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PROGRESS OF THE PHOTOVOLTAIC TECHNOLOGY INCUBATOR PROJECT TOWARDS AN ENHANCED U.S. MANUFACTURING BASE

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ABSTRACT

In this paper, we report on the major accomplishments of the U.S. Department of Energy's (DOE) Solar Energy Technologies Program (SETP) Photovoltaic (PV) Technology Incubator project. The Incubator project facilitates a company's transition from developing a solar cell or PV module prototype to pilot- and large-scale U.S. manufacturing. The project targets small businesses that have demonstrated proof-of-concept devices or processes in the laboratory. Their success supports U.S. Secretary of Energy Steven Chu's SunShot Initiative, which seeks to achieve PV technologies that are cost-competitive without subsidies at large scale with fossil-based energy sources by the end of this decade. The Incubator Project has enhanced U.S. PV manufacturing capacity and created more than 1200 clean energy jobs, resulting in an increase in American economic competitiveness. The investment raised to date by these PV Incubator companies as a result of DOE's $ 59 million investment totals nearly $ 1.3 billion.

INTRODUCTION

The DOE's SETP PV Technology Incubator project facilitates a company's transition from developing a solar cell or PV module prototype to pilot- and large-scale U.S. manufacturing. The primary objective of the PV Incubator project is to accelerate the development of cutting-edge, state-of-the art disruptive and high-impact PV technologies. DOE funds this research through the National Renewable Energy Laboratory (NREL). The project targets small businesses that have demonstrated proof-of-concept devices or processes in the laboratory.

Companies are selected through competitive awards to receive funding and technical support to overcome barriers in the path to commercialization and market acceptance. After 18 months of research activities, a successful project is expected to have a commercially viable PV product and be capable of pilot-scale manufacturing with processes that are representative of, or feasible to implement in, large-scale commercial manufacturing. It is anticipated that these emerging PV companies will begin entry into the market in the next one to two years. Their success supports U.S. Secretary of Energy Steven Chu's SunShot Initiative, which seeks to achieve PV technologies that are cost-competitive without subsidies at large scale with fossil-based energy sources by the end of this decade. This will increase American economic competitiveness and enhance U.S. PV manufacturing capacity, which will result in high-tech jobs and help the United States gain global leadership in the PV technology market. An overview of the PV Technology Incubator projects is presented in the following along with scientific highlights of the small businesses and their success stories.

HIGHLIGHTS OF PV TECHNOLOGY INCUBATOR PROJECTS

SETP is funding a wide range of PV technologies that will lead to numerous potential applications in various markets. SETP's primary goals with respect to PV technology are: 1) foster innovative research and development (R&D) efforts that will support the SunShot Initiative and 2) ensure that PV technologies achieve sufficient market penetration to facilitate expansion of the U.S.-based solar industry.

A further goal of the PV Technology Incubator project is to shorten the timeline for small businesses to transition PV technologies into pilot- and large-scale manufacturing. The PV Technology Incubator project targets innovative R&D on solar cell and PV module prototypes and emphasizes activities focused on the technical barriers to manufacturing scale-up and commercialization in the next one to two years. It also provides significant opportunities for collaboration between NREL engineers and scientists and the U.S. PV industry to develop and improve potentially disruptive and high-impact solar energy technologies. Companies selected are diverse and able to meet the objectives established by SETP. This phase of the PV technology development pipeline targets solar cells and prototype power modules. The ultimate goals of the project are to achieve more efficient use of materials, better performance, and higher product reliability, all of which will lower costs and improve manufacturing processes.

The most recent PV Technology Incubator project initiative is composed of two parts: Tier 1 (formerly known as Pre-Incubator) and Tier 2 (formerly known as Incubator). The four awardees in the 2010 solicitation are shown in Table 1. These awards are expected to be completed in the summer of 2011. The Tier 2 small business awardees will then participate in stage gate reviews in late 2011, nine months after the subcontract award.

Table 1 Subcontractors Selected in Response to the 2010 PV Technology Incubator Solicitation

Subcontractor	Project Description
Crystal Solar (Tier 2)	Crystal Solar is developing a new PV technology for the fabrication, handling, processing, and packaging of very thin single-crystal silicon wafers (three times thinner than standard cells). This solution uses much less silicon, eliminates many of the wasteful and expensive wafer processing steps, and addresses the problem of handling very thin silicon wafers.
Caelux (Tier 1)	Caelux is developing a flexible solar cell manufacturing process and design that minimizes the amount of semiconducting material used. This has the potential to significantly improve device efficiency while dramatically reducing production costs.
Solexant (Tier 1)	Solexant is developing a new thin-film material from substances that are non-toxic and not rare. These solar cells will be constructed with a nanoparticle ink that can be printed and will result in commercially viable solar cell efficiencies using scalable, low-cost processes.
Stion (Tier 1)	Stion is developing a thin-film technology that will allow two high-efficiency thin-film solar devices to be stacked, allowing for much better absorption of light and power generation. The device is constructed in a way that significantly reduces cost, simplifies manufacturing, and reduces materials utilization over traditional designs.

MAJOR ACCOMPLISHMENTS OF ROUNDS 1 AND 2 OF THE PV TECHNOLOGY INCUBATOR SUBCONTRACTS

Abound Solar has developed a low-cost, high-throughput approach to fabricating high-efficiency thin-film CdTe power modules. The company has an installed manufacturing capacity of ~64 MW in Colorado, with plans to expand to 200 MW by 2012. The company's thin-film CdTe modules have passed IEC and UL certification. Several installations have been deployed in the United States and Europe. Abound Solar has won a DOE loan guarantee program for $400 million.

CaliSolar has developed new processes and metallization techniques for the production of high-efficiency multicrystalline solar cells using upgraded metallurgical-grade silicon and new production-suitable cell contact metallization techniques. The company reduced the bulk carrier lifetime and optimized the front and rear contact grid structures for upgraded metallurgical silicon cells and then demonstrated 17% solar cell efficiencies based on these processes. CaliSolar is now producing 75 MW of multicrystalline solar cells at "an average efficiency of 14.5% at the end of the project, exceeding 16.5% now" in their California factory.

PrimeStar Solar, a wholly owned subsidiary of General Electric (GE), has installed a low-cost, high-efficiency thin-film CdTe module manufacturing line (30 MW) in Colorado. The company has achieved a 12.8% aperture-area efficiency, independently verified by NREL. This surpasses all previously reported records for thin-film CdTe modules. The modules use a glass-on-glass construction and are currently undergoing reliability testing to validate long-term performance. GE has major expansion plans for a 400-MW thin-film CdTe module manufacturing plant in the United States and has already received orders for over 100 MW of their thin-film CdTe products.

SoloPower has developed a high-efficiency, low-cost, roll-to-roll electroplating-based CIGS cell and module manufacturing technology. Progress was demonstrated in the fabrication of both 12%-efficient, 100-cm^2 cells fabricated with the roll-to-roll reaction process and the achievement of a 10%-efficient aperture area 1-m^2 module with these CIGS cells. SoloPower has continued to build on this success and is now at >1 MW of production using this roll-to-roll electroplating-based CIGS technology. SoloPower recently won a DOE loan guarantee program for $200 million.

SolFocus has developed a 500X concentrating photovoltaic (CPV) module with a folded reflective design in a compact frame. The company has developed a new reflective optics panel and made substantial testing and reliability improvements. These optimizations resulted in performance improvements, raised the module efficiency from 17% to over 25%, automated module assembly, and improved manufacturability. Work on accelerated testing led to the identification of sources for improved reliability. These successes have accelerated the development of SolFocus' flagship CPV module, the SF1100, from prototype to commercial product. This commercialized product has passed certification milestones and has resulted in signed contracts of more than 10 MW of the product for worldwide deployment.

1366 Technologies has established that texturing of commercial multicrystalline wafers using its "patterning method" can be done on a commercial scale and that metallization can be done on a pilot scale. Most metallization benefits are attributed to finger grid lines, which result in less shadowing, rather than to the nature of the emitter. 1366 promised the development of <50-micron-wide grid lines for commercial multicrystalline silicon wafers. Cross-sections showed that 30 to 35-micron-wide gridlines were achieved. 1366 reported that the efficiency improvements observed for the self-aligned cell depend on other factors such as wafer quality and back contacts. NREL has verified a total-area conversion efficiency of 18.0% for this silicon solar cell.

Spire Semiconductor has developed multijunction GaAs-based CPV cells that have achieved a world-record efficiency at ~500X concentration in a structure that both delivers reliable performance and can be manufactured at low cost. The triple-junction device structure consists of InGaP/GaAs/InGaAs, with corresponding bandgaps of 1.9 eV, 1.42 eV, and 0.94 eV, respectively. Spire has delivered three 1-cm^2 multijunction GaAs-based CPV cells with conversion efficiencies in the range of 40.8% to 42.2% (1 cm^2 area) at 500X concentration, independently verified by NREL. Spire has demonstrated stable performance of their CPV multijunction cells at 165°C after 2,000 hours of continuous testing. The company is also collaborating with CPV system integrators to incorporate the Spire CPV multijunction cells in a system configuration.

Innovalight has developed high-throughput cell printing technologies for selective emitters using their "Silicon Ink" technology with optimized sintering, metallic contact grids, and front-surface texturization processes to achieve a 1% absolute increase in monocrystalline silicon cell efficiencies. Using standard production line processes, 125 mm x 125 mm cells with Silicon Ink selective emitters produced 17%-efficient multicrystalline silicon cells and 18.5%-efficient monocrystalline silicon cells under this subcontract. Production rates in Innovalight's facilities were increased to 300 wafers/hour for patterning with an industrial ink-jet printer and 1,500 wafers/hour for patterning with an industrial screen printer.

Solexel's monocrystalline silicon solar cells are grown on and harvested from a crystalline silicon template that can be reused numerous times to yield many thin-film silicon substrates (TFSS) processed into solar cells. Solexel has demonstrated 44 successful TFSS releases from a single template and has also achieved an NREL-verified conversion efficiency of 14.4% on 156 mm x 156 mm TFSS solar cells. Solexel aims to reduce the TFSS thickness to 30 µm or less, which constitutes a significant reduction in the amount of material required for typical silicon solar cells.

MAJOR ACCOMPLISHMENTS OF ROUND 3 OF THE PV TECHNOLOGY INCUBATOR SUBCONTRACTS

Alta Devices is focused on improving the production economics of high-efficiency solar PV applications. The unique Alta cell/module architecture employs front and back contacts with minimal efficiency loss, antireflection coatings, and optimized cell geometry and matrix interconnect schemes. Progress to date includes an NREL verified thin-film sub-module efficiency of 20%.

Solar Junction is working toward the development of InGaAs/GaAs/GaInNAs triple-junction cells using high-quality dilute nitride compounds with tunable bandgaps of 0.8 to 1.4 eV. Efforts have focused on developing each of the individual cell structures and tunnel-junction resistivity. Successes include demonstrating a 5.5 mm x 5.5 mm cell performance capability for: InGaP cells with V_{oc} = 2.0V at 500-suns; GaAs cells with J_{sc} = 14.8 mA/cm^2 (goal was 13.5 mA/cm^2); and GaInNAs sub-cells with a V_{oc} = 0.62 V_{oc} (goal was 0.55 V_{oc}). This progress has resulted in an NREL-verified world-record efficiency for these integrated lattice-matched triple-junction cells of η = 43.5% at greater than 400X, and the cells still maintained an efficiency as high as 43% out to 1,000X.

TetraSun is developing thin high-efficiency crystalline-silicon solar cells using a modified back-surface passivation and contact as a replacement for the standard screen print and fire aluminum/silver back surface. This structure offers an alternative to the standard industry back-surface aluminum process to eliminate wafer bowing and also allows thinner cells (<160 µm). Using inexpensive Cu for metallization is expected to result in lower-cost crystalline silicon solar cells. The increased voltage results in an improved temperature coefficient of -0.35%/K. Progress to date has demonstrated an 18.0%-efficient 148-cm^2 crystalline silicon cell with V_{oc} = 0.665 V, I_{sc} = 5.218 A, and FF = 77.1% (goal was η = 17.5%).

Semprius develops micro-cell-based high-performance, low-cost high-concentration photovoltaic (HCPV) modules via GaAs substrate re-use, short optical path, >1,000X concentration, plano-convex silicone-on-glass primary and glass ball lens secondary optics and zero-cost thermal management (<85^{o}C cell temperature at 1,000X). The transfer-printed, micro-cell-based approach enables massively parallel manufacturing of module arrays using standard techniques from the microelectronics and opto-electronics industries. The company targets a very low levelized cost of energy, competitive with fossil fuels, when in high-volume production.

MAJOR ACCOMPLISHMENTS OF ROUND 1 OF THE PV TECHNOLOGY PRE-INCUBATOR SUBCONTRACTS

1366 Technologies has developed initial proof of concept for a new process to grow kerfless silicon wafers directly from melt, thereby reducing the high cost and waste associated with wire sawing and enabling silicon-based PV technology to achieve a module cost well below $1/W. Initial experiments growing kerfless tin wafers were used as a baseline demonstration and guided development of the final kerfless silicon wafer process. 1366 built custom equipment to validate the process in silicon, then developed sufficient understanding of the underlying physics to successfully fabricate 200-micron-thick silicon wafers. These initial 50 mm x 50 mm silicon wafers were used to make prototype solar cells via standard industrial processing, and more recently 1366 has begun producing the industry-standard 156 mm x 156 mm silicon wafers.

Ascent Solar Technologies focused on the use of metal-oxide window layers to replace CdS and allow for an increase in the CIGS absorber layer bandgap from traditional 1.15 eV to >1.35 eV. This approach has the potential to overcome performance-limiting aspects of conventional CIGS solar cells, particularly in the building integrated photovoltaic (BIPV) market. The project was successfully completed with the demonstration of CdS-free CIGS devices with E_g > 1.35 eV, area≥ 1cm ^{2} and efficiency > 11%.

Banyan Energy focused on improving the performance, manufacturability, and economic viability of low-profile waveguide optics to serve the utility silicon PV industry. Banyan has built and demonstrated the world's first Aggregated Total Internal Reflection (ATIR) solar modules. The 7X prototype concentrator optic had a measured optical efficiency greater than 84% and a measured misalignment tolerance greater than ±3°. Beyond demonstrating the superior performance of an entirely new type of concentrator optic, a scalable module design for production was implemented and demonstrated.

Crystal Solar has developed the integration of very thin (~50 μm) single-crystal silicon wafers with non-silicon (ceramic) substrates for silicon solar cell fabrication. Ceramics with a coefficient of thermal expansion (CTE) matched to silicon were synthesized, and a novel technique for dispensing the ceramic paste precursors in a pre-determined pattern onto the silicon films was developed. Additionally, a process to form porous silicon films was also developed, which results in the separation of the silicon epi-layer from the monocrystalline silicon wafer on which it is grown. A solar cell fabrication process was developed using these wafers and a total area solar cell efficiency of 8.0% on 125 mm x 125 mm was independently verified by NREL.

EPIR Technologies worked on the growth of high-quality single-crystal CdTe cells on silicon substrates as an alternative to existing multijunction cell architectures that offers benefits in material cost at competitive efficiencies. EPIR has demonstrated the ability to grow large-area, high-quality, epitaxial CdTe with minority carrier lifetimes > 100 ns. In addition, high p-type doping levels have been reproducibly achieved, with N_a>1e^{17} cm^{-3}, sufficient for c-CdTe absorber layers.

Lightwave Power (LWP) and Iowa State University (ISU) developed a new photonic hexagonal lattice design using a scattering matrix method to increase light absorption in thin films of silicon. New polymers were developed for nano-imprinting the photonic design, and these polymers were printed onto a flexible kapton substrate. Tandem-junction a-Si/uc-Si solar cells were deposited on the nano-imprinted photonic flexible plastic substrates at ISU and a total-area conversion efficiency of 7.6% was achieved for the tandem junction a-Si/uc-Si solar cell, independently verified at NREL. Several potentially patentable new device designs were developed at LWP and ISU as a result of these research activities.

Luna Innovations worked on the development of an organic photovoltaic (OPV) device based on a C80 metallo-fullerene isomer rather than the more standard C60 PCBM. This project combines the C80 acceptor and high-performance Plextronics donor polymers in an attempt to achieve a level of tunability (absent from the standard C60 fullerene) that can potentially improve device performance through the optimization of band alignments. Luna demonstrated a 4.9%-efficient C_{80}-based device and, separately, demonstrated a 40% increase in open circuit voltage relative to standard C_{60}-based devices.

MicroLink Devices has developed triple-junction devices fabricated by wafer-bonding a dual-junction InGaP/GaAs cell with a Ge single-junction cell. This work is the foundation for moving to >4-junction devices once the wafer bonding process has been optimized. The combination of wafer bonding and epitaxial lift-off (ELO) may reduce the cost of multijunction solar cells and avoids long metalorganic chemical vapor deposition (MOCVD) growth runs. The company achieved 0.32-cm^2 triple-junction InGaP/GaAs/Ge wafer-bonded cells with 25% efficiency at one-sun (NREL verified) and further improved to 29.7% efficiency at one-sun in January 2011.

SpectraWatt worked on using low-cost films composed of absorbing and emitting nanomaterials in order to improve the spectral response of solar cells without interfering with the behavior of the platform device. As the added layer is not part of the active electrical device architecture, this coating approach is potentially applicable to all PV technologies. Additionally, this approach allows for relaxed design rules for the underlying cell structure. A 0.5% absolute efficiency increase of factory-quality CIGS mini-modules was reproducibly demonstrated.

FUTURE PLANS

This phase of the PV technology development pipeline targets solar cells and prototype power modules. However, the success of this project has warranted the creation of the SunShot Incubator Project which will encompass concentrating solar power and balance of system innovations. The ultimate goals of the project are to achieve more efficient use of materials, better performance, and higher product reliability, all of which will lower costs and improve manufacturing processes.

SUMMARY

The PV Technology Incubator Project has enhanced U.S. PV manufacturing capacity and created over 1200 clean energy jobs, resulting in an increase in American economic competitiveness. Additionally, thousands of clean tech jobs are expected to be created in the next several years. The PV capacity potential expected from these small start ups is 100's to 1000's of MWs in the United States. The investment raised to date by these PV Incubator companies as a result of DOE's $ 59 million investment total nearly $ 1.3 billion. The small start-ups fostered by these innovative research activities are contributing toward U.S. global leadership in the market for solar photovoltaic technologies.

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