed for display applications (to avoid the need for fine metal masks), its use could increase material usage in the fabrication of lighting panels by eliminating the deposition of organics between panels and around the edges of the substrate.

Several U.S. companies have many years of experience in the design and delivery of organic deposition equipment for R&D laboratories, but none have been successful in supplying tools that have the capacity for commercial production. The development of scalable tools that enable the production of multi-stack devices with short cycle times will accelerate the adoption of OLED lighting panels and broaden the participation of U.S. companies in the industry.

Manufacturing Opportunity: Rapid Deposition of Organic Materials. OLED lighting panels in current commercial production incorporate up to 40 layers of organic materials with a total thickness around 200 nm to 500 nm. Manufacturing lines have typical cycle times of 3 to 6 minutes. Reducing this time to 1 minute or less provides the most attractive route to increased throughput and lower manufacturing cost. Deposition of organic layers without compromising film morphology or production yield is one of the greatest challenges in meeting this goal. The development of alternative techniques to the standard vacuum thermal evaporation may be necessary to avoid the use of high source temperatures that threaten the integrity of the organic molecules. New deposition techniques should allow co-deposition of multiple materials and be consistent with the sequential deposition of multiple layers without intermediate curing. Additive patterning techniques that enable the formation of multiple panels on a substrate without the deposition of organic materials between and around the panels would be preferred. The processes that are developed should be scalable to substrates of size up to 2 m^2 or web widths up to 1.5 m.

4.3.2 Cathode Deposition

In OLED lighting panels, the light is emitted through the transparent anode so the cathode is not required to be transparent, but instead should have good reflectivity. High reflectivity is critical since light extraction strategies can result in the photons striking the cathode several times before escaping. Silver is currently the preferred material for the bottom surface of the cathode, due to its high reflectivity over most of the visible spectrum. Although materials such magnesium, aluminum or ytterbium can be incorporated to improve the electron injection efficiency, these layers have high absorbance at the visible wavelength range. If transparency is required, the thickness of the Ag can be reduced to below 20 nm or a more transparent layer can be combined with a metal grid.

The cathode must be deposited in such a manner to avoid damage to the underlying fragile organics. VTE is the preferred technique, but the deposition rates are relatively low (< 1 nm/s) and high evaporation temperatures (~600^0C) may be needed. The evaporation source must be designed to avoid the production of contaminants that may lead to pinholes or particulates in the cathode. [127] DC magnetron sputtering allows faster deposition rates than VTE but can lead to unacceptable leakage current if the operating conditions are not optimized. [128] However, reducing the deposition rate does not always result in better layers. The thickness uniformity targets for the cathode are more relaxed than for the organic layers and are typically around 10%. [129]

Cathode deposition requires a mask that differs from that used for the organic layers. The organic materials cannot extend to the edge of the panels and must be sealed to prevent lateral ingress of water and oxygen, whereas the cathode must allow contact with the external electrical circuit.

4.3.3 Encapsulation

The organic layers must be protected against ingress of water and moisture through the top surface. This challenge has many similarities to that of substrate barriers, as described in Section 4.2.2. Permanent protection can be provided immediately after the cathodes are deposited. This is done in high-volume display manufacturing by in-situ formation of a multi-layer structure with organic layers deposited by IJP and dense inorganic layers by PECVD. This approach is likely too expensive for general lighting applications. An alternative strategy is to add a temporary passivation layer on top of the cathode and to provide more permanent protection later, for example through the lamination of a prepared barrier film or by adding a metal cover after panel separation. The passivation layer can be a single inorganic layer, perhaps formed by ALD, which gives better coverage over particles and can lead to thinner layers that are more amenable to bending. [130]

To ensure longer term protection, several companies now provide barrier films in roll form that can be laminated to the processed substrate. Alternatively, adhesive encapsulation films can be used to bind a thin glass or metal foil on top of the OLED. [131] Whichever approach is taken, there is an urgent need for an encapsulation technique that meets DOE SSL cost and performance targets and is scalable to high-volume production.

Manufacturing Opportunity: Affordable Encapsulation Techniques. The encapsulation techniques for OLED displays are effective but too expensive for OLED lighting applications, due to multiple layers of inorganic and organic materials that must be deposited in different fabrication environments. A simpler, less costly approach is needed that meets the goal of reducing ingress of H_2O to 10^{-6} g/m^2-day and of O_2 to 10^{-4} cm^3/m^2-day. The proposed fabrication techniques could be suitable either for in-situ deposition by the OLED manufacturer or for prefabrication by a film supplier for lamination during OLED production. The proposed method should be scalable to sheet areas up to 2 m^2 or web widths of up to 1.5 m. The cost target in high-volume production should be around \$20/m^2 or less.

4.4 Substrate Patterning and Panel Separation

For the substrate to be separated into panels, it is necessary to ensure that separate electrical connection can be made to the cathode and anode and the two electrodes must be isolated to prevent shorting. The panel edges must be sealed to prevent the entry of water and oxygen into any organic or polymer layers through the edges. A simple structure for a flexible panel is shown in Figure 4-5. If polymer films are used as part of a transparent electrode or inserted between the anode and the substrate, they must also be prevented from reaching the edges of the panel.

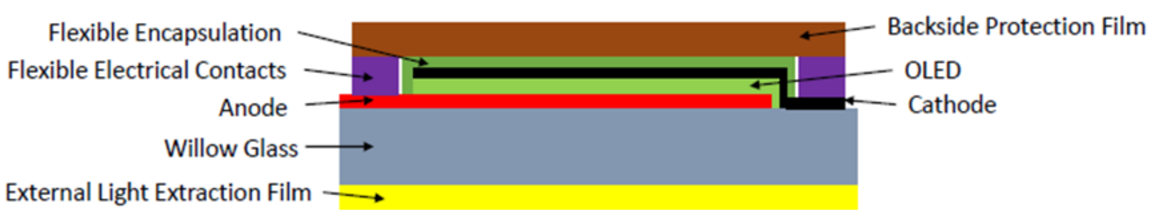

Figure 4-5 OLED panel with films added after singulation. [132]

These sealing and electrode requirements provide one of the motivations for the use of printing techniques for the deposition of all layers that allow lateral permeation of water and oxygen. For example, patterning of internal extraction layers and anodes has been demonstrated using ink-jet printing, slot-die coating and flexographic techniques. Solution printing is not yet practical for deposition of multiple organic layers, due to solvent incompatibilities as well as the poorer performance of soluble organic materials.

When vapor phase deposition techniques are used, the patterning is achieved through the use of shadow masks. This can be problematic within in-line processing and is especially challenging for R2R systems since masking is more amendable to a batch process. The attachment, detachment, and transport of masks must be accomplished with great care, both to maintain accurate alignment and prevent contamination. Material that is deposited on the masks during processing can easily be shaken off if the masks are mis-handled and must be cleaned off regularly. To reduce contamination, deposition is usually performed from below the substrate, as shown in Figure 4-6.

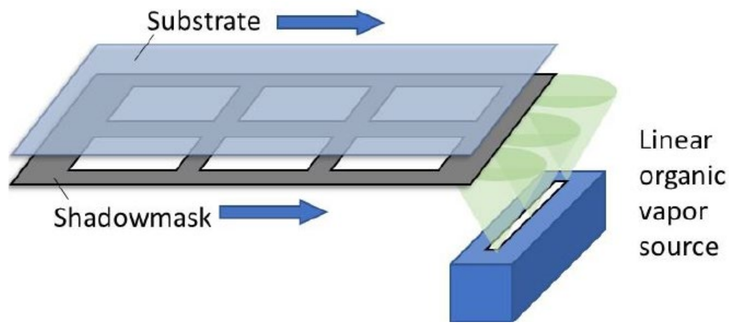

Figure 4-6 Deposition of organic materials through a shadow mask. [106]

An alternative approach is to deposit layers across the whole substrate and to remove the unwanted material near panel edges by laser ablation. The laser wavelength and intensity must be chosen carefully so as not to damage the underlying layers. Carbon dioxide (CO_2) infrared lasers are used for laser ablation in many other applications, but ongoing tests on the selective removal of organic materials have shown that collateral damage can be avoided more easily with a UV laser at 355nm. [133] Another study has demonstrated that inorganic encapsulation layers can be removed to reveal the underlying electrode contacts via ultra-short (10 picosecond) pulses from a visible laser at 532nm. [134]

The two preferred techniques for the separation of glass substrates into panels are scribing and laser cutting. Scribing involves scoring the surface of the glass with a small diamond wheel and mechanically breaking. This has been used successfully for glass of thickness down to 0.05 mm. [135] However, this process can render edges with microcracks and reduced tolerance for stress induced by bending. By using ultra-short pulses, laser cutting can be achieved through material disassociation rather than ablation. This results in a very low surface roughness, and an increased as-cut edge strength of the glass, compared to ablative laser processes or conventional score and break methods. Edge healing processes can be performed, if necessary, to increase the integrity of the edges. [136]

To allow for singulation and electrical connections, borders of approximately 10 mm are provided outside the lit area of each pattern. Thus, a panel with lit area of 100 mm x 100 mm may require a substrate area of 120 mm x 120 mm. Twelve such panels can be generated from a substrate of 400 mm x 500 mm, resulting in a substrate utilization factor of 60%. The ensuing deposition of organic materials on masks leads to a substantial increase in the cost of organic materials. Reducing the width of these borders is clearly a goal for future manufacturing R&D.

4.5 Roll-to-Roll Manufacturing

Almost all commercial manufacture of OLED panels on plastic substrates or ultra-thin glass has been accomplished by temporary attachment to a rigid substrate. The bonding and debonding processes involve added expense and introduce many opportunities for contamination and defect creation. An alternative way to control the positions of each panel is to replace the substrate sheets by a continuous web with good tension control. It has often been proposed that the use of R2R manufacturing could lead to greater throughput, with cost savings of ~ 15-20%. [137] Many prototype systems have been installed in research laboratories across the globe, including the Fraunhofer Institute in Dresden, the Holst Centre in Eindhoven, the Korea Institute of Machinery and Materials in Daejeon, CEREBA in Tokyo and ITRI in Taiwan. Efforts in the United States include those at Iowa State University, Sinovia, and the University of Massachusetts.

The first and only major commercial effort for R2R OLED production by Konica Minolta was unsuccessful in producing high-quality products, despite significant capital investment in 2014. Further research on the necessary materials and processes has been performed and it seems feasible that a successful commercial implementation could be launched within the next decade. Figure 4-7 describes a possible process flow. [132] This approach requires at least two transfers of the web into or out of vacuum. The transfers can be accomplished by intermediate rolling and unrolling, or by passing the web through narrow slits with sufficient pumping to maintain the required pressure differential. It is essential that very little oxygen or water passes through the slits and it may be necessary to perform all processes either in vacuum or in a nitrogen environment.

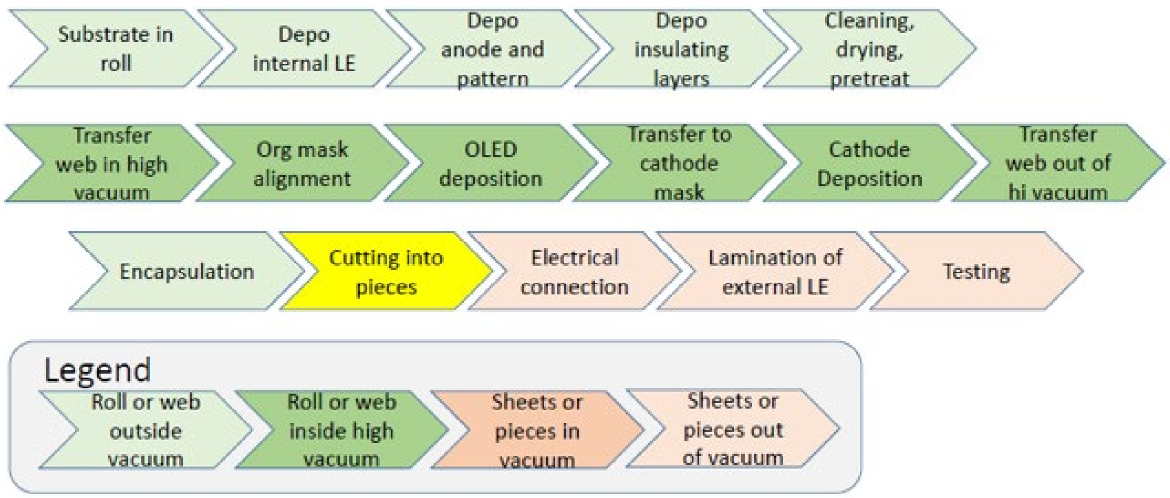

Figure 4-7 Process flow for R2R fabrication of OLED panels on thin glass. [132]

There are several major challenges with implementing R2R manufacturing, including the following:

- Processing times for each process must be synchronized, either within each stage of unwinding and rewinding, or throughout the whole fabrication
- The yield of each process must be very high (malfunctioning tools spotted swiftly)
- Contamination must be minimized
- The tension and temperature of the web must be controlled to maintain positional accuracy and avoid damage
- A method must be developed for mask handling or mask-free patterning techniques used

4.5.1 Roll-to-Roll Integrated Substrate

As with batch vacuum deposition, an integrated substrate could be used with R2R production with similar considerations described in Section 4.2.1 though compatible with the R2Requipment. The integrated substrate would need to be flexible and should include a transparent electrode, light extraction features, and barriers against moisture and oxygen ingress. The integrated substrate could be produced in a separate facility from the roll-to-roll to process and be in essence an incoming supply to the OLED manufacturer. Processes for roll-to-roll production of OLED lighting, and the integrated substrate in particular, could have cross cutting application into other large area, organic electronic applications, including those shown below in Figure 4-8.

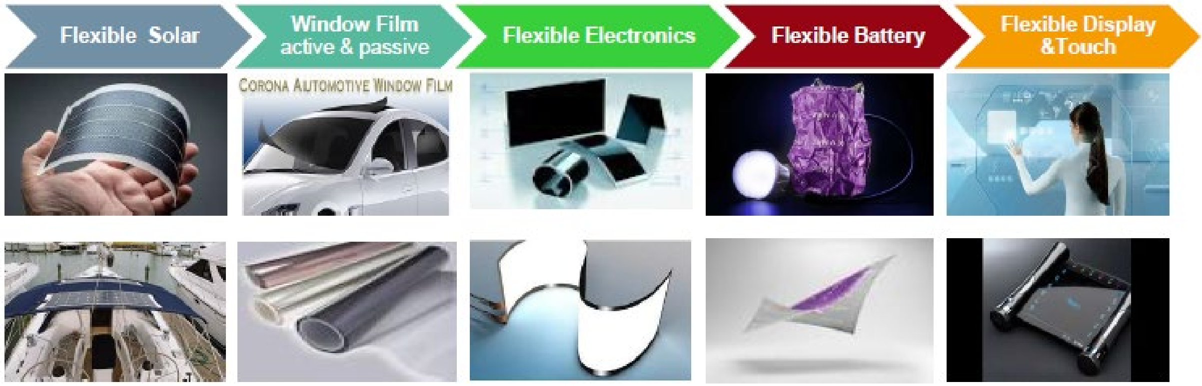

Figure 4-8 Applications of R2R vacuum coaters on ultrathin glass. [138]

4.5.2 Roll-to-Roll Deposition of Organic Layers and Cathode

The major challenges in the deposition of the organic layers and cathode onto thin webs in a roll-to-roll line include:

- Maintaining the tension in the web to avoid misalignment
- Keeping the web cool
- Avoiding contamination and scratching due to contact with rollers
- Synchronizing the rates of the many processes

In pioneering work at the Fraunhofer Institute in Dresden, the thermal stress on substrates caused by VTE was mitigated by placing the deposition chambers around a large cooling drum. The system shown in Figure 4-9 has 14 evaporators for organics, and two metal evaporators and a DC magnetron source are available to deposit the cathode. An ion beam source is used to treat the anode surface before deposition begins. Two additional rollers are used to remove the interleaved protective film before processing and add a new one on rewinding.

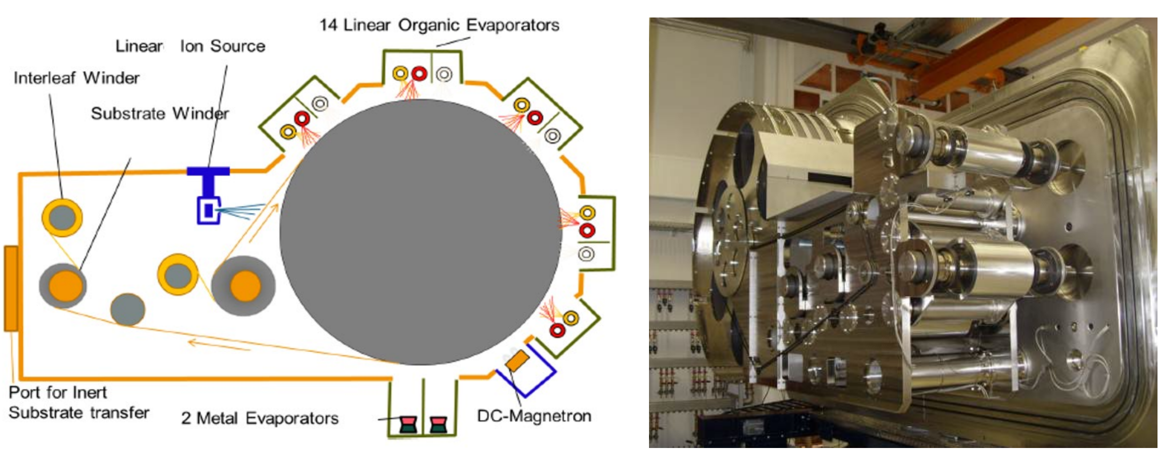

Figure 4-9 Roll-to-roll fabrication equipment at the Fraunhofer FEP in Dresden with evaporators and a DC magnetron arranged around a cooling drum. [139]

As noted in Section 4.3.2, experiments are underway at the University of Michigan to determine whether VTE and OVPD can be used sequentially in depositing the multiple organic layers. This study will provide valuable information as to whether webs can be passed safely between chambers at different pressures and whether the web tension and temperature can be maintained within acceptable levels without wrapping around cooling drums. This R&D system is designed to pass webs of width up to 95 mm at speeds up to 1.5 m/s, while maintaining positional accuracy of $\pm$0.5 mm. A schematic is shown in Figure 4-10.

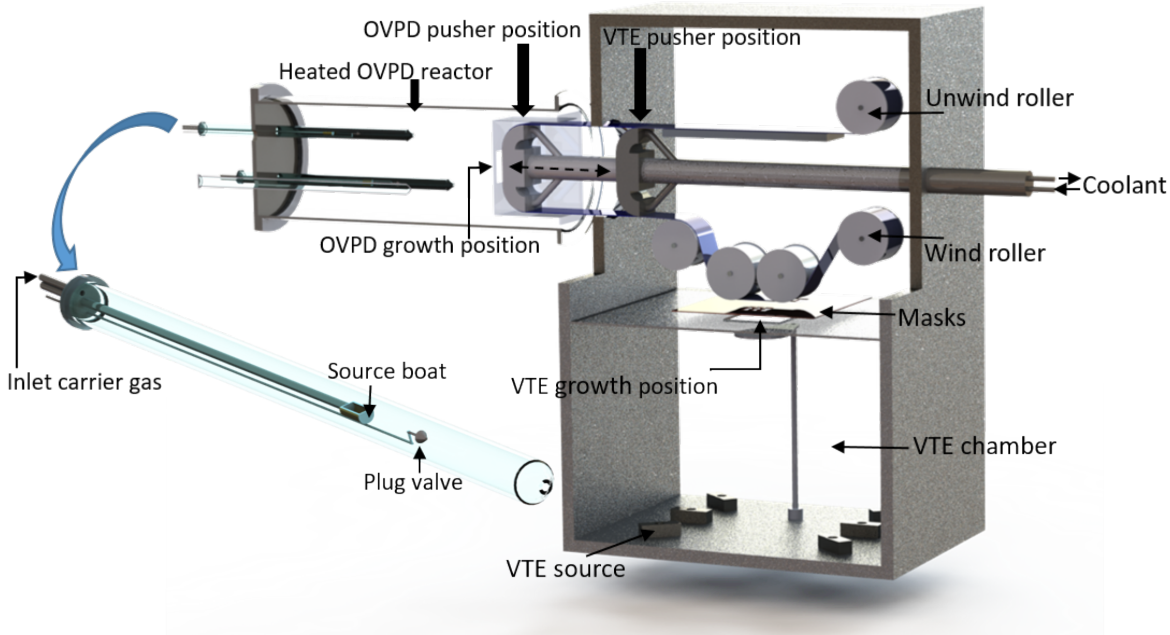

Figure 4-10 R&D equipment at the University of Michigan used to test the roll-to-roll deposition of organic materials using both VTE and OVPD. [140]

4.5.3 Roll-to-Roll Encapsulation and Panel Separation

In-situ encapsulation can be performed by the same methods used in sheet-to-sheet processing. While multi-layer barriers are still needed to provide the required protection, there will be greater incentive to use an approach that does not require passage through multiple deposition chambers with different vacuum requirements. The demonstration that extremely low permeation rates can be obtained by combing ALD and molecular layer deposition in the same reactor is an exciting recent discovery. [141] [142]

Separating the panels from the web needs extra care so that the accurate registration can be maintained. Die-cutting can be used, but the incisions must not extend to the edges of the web. The remaining strips at the edge of the web must be wide enough that the required tension can be maintained and the residual material rewound. More cutting options are available if the web can be stopped during the process, but singulation can be achieved in continuous web motion using a rotary die-cutter.

4.5.4 Roll-to-Roll In-line Testing

The development of in-line testing procedures is at an early stage but could be critical to profitable use of in-line or R2R fabrication. The techniques that are being explored include:

- Optical detection of particles, scratches and other structural defects: The line scan camera installed at the Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology (Fraunhofer FEP) offers defect resolution of 40 µm and is backed up with a moveable optical microscope with resolution of 1 µm. Micron sized defects that might cause irregularities in brightness are often obscured by diffusion in the light extraction films, but conductive particles of size less than 1 µm in the organic layers can lead to shorting.
- Spectroscopic analysis of transmitted or reflected light can provide measurements of layer thicknesses and of material content. Hyperspectral imaging is being used at the Fraunhofer Institute for Material and Beam Technology (Fraunhofer IWS) in Dresden to measure water content in films. [143] This technique offers the potential of real-time checks of the efficacy of water barriers.

- Transparent electrodes: Non-contact methods can be used to measure the sheet resistivity down to well below 1 Ω/□. [144]

4.6 Roll-to-Roll Back-End Processing

Since many panels are now produced from a single substrate and must be completed separately, the back-end processing contributes a major component of the total cost, principally in the BOM and labor cost. Efforts are made to use components that are used in other applications to help keep costs down. Little automation is involved at this stage making the labor higher. Perhaps the best way to reduce the relative costs of the back-end steps would be to manufacture larger panels. This will require further increases in yield and transparent anode structures with lower resistivity. Figure 4-11 shows a schematic of a rigid OLED panel ready for integration into a luminaire.

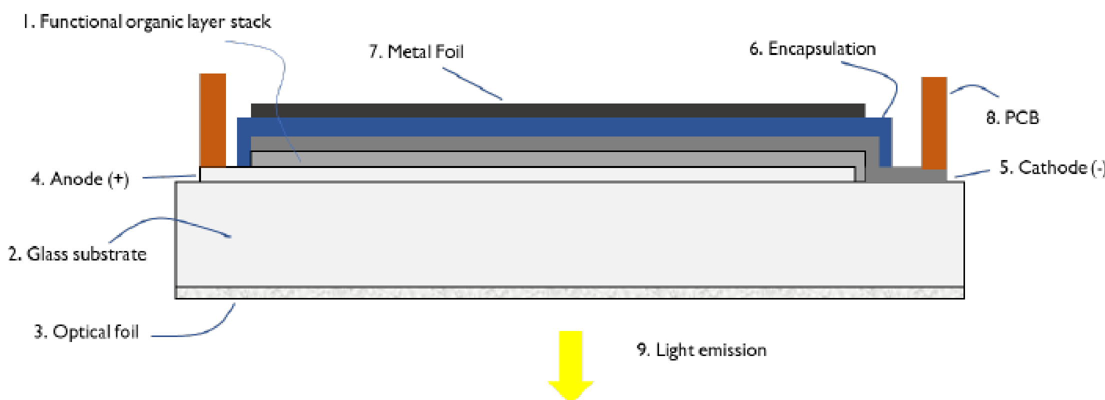

Figure 4-11 Integration of an OLED panel into a luminaire, providing extra physical protection and electrical connections to the power source through a printed circuit board [145]

Two foils have been attached after singulation. The optical foil attached to the glass front of the panel improves the extraction of light and the color uniformity over all angles, and the metal foil acts as a heat spreader and provides protection for the back of the panel. The perimeter of the panels must be checked to make sure that there are clean connections to the cathode and anode, with no leakage current, and that no polymer layers extend all the way to the edges. The connections are currently made on printed circuit boards, which need to be flexible for conformable panels. These PCBs are attached to the back of the panel, outside the lit area, to ensure that current is fed uniformly across the panel with a limited number of external connections, usually four. If desired, an extra thermal pad and metal plate can be added to the back to provide better heat dissipation and rigidity.

The thinness of OLED panels makes them extremely fragile and many installers may not exercise sufficient care to avoid damage to a bare panel. Frames can be provided to assist in mounting the panels to surfaces, or to install in a lighting fixture or piece of furniture. [146] The frame can also host an integrated constant-current driver. Alternatively, a connector can be supplied with OLED drivers and resistors integrated in the cable which support the recognition of the correct panel settings by the drivers.

4.6.1 Testing and Inspection

Standard optical and electrical equipment can be used to check the light emitted by the completed panels meets specifications with respect to intensity, spectrum and uniformity. The absence of pixilation makes the task much simpler than for OLED displays, although some of the same photometric equipment can be used. In contrast to the situation with LED packages, binning is not usually practiced.

Until recently, concern about early failures led to burn-in procedures being applied to every panel. This is no longer necessary, since significant progress has been made in understanding the causes of shorting and measures have been taken to almost completely eliminate the problem.

Although progress has also been made in increasing the operating lifetime of OLED panels, accelerated testing is still performed on samples from the production line. In addition, the DOE has supported tests by an independent laboratory at RTI International. A recent report from discusses the equipment that is needed for such testing and shows that substantial improvements have been made over the past six years, though further progress is still needed. [147]. Independent testing is also important for suppliers of OLED materials and components. The DOE has established an OLED Testing Program through which developers an submit samples to a Qualified Test Facility.[11]

4.7 OLED Panel Costs

The low volume of current production of OLED panels for lighting makes it difficult to make accurate forecasts of the potential for cost reduction in high-volume manufacturing. The traditional breakdown of costs between the bill of materials, equipment depreciation, labor and overhead is complicated by the fact that OLEDWorks, the dominant manufacturer, has chosen to sub-contract a major portion of the manufacturing. Thus, a significant proportion of the estimated cost of inorganic materials in Table 2-10 (Section 2.3.2) also includes depreciation, labor and overhead borne by the supplier of the integrated substrate. Three key areas that must be addressed to meet the future OLED cost targets are discussed in the following sections.

4.7.1 Organic Materials

Some guidance on the cost of organic materials in high volume can be obtained from the OLED TV panels produced by LG Display. To avoid the use of fine metal masks to create red, green, blue (RGB) sub-pixels, LG Display uses vacuum thermal evaporation to form a homogeneous sheet of white OLED emitters and creates the sub-pixels using patterned color filters. Although the peak brightness of these panels is typically between 500 and 1000 cd/m^2, the emitting layers must emit far more light than this. Over 75% of the light is absorbed in the color filters and other layers that are added to enhance the image quality. Therefore, the amount of light created in the organic stack is of the same magnitude as that omitted in lighting panels. The current unyielded cost of the organic materials used in open mask OLED display panels is estimated to be \$83/m^2. [148] This can be broken down as \$21/m^2 for dopants (26%), \$18/m^2 for hosts (21%) and \$44/m^2 for the transport and charge-generation layers (53%).

A team from the University of Michigan and Universal Display Consortium has suggested a model system for high-volume production of OLED lighting panels, based upon a 3-stack phosphorescent structure with a total thickness of 330 nm and average emitter doping percentage of 12.5%. [125] They assume that the emitter layers are deposited by OVPD, while VTE is used for the other layers. The required organic materials are summarized in Table 4-1. In comparison with current OLED display costs, the main difference is in the cost of the host, transport, and charge generation materials.

The steps that may lead to substantial reduction in the cost of organic materials include:

- Greater light extraction efficiency to reduce the number of photons required to produce the desired light output
- Reduced loss of material to the walls of the deposition system
- Increased substrate utilization above the current level of about 60% or the use of printing to limit deposition to the area occupied by panels
- Greater competition in the supply of high-performance materials

[11] Details of the program can be found at https://www.energy.gov/eere/ssl/oled-testing-opportunity.

Table 4-1 Estimates of the cost of organic materials for each square meter of OLED panel area [125]

Function	Load (g/m^2)	Utilization efficiency (%)	Supply (g/m^2)	Cost ($/g)	Cost ($/m²)
Transport & charge generation	0.35	30	1.2	10	12
Emitter hosts	0.22	60	0.36	30	11
Emitter dopants	0.27	60	0.045	400	18
Total	0.59	-	1.6	-	41

4.7.2 Integrated Substrates

As noted above, the basic substrate is either thin glass or plastic with a barrier coating. The price of glass substrates for flat panel displays has come down over the past decade from $40-50/m² to ~$12/m², with 600 million square meters (Mm²) of glass being supplied in 2019 for a total cost of around $7 billion. This cost reduction has been enabled by the construction of very large factories built by a small number of suppliers on sites adjacent to the flat panel display (FPD) makers. This supply enables the production of about 250M m² of display panels, with the "yielded" cost still over $25/m².

In OLED lighting applications, provision of the additional functional layers described in Section 4.2 adds substantially to the cost of integrated substrates. Although homogeneous sheets of ITO with the required conductivity may now be available at prices as low as $10/m² in high volume, the price for custom-patterned ITO is much higher, especially when the substrates are transported from Asia to the United States or Europe. Light extraction film technology is still under development and forms another major expense. Consequently, the current cost of rigid integrated substrates is over $100/m².

The replacement of display-grade glass by inexpensive plastic substrates, such as PET, does not offer an immediate solution, but could be successful with further development. In a recent DOE SSL project, a moisture barrier was added to a roll of PET by a relatively simple PVD process and the transparent conductor formed by flexographic printing of silver nanowires. [149] The base cost (unyielded) was estimated to be around $40/m², with 75% attributed to the substrate with barrier. Further expense would be needed to add an effective light extraction layer.

OLEDWorks is working with Corning Glass to develop R2R manufacturing of integrated substrates on ultra-thin glass. Their long-term cost target is $40/m².

4.7.3 Back End Processing

The cost of depositing the cathode is relatively modest, but that of encapsulation could be substantial if a hybrid multi-layer coating is required. An inorganic barrier layer backed by a thin metal cover may provide the least expensive solution. OLEDWorks has indicated that encapsulation contributes about 10% to their current bill of materials. Perhaps the greatest uncertainty in setting cost targets arises from the work that is required after the panels are separated. These steps currently represent around 35% of the BOM.

5 References

[1] DOE Solid-State Lighting Program, "Adoption of Light-Emitting Diodes in Common Lighting Applications," August 2020. [Online]. Available: https://www.energy.gov/sites/prod/files/2020/09/f78/ssl-led-adoption-aug2020.pdf.

[2] R. Steele, "LED and Lighting Market Review and Forecast," in *Strategies in Light*, San Diego, 2020.

[3] M. Shih, "The Worldwide Market for LEDs: Market Review and Forecast - Sample," Strategies Unlimited, 2020.

[4] J. Happich, "Increasing demand in backlight and lighting applications to reduce LED oversupply in 2012," EE News Europe, 20 February 2012. [Online]. Available: https://www.eenewseurope.com/news/increasing-demand-backlight-and-lighting-applications-reduce-led-oversupply-2012.

[5] IHS Markit, "LED Oversupply Likely to Continue as Suppliers Add Production Capacity," Power Electronics, 28 August 2013. [Online]. Available: https://www.powerelectronics.com/news/industry/article/21860559/led-oversupply-likely-to-continue-as-suppliers-add-production-capacity.

[6] DOE Lighting R&D Program, "2020 LED Manufacturing Supply Chain," March 2021. [Online]. Available: https://www.energy.gov/eere/ssl/articles/2020-led-manufacturing-supply-chain.

[7] DOE Lighting R&D Program, "2019 Lighting R&D Opportunities," January 2020. [Online]. Available: https://www.energy.gov/eere/ssl/downloads/2019-lighting-rd-opportunities.

[8] Veeco, "Veeco Ships Next Generation MOCVD Systems to China for High Volume LED Production," 17 September 2017. [Online]. Available: https://www.veeco.com/company/product-news/veeco-ships-next-generation-mocvd-systems-to-china-for-high-volume-led-production/.

[9] Veeco, "MOCVD Systems," [Online]. Available: https://www.veeco.com/technologies-and-products/mocvd-systems/.

[10] Veeco, "Addressing MicroLED Challenges Through MOCVD Technology Innovations," in *MicroLED Forum*, 2020.

[11] P. Mukish, "LED Front-End Manufacturing Trends," Yole Développement, 2014.

[12] I. Veeco Process Equipment and W. Quinn, "Driving Down HB-LED Costs. Implementation of Process Simulation Tools and Temperature Control Methods of High Yield MOCVD Growth," 2012.

[13] J. Montgomery, "Driving Down HB-LED Costs: Implementation of Process Simulation Tools and Temperature Control Methods for High Yield MOCVD Growth," in *DOE SSL Manufacturing R&D Workshop*, San Jose, CA, 2012.

[14] "Landscape shifts in LED manufacturing equipment sector," *LEDs Magazine,* 27 May 2018.

[15] "IHS Markit Forecasts Growing GaN LED Surplus," *Compound Semiconductor,* 27 March 2018.

[16] "The Global Lighting LED Packaging Market Slide Into Slump on Account of Lethargic Chip Market and Weak End Product Demand, Says TrendForce," TrendForce, 2019.

[17] "Epitaxy equipment market to grow from $940m to over $6bn by 2025, driven by VCSEL and disruptive LED devices," *Compounds & Advanced Silicon,* vol. 15, no. 1, 2020.

[18] "Epitaxy equipment market to grow from $940m to over $6bn by 2025, driven by VCSEL and disruptive LED devices," *Compounds & Advanced Silicon,* vol. 15, no. 1, 2020.

[19] Yole Développement, "Bulk GaN Substrate Market 2017," 2017.

[20] Osram Opto Semiconductors, "Success in research: First gallium-nitride LED chips on silicon in pilot stage," 12 January 2012. [Online]. Available: https://www.osram-group.com/en/media/press-releases/pr-2012/12-01-2012.

[21] "Patterned substrates enhance LED light extraction," *LEDs Magazine,* pp. 53-58, July 2014.

[22] Philips Lumileds, "Philips Lumileds Leads LED Industry with Mass Production on 150 mm Wafers," December 2010. [Online]. Available: http://www.ledsmagazine.com/articles/2010/12/philips-lumileds-mass-producing-leds-on-150-mm-wafers.html. [Accessed July 2014].

[23] LEDs Magazine, "Osram Opto expands LED capacity with 6-inch conversion," March 2011. [Online]. Available: http://www.ledsmagazine.com/articles/2011/03/osram-opto-expands-led-capacity-with-6-inch-conversion.html. [Accessed July 2014].

[24] Cree, "Cree to Produce Next-Generation LED Wafers with New Manufacturing Capability," 20 September 2010. [Online]. Available: https://www.cree.com/news-media/news/article/cree-to-produce-next-generation-led-wafers-with-new-manufacturing-capability.

[25] I. Black, "Evolving Challenges in LED Manufacturing," in *DOE SSL Manufacturing Workshop*, Boston, MA, 2013.

[26] J. Edmond, "Reinventing Lighting," in *DOE SSL R&D Workshop*, San Francisco, CA, 2015.

[27] M. Dineen, "Getting A Grip On Sapphire Etching," Oxford Instruments, 1 February 2015. [Online]. Available: https://compoundsemiconductor.net/article/96505/Getting_A_Grip_On_Sapphire_Etching/feature.

[28] A. Hawryluk and E. True, "Low Cost Lithography Tool for High Brightness LED Manufacturing," 2012.

[29] A. Hawryluk, "Low Cost Lithography Tools for High-Brightness LEDs," in *DOE SSL Manufacturing Workshop*, Boston, MA, 2011.

[30] IPG Photonics, "Scribing," [Online]. Available: https://www.ipgphotonics.com/en/applications/micromachining/scribing.

[31] R. Delmdahl, R. Patzel and J. Brune, "Large-area laser-lift off processing in microelectronics," *Physics Procedia,* no. 41, pp. 241-248, 2013.

[32] Disco, "DFL7560L - Laser Lift-Off Equipment with Wide Process Margin using DPSS Laser," [Online]. Available: https://www.disco.co.jp/eg/products/laser/dfl7560l.html. [Accessed January 2021].

[33] Ultron Systems, Inc., "WAFER / FRAME FILM MOUNTERS - Model UH114 Series: (UH114, UH114-8, UH114-12)," [Online]. Available: https://www.ultronsystems.com/USI-ProdMounters.html.

[34] M. Shih, "The Worldwide Market for LEDs: Market Review and Forecast," Strategies Unlimited, 2020.

[35] Samsung, "MP CSP Samsung LEDs," [Online]. Available: https://www.samsung.com/led/lighting/csp-leds/mp-csp/.

[36] Lumileds, "LUXEON CSP HL1," [Online]. Available: https://www.lumileds.com/products/high-power-leds/luxeon-csp-hl1/.

[37] Bridgelux, "VESTA® SERIES," [Online]. Available: https://www.bridgelux.com/products/vesta-series.

[38] M. Hansen, "LED Fundamentals: Designing for LEDs and Their Specific Attributes," *Architectural Lighting,* 22 September 2011.

[39] W. van Driel, X. Fan and G. Zhang, Solid State Lighting Reliability Part 2, 2013.

[40] Lumileds, [Online]. Available: https://www.lumileds.com/.

[41] Osram, "Chemical compatibility of LEDs – Part 1," Dataweek, 18 May 2016. [Online]. Available: https://www.dataweek.co.za/print.aspx?editorialtype=N&editorialid=54590.

[42] DOE Lighting R&D Program, "Lumen and Chromaticity Maintenance Behavior of Light-Emitting Diode (LED) Packages Based on LM-80 Data," March 2020. [Online]. Available: https://www.energy.gov/eere/ssl/downloads/lumen-and-chromaticity-maintenance-behavior-led-packages-based-lm-80-data.

[43] G. Dutt and R. Bhatkal, "LED Die Attach Selection Considerations," Alpha.

[44] I. Black and J. Neff, "LED System Solutions," in *DOE SSL Manufacturing Workshop*, San Jose, CA, 2012.

[45] Nordson ASYMTEK, "LED Dispensing Solutions: Small scal to high volume," 2011.

[46] "Philips announces new Luxeon Rebel LEDs with narrowed bin distribution," *LEDs Magazine,* 2 June 2010.

[47] P. F. Smet, A. B. Parmentier and D. Poelman, "Selecting conversion phosphors for white light-emitting diodes," *Journal of th Electrochemical Society,* no. 158, pp. R37-R54, 2011.

[48] J. Neff, "LED Color Conversion," in *DOE SSL R&D Workshop*, 2014.

[49] S. Weicheng, X. Yu, R. Hu, Q. Chen, Y. Ma and X. Luo, "Effect of the substrate temperature on the phosphor sedimentation of phosphor-converted LEDs," in *2017, 18th International Conference on Electronic Packaging Technology*, 2017.

[50] Samsung Electronics, "Increasing The Competitiveness Of The GaN-on-silicon LED," Compound Semiconductor, 30 March 2016. [Online]. Available: https://compoundsemiconductor.net/article/99020/Increasing_the_competitiveness_of_the_GaN-on-silicon_LED/feature.

[51] F. Garcia-Santamaria, J. E. Murphy, A. A. Setlur and S. P. Sista, "Concentration Quenching in K2SiF6:Mn4+ Phosphors," *The Electrochemical Society Jourlna of Solid State Science and Technology,* vol. 7, no. 1, 2017.

[52] U.S. Department of Energy, "Critical Minerals and Materials: U.S. Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains (FY 2021-FY 2031)," [Online]. Available: https://www.energy.gov/downloads/critical-minerals-and-materials.

[53] IFP Energies nouvelles, "Rare earths in the energy transition: what threats are there to the "vitamins of modern society"?," 7 January 2021. [Online]. Available: https://www.ifpenergiesnouvelles.com/article/les-terres-rares-transition-energetique-quelles-menaces-les-vitamines-lere-moderne.

[54] A. Y. Ku, A. A. Setlur and J. Loudis, "Impact of Light Emitting Diode Adoption on Rare Earth Element Use in Lighting: Implications for Yttrium, Europium, and Terbium Demand," *The Electrochemical Society Interface,* vol. 24, no. 4, pp. 45-49, 2015.

[55] "ARPA-E Rare Earth and Critical Materials Workshop Breakout Session: Phosphors," in *ARPA-E Rare Earth and Critical Materials Workshop*, 2010.

[56] J. Kurtin, "Ultra Narrow band downconverters for SSL," in *2019 DOE SSL R&D Workshop*, Dallas, TX, 2019.

[57] K. T. Shimizu, M. Bohmer, D. Estrada, S. Gangwal, S. Grabowski, H. Bechtel, E. Kang, K. J. Vampola, D. Chamberlin, O. B. Shchekin and J. Bhardwaj, "Toward commercial realization of quantum dot based white light-emitting diodes for general illumination," *Photonics Research,* vol. 5, no. 2, pp. A1-A6, 2017.

[58] DOE SSL Program, "Environmentally Robust Quantum Dot Downconverters for Highly Efficient Solid-State Lighting," [Online]. Available: https://www.energy.gov/eere/ssl/articles/environmentally-robust-quantum-dot-downconverters-highly-efficient-solid-state.

[59] DOE SSL Program, "Stable Cadmium-Free Quantum Dot Optical Down-Converters for Solid State Lighting," [Online]. Available: https://www.energy.gov/eere/ssl/articles/stable-cadmium-free-quantum-dot-optical-down-converters-solid-state-lighting.

[60] J. Owen, J. Kurtin and E. Chan, "Environmentally Robust Quantum Dot Downconverters for High Efficiency Solid State Lighting," in *DOE-IES Lighting R&D Workshop*, San Diego, CA, 2020.

[61] P. Palomaki, "Quantum Dot Downconverters for SSL," in *DOE SSL R&D Workshop*, Nashville, TN, 2018.

[62] R. Tuttle, "Silicone Encapsulant Needs - an LED Manufacturer's Perspective," in *DOE SSL R&D Workshop*, Raleigh, NC, 2016.

[63] Dow Corning, *Illuminating Innovations - Silicone Solutions for LED Packaging.*

[64] J. McDonald, "Advanced Silicone Materials for LED Lighting," in *DOE SSL R&D Workshop*, San Francisco, CA, 2015.

[65] M. Bockstaller, "Enhancing LED Performance: A Case For Research on Encapsulant Materials With Enhanced Thermal Conductivity," in *DOE SSL R&D Workshop*, Raleigh, NC, 2016.

[66] U.S. Department of Energy Solid-State Lighting Program, "KLA-Tencor's Inspection Tool Reduces LED Manufacturing Costs," March 2011. [Online]. Available: http://www1.eere.energy.gov/buildings/ssl/kla_led.html. [Accessed July 2014].

[67] A. Baker, "ANSI C78.377-201x Revision: New Nominal CCTs, Smaller Quadrangles & Circles," in *ALA Engineering Committee Meeting*, Plantation, FL, 2014.

[68] Cree, "LED Color Mixing: Basics and Background".

[69] Illuminating Engineering Society, "ANSI/IES LM-80-20, Approved Method: Measuring Luminous Flux And Color Maintenance Of LED Packages, Arrays, And Modules," American National Standards Institute, 2020.

[70] Vektrex, "LM-80 Test Solutions," [Online]. Available: https://www.vektrex.com/solutions/lm-80-test-solutions/.

[71] Illuminating Engineering Society, "Technical Memorandum: Projecting Long Term Lumen, Photon And Radiant Flux Maintenance Of LED Light Sources," American National Standards Institute, 2019.

[72] DOE SSL Program, "SSL R&D Manufacturing Roadmap," August 2014. [Online]. Available: https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf.

[73] Xicato, "Xicato XCA Module," [Online]. Available: https://www.xicato.com/products/light-sources/xca/.

[74] LBC Lighting, "New Trend in LED: Filament Bulbs," 4 November 2015. [Online]. Available: https://www.lbclighting.com/blogs/news/new-trend-in-led-filament-bulbs.

[75] LEDiL, "Guide to TIR Lenses," [Online]. Available: https://www.ledil.com/support/guide-to-tir-lenses/.

[76] Design Spark, "LED Secondary Optics Basics," 14 August 2019. [Online]. Available: https://www.rs-online.com/designspark/led-secondary-optics-basics.

[77] W. S. Beich and N. Turner, "Polymer Optics: A manufacturer's perspective on the factors that contribute to successful programs," *Polymer Optics Design, Fabrication, and Materials,* vol. 7788, 2010.

[78] M. Beukema, M. Cummings, F. De Buyl, J. Steinbrecher, B. Tuft and K. van Tiggelen, "Moldable optical silicone elastomers spark creativity in LED lighting," *Laser Focus World,* October 2019.

[79] White Optics, "Why Does Reflectance Matter?," [Online]. Available: https://www.whiteoptics.com/technology-applications/.

[80] T. Scully, "LED Optics Explained," LED Supply, 5 February 2019. [Online]. Available: https://www.ledsupply.com/blog/led-optics-explained/.

[81] Shenzhen TLD Automation Equipment Co., "High effeciency Straight line working station automatic assembly line of bulb lamp," [Online]. Available: http://www.led-facility.com/chanpin-405.html.

[82] M. Hand, "The Evolution of Manufacturing for Lighting," in *DOE Manufacturing R&D Workshop*, San Diego, CA, 2014.

[83] A. Mauk, "A bright future at Cree Lighting: Now-private company making continual advances," *The Journal Times,* 29 March 2020.

[84] Illuminating Engineering Society, "ANSI/IES LM-79-19, Optical and Electrical Measurements of Solid State Lighting Products," American National Standards Institute, 2019.

[85] "Luminaire and integrating sphere size impact measurement accuracy," *LEDs Magazine,* 26 May 2018.

[86] Instrument Systems, "LGS 1000 - Goniophotometer for large SSL/LED modules," [Online]. Available: https://www.instrumentsystems.com/en/products/goniophotometers-for-led-ssl/lgs-1000/.

[87] Gantri, "Mellow Fellow Table Light," Hyeonil Jeong, [Online]. Available: https://www.gantri.com/products/10001/mellow-fellow-table-light-by-hyeonil-jeong?s=md&c=snow. [Accessed 2019 October].

[88] Decimal, "Product Catalogue," [Online]. Available: https://www.decimalmade.com/. [Accessed October 2019].

[89] LED Professional, "Additive Manufacture of Optics Goes Digital by LUXeXceL B.V.," 5 July 2016. [Online]. Available: https://www.led-professional.com/resources-1/articles/additive-manufacture-of-optics-goes-digital-by-luxexcel-b-v.

[90] U.S. Department of Energy, "Print-Based Manufacturing of Integrated, Low Cost, High Performance SSL Luminaires," Eaton Corporation, [Online]. Available: https://www.energy.gov/eere/buildings/downloads/print-based-manufacturing-integrated-low-cost-high-performance-ssl.

[91] S. Garimella, "3-D Printed Electronics," in *Strategies in Light*, 2019.

[92] J. Trublowski, "Additively Manufactured Luminaire: R&D Challenges and Technology Gaps," in *DOE Lighting R&D Workshop*, 2021.

[93] K. Bulashevich and S. Karpov, "Impact of surface recombination on efficiency of III-nitride light-emitting diodes," *Rapid Research Letters,* vol. 10, no. 6, pp. 480-484, 2016.

[94] M. Wong, C. Lee, D. Myers, D. Hwang, J. Kearns, T. Li, J. Speck, S. Nakamura and S. DenBaars, "Size-independent peak efficiency of III-nitride micro-light-emitting-diodes using chemical treatment and sidewall passivation," *Applied Physics Express,* vol. 12, no. 9, 2019.

[95] C. Morath, "Epitaxy requirements for Micro-LED Display," in *DOE SSL R&D Workshop*, Nashville, TN, 2018.

[96] R. Pathak, "LED Light Sources for Dynamic Lighting Applications," in *DOE-IES Lighting R&D Workshop*, 2021.

[97] Light Enabled Systems & Applications, "Spatially Adaptive Tunable Lighting Control System with Expanded Wellness and Energy Saving Benefits," in *DOE-IES Lighting R&D Workshop*, 2021.

[98] E. Virey, "Status of the MicroLED Industry," in *Phosphor Global Summit*, 2019.

[99] E. Chow, "MicroAssembly Chip Printer for LEDs and Beyond," in *DOE-IES Lighting R&D Workshop*, San Diego, CA, 2020.

[100] International Association of Lighting Designers, "IALD Position Paper on Circular Economy," 2020.

[101] B. Koerner, "Sustainability for Competitive Advantage," in *DOE-IES Lighting R&D Workshop*, 2021.

[102] A. Smith, "Sustainable Manufacturing," in *DOE-IES Lighting R&D Workshop*, 2021.

[103] J. Pearce, "How to turn plastic waste in your recycle bin into profit," The Conversation, 11 January 2021. [Online]. Available: https://theconversation.com/how-to-turn-plastic-waste-in-your-recycle-bin-into-profit-147081.

[104] D. Hsieh, "OLED Competitions: Korea vs. China, Technology vs. Application, Flexible vs. Foldable," in *OLED World Summit*, 2020.

[105] B. O'Brien, "AMOLED Materials Market to Grow to $1.4 Billion in 2021," Display Supply Chain Consultants, 16 August 2021. [Online]. Available: https://www.displaysupplychain.com/blog/amoled-materials-market-to-grow-to-1-4-billion-in-2021.

[106] J. Spindler, "OLED Manufacturing Challenges," in *DOE-IES Lighting R&D Workshop*, 2021.

[107] M. Boroson, "OLED Lighting Status and Needs," in *DOE SSL R&D Workshop*, Dallas, TX, 2019.

[108] R. Prasad, "Transparent Ultra-Barrier Films for OLED Devices," *Society for Information Display, 2017 International Symposim Digest of Technical Papers,* vol. 48, no. 1, pp. 195-196, 2017.

[109] D. Munoz-Rojas, T. Maindron, A. Esteve, F. Piallat, J. Kools and J.-M. Decams, "Speeding up the unique assets of atomic layer deposition," *Materials Today Chemistry,* vol. 12, pp. 96-120, 2019.

[110] Y. Li, Y. Xiong, H. Yang, K. Cao and R. Chen, "Thin film encapsulation for the organic light-emitting diodes display via atomic layer deposition," *Journal of Materials Research,* vol. 35, no. 7, pp. 681 - 700, 2020.

[111] E. Jeong, J. Kwon, K. Kang, S. Jeong and K. Choi, "A review of highly reliable flexible encapsulation technologies towards rollable and foldable OLEDs," *Journal of Information Display,* pp. 19-32, 2019.

[112] S. Monickam, T. Newman, B. Szychowski, S. G. Williams and S. Choi, "High Refractive Index Materials for Display and Lighting Applications," *Society for Information Display, International Symposium Digest of Technical Papers,* vol. 51, no. 1, pp. 86-89, 2020.

[113] S. Monickam, "Internal Light Extraction Technology for OLED Lighting," in *DOE-IES R&D Workshop*, 2021.

[114] S. Forrest, "Eliminating Plasmon Losses in High Efficiency White Organic Light Emitting Devices for Light Applications," in *DOE-IES Lighting R&D Workshop*, San Diego, CA, 2020.

[115] G. Burwell, N. Burridge, O. Sandberg, E. Bond, W. Li, P. Meredith and A. Armin, "Metal Grid Structures for Enhancing the Stability and Performance of Solution-Processed Organic Light-Emitting Diodes," *Advanced Electronic Materials,* vol. 6, no. 12, 2020.

[116] W. Gaynor, "Integrated Plastic Substrates for OLED Lighting," in *DOE SSL R&D Workshop*, Dallas, TX, 2019.

[117] J. Spindler, "OLED Manufacturing and Integration Challenges," in *DOE-IES Lighting R&D Workshop*, San Diego, CA, 2020.

[118] Display Supply Chain Consultants, "OLED Materials Market Will Grow to More Than $2 Billion by 2023," Display Daily, 2020. [Online]. Available: https://www.displaydaily.com/article/press-releases/oled-materials-market-will-grow-to-more-than-2-billion-by-2023.

[119] UBI Research, "The OLED emitting material market will grow to $ 1.9 billion by 2020," [Online]. Available: http://en.olednet.com/category/focuson-en-en-en/market/.

[120] J. Hamer and D. Scott, "Innovative High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting," 2017.

[121] J. Spindler, "OLED Manufacturing Equipment and Methods," in *Handbook of Advanced Lighting Technology*, Springer, 2017, pp. 417-440.

[122] P. Burrows, S. Forrest, L. Sapochak, J. Schwartz, P. Fenter, T. Buma, V. Ban and J. Forrest, "Organic vapor phase deposition: a new method for the growth of organic thin films with large optical non-linearities," *Journal of Crystal Growth,* vol. 156, no. 1-2, pp. 91-98, 1995.

[123] J. Kreis, "Carrier-gas enhanced Vapor-Phase Deposition:Disruptive Approach or Complementary Production Technology for advanced organic electronic devices," in *Large Area Organic and Printed Electronics Conference*, 2012.

[124] AIXTRON, "OLED project Phase II completed / Asian display manufacturer grants final acceptance for Gen 2 OVPD(R) system," 17 December 2020. [Online]. Available: https://www.aixtron.com/en/press/press%20releases/OLED%20project%20Phase%20II%20completed%20/%20Asian%20display%20manufacturer%20grants%20final%20acceptance%20for%20Gen%202%20OVPD%28R%29%20system_n1602.

[125] S. Forrest, B. Qu, M. Hack and M. Shtein, "R2R Manufacturing of WOLED Lighting -Methods-Results-Costs," in *DOE-IES Lighting R&D Workshop*, 2021.

[126] Universal Display Corporation, "Universal Organic Vapor Jet Printing," [Online]. Available: https://oled.com/solutions/oled-technologies/universal-ovjp-organic-vapor-jet-printing/.

[127] D. Hanser, M. Gossen, R. Bresnahan, M. O'Steen and S. Priddy, "OLEDs: Reducing particle defects in cathode film layers improves OLED yield," *Laser Focus World,* 1 July 2018.

[128] T. Gil, C. May, H. Lakner, K. Leo and S. Keller, "Al Top Cathode Deposition on OLED Using DC," *Plasma Processes and Polymers,* vol. 6, pp. S808-S812, 2009.

[129] E. Matsumoto, "Development of the OLED Mass-Production System," *Society for Information Display, International Symposium Digest of Technical Papers,* vol. 51, no. 1, pp. 917-920, 2020.

[130] O. Sneh, "OLED Encapsulation," in *DOE SSL R&D Workshop*, 2019.

[131] S. Ohashi, E. Baba, M. Okuno, M. Hosoi, Y. Shindo and M. Takada, "High-Transparency Adhesive-Encapsulation Film for OLED Device," *Society for Information Display, International Symposium Digest of Technical Papers,* vol. 51, no. 1, pp. 1036-1039, 2020.

[132] J. Hamer and W. Doetter, "OLED Lighting Production on Thin Glass," 4 April 2017. [Online]. Available: https://www.oledworks.com/wp-content/uploads/2017/04/OLED-Production-on-Thin-Glass-Hamer-Doetter-V15-2017-04-04.pdf.

[133] J. Spindler, "Mask-Free OLED Fabrication Process for Non-Tunable and Tunable White OLEDs," in *DOE Lighting R&D Workshop*, 2020.

[134] C. May, "OLED Manufacturing Challenges – some input by Fraunhofer FEP," in *DOE-IES Lighting R&D Workshop*, 2021.

[135] S. Pennetier, A. Ronfini and J. Stoddard, "Advances in Prototyping with Ultra-Thin Glass," Glass on Web, 31 August 2020. [Online]. Available: https://www.glassonweb.com/article/advances-prototyping-with-ultra-thin-glass.

[136] S. Garner, D. Chowdhury and S. Lewis, "Ultrathin Glass Substrates for Thin, Lightweight, Flexible OLED Lighting," *Information Display,* vol. 35, no. 4, pp. 9-13, 2019.

[137] C. May, "OLED Lighting Design and Roll-to-Roll Manufacturing," *Society for Information Display, International Symposium Digest of Technical Papers,* vol. 51, no. 1, pp. 90-92, 2020.

[138] A. Nilsson, T. Dietsch and C. Deus, "Roll-to-Roll PVD Coating System for Flexible Glass for Applications in the Field of Flexible Electronics and Others," in *Society of Plastic Engineers FlexPacCon*, 2017.

[139] M. Stanel, T. Wanski and S. Mogck, "Present status of Roll-to-Roll Fabrication for OLED lighting," in *AIMCAL, Web Coating and Handling Conference*, Dresden, Germany, 2016.

[140] J. Kim, F. S. R., M. Shtein, M. Hack, B. Qu and M. Kastelic, "From Deposition to Encapsulation: Roll-to-Roll Manufacturing of Organic Light Emitting Devices for Lighting," in *DOE-IES Lighting R&D Workshop*, 2021.

[141] K. Yoon, H. Kim, K. Han, S. Kim, Y.-E. K. Lee, N. Shrestha, S. Song and M. Sung, "Extremely High Barrier Performance of Organic–Inorganic Nanolaminated Thin Films for Organic Light-Emitting Diodes," *ACS Appl. Mater. Interfaces,* vol. 9, no. 6, pp. 5399-5408, 2017.

[142] M. Docherty, "Status and overview of plasma-enhanced atomic & molecular layer deposition for flexible OLED encapsulation," *4th Year Literature Review Project,* 2019.

[143] W. Grahlert, "Fast and inline-capable determination of the water vapor transmission rate (WVTR) of barrier webs using hyperspectral imaging (HSI)," in *Proflex*, Dresden, Germany, 2019.

[144] Stein Labs, LLC, "Non-Contact Sheet Resistance/Resistivity Measurement Systems," [Online]. Available: http://www.steinlabs.com/non-contact-in-line.html.

[145] OLEDWorks, "Bright 3 Design-in Guide," June 2020. [Online]. Available: https://www.oledworks.com/resources/download-information/.

[146] G. Phelan and M. Fusco, "Designers Light Forum," 14 March 2018. [Online]. Available: https://leducation.org/LED2018_Presentations/LED2018_Phelan_Fusco.pdf.

[147] RTI International, "Stress Testing of Organic LightEmitting Diode Panels and," U.S. Department of Energy, 2018.

[148] Display Supply Chain Consultants, "Quarterly Advanced TV Display Cost Report, Q4 2020," 2020.

[149] W. Gaynor, "Integrated Plastic Substrates for OLED Lighting," in *DOE SSL R&D Workshop*, Dallas, TX, 2019.

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