Photovoltaics

The Photovoltaics (PV) subprogram funds R&D that is critical to continued advances in solar cell and module technology. These advances enable lower costs, increased efficiency and improved reliability to support the widespread deployment of electricity produced directly from sunlight ("photovoltaics"). The PV portfolio includes research directed toward the SunShot Initiative goals as well as critical challenges beyond SunShot.

To meet the SunShot Initiative goal of an unsubsidized utility-scale PV system cost of $1/W and to attain a levelized cost of energy (LCOE) of $0.06/kWh by 2020, the PV program has the following targets:

- Module cost of $0.50/W (including margin)
- Module efficiency of 20%

While module costs have decreased dramatically since the start of the SunShot Initiative, an additional 1/3 cost reduction is necessary. Further, increases in module efficiency enable decreases in the balance of systems costs (Fig. 1).

As the goals of the SunShot Initiative come within sight, the PV subprogram aims to address the next generation of challenges to support increased PV deployment, including

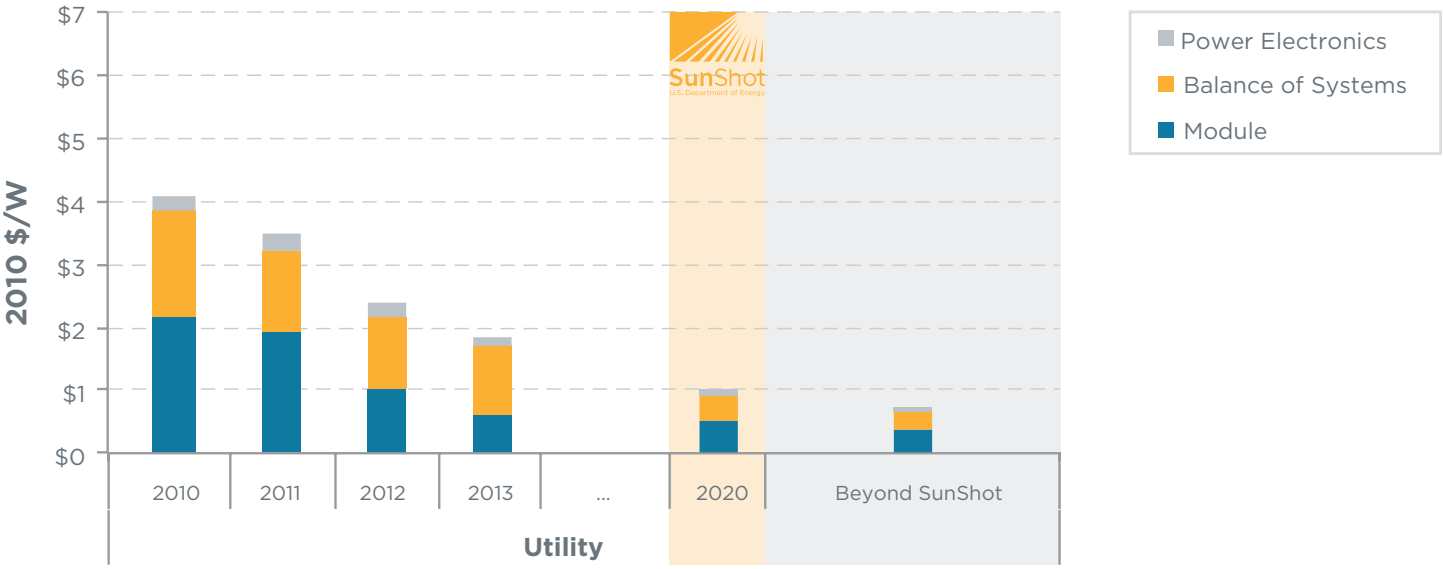

Figure 1. Evolution of the component costs of a PV system over time, also showing the SunShot targets and future reductions beyond SunShot. The PV subprogram work impacts the module and balance of systems costs.

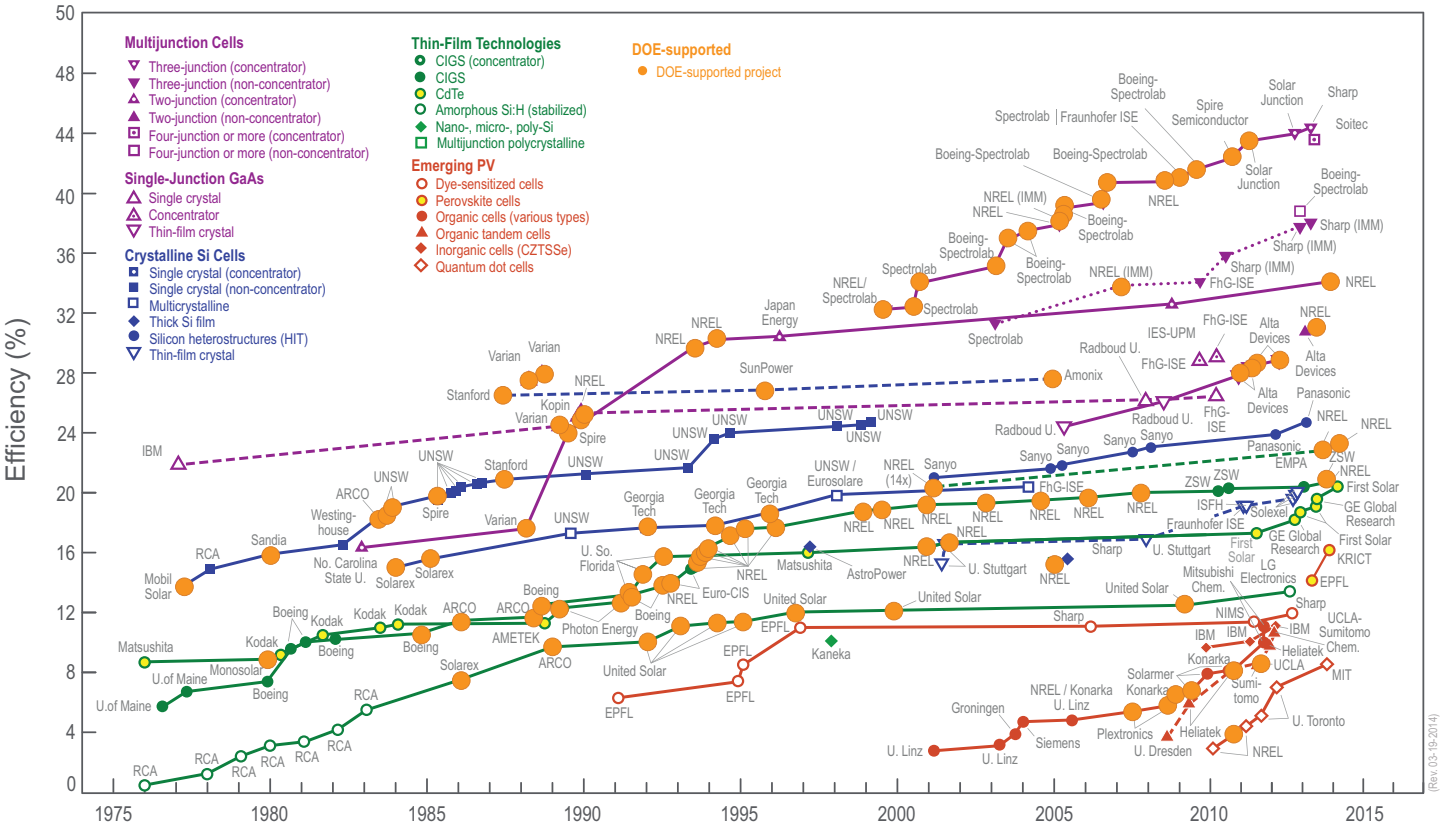

Figure 2. Record solar cell efficiencies of different technologies over the past several decades. Over one-half (orange dots) were funded by the PV subprogram and its precedessors. (Chart courtesy of NREL)

further reductions in the cost of PV electricity as well as reliability and life cycle sustainability. We also support the development of a skilled and diverse workforce of researchers prepared to address current and future challenges in the PV field. Accordingly, the PV portfolio spans work from early-stage solar cell research until the point of commercialization. It includes work on materials, processes, and device structure and characterization techniques. Just a few examples of our projects include a combinatorial approach to find new earth abundant absorber materials, new silicon solar cell structures using organic and metal oxide heterojunctions, high efficiency III-V on Si multijunction solar cells, the development of a two-photon photoluminescence technique to separate bulk and surface lifetimes in thin films, and model systems for CdTe and CZTS solar cells to probe fundamental efficiency limits.

The PV subprogram helps to maintain U.S. leadership in PV R&D, with a strong record of impact over the past several decades. For example, over one half of the solar cell efficiency records on the National Renewable Energy Laboratory's chart (Fig. 2) were supported by the PV subprogram and its predecessors.

The projects in the portfolio currently represent nearly $200 million of investment (Fig. 3), made over periods from two to five years. About half of the funding is National Laboratory R&D through lab proposal development process agreements to the National Renewable Energy Laboratory (NREL). This funding to NREL represents a sustained commitment to high impact research and expertise across PV technologies, including thin films, silicon, III-V materials, performance testing, characterization, organic photovoltaics (OPVs), and new material development.

The remaining funding in the PV portfolio is primarily awarded through our competitive funding opportunity announcement (FOA) process to universities, national laboratories and industry. We currently have 10 active funding programs. Next Generation Photovoltaic Technologies (NextGen) 2 funds the development of early-stage, transformational PV technologies. The Foundational Program to Advance Cell Efficiency (F-PACE) 1 funds, in partnership with National Science Foundation (NSF), significant advancements in existing solar cell technologies. F-PACE 2 focuses on the development of model systems to understand and overcome barriers to increasing efficiency in Si and thin film solar cells. The Bridging Research Interactions through collaborative Development Grants in Energy (BRIDGE) program supports collaborative research teams using DOE Office of Science research facilities to reduce the cost of solar electricity. We help to build a diverse and talented workforce of solar researchers through the Minority University Research Associates (MURA) and Diversity in Science and Technology Advances National Clean Energy in Solar (DISTANCE) programs, which fund solar research at minority education institutions, and the SunShot Postdoctoral Research Awards, which fund recent Ph.D graduates across the country. The Physics of Reliability: Evaluating Design Insights for Component Technologies in Solar (PREDICTS) program works to improve reliability by funding the development of physics-based models for PV degradation mechanisms. In addition, we have a partnership with NSF to fund the Quantum Energy and Sustainable Solar Technologies (QESST) center at Arizona State University, and a partnership with DOE's Office of Science to fund Solar Energy Research for India and the U.S. (SERIIUS).

PV R&D portfolio funding distribution

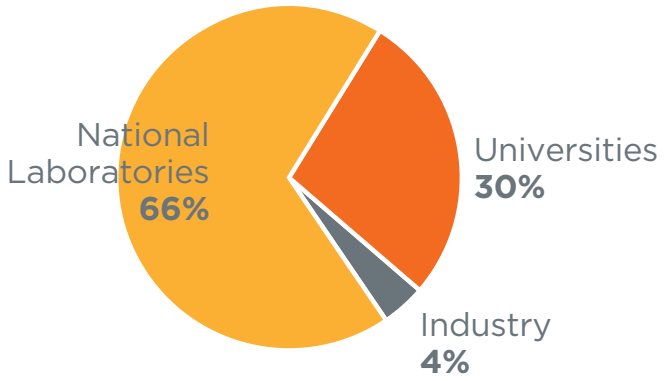

Figure 3. Distribution of funding in the PV portfolio by recipient type, including both FOAs and National Laboratory R&D.

The activity areas of our portfolio are Next Generation Photovoltaics, Training Next Generation Researchers, Advancing Photovoltaic Efficiency, and Cross-Cutting Photovoltaic Efforts, each of which are detailed herein.

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U.S. Department of Energy

Next Generation Photovoltaics

This activity area encompasses research that has the potential to dramatically lower costs and/or increase efficiencies of PV module beyond the SunShot targets of $0.50/W and 20%, respectively. It includes early-stage, applied research on new materials and device structures funded through the Next Generation Photovoltaics 2 (NextGen 2) and BRIDGE programs as well as National Laboratory R&D. The research supported by these programs will facilitate the entry of novel competitive technologies into the PV marketplace.

TRANSFORMING ORGANIC PHOTOVOLTAICS INTO A FULLY PRACTICAL ENERGY SOLUTION

University of Michigan | Ann Arbor, MI | $1.5M | NextGen 2 | 09/2011–10/2015

This research effort addresses efficiency, reliability, cost and scalability issues that must be resolved to transform OPVs into a competitively viable product. Small molecular-weight, organic nanocrystalline cells are stacked to form a high-efficiency tandem architecture. The research team is using low-cost, light in-coupling schemes to enhance efficiency, exploring liquid phase and organic vapor phase deposition, and subjecting prototype devices to reliability testing.

SOLUTION PROCESSED PV ABSORBERS BASED ON COLLOIDAL NANOCRYSTALS LINKED WITH METAL CHALCOGENIDE LIGANDS

University of Chicago | Chicago, IL | $1.5M | NextGen 2 | 09/2011–10/2015

Researchers on this project are developing solution-processed, all-inorganic PV absorber layers composed of colloidal nanocrystals. These are being electronically coupled through novel molecular metal chalcogenide ligands, which provide band-like carrier transport while preserving quantum confinement effects. At the end of the project, the research team plans to deliver a 20% efficient tandem cell composed of cadmium telluride (CdTe) nanocrystals for the top junction and lead sulfide (PbS) for bottom junction.

HOLE-BLOCKING LAYERS FOR SILICON/ORGANIC HETEROJUNCTIONS: A NEW CLASS OF HIGH-EFFICIENCY LOW-COST PV

Princeton University | Princeton, NJ | $1.4M | NextGen 2 | 10/2011–10/2015

The aim of this project is to develop silicon/organic and silicon/metal oxide heterojunctions as a new class of high-efficiency, low-cost PV technology. Instead of a conventional p-n junction, a silicon/organic heterojunction is used to separate carriers, and a silicon/metal oxide interface provides a hole-blocking layer. These devices are fabricated by spin-coating or spraying a thin layer of an organic semiconductor on silicon. This low-cost, room-temperature process eliminates the need for the high-temperature diffusion steps typically used to fabricate p-n junctions.

SINGLE-CRYSTALLINE InGaAs/InP DENSE MICRO-PILLAR FOREST ON POLY-SILICON SUBSTRATES FOR LOW-COST HIGH-EFFICIENCY SOLAR CELLS

University of California | Berkeley, CA | $1.5M | NextGen 2 | 09/2011–12/2015

Researchers on this project are developing a unique method to grow defect-free, III-V micro-pillar structures on single- and poly-crystalline silicon substrates. This approach combines the high-conversion efficiencies of compound semiconductor materials with the low costs and scalability of silicon-based materials. The dense forest of micron-sized indium gallium arsenide/ indium phosphide (InGaAs/InP) pillars provides omnidirectional, broadband light trapping and reduces the amount of rare earth materials required.

NEW MATERIALS FOR IMPLEMENTING TANDEM CIGS

University of Minnesota | Minneapolis, MN | $1.5M | NextGen 2 | 09/2011–12/2015

Researchers on this project are aiming to demonstrate the first functional copper indium aluminum gallium diselenide / copper indium gallium diselenide (CIAGS/CIGS) tandem solar cell. The researchers are combining aluminum with both gallium and indium to form a wide band gap absorber and developing a novel tunnel junction using thermal and air-stable oxides. Finally, they are introducing a graded $Cd_xZn_{1-x}S$ layer using a novel continuous flow chemical bath deposition system which can better control process conditions and reduce particle loading.

COMBINATORIAL PLATFORM FOR DISCOVERY OF NANOCRYSTAL-INK BASED EARTH ABUNDANT ELEMENT PV WITH EFFICIENCY GREATER THAN 20%

University of Washington | Seattle, WA | $0.49M | NextGen 2 | 09/2011–12/2015

The University of Washington research team is employing solution-phase chemistry methods used for CZTSSe device fabrication to conduct high-throughput experiments with a novel combinatorial deposition platform. This approach allows for the discovery of alloying and doping strategies that produce a back surface field and defect passivation strategies that can dramatically decrease recombination and increase the minority carrier lifetime. By using photoluminescence, current-voltage, capacitance-voltage, and external quantum efficiency analysis, the researchers hope to rapidly converge on practical routes to high-efficiency CZTSSe-based solar cells.

PYRITE IRON SULFIDE SOLAR CELLS MADE FROM SOLUTION

University of California | Irvine, CA | $1.2M | NextGen 2 | 09/2011–12/2015

The goal of this project is to build a prototype solar cell made from nontoxic, inexpensive, and earth-abundant iron pyrite (FeS_2), also known as Fool's Gold, with an efficiency of 10% or greater. The research team is developing a stable p-n heterojunction using innovative solution-phase pyrite growth and defect passivation techniques. A pyrite-based device offers a pathway to meeting SunShot cost targets, 20% module efficiency, and terawatt scalability using a proven, manufacturable geometry that is suitable for rapid scale-up up by a U.S. thin film PV industrial partner.

DEVELOPMENT OF III-Sb QUANTUM DOT SYSTEMS FOR HIGH EFFICIENCY INTERMEDIATE BAND SOLAR CELLS

University of California | Los Angeles, CA | $0.9M | NextGen 2 | 09/2011–12/2015

The primary objective of this project is to identify and develop a III-Sb quantum dot absorbing medium for intermediate band solar cells (IBSC) via thorough experimental analysis supported by sophisticated band structure modeling. This is of interest because the theoretical efficiency limit of IBSCs is on par with triple junction solar cells. The team is working on band structure calculations, quantum dot solar cell device design, materials development, and in-depth experimental analysis of the quantum dot superlattice properties using TEM, QE and 2 photon absorption experiments. The team will be targeting the demonstration of a 20% IBSC with no open circuit voltage loss.

HOT CARRIER COLLECTION IN THIN FILM SILICON WITH TAILORED NANOCRYSTALLINE/AMORPHOUS STRUCTURE

Colorado School of Mines | Golden, CO | $1.4M | NextGen 2 | 09/2011–12/2015

Researchers on this project are developing a new approach to the synthesis of hydrogenated nanocrystalline silicon (nc-Si:H), which exploits hot carrier collection as a way of boosting conversion. By using a novel gas phase plasma process, the research team is creating engineered films that incorporate quantum-confined Si nanocrystals with tailored surface termination. These engineered composites of amorphous and nanocrystalline Si have the potential to dramatically increase the efficiency of single junction and multijunction thin film Si solar cells by mitigating photo-induced degradation, increasing absorption, and offering the possibility of hot carrier devices.

BEYOND THE LAMBERTIAN LIMIT—NOVEL LOW-SYMMETRY GRATINGS FOR ULTIMATE LIGHT TRAPPING ENHANCEMENT IN NEXT-GENERATION PHOTOVOLTAICS

University of Delaware | Newark, DE | $1.2M | NextGen 2 | 09/2011–12/2015

This project is addressing the efficiency limit and high fabrication cost of current light-trapping methods by developing novel low-symmetry gratings (LSG) for next-generation thin crystalline silicon and copper indium gallium selenide (CIGS) PV solar cells. The LSG design achieves light-trapping enhancement exceeding the $4n^2$ Lambertian limit within a specified range of photon wavelengths and can be fabricated using a low-cost, single-step nano-imprint/molding technique.

NEXT-GENERATION SULFIDE MATERIALS: OPTIMIZING CZTS AND DEVELOPING SnS BY SYSTEMATIC DEFECT ENGINEERING

Massachusetts Institute of Technology | Cambridge, MA | $1.5M | NextGen 2 | 09/2011–12/2015

MIT is using systematic defect engineering to advance thin film PV cells based on tin sulfide (SnS), which offers high optical absorption and high carrier mobilities. Because tin and sulfur are earth-abundant materials and require processing temperatures below 400°C, use of these materials in thin film PV cells has the potential to lead to low-cost fabrication. A rapid ramp-up of efficiency is also possible by leveraging the decades of development of similar thin film materials.

SOLAR UPCONVERSION WITH METAL-ENHANCED BIMOLECULAR COMPLEXES

Leland Stanford Junior University | Stanford, CA | $1.3M | NextGen 2 | 09/2011–12/2015

This effort aims to develop an efficient medium capable of using plasmonic materials and processes to convert low-energy transmitted photons to higher-energy photons, which can then be absorbed by any type of commercial solar cell. The research team is using electrodynamic simulations and *ab-initio* quantum computations to optimize existing upconversion processes and design new molecular complexes for high-efficiency PV upconversion in a solution-processable, scalable platform.

AN INTEGRATED APPROACH TO ORGANIC PHOTOVOLTAICS

National Renewable Energy Laboratory | Golden, CO | $4.4M | National Laboratory R&D | 10/2012–09/2015

OPVs could become a low-cost technology amenable to high-throughput fabrication techniques. However, OPVs need to overcome short device lifetimes and low efficiencies. This project integrates theory, computation, and characterization to discover and develop new materials for OPV that advance efficiency and improve lifetime. There are three integrated research tasks: **1)** the design and development of new absorber materials through combinatorial computational methods coupled to their direct synthesis, characterization, and device optimization; **2)** the development of charge-selective hole and electron contacts that optimize interface properties, performance, and stability for new active layer materials; and **3)** the investigation of device and materials degradation mechanisms and mitigation strategies to extend device lifetime.

MULTIFUNCTIONAL TRANSPARENT CONDUCTING OXIDES

National Renewable Energy Laboratory | Golden, CO | $1.5M | National Laboratory R&D | 10/2012–09/2015

This agreement pursues the development of promising transparent conducting oxides (TCO) for use in PV cells. The first goal is to demonstrate earth-abundant TCOs using industrially-compatible processing conditions with material parameters comparable to TCOs commonly used today. The second goal is to model and demonstrate deposition of amorphous TCOs with tunable material properties that are flexible and/or cost effective. By furthering basic theory, demonstrating new materials, and optimizing processing, improved contacts can be created for multiple PV technologies.

RAPID DEVELOPMENT OF EARTH-ABUNDANT THIN-FILM SOLAR CELLS

National Renewable Energy Laboratory | Golden, CO | $1.5M | National Laboratory R&D | 10/2012–09/2015

In order to diversify the materials base for inorganic thin film solar cells, which may allow for new technologies with reduced costs, an accelerated development technique is being pursued. The approach initially focuses on ternary copper sulfides and iteratively combines predictive first-principles theory and high-throughput experiments. Both individual materials and PV device prototypes will be developed using the high-throughput technique to accelerate the development process. The results of this project have the potential to drastically expand the materials options for PVs and produce new earth abundant thin film solar cells that are competitive with incumbent technologies.

LOW-COST, HIGH-EFFICIENCY, ONE-SUN HYDRIDE VAPOR PHASE EPITAXY III-V SOLAR CELLS

National Renewable Energy Laboratory | Golden, CO | $1.5M | National Laboratory R&D | 10/2012–09/2015

This project aims to develop a new III-V, one-sun solar cell concept that has the potential to outperform silicon modules in both efficiency and cost. This will be achieved by growth of III-V materials by HVPE in a revolutionary, in-line reactor, rather than by expensive metallorganic vapor phase epitaxy (MOVPE) in a traditional batch reactor. The many advantages of HVPE include much lower precursor costs (pure metals rather than organometallic engineered molecules, representing a 5–10x savings), higher deposition rates (1–5 μm/min or 10–50x faster), significantly increased material utilization (much lower arsine overpressure), and inherent cost savings due to atmospheric-pressure, in-line growth. This technology is expected to reach grid parity cost points, along with favorable balance-of-system (BOS) efficiencies, by significantly lowering the cost of III-V material growth and by applying a simple, fast layer-transfer process to reuse an epitaxial template wafer.

RATIONAL DESIGN OF WIDE BANDGAP BUFFER LAYERS FOR HIGH-EFFICIENCY THIN-FILM PV

Lawrence Livermore National Laboratory | Livermore, CA | $0.31M | BRIDGE | 11/2012–11/2015

LLNL is working in collaboration with the University of Illinois at Urbana-Champaign and industry partners to provide critical understanding of the role of bulk and interface defects in limiting the performance of buffer layer materials necessary for the fabrication of stable, high efficiency thin film PV devices. This project is innovative in its application of first-principles atomic scale modeling to the design of buffer layer materials for thin film PV, as well as in coordinating complimentary state-of-the-art computational and experimental efforts to accelerate progress, expanding the breadth of expertise and resources being applied to PV system design.

DEVELOPING A TRANSPARENT EMITTER LAYER FOR CIGS SOLAR CELLS THROUGH SYNCHROTRON INVESTIGATIONS

National Renewable Energy Laboratory | Golden, CO | $0.3M | BRIDGE | 11/2012–11/2015

Spectroscopic and diffraction measurements are being used in multiple energy ranges to probe different parts of transparent emitter layers (surface, near surface and bulk) and interfaces in CIGS thin-film PV devices. NREL is working in collaboration with Stanford Synchrotron Radiation Lightsource to apply synchrotron radiation methods and other tools to support the development of a transparent emitter layer.

VAPOR TRANSPORT DEPOSITION FOR III-V THIN FILM PHOTOVOLTAICS

University of Oregon | Eugene, OR | $0.45M | BRIDGE | 11/2012–11/2015

Scientists at the University of Oregon are researching vapor transport (VT) deposition technology for III-V solar materials. Using photoelectrochemical (PEC) test cells, they have shown that n-doped Gallium Arsenide (n-GaAs) deposited in a simple close-space VT reactor has diffusion lengths of 1.5 μm^{-1} even when deposited at rates of ~0.5 μm min^{-1}. Device physics simulations show that by controlling doping and forming solid-state junctions, AM1.5G (air mass global) efficiencies greater than 24% should be attainable.

COLLABORATIVE ATOMIC-SCALE DESIGN, ANALYSIS, AND NANO-FABRICATION FOR RECORD BREAKING, SINGLE CRYSTAL $Zn_xCd_{1-x}Te$ SOLAR CELL ARRAYS

University of Texas | El Paso, TX | $0.9M | BRIDGE | 11/2012–11/2015

The goal of this project is to create a new collaborative capability to work around fundamental barriers to achieving high open-circuit voltages (VOC ≥ 1.0 V) in CdTe/CdS solar cells. The project will create a patterned thin film design, deposition and analysis capability to create uniform $Zn_xCd_{1-x}Te$/CdS solar cell arrays that will reduce the defect-density from 1014 to 1012 cm^{-3} and increase the V_{oc} from 0.85 V to 1.0 V.

IN-SITU ROLL-TO-ROLL PRINTING OF HIGHLY EFFICIENT ORGANIC SOLAR CELLS

SLAC National Accelerator Laboratory | Menlo Park, CA | $0.88M | BRIDGE | 11/2012–11/2015

The objective of this project is to develop a roll-to-roll printing setup for organic solar cells that will capture important aspects of existing industrial printing methods and will allow the printing process to be studied *in-situ* with both small and wide angle X-ray scattering. This novel ability will enable a more rapid rate of improvement in solar cell performance by allowing the team to directly tune the printing conditions and the ink formulations based on the feedback from the scattering experiments.

Training Next Generation Researchers

This activity area funds solar energy research to produce a talented and diverse workforce of scientists and engineers prepared to address future challenges in solar energy R&D. This area includes the MURA and DISTANCE programs and the SunShot Postdoctoral Research Awards.

COST EFFECTIVE POLYMER SOLAR CELLS RESEARCH AND EDUCATION

Norfolk State University | Norfolk, VA | $0.3M | MURA | 09/2010–08/2014

The research objective is to investigate and develop polymer-based solar cells for potential cost-competitive, durable, lightweight, flexible, and high efficiency solar energy conversion applications. A donor/acceptor bicontinously ordered nano structure type solid state morphology is targeted. The educational objectives of this project include training a next generation of young scholars, scientists and/or technical workforce to work on solar energy technology.

PRODUCTION AND CHARACTERIZATION OF NOVEL PHOTOVOLTAIC MATERIALS

North Carolina Central University | Durham, NC | $0.3M | MURA | 09/2010–09/2014

This project enhances PV research and training efforts at NCCU focused on the development of novel nanoscale materials for PV applications. A unique ultrafast pulsed laser deposition and pulsed electron deposition facility is used to systematically study complex ternary and quaternary III-V and chalcopyrite semiconductor quantum dots (QDs) and nanowires (NWs) that are anticipated to play an important role in the development of advanced PV cells. Theoretical modeling of the electronic structure and carrier dynamics of QDs and NWs will complement the experimental research.

CREATING GREEN TALENT IN THE SOUTHWEST: A COMPREHENSIVE RESEARCH AND EDUCATION PROGRAM IN SOLAR CELL TECHNOLOGY AT THE UNIVERSITY OF NEW MEXICO FOR HISPANIC AND NATIVE-AMERICAN BACCALAUREATE STUDENTS

University of New Mexico | Albuquerque, NM | $0.3M | MURA | 09/2010–09/2014

This project establishes a third generation PV laboratory at the Center for High Technology Materials where undergraduates will be exposed to research in nanotechnology-based PVs and ultra-high concentration solar cells, as well as a research effort in the Electrical and Computer Engineering (ECE) department on smart grids for future power distribution. Additionally, new core ECE courses are being developed that will be taken by all undergraduates, which will introduce them to PVs from both a device and a power systems perspective.

NEW NANOSTRUCTURED MATERIALS FOR EFFICIENT PHOTON UPCONVERSION

University of Delaware | Newark, DE | $0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

In this research effort, new designs are being developed for nanostructured materials that maximize upconversion efficiency and can be easily integrated with existing PV devices. The three objectives for this project are: **1)** use well-controlled model systems to develop a fundamental understanding of the photophysical processes impacting upconversion efficiency, **2)** develop new nanostructured devices with high upconversion efficiency and minimal energy sacrifice and **3)** develop implementations of this design that can be produced and processed at commercially-relevant scales.

STOICHIOMETRY, INTERFACES, AND DEFECTS IN Cu_2S PHOTOVOLTAICS: A MODEL SYSTEM FOR ATTAINING STABILITY

Argonne National Laboratory | Lemont, IL | $0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

This research aims to synthesize Cu_2S PV "model systems" by atomic layer deposition (ALD). Precisely defined ALD model systems will enable a fundamental understanding of the optoelectronic stability in Cu_2S-based devices. An in-depth look into the photophysical properties of such devices will further shed light on the importance of interfaces in thin film PV devices. The potential impact of these studies will provide the grounds to understand why theoretical device efficiencies are rarely obtained in large-scale fabrication.

IN-SITU, NON-DESTRUCTIVE OPTOELECTRONIC CHARACTERIZATION OF BURIED INTERFACES IN SOLAR MATERIALS USING TWO-PHOTON TOMOGRAPHY

The Molecular Foundry, Lawrence Berkeley National Laboratory | Berkeley, CA | $0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

Developing new characterization tools that can non-destructively probe within PV materials *in-situ* enables researchers to zero in on limiting factors of their devices and provide insight into potential improvements. To meet this need, this project develops a two-photon microscopy technique that allows for 3D imaging of of grains and grain boundaries in CdSe and CdTe polycrystalline materials. This microscopy technique operates on the principle that semiconductors are generally transparent to sub-bandgap light, thus using a pulsed infrared laser source to probe through the material.

MAGNETICALLY GUIDED NANO-MICRO SHAPING AND SLICING OF SILICON

University of California | La Jolla, CA | $0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

This research effort has enabled the first successful direction-guided, nano/microshaping of silicon. The technique, utilizing a narrow array of Au/Fe/Au trilayer etch lines, is particularly effective in producing only micrometer-thick Si sheets by rapid and inexpensive means with 20 μm level slicing loss of Si material, thus greatly reducing the waste of Si material compared to the ~200 μm kerf loss per slicing in the typical saw-cut Si solar cell preparation. Such nano/ microshaping may enable a whole new family of novel Si geometries and exciting applications. Micrometer thin, massively parallel silicon sheets, very tall Si microneedles, zigzag bent Si nanowires, and tunnel drilling into Si substrates have already been demonstrated.

BOOSTING SOLAR VOLTAGE OUTPUT BY EFFICIENT EXTRACTION OF AUGER ELECTRONS

University of Washington | Seattle, WA | $0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

A concept for increasing voltage in solar cell devices is proposed using non-radiative (Auger) de-excitation of metastable excited states of dopant ions. This hot carrier capture via interfacial electron transfer could be used to augment both PV and photoelectrochemical devices. The test case uses photoexcitation of CdS nanocrystals followed by efficient picosecond energy transfer to Mn^{2+}, with a long-lived (ms) excited state lifetime. Electrons injected into the CdS then capture this energy via Auger de-excitation, generating hot electrons to be extracted at a higher potential.

HIGH-EFFICIENCY THIN-FILM Fe_2SiS_4 AND Fe_2GeS_4-BASED SOLAR CELLS PREPARED FROM LOW-COST SOLUTION PRECURSORS

Delaware State University | Dover, DE | $0.33M | DISTANCE | 09/2013–09/2016

The objectives of this project are to introduce a solar course at Delaware State University and initiate a solar research program debuting with the development of a novel thin film PV technology using solution nano-precursors to Fe_2SiS_4 and Fe_2GeS_4-based absorber layers in solar devices. This technology aims to create low cost solar cells by using solution processing of sustainable, inexpensive materials, coupled with reduced installation costs by enabling use of lightweight, flexible substrates. The solar cell devices target an efficiency of at least 5%.

COMPLETE ELECTROCHEMICAL ACCESSIBILITY OF METAL-ORGANIC FRAMEWORK FILMS DEPOSITED IN A LAYER-BY-LAYER FASHION

Northwestern University | Evanston, IL | $0.2M | SunShot Postdoctoral Research Awards | 10/2013–09/2015

Metal-organic frameworks (MOFs) have been shown to possess interesting properties that may prove beneficial for efficient solar energy conversion schemes. For example, light harvesting MOF crystals have been prepared which exhibit ultrafast energy migration. This fast energy migration is hypothesized to be facilitated by the spatial separation of chromophores and the anisotropy of the crystals. The main objective of this project is to prepare oriented and well-characterized MOF films through the liquid phase layer-by-layer method, where individual components of the MOF are introduced to the substrate one at a time, and study them for their potential application in PVs.

EARTH-ABUNDANT MATERIALS FOR TERAWATT SOLAR ENERGY

Massachusetts Institute of Technology | Cambridge, MA | $0.2M | SunShot Postdoctoral Research Awards | 10/2013–09/2015

This research effort is split into two distinct but related research directions on SnS and Cu_2ZnSnS_4 (CZTS). Because SnS evaporates congruently, akin to CdTe, this presents the possibility of developing a closed space sublimation growth process for SnS similar to that developed by First Solar for CdTe. The second half of the project focuses on studying the beneficial effects of chemical and structural disorder in CZTS thin films. The team will study intentionally disordered CZTS (d-CZTS) that may provide the benefits of crystalline CZTS while not suffering from the effects of phase disorder.

TRANSITION METAL CHALCOGENIDES FOR SOLAR FLOW BATTERIES

Cornell University | Ithaca, NY | $0.2M | SunShot Postdoctoral Research Awards | 10/2013–09/2015

This work attempts to demonstrate the feasibility of a Solar Flow Battery (SFB), a photoelectrochemical device for simultaneous solar energy capture and storage using semiconductor photoelectrodes and flow battery redox couples. A model has been built to estimate limiting and achievable efficiencies for semiconductor photoelectrochemical cells driving energy storage reactions using arbitrary redox couples. Transition metal chalcogenides and relatively narrow-bandgap metal oxides appear to be promising semiconductor candidates for SFB systems. Promising electrolytes have also emerged from these modeling studies, including hydrohalic acids, metal-halogenide couples, vanadium couples, and cerium couples.

Advancing Photovoltaic Efficiency

Projects in this activity area focus on improving the power conversion efficiency of established solar cell materials, including Si, CdTe, CIGS and III-Vs, as well as addressing technological barriers to further advancement. This work enables progress towards and beyond the SunShot targets. Programs in this area include F-PACE 1 and 2 as well as National Renewable Energy Laboratory R&D. A goal of this area is to sponsor at least three new world records for PV efficiency each year.

ACCELERATING CPV SYSTEM EFFICIENCIES TO CREATE A SUSTAINABLE TERAWATT PLATFORM

National Renewable Energy Laboratory | Golden, CO | $3.5M | F-PACE 1 | 09/2011–09/2014

A partnership between NREL, Spectrolab, and the University of California–Berkeley is working to reduce the cost of concentrating photovoltaics (CPV) modules by increasing the CPV cell efficiency. This project team aims to increase cell efficiencies to 48% by inserting selective reflectors between the junctions of the multijunction solar cells, thereby increasing the photovoltage. The work will strive to define the fundamental physics in parallel with implementing the concept.

III-V/ACTIVE-Si INTEGRATION FOR LOW-COST HIGH-PERFORMANCE CONCENTRATOR PHOTOVOLTAICS

Ohio State University | Columbus, OH | $1.2M | F-PACE 1 | 09/2011–11/2014

This project works toward a paradigm shift for CPV technology, which is currently constrained by germanium Ge and GaAs substrates in terms of cost and efficiency barriers. The project integrates GaAsP and Ga-rich GaInP based subcells with a Si substrate to achieve high efficiencies with a roughly 100-time reduction in substrate cost per area. This yields a path to achieve panels at $0.50/W and provides access to the economies of scale afforded by a Si wafer based manufacturing infrastructure.

TECHNOLOGY ENABLING ULTRA-HIGH CONCENTRATION MULTI-JUNCTION SOLAR CELL

North Carolina State University | Raleigh, North Carolina | $1.0M | F-PACE 1 | 09/2011–11/2014

A major opportunity for improving cost efficiency in CPV systems lies in operating at higher solar energy concentrations. In collaboration with Spectrolab, this project is designing a tunnel junction between the top and middle cells of an indium gallium phosphide/gallium arsenide/germanium (InGaP/GaAs/Ge) triple junction structure that is functional at a concentration of 2,000 suns. The researchers are growing the tunnel junction from aluminum gallium arsenide (AlGaAs) and InGaP while using very thin aluminum gallium arsenide (AlGaAs) layers to inhibit diffusion.

REDUCED $Cu(InGa)Se_2$ THICKNESS IN SOLAR CELLS USING A SUPERSTRATE CONFIGURATION

University of Delaware | Newark, DE | $1.1M | F-PACE 1 | 09/2011–11/2014

To reduce the cost of $Cu(InGa)Se_2$ manufacturing, the research team is halving the thickness of the absorber layer. Project efforts include developing the technology and underlying science for using a superstrate cell configuration, which is essentially an upside-down version of the conventional $Cu(InGa)Se_2$ configuration. The anticipated outcome of the project is a CIGS solar cell with 0.7 μm thickness and 17% efficiency.

HIGH-EFFICIENCY, COMMERCIAL-READY CdTe SOLAR CELLS

Colorado State University | Fort Collins, CO | $1.5M | F-PACE 1 | 09/2011–12/2014

The goal of this research is to improve the relative efficiency of cadmium telluride (CdTe) solar cells used in commercial modules by about 30% without increasing manufacturing costs. This is being accomplished by modifying the basic cell structure for higher voltage and fill factor and incorporating plasma processes for final substrate cleaning and modification of the CdS window for increased band gap (higher current). Combined with modest decreases in production costs and anticipated advances elsewhere, this effort contributes to a reduction of the reported $0.75/W module cost to the $0.50/W target.

HIGH-THROUGHPUT CIGS SOLAR CELL FABRICATION VIA ULTRA-THIN ABSORBER LAYER WITH OPTICAL CONFINEMENT AND (Cd, CBD)-FREE HETEROJUNCTION PARTNER

Old Dominion University | Norfolk, VA | $1.1M | F-PACE 1 | 09/2011–03/2015

Old Dominion University, in collaboration with The University of Toledo and the University of Illinois at Urbana-Champaign, is developing a high-throughput and high-efficiency CIGS solar cell fabrication process via the use of an ultra-thin absorber layer, optical confinement and a heterojunction partner without cadmium (Cd) or use of chemical bath deposition (CBD). These new designs and processes aim to reduce CIGS material costs by a factor of ten, multiply throughput production by at least a factor of five, and achieve module costs of less than $0.44/W with efficiencies higher than 20%.

DEVELOPMENT OF HIGH ELECTRONIC QUALITY CdTe FILMS REQUIRED FOR 1 V V_{oc} CdTe CELLS

University of South Florida | Tampa, FL | $0.99M | F-PACE 1 | 09/2011–01/2015

Thin film CdTe is today's lowest cost PV technology, but the open-circuit voltage of these solar cells has stayed at 0.85 volts (V) for nearly 20 years. In order to reach the practical potential of thin film CdTe cells, the open-circuit voltage of the cell must increase to about 1 V. The main goal of this project is to demonstrate that CdTe films with doping concentrations greater than 1016 cm^{-3} and lifetimes in the range of 1–10 ns can be prepared, which is consistent with a V_{oc} of 1 V. Increasing the V_{oc} to this level paves the way toward reaching 20% cell and 17% module efficiencies.

UNDERSTANDING THE EFFECT OF Na IN IMPROVING THE PERFORMANCE OF $CuInSe_2$-BASED PV

University of Delaware | Newark, DE | $0.96M | F-PACE 1 | 09/2011–11/2014

Together with the University of Illinois at Urbana-Champaign, this project strives to find the pathways through which sodium (Na) improves the performance of CIGS-based PV devices. The researchers are growing CIGS films with different amounts of Na for full characterization. They are also fabricating devices to highlight correlations of operation, Na dosage, and the method of incorporation. This investigation helps provide a basic scientific and engineering understanding of the role of Na in CIGS PV that is needed for advancement toward the $0.50/W module manufacturing goal.

NOVEL CONTACT MATERIALS FOR IMPROVED PERFORMANCE CdTe SOLAR CELLS

University of Illinois | Urbana Champaign, IL | $1.1M | F-PACE 1 | 09/2011–11/2014

This project is developing new materials for front and back contacts used in CdTe PV cells. The new materials will reduce the back-contact barrier to zero and produce an ohmic contact, which increases the current flow and thus the efficiency of the PV cell. These advances are expected to increase device performance and process flexibility, providing lowered costs and greater yields.

ADVANCED PRECURSOR REACTION PROCESSING FOR $Cu(InGa)(SeS)_2$ SOLAR CELLS

University of Delaware | Newark, DE | $1.2M | F-PACE 1 | 09/2011–11/2014

This project seeks to improve the manufacturability of CIGS-based PV modules by advancing the precursor reaction approach currently employed by a number of commercial entities. In partnership with the University of Florida, the researchers are investigating pathways to improved module performance and yield by modifying the interface between the CIGS absorber layer and molybdenum (Mo) back contact, and to increased throughput by studying precursor structures for rapid (<5 minute) processing. This approach can also allow for the omission of toxic hydrogen selenide (H_2Se) gas from the manufacturing process.

IMPROVING V_{oc} OF CdTe THIN FILM SOLAR CELLS: UNDERSTANDING AND TAMING THE GRAIN BOUNDARIES

Oak Ridge National Laboratory | Oak Ridge, TN | $1.0M | F-PACE 1 | 09/2011–11/2014

This effort aims to develop technologies that can overcome the open circuit voltage (V_{oc}) limitations in cadmium telluride solar cells by understanding and controlling the grain boundaries (i.e., the bounding surface between crystals). The research team is working to improve minority carrier lifetimes from less than a few nanoseconds (ns) to more than 10 ns, which would lead the enhancement of V_{oc} from 840 mV to more than 1 V.

HIGH TEMPERATURE ROLL-TO-ROLL CdTe ON FLEXIBLE GLASS

National Renewable Energy Laboratory | Golden, CO | $1.5M | F-PACE 1 | 09/2011–11/2014

NREL, Corning, Inc., and the Colorado School of Mines are developing highly efficient CdTe devices on flexible glass superstrates using high-temperature roll-to-roll processing. This approach combines the high deposition rates available in the existing CdTe manufacturing technologies with the throughput and capital equipment cost reductions offered by roll-to-roll processing and the balance-of-system savings enabled by flexible PV. The processing techniques explored here have the potential for efficiencies up to 18% and module costs below $0.50/W.

ENABLING THE CIGS THIN-FILM PV TECHNOLOGY TO MEET THE DOE GOAL OF $0.50/W MODULE PRICE

National Renewable Energy Laboratory | Golden, CO | $6.2M | F-PACE 1 | 09/2011–11/2014

This effort is providing near- and mid-term research to advance thin film competitiveness via improved module performance and reliability of thin film PV technologies. The project is enhancing the buffer and transparent conducting oxide layers and broadening the approach to processing copper indium gallium diselenide (CIGS) cells. Successful completion of this project would include demonstration by the industry partners of a greater than 16% efficient commercial module and a $0.23/W reduction in cost of module manufacturing through the efficiency improvements.

LOW COST BACK CONTACT HETEROJUNCTION SOLAR CELLS ON THIN CRYSTALLINE SILICON WAFERS: INTEGRATING LASER AND THIN FILM PROCESSING FOR IMPROVED MANUFACTURABILITY

University of Delaware | Newark, DE | $3.8M | F-PACE 1 | 09/2011–12/2014

This project aims to provide a pathway to $0.50/Wp modules using thin, kerfless, back-contacted, heterojunction silicon solar cells (IBC-SHJ). The proposed IBC-SHJ approach offers advantages over other high-efficiency silicon cell architectures, including compatibility with thin silicon wafers (<50 μm), by using low-temperature fabrication processes and a simplified laser-based manufacturing process that reduces the number of processing steps. By collaborating with IPG Photonics for laser processing and MIT for defect impact minimization, this award aims to fabricate a >20% efficient IBC-SHJ cell.

DEVELOPMENT OF LOW-COST, HIGH-EFFICIENCY, COMMERCIAL-READY, ADVANCED SILICON SOLAR CELLS

Georgia Institute of Technology | Atlanta, GA | $1.5M | F-PACE 1 | 09/2011–12/2014

The objective of this project is to raise the efficiency of three promising silicon technologies beyond 20%: conventional p-type crystalline Si (Czochralski and monocast), n-type Cz, and ~50 µm thick epitaxial Si. Efficiency gains will happen through four technology innovations: **1)** fine-line printing to reduce shadow losses; **2)** reduced contact losses to increase fill factor; **3)** improved surface passivation to lower surface recombination velocity; and **4)** improved back surface reflectance. These innovations will be addressed with industrially-relevant technologies, reducing time between bench-top validation and factory implementation.

CVD-BASED VALENCE-MENDING PASSIVATION FOR CRYSTALLINE SILICON SOLAR CELLS

Arizona State University | Tempe, AZ | $1.5M | F-PACE 1 | 09/2011–12/2014

This project combines innovative silicon surface passivation and all aluminum contacts to create a new processing path towards cost-effective >20% efficient crystalline silicon solar cells. The surface passivation enables lower contact resistance between the metal/silicon, allowing less metal to be used. Cost would be further reduced by replacing silver with aluminum. Silver is the typical contact material in silicon solar cells and it is the second most expensive input material in the cell. In addition, the surface passivation of grains in multi-crystalline silicon will be explored in hopes of increasing the efficiency of cells made on this substrate.

HIGH-EFFICIENCY III-V MULTI-JUNCTION SOLAR CELLS

National Renewable Energy Laboratory | Golden, CO | $6.9M | National Laboratory R&D | 10/2012–09/2015

This agreement integrates three parallel thrusts to create a 48% efficient four junction solar cell. First, process optimization will reduce electrically-active defects in and create a conductive buffer to the fourth junction. Second, degradation rates and the radiative interaction between junctions will be analyzed and quantified. Third, the fourth junction will be optimized for efficiency.

NEXT GENERATION SILICON PHOTOVOLTAICS

National Renewable Energy Laboratory | Golden, CO | $8.6M | National Laboratory R&D | 10/2012–09/2015

This project is geared towards producing high efficiency tandem solar cells based on silicon (Si) technology. There are two areas of focus: **1)** developing techniques to achieve high efficient single junction Si solar cells through contact passivation; and **2)** modeling and realization of novel III-V materials and processes for producing a 30% efficient silicon tandem solar cell. The production of a tandem Si solar cell has the possibility of moving towards two junction efficiencies with lowered costs.

CdTe TECHNOLOGY: UNDERSTANDING HOW DEFECTS IN CdTe LIMIT THE PERFORMANCE OF SOLAR CELLS

National Renewable Energy Laboratory | Golden, CO | $10.0M | National Laboratory R&D | 10/2012–09/2015

This project works to increase the open-circuit voltage and fill factor of CdTe solar cells. The approach is to examine single crystals grown by molecular beam epitaxy and polycrystalline CdTe films with different grain sizes to understand and increase carrier concentration and lifetime. Stoichiometry and doping are varied to influence lifetime and recombination by grain boundary type is studied.

CIGS TECHNOLOGY: OVERCOMING BARRIERS TO INCREASE EFFICIENCIES AND REDUCE COST

National Renewable Energy Laboratory | Golden, CO | $9.0M | National Laboratory R&D | 10/2012–09/2015

Research in this project addresses the scientific issues that need to be overcome for CIGS solar cells to be successful in volume manufacturing. To increase cell voltage and efficiency, work is being done on higher bandgap devices (1.15 eV to 1.4 eV) than typically used. To increase current without compromising junction quality or incurring metastable behavior, CdS is being replaced by more transparent ZnOS. In addition, absorber processing is being simplified by using a two-step approach where metal precursors are prepared by evaporation and selenized rapidly in selenium vapor at high temperature.

NEXT-GENERATION EARTH-ABUNDANT THIN FILM CZTS PHOTOVOLTAICS

National Renewable Energy Laboratory | Golden, CO | $6.9M | National Laboratory R&D | 10/2012–09/2015

Kesterites (i.e., "CZTS," $Cu_2ZnSnSxSe_{4-x}$, and related alloys) can contribute to SunShot goals by providing an earth-abundant, thin film alternative to CIGS and CdTe. However, a substantial increase in kesterite performance is needed, requiring a greater fundamental understanding of kesterite materials. CZTS work at NREL is aimed toward developing this basic understanding of defects and interfaces in the kesterite materials system and how to control them during film processing. Defects and interfaces are studied in a variety of systems, ranging from theoretical models to simplified experimental samples and geometries, and to the best device quality polycrystalline thin films.

THIN SILICON SOLAR CELLS: A PATH TO 35% SQ LIMITS

Arizona State University | Tempe, AZ | $3.4M | F-PACE 2 | 09/2013–09/2016

Arizona State University is leading a collaborative effort with the Massachusetts Institute of Technology, the California Institute of Technology, the University of New South Wales, and the Swiss Federal Institute of Technology to fabricate a novel device structure for ultra-thin crystalline silicon (c-Si) solar cells based on carrier selective contacts. A series of optical and material innovations will be developed that result in novel ultra-thin silicon solar cells with targeted efficiencies of 29%. If successful, such a cell using carrier selective contacts could approach the Shockley–Queisser (SQ) limit for silicon using a potentially commercializable device structure.

OVERCOMING THE FUNDAMENTAL BOTTLENECKS TO A NEW WORLD SILICON SOLAR CELL

Georgia Institute of Technology | Atlanta, GA | $3.5M | F-PACE 2 | 09/2013–09/2016

The Georgia Institute of Technology has partnered with the National Renewable Energy Laboratory and Fraunhofer ISE to drive crystalline silicon (c-Si) solar cell efficiency past 26.5% through a fundamental and applied research program. The team's approach includes strategies of passivated contacts via tunnel dielectrics, emitter optimization, and enhanced light trapping through the development of photonic crystals and a plasmonic backside reflector. These improvements will help realize efficiency improvements that could be incorporated into the existing silicon PV technologies that represent the majority of the current PV market.

DRIVING CZTS TO THE SQ LIMIT: SOLVING THE OPEN CIRCUIT VOLTAGE PROBLEM

IBM Thomas J. Watson Research Center | Yorktown Heights, NY | $4.4M | F-PACE 2 | 09/2013–09/2016

IBM is collaborating with the University of Delaware, the University of California in Santa Barbara, and Harvard University to address the open-circuit voltage deficit of copper zinc tin selenide (CZTS) technology through a model single crystal-based approach. This work will drive voltage and efficiency improvements toward the Shockley-Queisser (SQ) limit with targeted device efficiencies exceeding 18%. Achievement of the goals of this project would enable a system that uses relatively abundant material inputs with high performance and potentially low cost.

APPROACHING THE SHOCKLEY-QUEISSER LIMIT WITH EPITAXIAL CdTe

National Renewable Energy Laboratory | Golden, CO | $4.5M | F-PACE 2 | 09/2013–09/2016

NREL, in collaboration with First Solar, Texas State University, Colorado State University, the Colorado School of Mines, and Washington State University, is using epitaxial cadmium telluride (CdTe) films grown by molecular beam epitaxy (MBE) to reach power conversion efficiencies greater than 24%. While traditional CdTe cells use a polycrystalline CdTe layer, this project will probe the limits for CdTe PV using epitaxial materials on single-crystal substrates to develop a model CdTe cell. The insight provided in these investigations has the potential to advance the polycrystalline CdTe industry though a better understanding of interfaces, critical defects, surface passivation, and doping strategies for CdTe devices.

Cross-Cutting Photovoltaics Efforts

This activity area includes projects that focus on characterization and/or testing of PV cells and modules through National Renewable Energy Laboratory R&D and the BRIDGE program, as well as reliability through the PREDICTS program. In addition, it includes core funding at NREL to support facilities, external partnerships and other cross-cutting needs. The QESST center, which houses a wide range of research from early-stage PV through manufacturing, and the SERIIUS partnership are also in this area.

QUANTUM ENERGY AND SUSTAINABLE SOLAR TECHNOLOGIES ENGINEERING RESEARCH CENTER (QESST ERC)

Arizona State University and Partners | $6.0M | 05/2011–05/2016

A joint research center of the DOE and National Science Foundation (NSF), QESST is committed to research that spans the three leading commercial PV technologies: silicon, thin films, and tandem devices, while blurring the traditional lines between technologies by recognizing and exploiting their commonalities. This research is organized into three complementary thrusts—Terawatt Manufacturing, Moore's Law Devices, and Advanced Enablers—and two demonstrative testbeds—Student-Led Pilot Line and Integration, Modules and Power Management. In addition, two themes—Sustainability and Education Research—permeate all areas of QESST research. QESST has 10 academic partners in the U.S. and around the world, and 48 industrial partners that span manufacturing, materials, production and installation of solar technologies.

SOLAR ENERGY RESEARCH INSTITUTE FOR INDIA AND THE UNITED STATES (SERIIUS)

National Renewable Energy Laboratory | Golden, CO | $6.7M | 10/2011–09/2016

The Solar Energy Research Institute for India and the United States (SERIIUS) creates a bi-national network for fostering new ideas and collaborations to expedite a sustainable industry. SERIIUS is a joint effort between NREL and the Indian Institute of Science in Bangalore to address critical barriers for solar energy development in India that intersect the grand challenges for solar energy in the U.S. SERIIUS has three research thrusts: **1)** Sustainable Photovoltaics, which aims to develop next-generation materials, devices, and advanced manufacturing processes tailored to the needs, environment, and resource availability of India and the U.S.; **2)** Multiscale Concentrated Solar Power, which aims to overcome critical science and engineering challenges for reliable multiscale (including small 25–500 kW) CSP systems; and **3)** Solar Energy Integration, which aims to identify and assess key technical, economic, environmental, and policy barriers, enabling a research agenda for technical readiness in India and to benefit the United States.

PV PARTNERING AND BUSINESS DEVELOPMENT AGREEMENT

National Renewable Energy Laboratory | Golden, CO | $12.0M | National Laboratory R&D | 10/2012–09/2015

The primary goal for this agreement is to expand NREL's high-impact, collaborative partnerships with industry and academia in activities that exploit complementary capabilities and support the SunShot goals. There are two distinct partnering modes: non-proprietary partnering opportunities, which aim to publish the research outcomes in prominent journals, and proprietary

partnering opportunities, which aim to develop intellectual property that will increase the speed of product commercialization and expand the scale of PV deployment. Additional outreach activities focus on workforce development opportunities for graduate students and postdocs.

NATIONAL CENTER FOR PHOTOVOLTAICS CORE (NCPV) R&D SUPPORT

National Renewable Energy Laboratory | Golden, CO | $14.2M | National Laboratory R&D | 10/2012–09/2015

This agreement provides cross-cutting support required by the core R&D agreements that make up the other PV laboratory agreements. Specifically, this agreement funds infrastructure support teams (Engineering & Informatics) and basic maintenance and limited enhancement of cross-cutting capabilities (Measurement & Characterization and Device Processing). The direct funding of these cross-cutting activities through this agreement allows for more efficient management, increased flexibility in response to changes in program needs, and aids in ensuring that these crucial activities and capabilities are sustainably maintained as core competencies within the National Center for Photovoltaics.

NCPV DIRECTOR'S INITIATIVE AND CAP-EX

National Renewable Energy Laboratory | Golden, CO | $5.2M | National Laboratory R&D | 10/2012–09/2015

The National Center for Photovoltaics (NCPV) Director's Initiative was established in fiscal year 2011 as a vehicle for funding small R&D projects, unplanned laboratory equipment purchases, and other PV-related initiatives at the discretion of the NCPV Director. The funds have been used to catalyze high-risk research by making modest enhancements to R&D capabilities through equipment purchases as well as providing seed money for strategic hires. The Cap-Ex funds ($4.5 million) are also allocated by the NCPV Director to support the greatest needs of NCPV.

CELL AND MODULE PERFORMANCE

National Renewable Energy Laboratory | Golden, CO | $8.1M | National Laboratory R&D | 10/2012–09/2015

This agreement supports the independent evaluation of cell and module contract deliverables, providing the U.S. PV industry with accurate and independent efficiency measurements and calibrations for all PV technologies and material systems. This partnership allows the DOE Solar Program to fairly evaluate atypical cells in cases when the data are impacted by artifacts such as metastability, spurious photocurrents, bias rate, nonlinearity, and other issues such as contacting and area definitions. The NREL team supports commercial testing and module qualification labs by providing required ISO 17025-accredited calibrations. The team also supports domestic and international PV cell and module standards development.

OVERCOMING SPATIAL, ENERGY, AND TEMPORAL LIMITS IN CHARACTERIZATION OF THE ELECTRONIC, OPTICAL, AND STRUCTURAL PROPERTIES OF PV MATERIALS

National Renewable Energy Laboratory | Golden, CO | $3.5M | National Laboratory R&D | 10/2012–09/2015

This agreement pushes the limits of measurement techniques useful for PV materials. The focus is on two electrical techniques, admittance spectroscopy / deep-level transient spectroscopy (AS/DLTS) and scanning capacitance microscopy, as well as two optical techniques, two-photon time resolved photoluminescence and tip-enhanced Raman scattering. Developing these advanced measurement techniques and capabilities will further knowledge of how material structure impacts PV device performance.

DEVELOPING SPECTROSCOPIC PHOTOEMISSION ELECTRON MICROSCOPY (PEEM) FOR IMAGING NANOSCALE VARIATIONS IN THE CHEMICAL AND ELECTRONIC STRUCTURE OF THIN FILM MATERIALS

Sandia National Laboratories | Albuquerque, NM | $0.3M | BRIDGE | 11/2012–11/2015

Spectroscopic photoemission electron microscopy (spec-PEEM) enables real-time imaging of PV materials and devices with unprecedented nanoscale (5-10 nm) sensitivity to chemical and electronic properties. Current microscopes do not have sufficient or concurrent spatial, spectral, temporal or contrast capabilities to image these nanoscale properties.

IN-SITU X-RAY ANALYSIS OF RAPID THERMAL PROCESSING FOR THIN-FILM SOLAR CELLS: CLOSING THE GAP BETWEEN PRODUCTION AND LABORATORY EFFICIENCY

SLAC National Accelerator Laboratory | Menlo Park, CA | $0.9M | BRIDGE | 11/2012–11/2015

This project seeks to develop a rapid-thermal-processing / X-ray-diffraction and fluorescence facility (RTP/XRD-F) for *in-situ,* real-time investigations of the structural and chemical evolution of PV materials from the initial precursors to final products. It will enable better processing steps to yield higher efficiency, less expensive devices and will be used for $Cu(InGa)Se_2$ (CIGS), Cu_2ZnSnS_4 (CZTS), In-free transparent conducting oxides, and metal contacts to Si cells.

THREE-DIMENSIONAL MINORITY CARRIER LIFETIME MAPPING OF THIN FILM SEMICONDUCTORS FOR SOLAR CELL APPLICATIONS

Plant PV, Inc. | Berkeley, CA | $0.45M | BRIDGE | 11/2012–11/2015

This project seeks to address the difficulty of accurately measuring bulk minority carrier lifetimes in novel semiconductor materials for thin film PV cells. Plant PV is developing a two-photon lifetime tomography technique to separate bulk minority carrier lifetime from surface recombination effects. This technique will enable rapid screening of PV materials by avoiding the need to construct full devices. This project will also develop three-dimensional minority carrier lifetime and charge collection efficiency maps that will be useful in identifying efficiency bottlenecks for new and conventional (e.g., CdTe, CIGS) thin film PV materials.

HOW GRAIN BOUNDARIES AFFECT THE EFFICIENCY OF POLY-CdTe SOLAR CELLS: A FUNDAMENTAL ATOMIC-SCALE STUDY OF GRAIN BOUNDARY DISLOCATION CORES USING CdTe BI-CRYSTAL THIN FILMS

University of Illinois | Chicago, IL | $0.90M | BRIDGE | 11/2012–11/2015

This team is developing a fundamental understanding of the role of grain boundaries on the minority carrier lifetime and V_{oc} in CdTe thin films by **1)** fabricating epitaxial CdTe thin films on b-crystal substrates with well-defined grain boundary structures; **2)** studying the atomic and electronic structures of the grain boundary dislocation cores and interfacial transport properties; and **3)** performing first-principles calculations to determine the density of mid-gap states and find potential passivants.

NOVEL PHOTON MANAGEMENT FOR THIN-FILM PV

University of Utah | Salt Lake City, UT | $0.45M | BRIDGE | 11/2012–11/2015

The objective of this project is to enable commercially viable thin film PVs with efficiencies greater than 20% using a novel optical spectral-separation technique at costs below current technologies. The team is developing processes for cost-effective manufacturing of integrated arrays of PV cells, for manufacturing polychromats in glass and for packaging the entire device.

IN-SITU X-RAY NANOCHARACTERIZATION OF DEFECT KINETICS IN SOLAR CELL MATERIALS

Arizona State University | Tempe, AZ | $0.85M | BRIDGE | 12/2012–12/2015

This collaborative research team is addressing the non-radiative recombination that limits the open circuit voltage of $Cu(In,Ga)Se_2$. The team is utilizing *in-situ* synchrotron-based nano-X-ray fluorescence microscopy (nano-XRF), and x-ray absorption nanospectroscopy (nano-XAS) coupled with nano-x-ray beam induced current (nano-XBIC) to understand the mechanisms that govern the electronic activity at grain boundaries and dislocations in CIGS absorber layers under operating, processing and growth conditions.

UNIFIED NUMERICAL SOLVER FOR DEVICE METASTABILITIES IN CdTe THIN-FILM PV

Arizona State University | Tempe, AZ | $1.4M | PREDICTS | 09/2013–09/2016

ASU, in collaboration with First Solar, Colorado State University, and NREL, is developing a tool to study the fundamentals behind the performance and metastabilities of CdTe thin film PVs. The core of the solution will be a multi-level solver that combines macroscopic diffusion-reaction equations describing subsystems of point defects combined with the global Poisson equation. This will form a closed system that can be solved in time domain and quasi-3D space utilizing cylindrical grains.

COUPLED THERMO-MECHANICAL AND PHOTO-CHEMICAL DEGRADATION MECHANISMS THAT DETERMINE RELIABILITY AND OPERATIONAL LIFETIMES FOR CPV TECHNOLOGIES

Stanford University | Stanford, CA | $1.1M | PREDICTS | 09/2013–09/2016

Stanford, in collaboration with NREL and Spectrolab, is investigating coupled intrinsic thermo-mechanical and photo-chemical degradation mechanisms that determine the reliability and operational lifetimes for concentrated photovoltaic (CPV) technologies. The research approach will result in quantitative metrologies to characterize degradation processes during PV operation, detailed kinetic models of degradation mechanisms, and reliability benchmarking of materials and interfaces in CPV devices and modules. The approach is based on fundamental materials science and reliability physics and development of accelerated testing protocols for more accurate lifetime predictions.