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Identifying Critical Pathways to High Performance PV

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IDENTIFYING CRITICAL PATHWAYS TO HIGH PERFORMANCE PV

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ABSTRACT

The High-Performance Photovoltaic (HiPerf PV)Project was initiated by the U.S. Department of Energy to substantially increase the viability of photovoltaics (PV) for cost-competitive applications so that PV can contribute significantly to our energy supply and our environment in the 21st century. To accomplish this, the NCPV directs in-house and subcontracted research in high-performance polycrystalline thin-film and multijunction concentrator devices. Details of the subcontractor and in-house progress will be described toward identifying critical pathways of 25% polycrystalline thin-film tandem cells and developing multijunction concentrator modules to 33%.

INTRODUCTION

The HiPerf PV Project aims at exploring the ultimate performance limits of existing PV technologies, approximately doubling their sunlight-to-electricity conversion efficiencies during its course. This work includes bringing thin-film tandem cells and modules toward 25% and 20% efficiencies, respectively; and developing multijunction pre-commercial concentrator modules able to convert more than one-third of the sun's energy to electricity (i.e., 33% efficiency).

The project consists of three phases that focus on a specific approach to solving the challenges associated with high efficiencies. Phase I, "Identifying Critical Paths," seeks to identify problems, approaches, and alliances. The first HiPerf PV subcontract solicitation [1] completed in 2000 allows the NCPV to provide 2 years of funding to top-ranked companies and universities.

The in-house portion of HiPerf PV is coordinated through three teams. The High Performance Thin-Film Team leads the investigation of tandem structures and low-flux concentrators. The High Efficiency Concepts and Concentrators Team was expanded to lead high-flux concentrator development. The Thin-Film Process Integration Team, will perform fundamental process and characterization research, working toward resolving the complex issues of making thin-film multijunction devices successfully.

The HiPerf PV Project investigates a wide range of complex issues and provides initial modeling and baseline experiments of several advanced concepts to clarify the challenges and identify critical paths for the longer-term development and application of high-performance PV technologies. The first phase is critical as it provides a means to accelerating towards the most promising paths for implementation, followed by commercial-prototype products. These latter efforts constitute the second and third phases of this planned research program. Throughout the life of the project, both revolutionary technology change and multiple incremental improvements will be given their due. During the project period, the alignment of paths, toward established targets and extensive collaboration should produce significant contributions to the entire PV industry.

PROJECT GOALS AND OBJECTIVES

The HiPerf PV Project is expected to enable progress of high-efficiency technologies towards commercial-prototype products. Table 1 summarizes the near-term key targets for the HiPerf PV Project. These project targets are based on schedules of Phase I awards and planned completion dates of the new Science and Technology Facility.

Near-Term Key Targets	Date
T1. Demonstrate a 20% Efficiency Thin-Film Cell under Low Concentration (Completed)	2001
T2. Identify Key Issues and Pathways to Achieving a 25% Polycrystalline Thin-Film Tandem Cell	2003
T3. Identify Key Issues and Pathways to Achieving a 33% Prototype Concentrator Module	2003
T4. Establish Diagnostic Development Workgroup Towards Implementation of Thin-Film Process Integration	2003
T5. Develop Consensus Spectrum Standard for Measuring Multi-junction Concentrator Cells	2003
T6. Demonstrate a multi-junction 34% Cell under Concentration	2004
T7. Fabricate a Polycrystalline Thin-Film Tandem Cell of 15% Efficiency	2004
T8. Full Implementation of Thin-Film Process Integration	2006

Table 1. Near-Term High Performance PV Project Targets

With regard to Target 2 of Table 1, we are focusing on the development of a wide-band gap top cell with at least 15% efficiency, optical band gap in the range $1.6 \leq E_g \leq 1.8$ eV, and minimal sub-band gap absorption. The wide band gap cell must be identified and developed in advance of other critical issues because the rest of the tandem device structure and processing will be determined largely by the choice of this cell. However, the design structure in terms of monolithical integration or mechanical stacking cannot be disregarded while identifying critical issues.

Recent work by Coutts *et al*.[2] modeling state-of-the–art thin-film devices demonstrates that a current-matched 28% efficient tandem is possible with a top-cell absorber of 1.7 eV and a bottom-cell absorber of 1.1 eV. The calculations are based on assuming that all interfaces are specular, there is no interdiffusion and the top p-type absorber is chalcopyrite.

For Target 3 listed in Table 1, we are investigating device design and development of monolithic, wafer-bonded, and mechanical stacked structures on different substrates. Additionally, PV concentrator receiver design issues are being addressed, and the design spectrum for spectra are being revisited for appropriate measurement conditions of these multijunction concentrator cells. Recently, three-junction GaInP/GaAs/Ge cell grown by Spectrolab was measured under concentration, and, using the AM1.5 global reference spectrum to have an efficiency of 34%. If a fourth junction, with a band gap of about 1 eV, is added to this structure to make a GaInP/GaAs/?/Ge cell, the theoretical efficiency is more than 50%. In the past, world-record efficiencies have reached 80% to 90% of theoretical efficiencies, implying that a four-junction concentrator cell will surpass 40% efficiency if the appropriate material systems can be identified.

SUBCONTRACTOR R&D

Ten of eleven awards are completed, and, we are well into Phase I of Identifying Critical Pathways. The in-house and subcontracted research activities are beginning to work closely together toward achieving project goals. The majority of the subcontracts have scheduled deliverables to NREL for the specific purpose of collaborating with the in-house teams. Table 2 lists the subcontracts currently active in Phase I, beginning with the polycrystalline thin-film awards, followed by the multi-junction concentrator awards, followed by a description of R&D progress by each subcontractor.

Subcontractor	Title
*Astropower	InGaP/GaAs-on-Ceramic Thin-Film Monolithically Interconnected, Large Area, Tandem Solar Cell Array
University of Delaware	Thin Film Multijunction Solar Cells: Development of a High-Bandgap Cell
University of Toledo	Polycrystalline Thin-Film Tandem Photovoltaic Cells
University of South Florida	Development of a II-VI-Based High Performance, High Band Gap Device for Thin-Film Tandem Solar Cells
University of Florida	Identification of Critical Paths in the Manufacturing of Low-Cost High-Efficiency CGS/CIS Two-Junction Tandem Cells
Global Solar	Progress Toward 20% Efficient $CuIn_xGa_{1-x}Se_2$ Photovoltaic Devices on Foil Substrates
University of Illinois	$Cu(In,Ga)Se_2$ Heterojunction Solar Cells for Extreme High-Efficiency Photovoltaic Concentrators
Entech, Inc.	Near-Term Integration of III-V Cells Operating at 440X, Into Entech's Field-Proven Concentrator Module
SunPower Corporation	Lens-Based Concentrator Modules: Exploring Critical Optical and System Integration Issues
Spectrolab, Inc.	High Efficiency, Low-Cost, III-V Concentrator PV Cell & Receiver Module
Emcore	A Three-Junction Solar Cell for High-Concentration Applications

Table 2. Polycrystalline Thin Film Tandem Cell Subcontractor R&D (*currently under negotiation)

Polycrystalline Thin-Film Tandem Cell Subcontractors

The University of Delaware is using two approaches to develop a polycrystalline thin-film tandem cell. The first approach, to design and construct a new system for elemental evaporation of $Cu(InGa)(SeS)_2$, has been completed. Good spatial uniformity, with less than 10% thickness variation was demonstrated for the metal sources. The first $Cu(InGa)Se_2$ films have now been deposited, and procedures for simultaneous control of the Se and S will be implemented. The second approach is to develop $Cd_{1-x}Zn_xTe$ thin-film solar cells. Evaporation from independently controlled CdTe and ZnTe sources allows excellent composition control, and films have been deposited over the complete composition range $0 \leq x \leq 1$. Broadening of x-ray diffraction peaks and a change in surface morphology, including a decrease in grain size, suggest that a degree of disorder exists within the alloy films compared to CdTe or ZnTe films. $CdS/Cd_{1-x}Zn_xTe$ solar cells have been fabricated without post-deposition treatment and had single-phase composition prior to treatment.

The University of Florida is working toward identifying critical issues associated with the design and manufacture of a monolithic two-junction tandem cell consisting of a CIS bottom cell and a CGS top cell connected via a heavily-doped tunnel junction. Recently, the carried out numerical simulation studies of a $CuGaSe_2/CuInSe_2$ two-junction tandem solar cell using the AMPS-1D program. The results predict that an efficiency of 25% is realizable for an optimized four-terminal tandem cell. The analysis considered bottom-cell thickness values ranging from 200 nm to 2000 nm. Additionally, they studied the quantum efficiency (QE) curves for the CGS top cell and CIS bottom cell. The simulation efficiencies were 15.65% and 8.36% for the CGS (1400 nm) top and CIS (2000 nm) bottom cells, respectively, yielding a total tandem composite efficiency of 24.01%. Values of Jsc were 17.20 and 21.08 mA/cm^2 for the CGS (1400 nm) top and CIS (2000 nm) bottom cells, respectively.

The University of Toledo is looking to optimize back contacts to CdTe that are based on reactively sputtered ZnTe:N. To be used as a back contact with a CdTe or CdZnTe top cell, this contact must be transparent to photons of energy below the top-cell band gap. Unfortunately, the conductivity of p-ZnTe:N is typically a few Ohm-cm and, therefore, is much too resistive to use with a metal grid structure. Thus, they have usually used the ZnTe:N together with a final continuous layer of nickel which serves as a functional, copper-free back contact to a single-junction CdTe device. They have succeeded in utilizing sputtered ZnO:Al to replace the Ni, which maintains the transparency while giving the high lateral conductivity needed for the grid structure suitable for the top cell in a four-terminal tandem structure. Furthermore, because the ZnO:Al is already used for top contacts in CIS cells, it suggests that this structure should be able to function as a recombination layer in two-terminal tandem cells with a CdZnTe top cell and a CIS bottom cell.

The University of South Florida is working on identifying critical issues associated with developing a high-band gap II-VI based device that can serve as the top cell in an all-thin-film tandem structure that can achieve an efficiency of 25%.They have been depositing CdZnTe films by co-sublimation, referred to as close-spaced co-sublimation. Preliminary results indicate that they can obtain single-phase films with this process as indicated by XRD with x (zinc content) up to 30%. The composition estimated from XRD was also verified with EDS, within 1%-2% in the films that they did compare. Some of the films were also used in "solar cell structures", i.e. glass/SnO_2/CdS/CZT/graphite, which is essentially the same configuration they use for CdTe. At this time their most positive result is Voc's in excess of 700 mV.

Global Solar is working toward improving the efficiency of CIGS devices on metal foils for use with concentrator systems by (1) understanding and eliminating efficiency differences between the best devices on foil and the best devices on glass, and (2) increasing blue light collection through elimination or modification of the CdS layer. They have constructed a research-sized evaporator to fabricate CIGS films in small quantities. The system provides GSE with an avenue to quickly answer questions regarding high performance devices and associated production issues. The small system size, careful rate and temperature monitoring, and use of the NREL three-stage process should allow answering such questions with speed and accuracy not possible when using large-scale production equipment.

Concentrator Subcontractors

The University of Illinois is examining possible approaches for the use of single crystal epitaxial CIGS as the 1.0 eV energy-gap absorber layer in a four-junction solar cell. Their first approach is growth of epitaxial CIGS on n+ GaAs substrates. To date they have obtained substrates with various orientations, and epitaxial layers have been grown. Additionally, the CIGS-GaAs diodes produced show good J/V and photovoltage. The second configuration they are working on is the growth on a Ge substrate.

Spectrolab is working toward achieving an ultra-high efficiency, low-cost III-V solar cell, either through a monolithic structure or by mechanical-stacking or wafer-bonded integrated cells. Additionally, they are developing a modul- packaging design and process that enable efficient heat management of the solar cells and ensure reliable interconnects under thermal cycling. The ultimate result of this work will be to identify the critical paths towards achieving a 33% solar conversion module within the cost targets of under $1/watt.

SunPower's objective is to assess the optical options available for high performance Fresnel lens concentrators. Specifically assessing available lens technologies, new and emerging optic technologies, and key optics-to-cell system integration and reliability issues

ENTECH worked toward designing and developing a full-size, 27% efficient, 440X concentrator module. This was to include the following developments: 21X color-mixing primary lens and secondary lens and 33%-efficient prism-covered triple-junction solar cell operating at 370 suns average irradiance. Additionally, extensive work was conducted on integrating the photovoltaic receiver including heat spreader, cell-to-cell interconnects, bypass diode protection, dielectric isolation, encapsulation, and secondary optics. It was found that adapting the new optics, cells, and receiver technology to it's existing module and sun-tracking array products requires future effort.

Emcore is developing techniques to demonstrate a greater than 40%, 500x, AM1.5D efficient two-terminal, lattice-mismatched cell. The final cell will have a minimal area of 0.5 cm^2 lattice-mismatched $Ga_xIn_{1-x}P/Ga_xIn_{1-x}As$ dual junction cell on a diffused Ge junction with the appropriate buffer layer. The developed cells are to be demonstrated and tested in an Amonix concentrator system.

NREL IN-HOUSE R&D

In-House Polycrystalline Thin-Film tandem Cells

The in-house activities concern fundamental studies of the various components of monolithic dual-junction device. Two top-cell materials have been chosen for the initial phase of the research: $CuGaSe_2$ and $Cd_xZn_{1-x}Te$, with band gap around 1.7 eV. The effort has focused on: (1) the growth processes to produce phase pure thin films; and (2) growth on transparent conducting (TC) substrates such as

SnO_2, ITO, etc. for the case of $CuGaSe_2$, and ZnTe:Cu transparent contact for CdZnTe. Of significant interest is the optical characterization of the top cell to assess optical resources available to the bottom cell.

The experimental work is being guided by the modeling of two-junction thin film tandem stacks [3]. The model calculates the reverse saturation current density as a function of bandgap by using equivalent data from the best thin-film cells, of known bandgaps, characterized at NREL. The work emphasizes the crucial role that the properties of transparent conductors and the shorting junction have on the overall performance of the device.

To date, most of the effort has been applied to thin-film growth of CGS and CdZnTe to optimize the performance of the top cell. In addition, the team has been investigating a bifacial device structure using $CuGaSe_2$ and $Cu(In,Ga)Se_2$ as the absorber pair on either side of a transparent conducting glass substrate [4].

In-House Concentrator

The in-house concentrator activities focus on the addition of a 1-eV GaInAsN junction to a GaInP/GaAs/Ge cell. This structure has the potential of reaching efficiencies in the 35%-40% range [5]. The topics being addressed include materials measurements, spectra issues, and stability/degradation issues.

Recent work has shown that the direct reference spectrum is not representative of sunny conditions in regions with a high annual direct-normal energy where concentrators might be deployed (the Sun Belt).A new proposed direct reference spectrum and its effect on the short-circuit current is being investigated by NREL for evaluating III-V concentrator cells [6-8].

Recently, an analysis was completed to estimate the maximum efficiency that is realistically achievable for the GaInP/GaAs/Ge cell under concentration, assuming that all parts of the device, including the front grids, are optimized as well as is practically possible. NREL researchers project achievable 3 junction concentrator cell efficiencies in the 37% range for the AM1.5G and low-AOD spectra, and in the 35% range for the AM1.5D spectrum. Increasing the cell size to 1 cm^2 lowers projected efficiencies by ~1%.

CONCLUSIONS

Phase I, Identifying Critical Paths, of the HiPerf PV Project, is underway with in-house and subcontracted research in high-performance polycrystalline thin film's and multijunction concentrator devices. Ten of eleven subcontracts active are making headway.

In pursuit of long-term DOE-goals, the HiPerf PV Project is focused to assure that tandem thin film modules reach efficiency levels consistent with cost-competitive goals, and that concentrator cells reach performance levels that would allow concentrator PV to be deployed appropriately to produce cost-competitive electricity.

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