SSL R&D WORKSHOP

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OLED Manufacturing Challenges

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Cost Reductions are Essential

- LED prices are decreasing at 30% per year
- All OLED costs must come down
  - Equipment depreciation
  - Organic materials
  - Inorganic structural materials
  - Waste through inefficient deposition and low yields
- Synergy with other applications will help
  - OLED displays
  - Quantum dot displays
  - Touch screens

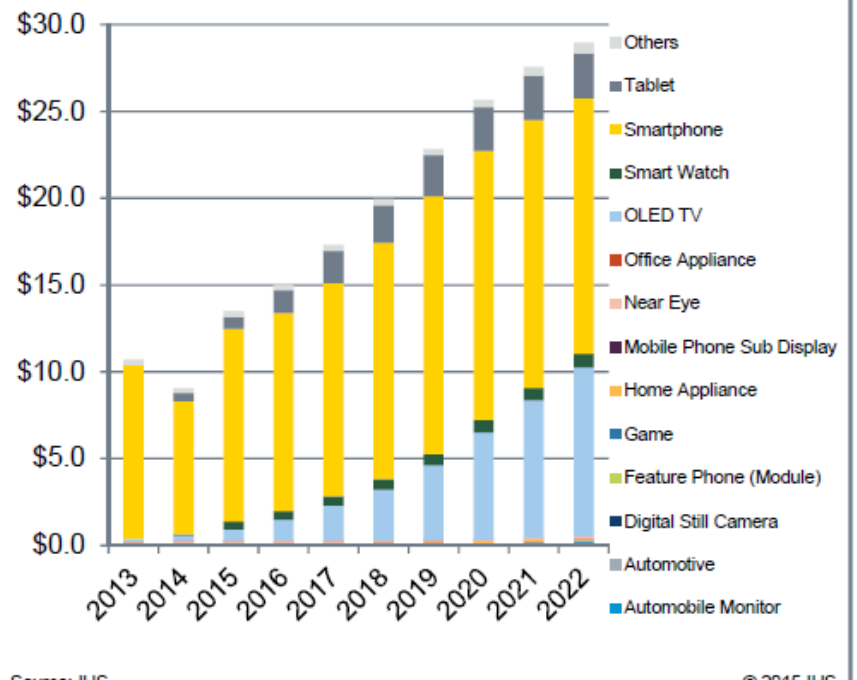
US DOE's OLED Cost Reduction Goals ($/m^2)

	2014	2015	2017	2020	2025
Substrate Area (m^2)	0.17	0.17	1.38	2.7	5.5
Capital Cost ($M)	75	75	200	300	400
Cycle Time (minutes)	3	2	1.5	1	1
Capacity (1000m^2/year)	14	25	300	1,000	2,400
Depreciation ($/m^2)	1,050	600	125	60	35
Organic Materials	200	150	100	35	15
Inorganic Materials	200	200	120	50	30
Labor	150	100	20	10	5
Other Fixed Costs	75	50	15	10	5
Total (unyielded) ($/m^2)	1,675	1,100	355	160	90
Yield of Good Product (%)	50	60	70	80	90
Total Cost ($/m^2)	**3,350**	**1,850**	**550**	**200**	**100**

OLED is becoming a $30B industry

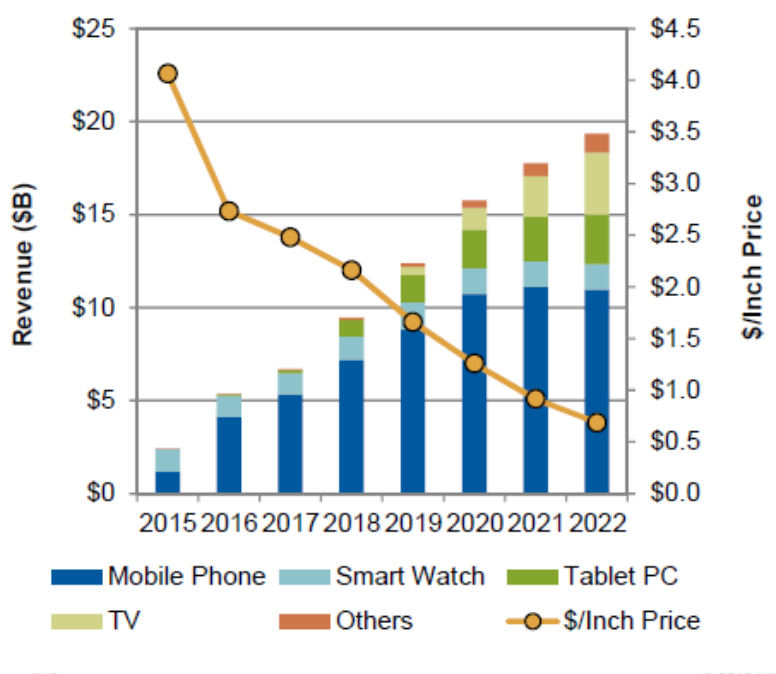
- Smartphone demand will be boosted the shipment units again as the cost of rigid AMOLED gets competitive than LCD. Flexible AMOLED will be focused as a innovative form factor.
- OLED TV demand will rapidly increase the shipment area as the yield rate goes down continuously.

AMOLED Display Revenues Forecast



Source: IHS © 2015 IHS

Flexible Display Revenue by Application & Price/Inch



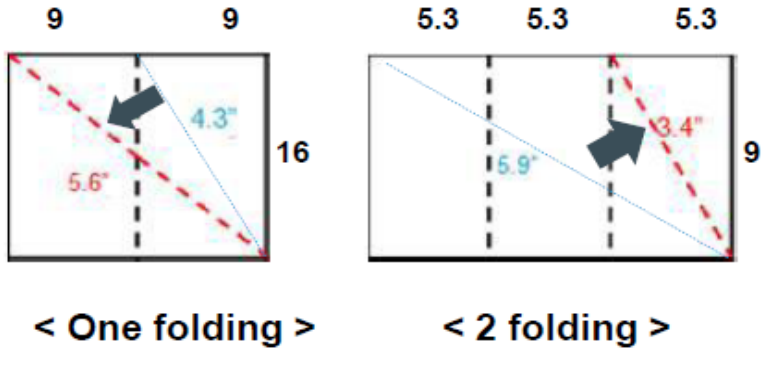
Source: IHS © 2015 IHS

Source: David Hsieh, IHS Taiwan

Considering Foldable Application

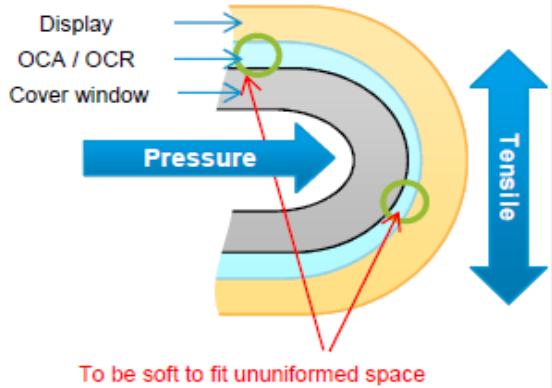
- The key points are :
  - Securing a bending radius of 1 mm
  - Cover windows should be changed from rigid-glass to flexible-plastic
  - Display should be endure repeats of over 200,000 folding,
  - Screen ratio & resolution is changed when it folded & unfolded,

Display size changes of foldable display



Source: IHS © 2015 IHS

Requirements of OCA/OCR



Source: IHS © 2015 IHS

Characteristics by folding type

Type	C type	G type	S type
Shape			
# of folding	1 time	2 time	2 time
Folding direction	1 way	1 way	2 way
# of display	2 screen	3 screen	3 screen
Inside display	-	1 screen	2 screen
Outside display	2 screen	2 screen	1 screen
Thickness	Thin	Medium	Thick
Difficulty	Low	Mid	High

Source: IHS © 2015 IHS

Source: David Hsieh, IHS Taiwan

Tipping Point #4 Cost

- Cost of mobile AMOLEDs have recently reached parity with LCDs
- WOLED TV still approximately 2X to almost 4X more costly than equivalent LCD

Manufacturing Cost of 5"FHD Rigid OLED at G5.5 LTPS by yield

Source: IHS Note all costs on this slide refer to module costs, not set © 2015 IHS

Manufacturing Cost Simulation: Rigid/Flexible AMOLED and LCD

	Rigid AMOLED	Flexible AMOLED	LTPS LCD
5.0" FHD Smart Phone Module	**2016**	**2016**	**2016**
Yielded Array Material Cost	$0.29	$1.16	$0.33
Yielded Cell & OLED patterning Material Cost	$1.84	$2.22	$2.21
Yielded Encapsulation Material Cost	$0.18	$0.02	
Yielded Module Component Total	$4.73	$4.79	$7.13
Indirect Expense Total	$0.70	$1.23	$0.97
Personnel Cost	$3.34	$3.77	$2.33
Depreciation Cost	$4.58	$8.20	$2.31
Total Yield	80.7%	60.4%	81.3%
Manufacturing Total Cost	$15.65	$21.39	$15.29

Source: IHS Note: Fab operation % not shown © 2015 IHS

- 4K AMOLED still summers very low yields <50%, while FHD yields are much higher and closer to 2X
- The story for TVs is quite similar to mobile, the cost difference is mainly due to depreciation and low yield.

Source: David Hsieh, IHS Taiwan

Flexible Panels from LG Display

TYPE	FLEXIBLE	
MODEL	P6BD30A	P6BD40A
CCT(K)	3,000	4,000
Thickness(mm)	0.41	0.41
Efficacy(lm/W)	50	50
CRI	85	85
Flux(lm)	150	150
Uniformity(%)	>70	>70
Voltage(V)	6.1	6.1
Power Consumption(W)	2.99	2.99
DC Current(mA)	490	490
LT70(K Hrs)	20	20

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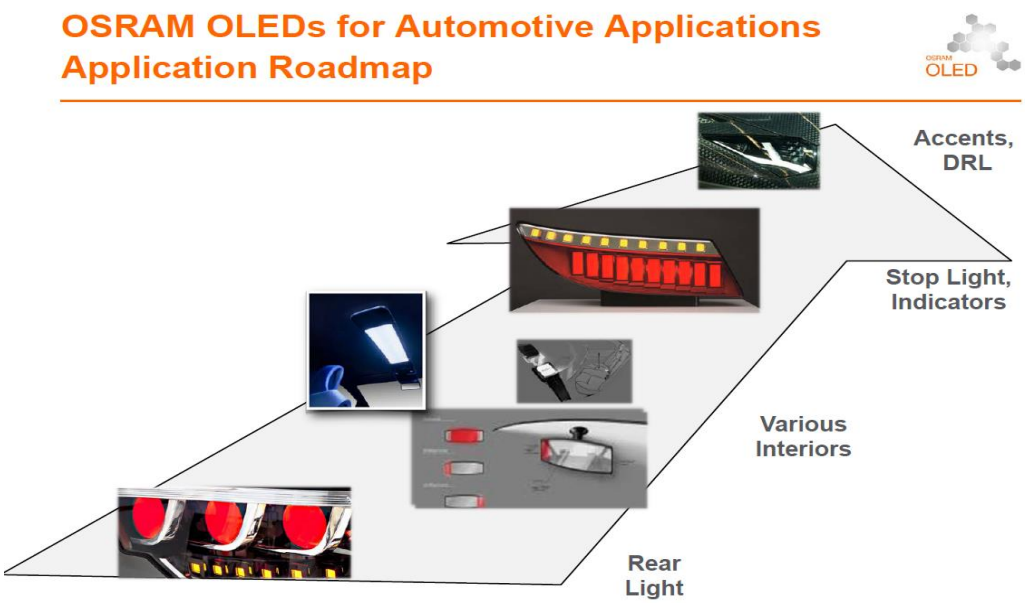
Transparent Connections from LG

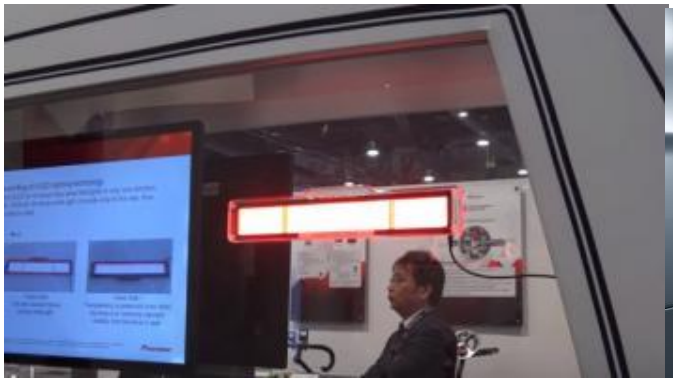
By attaching LG Display OLED light panels on glass and providing power through transparent mesh conductive film, the OLED light panel generates a floating light effect.

Focus on Automobile Applications

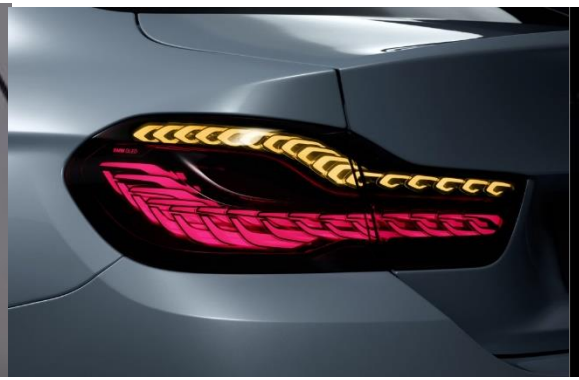
Astron Fiamm
LG Display
MC Pioneer
Osram
Yeolight



Pioneer concept: Transparent panel for rear window



BMW 2015 demo



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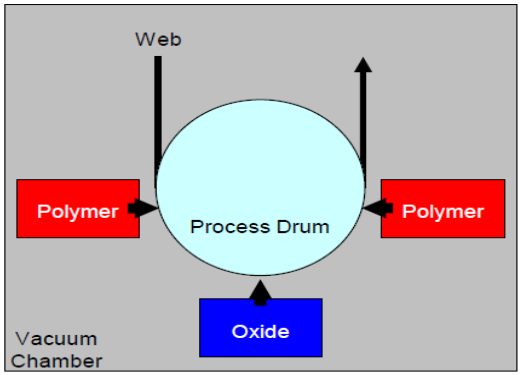
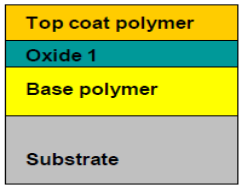
Thin Film Encapsulation

- Many companies have reported progress
  - LG, Konica Minolta, Osram, Philips, Samsung…
- Multi-layer barrier films can be bought from 3M
- Multi-layer hybrid solutions are expensive
- Aixtron and Vitriflex are developing all inorganic films
- Kateeva has large-scale printers for organic materials

Barrier Films from 3M

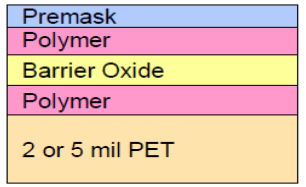
3M Barrier Films for General Use





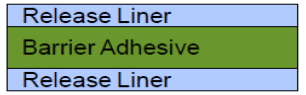
- Multilayer Construction
  - *Substrate*
  - *Polymer layers*
  - *Oxide layers*
- Polymers planarize & protect
- Oxides provide barrier
  - *High transparency & clarity*
  - *Low haze*
  - *Good flexibility*
- Tortuous path from Multi-dyads
  - *Can increase barrier performance:*

Commercialized:

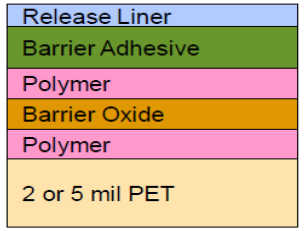


FTB3-50 and FTB3-125

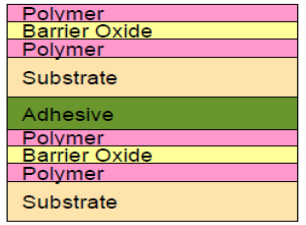
Developmental:



FTBA-25



FTB3-50a and FTB3-125a



FTB6 -125L

Commercial availability has been enabled by the demand for quantum dot films

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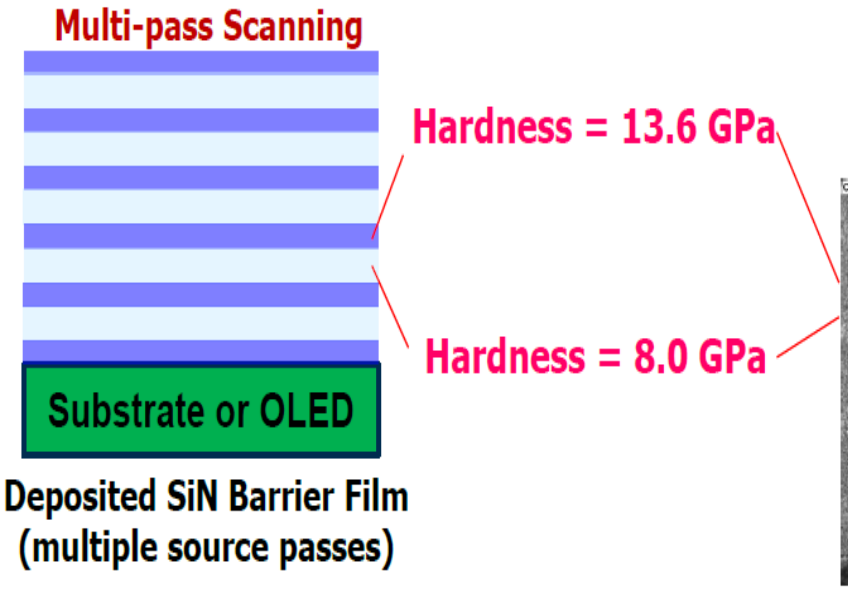
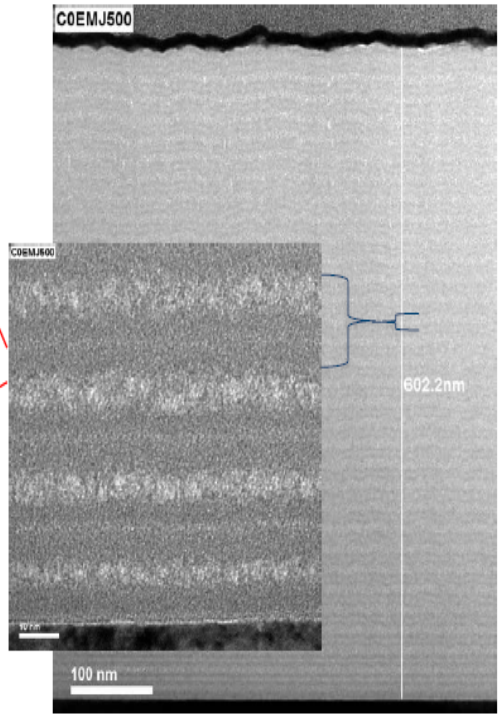
OptoCap™ Barrier From Aixtron

AIXTRON's OPTACAP™ PECVD system generates a multilayer structured barrier that provides simultaneously
low stress, low cost, highly flexible and an excellent barrier



TEM performed by EAG



Hard layers provide moisture barrier and are thin enough to bend

Softer layers decouple the hard layers and reduce the film stress

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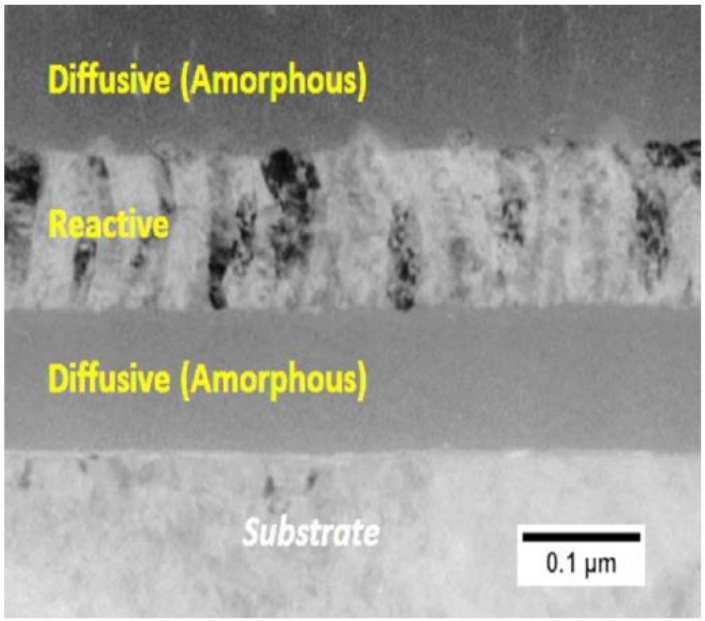
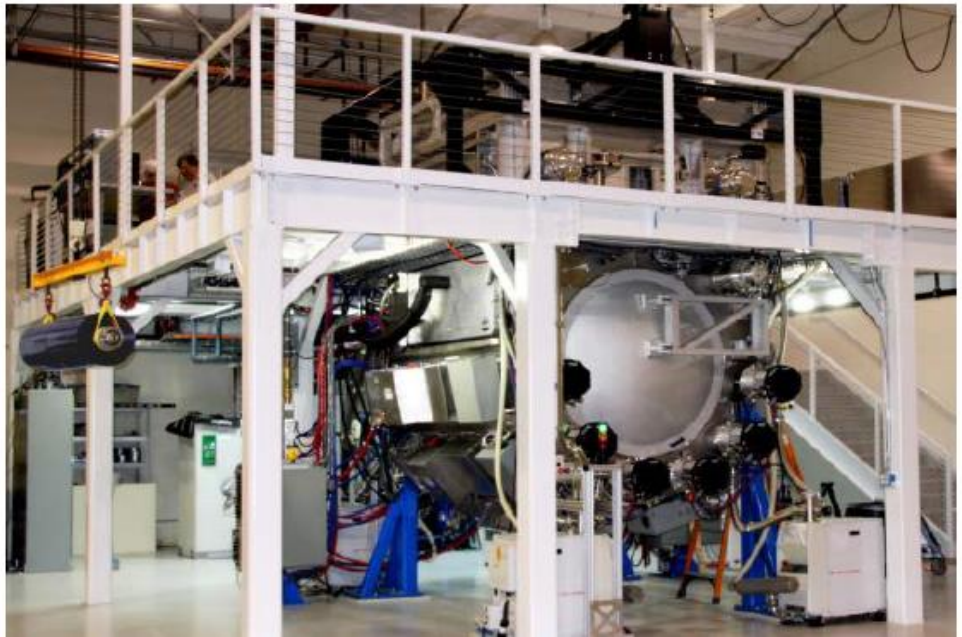
Multi-layer Metal Oxide Film from Vitriflex

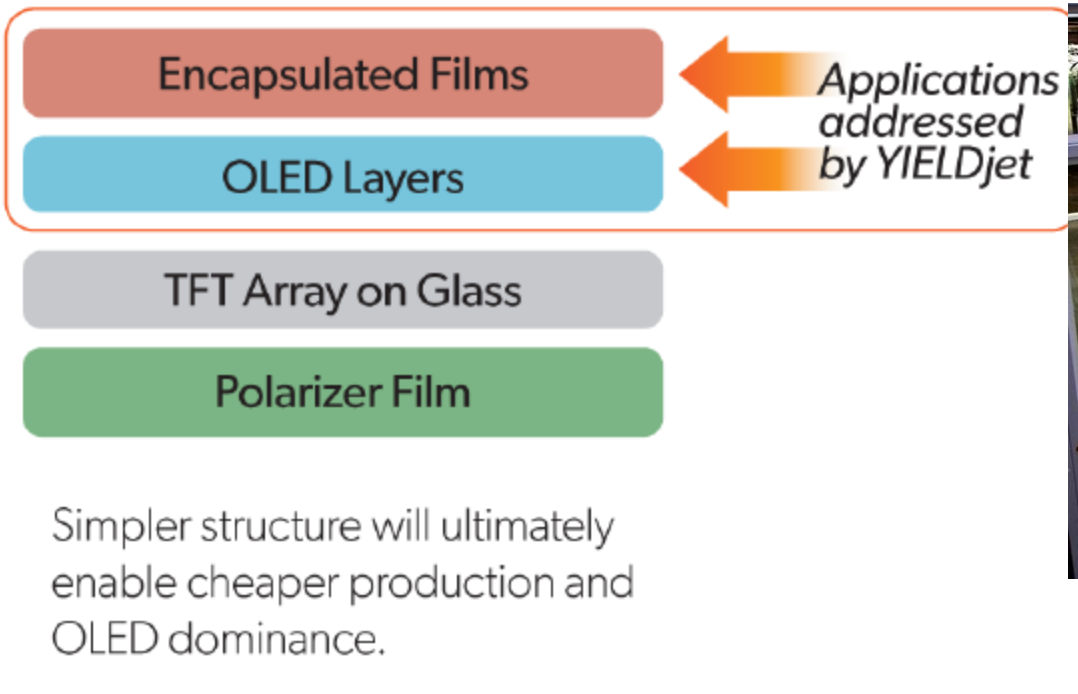


- Amorphous diffusive layer structure effectively reduces 'intrinsic' film growth defects
- Adjacent diffusive layers reduce flux of water vapor and oxygen reaching reactive layer
- Layers can be combined and tuned for enhanced optical transmission

- Flexible barrier stack
- OTR: 10^{-4} cc/m^2/day/atm
- WVTR: 10^{-6} g/m^2/day
- Roll-to-roll deposition
- Low material costs



Ink Jet Printer from Kateeva



Source: Conor Madigan, Kateeva

- **For lifetime, material improvements have made a big impact, but another issue is critical: N2 processing**
- **Air has chemically active impurities (ozone, water, oxygen, etc.)**
- **These impurities can invade OLED layers during coating – to get the best lifetime, especially T95, an inert N2 environment is essential**
  - Typically we see improvements in T95 of 50% or more

From Prototype to Production is Difficult

Habataki

Konica Minolta

High efficiency

Tunable color

Capacity: 1 million panels per month
High volume production due in 2014

Irodori

Thickness: 0.35mm
Weight: 0.06g/cm^2

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