Program and Abstracts

DOE Solar Program Review Meeting 2004

October 25–28, 2004

Denver Marriott Tech Center
Denver, Colorado

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Message from the Chairpersons

Welcome to the DOE Solar Energy Technologies Program Review Meeting, a review of developments and achievements within the DOE solar arena during the course of FY 2004.

Reflecting the need for a stronger America in the form of energy independence and clean environment now and in the future, the DOE Solar Program supports a diverse range of solar technologies in varying stages of maturity. As such, the program promotes accelerated R&D of existing technologies for the near term and fundamental research needed for the long run.

Orchestrated by the program's *Multi-Year Technical Plan: 2003–2007 and Beyond,* the response to these challenges is an impressive matrix of multidisciplinary research projects. This energy revolution is born of fundamental concepts, developed through working laboratory-scale devices and carried on to commercial products. It is fueled by individuals, groups, and effective partnering between universities, private industry, and national laboratories.

Developing renewable energy technologies is the pragmatic and ethical imperative of our time. We are all charged by the future with the clear responsibility for implementing the renewable energy technologies that will ensure a clean environment. Correspondingly, then, if the full-scale deployment of these technologies is the required end game, this meeting is a review of present and possible future developments of the game plans.

The emphasis of this meeting is on innovation at every level of the program, from atoms to arrays… from fundamental research to market analysis. The program has been structured to facilitate interaction among participants. We encourage you to take advantage of this gathering of the solar community—as technologists, colleagues, and friends—to exchange ideas and collaborate on the next steps in your game plan.

General Chair: Richard Matson, NREL

Co-chairs: Dan Friedman, NREL; Fannie Posey-Eddy, NREL; Charles Hanley, SNL

Organizers
This meeting was organized by the National Renewable Energy Laboratory and Sandia National Laboratories under contract to the U.S. Department of Energy.

Acknowledgements
The chairpersons would like to acknowledge the support of the more key players responsible for bringing this meeting together. To wit: Susan Moon and associates in communications, Sara Huntley and Ivilina Thornton in the conferences group, the individual session organizers, and Tom Surek as conference advisor—all consummate professionals in their own right.

DOE Solar Energy Technologies Program Review Meeting
Denver, Colorado, October 25–28, 2004

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3:40–4:00 p.m., Coffee Break

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Solar Heating and Lighting

Exploratory PV

Thin Films: CIS and CdTe

Solar Resource Characterization

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PARALLEL ORAL SESSIONS
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3:40–4:00 p.m., Coffee Break

PARALLEL ORAL SESSIONS
4:00–6:00 p.m.

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<u>Balance of Systems</u>
Chair: Ward Bower
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Chair: Michael Quintana
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Chair: Christopher Cameron
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10:10–10:30 a.m., Coffee Break

PARALLEL ORAL SESSIONS
10:30 a.m.–12:10 p.m.

Silicon I: Crystalline
Chair: Howard Branz
Room: Evergreen A

12:10–1:40 p.m., Lunch, Room: Columbine Center
Speaker: Charles Korman, GE Global Research
Vision of GE Energy

PARALLEL ORAL SESSIONS
1:40–3:40 p.m.

PV Module Reliability

Silicon

Thursday, October 28, 2004

7:30–8:30 a.m., Continental Breakfast

Plenary Session IV-A: Solar Future
Chair: Robert Margolis
8:30–10:00 a.m., Room: Evergreen A-B

10:00–10:20 a.m., Coffee Break

Plenary Session IV-B: Solar Future
Chair: Robert Margolis
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Review Meeting Wrap-Up

2004 Solar Program Review Meeting — Schedule

MONDAY	TUESDAY	WEDNESDAY	THURSDAY
PLENARY I-A Opening Session *8:30-9:50 AM* *Room: Evergreen A-C*	PLENARY II Systems-Driven Approach *8:30-10:10 AM* *Room: Evergreen A-C*	PLENARY III Program Highlights *8:30-10:10 AM* *Room: Evergreen A-C*	PLENARY IV-A Solar Future *8:30-10:00 AM* *Room: Evergreen A-B*
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PLENARY I-B Opening Session and Rappaport Award *10:20 AM-12:10 PM* *Room: Evergreen A-C*	HiPerf. II: III-V & Conc. (*Evergreen A*) | CdTe (*Evergreen B*) | Technol. Adoption I (*Evergreen C*) *10:30 AM-12:10 PM*	Silicon I: Crystalline (*Evergreen A*) | Exploratory II (*Evergreen B*) | Conc. Solar Power I (*Evergreen C*) *10:30 AM-12:10 PM*	PLENARY IV-B Solar Future *10:20-11:50 AM* *Room: Evergreen A-B* Wrap-Up *11:50 AM-12:00 PM*
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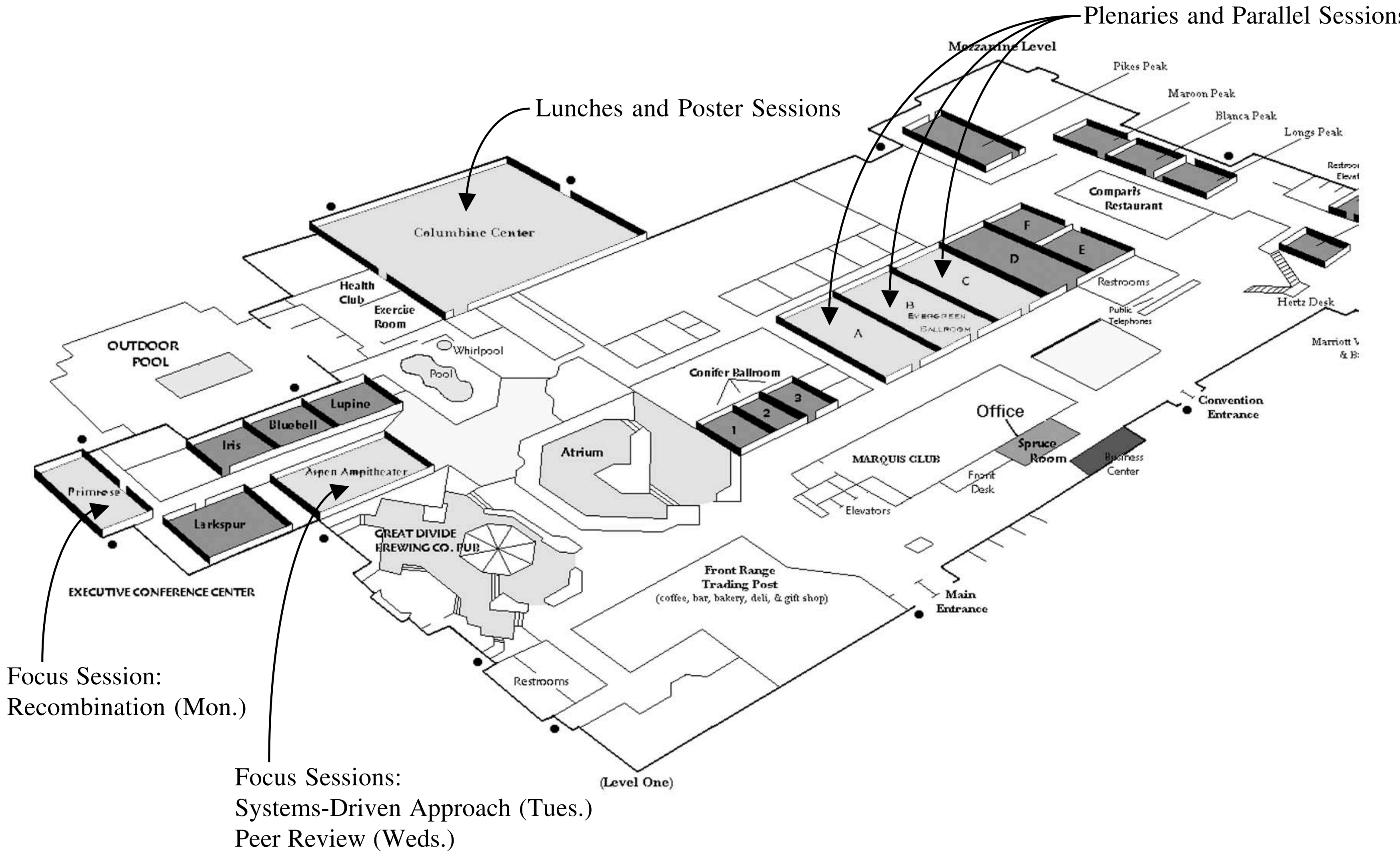
Coffee Break ***3:40-4:00 PM***	**Coffee Break** ***3:40-4:00 PM***	**Coffee Break** ***3:40-4:00 PM***	
POSTERS/RECEPTION HiPerf., Exploratory, CIS, CdTe, Solar Heat & Light, Misc. *4:00-6:00 PM (reception@4:45 PM)* *Room: Columbine Center*	PV Manuf. R&D II (*Evergreen A*) | Balance of Systems (*Evergreen B*) | PV Sys.Eng Reliability (*Evergreen C*) *--- 4:00-6:00 PM ---*	POSTERS/RECEPTION Silicon, Tech Adopt., PVMR&D, BOS, PV Sys. Eng. Reliab., Module Reliab. *4:00-6:00 PM (reception@4:45 PM)* *Room: Columbine Center*	
FOCUS SESSION Recombination in PV Materials *7:00-9:00 PM* *Room: Primrose*	FOCUS SESSION Systems-Driven Approach *7:00-9:00 PM* *Room: Aspen Amphitheater*	FOCUS SESSION Peer Review *7:00-9:00 PM* *Room: Aspen Amphitheater*	

2004 Solar Program Review Meeting — Room Locations

Denver Tech Center Marriott



Abstracts

Monday, October 25, 2004

Plenary Session I-A: Opening Session
Chair: Richard Matson
8:30–9:50 a.m.

9:20 - The SEIA Roadmap for U.S. Market Leadership and Technology Ownership
Rhone Resch
Solar Energy Industries Association

The center of the burgeoning solar industry is shifting toward Europe and Japan, where world-leading incentives and investment policies have spurred market growth. Lack of comparable national policies in the United States is causing the domestic market to lag overseas markets in both size and growth. The U.S. solar industry has responded with a call to action—an agenda for federal policies that will help the U.S. reclaim market leadership and maintain technology ownership. Recommended actions include: (1) tax incentives that are structured to kick-start demand; (2) increased R&D funding across the board; (3) national net metering and interconnection standards; (4) increased government procurement of solar power; and (5) leveraged support for state incentives. Presenter will discuss policy requirements and targets for PV, CSP, and SWH in review of the PV Roadmap, the Building Water Heating Roadmap, and the CSP Technology Transition Plan. Solar can provide half of all new U.S. electricity generation by 2025, with the industry employing 260,000 U.S. workers by 2030. Federal actions will require coordinated effort from businesses, state and national solar advocacy organizations, and champions at all levels of state and federal government.

Plenary Session I-B: Opening Session
Chair: Stan Bull
10:20–11:50 a.m.

11:10 - ¢/kWh or kWh/$?
Peter Johnston
Arizona Public Service

Arizona Public Service (APS) is one of the few public utilities in the nation that is leading the way in the development and implementation of solar energy technologies. Over the years, APS has conducted research and development on integrated systems employing various PV module technologies, mounting configurations (tracking vs. fixed axis), large-scale concentrating PV systems, and dish-engine concentrator systems and has recently begun to investigate a 1-MW solar trough concentrator system. The utility also conducts R&D on distributed generation, energy storage, hydrogen, and alternative fuels. In a state with high insolation and over 300 days of sunshine each year, APS has long sought ways to improve the business case and reduce the technical risk of employing solar energy technologies to meet its customers' needs. These days, with Arizona having one of the more aggressive solar-based renewable portfolio standards in the country, APS has been implementing even more systems throughout its territory and continues to lead and learn about improving solar and related technologies and reducing their costs.

12:10 - Scientific Challenges in the Development of Sustainable Energy
Nathan S. Lewis
California Institute of Technology

This presentation will describe and evaluate the technical, political, and economic challenges involved with widespread adoption of renewable energy technologies. First, we estimate the available fossil fuel resources and reserves based on data from the World Energy Assessment and World Energy Council. In conjunction with the current and projected global primary power production rates, we then estimate the remaining years of supply of oil, gas, and coal for use in primary power production. We then compare the price per unit of energy of these sources to those of renewable energy technologies (wind, solar thermal, solar electric, biomass, hydroelectric, and geothermal) to evaluate the degree to which supply/demand forces stimulate a transition to renewable energy technologies in the next 20–50 years. Secondly, we evaluate the greenhouse gas buildup limitations on carbon-based power consumption as an unpriced externality to fossil-fuel consumption, considering global population growth, increased global gross domestic product, and increased energy efficiency per unit of globally averaged GDP, as produced by the Intergovernmental Panel on Climate Change (IPCC). A greenhouse gas constraint on total carbon emissions, in conjunction with global population growth, is projected to drive the demand for carbon-free power well beyond that produced by conventional supply/demand pricing tradeoffs, at potentially daunting levels relative to current renewable energy demand levels. Thirdly, we evaluate the level and timescale of R&D investment that is needed to produce the required quantity of carbon-free power by the 2050 time frame, to support the expected global energy demand for carbon-free power. Fourth, we evaluate the energy potential of various renewable energy resources to ascertain which resources are adequately available globally to support the projected global carbon-free energy demand requirements. Fifth, we evaluate the challenges to the chemical sciences to enable the cost-effective production of carbon-free power on the needed scale by the 2050 time frame. Finally, we discuss the effects of a change in primary power technology on the energy supply infrastructure and discuss the impact of such a change on the modes of energy consumption by the energy consumer and additional demands on the chemical sciences to support such a transition in energy supply.

High-Performance PV I: Thin Films (parallel)
Chair: Tim Gessert
1:40–3:40 p.m.

1:40 - High-Performance Photovoltaic Project Overview
Martha Symko-Davies and Robert McConnell
National Renewable Energy Laboratory (NREL)

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. This paper describes the recent research accomplishments in the in-house directed efforts as well as the research efforts underway in the subcontracted area.

2:00 - Advances in Polycrystalline Thin-Film Tandem Solar Cells
Timothy J. Coutts
National Renewable Energy Laboratory (NREL)

Modeling of state-of-the-art single-junction thin-film solar cells, suggests that it may be possible to achieve an efficiency of 25% for a tandem cell based on top and bottom subcells with bandgaps of 1.5-1.8 eV and 1.1 eV, respectively. Many design possibilities are feasible, for both monolithic and mechanically stacked combinations, but our efforts at NREL are presently focused on potentially suitable top cells based on copper gallium selenide (CGS) and telluride-based alloys, mainly because at least two-thirds of the device power will derive from the top cell. We shall discuss our results on record performance CGS cells, highly transparent CdTe top cells, novel results on cadmium magnesium telluride films, and early results on complete tandem devices.

2:20 - Growth and Characterization of CdZnTe and $Cu(InGa)(SeS)_2$ for Wide-Bandgap Solar Cells

William N. Shafarman and Brian E. McCandless
Institute of Energy Conversion, University of Delaware

$Cd_{1-x}Zn_xTe$ and $Cu(InGa)(SeS)_2$ thin films are being developed for the absorber layers in wide band gap solar cells that could be incorporated into thin film tandem devices. For each material, advances in film formation, characterization, and device issues will be reported for materials with band gaps greater than 1.5 eV. $Cd_{1-x}Zn_xTe$ films are deposited by physical vapor deposition or vapor transport. The focus is on characterizing the chemical stability during post-deposition treatments and back contact formation to form single-phase films with controlled incorporation of Zn. With the $Cu(InGa)(SeS)_2$ films, deposited by elemental evaporation, the emphasis is on controlling the incorporation of the S and Se species during film growth in which different deposition conditions preferentially favor one species. For each material the relationships between film formation and device behavior will be discussed and future prospects for high efficiency addressed.

2:40 - Properties of Surface-Modified $CuGaSe_2$ (CGS) Solar Cells with Improved Performance

Jehad A. AbuShama and Rommel Noufi
National Renewable Energy Laboratory (NREL)

We report the growth and characterization of improved efficiency surface-modified CGS thin-film solar cell. This cell exhibits the following NREL-confirmed device operating parameters: V_{oc} = 0.823 volts, J_{sc} = 18.61 mA/cm, fill factor = 66.8%, and total-area-efficiency = 10.2%. CGS is a candidate top cell absorber material for thin film tandem devices. Its bandgap is ideal at 1.68 eV. This particular device has a bandgap of 1.64 eV. Improving CGS device efficiency has proven to be a challenge over the past several years. The recent understanding of the differences in structural and electronic properties between $CuIn(Ga)Se_2$ (CI(G)S) and CGS thin films and devices has led to varying the growth process in a way that is likely to make the CGS surface region $CuInSe_2$ (CIS)-like and to minimize defects in the material. This change led to a gain in the current density of about 3.7 mA/cm^2 versus the previous record cell.

3:00 - Progress in Thin-Film Si Bottom Cell for High-Performance Thin-Film Tandem Solar Cells

Roger Aparicio[1], Vijay Yelundur[2], Steven Hegedus[1], Ajeet Rohatgi[2], and Robert Birkmire[1]
[1]Institute of Energy Conversion, University of Delaware
[2]University Center of Excellence for Photovoltaics Research and Education, School of Electrical and Computer Engineering, Georgia Institute of Technology

High performance thin film tandem cells incorporating a thin film Si bottom cell with a wide bandgap $CuInSe_2$-based top cell have the potential to achieve efficiencies well over 25%. Preliminary results in the development of the thin Si bottom cells are reported. The strategy is initially to use c-Si and mc-Si wafers as test vehicles to establish process compatibility and resolve critical processing issues. The results of key components of this strategy will be reported, including survivability of the c-Si p-n junction after $CuInSe_2$-based film deposition, deposition of thin film Si emitters and passivation layers, and deposition of a low recombination Si back contact. In addition, a comparison of solar cells with a-Si and μc-Si deposited emitters on c-Si and mc-Si wafers will be presented.

3:20 - Toward a Tandem Cell with All II-VI Semiconductors by Magnetron Sputtering

Alvin D. Compaan, Shanli Wang, and Akhlesh Gupta
Dept. of Physics and Astronomy, Univ. of Toledo

A monolithic tandem cell based on alloys of cadmium telluride is an attractive possiblity since energy gaps of 1.7 eV and 1.0 eV are readily achieved in this system. Here we report the results of studies of CdS/CdMnTe and of CdS/HgCdTe superstrate cells with SnO_2:F TCO and Cu/Au back contacts. We also report on the behavior of ZnTe:N/ZnO:Al and ZnTe:Cu/ZnO:Al interconnect layers and their incorporation into tandem devices. We have fabricated a CdTe/HgCdTe tandem cell with 20% Hg and with V_{oc} = 960 mV and spectral response to ~1000 nm but with poor current matching. Difficulties in obtaining high performance junctions from CdS/CdMnTe have led us to examine the use of thin CdTe to achieve current matching in the II-VI monolithic tandem. Optical behavior of a thin CdTe top cell with transparent back contact will be presented as well as its use in a CdTe/HgCdTe tandem cell.

Exploratory PV I: Next-Generation Thin Films (parallel)
Chair: Brian Gregg
1:40–3:40 p.m.

1:40 - Polymer-Based Nanocomposites for Solar Energy Conversion

Sean E. Shaheen[1], Dana C. Olson[2], William J. Mitchell[1], Garry Rumbles[1], and David S. Ginley[1]
[1]National Renewable Energy Laboratory
[2]Dept. of Physics, Colorado School of Mines

Organic semiconductor based photovoltaic devices offer the promise of low cost photovoltaic technology that can be easily manufactured on an industrial scale using environmentally friendly materials. Existing organic photovoltaic devices are currently limited to solar power conversion efficiencies of 3%–4% as a result of poor overlap between the absorption spectrum of the organic chromophores and the solar spectrum, non-ideal band alignment between the donor and acceptor species, and low charge carrier mobilities. To address the issue of light absorption, we are investigating the development of low band gap silole-containing systems that can exhibit band gaps below 1.5 eV. Additionally, we are working on developing nanostructured oxide/conjugated polymer composite materials. These composites can be fabricated using low temperature solution based techniques and can take advantage of high electron mobilities attainable in oxide semiconductors. Here we discuss the synthesis and preliminary device results of these novel materials and composites.

2:00 - Dye- and Semiconductor-Sensitized Nanoparticle Solar Cell Research at NREL

Arthur J. Frank, Nikos Kopidakis, Kurt D. Benkstein, Jao van de Lagemaat, and Nathan R. Neale
National Renewable Energy Laboratory

The major objective of our research is to develop efficient, durable and low-cost liquid-junction and solid-state solar cells based on sensitized nanoporous films. Sensitizers include quantum-scaled semiconductors and molecular dyes (collaboration with DOE Office of Science Program). Toward this end, we conduct experimental and theoretical studies to understand the unique physical and chemical factors governing cell performance. Scientific issues studied include the influence of film and particle morphologies and the sensitizer and hole-transporting medium properties on the electron transport and recombination dynamics and the light-harvesting, charge-injection and charge-collection efficiencies. Recently, we investigated (1) the possibility of increasing the photocurrent by using a nanoparticle photonic crystal layer coupled to a conventional TiO_2 nanoparticle film and (2) the relationship between transport and recombination and cell performance, (3) the percolation phenomena and transport dynamics, and (4) morphological factors of core-shell nanoparticle films and their PV properties. In this presentation, we discuss (2).

2:20 - Ultra-High-Efficiency Excitonic Solar Cell

Benjamin T. King[1], Josef Michl[2], Arthur J. Nozik[3], Mark A. Ratner[4], and Michael Winokur[5]
[1]*Dept. Chem., Univ. of Nevada*
[2]*Dept. Chem. Biochem., Univ. of Colorado*
[3]*National Renewable Energy Laboratory*
[4]*Dept. Chem., Northwestern Univ.*

We are starting a research program aimed at an improvement of the efficiency of titanium dioxide nanoparticle/dye solar cells. The salient proposed goals are (i) doubling the number of electrons injected by the use of a dye aggregate capable of exciton splitting (conversion of a singlet excited state into two triplet excited states), (ii) reduction of voltage losses by fine tuning of the redox potential of the shuttle anion, (iii) replacement of liquid electrolyte by a hole-conducting polymer.

2:40 - Interface and Electrode Engineering for Next-Generation Organic Photovoltaic Cells

Thomas O. Mason[1], Robert P. H. Chang[1], Arthur J. Freeman[2], Tobin J. Marks[3], and Kenneth R. Poeppelmeier[3]
[1]*Northwestern University, Dept. of Materials Science and Engineering*
[2]*Northwestern University, Dept. of Physics and Astronomy*
[3]*Northwestern University, Dept. of Chemistry*

We report on our cross-disciplinary effort to develop next-generation organic photovoltaic cells through interface and electrode engineering. Building upon our established expertise with high performance n-type transparent electrodes (transparent conducting oxides, TCOs) and organic light-emitting diodes (OLEDs), we are developing 1) compatible nanostructured TCO electrodes for more efficient current collection, 2) n-type TCOs with better OPV properties, including matched band-offsets and greater corrosion resistance for enhanced durability, 3) p-type TCOs with order-of-magnitude enhancement of conductivity for next-generation OPVs, 4) high-efficiency carrier injection/adhesion layers for OPVs with greater current-collection capability and improved interfacial stability, and 5) growth of optimized electrode materials on plastic substrates. Our aim, in collaboration with industrial partners, is to deliver OPV-optimized electrodes/interfaces for organic solar cells with breakthrough performance characteristics.

3:00 - Band Structures and Optical Properties of Transparent Conducting Oxides: Cd_2SnO_4, Zn_2SnO_4, and $CdIn_2O_4$

Su-Huai Wei and David Segev
National Renewable Energy Laboratory

Cd_2SnO_4, Zn_2SnO_4, and $CdIn_2O_4$ are transparent conducting oxides (TCO) that have unique physical properties. They have been used as promising transparent electrodes in optoelectronic devices such as solar cells. Using first-principles band structure and total energy method, we find that Cd_2SnO_4, Zn_2SnO_4, and $CdIn_2O_4$ are more stable in the orthorhombic, inverse spinel, and normal spinel structures, respectively. Our calculations show that the band structure of these compounds depends strongly on the crystal structures. For example, the band gap of $CdIn_2O_4$ in the normal spinel structure is about 1 eV larger than in the inverse spinel structure. For Cd_2SnO_4 and Zn_2SnO_4, they can be used as TCO only if they form the orthorhombic or the inverse spinel structures. Other physical properties such as structure factors, electron effective masses and optical transition matrix elements for these compounds will also be presented.

3:20 - Toward a Unified Treatment of Electronic Processes in Organic Semiconductors

Brian A. Gregg, Russell A. Cormier, Si-Guang Chen, Howard M. Branz, and Pauls Stradins
National Renewable Energy Laboratory

A heuristic approach to describing excitonic processes, doping and transport in organic semiconductors is developed and applied to understanding photovoltaic applications. A simple equation is proposed that semiquantitatively defines “excitonic” semiconductors, XSCs, a classification that includes most organic semiconductors and some inorganic materials. The same electrostatic and spatial factors that cause exciton formation upon light absorption in XSCs, as opposed to the formation of free electron-hole pairs, also control the doping process and carrier transport. Quantitative doping studies in liquid crystal perylene diimides establish that most added charge carriers are not free but rather are electrostatically bound to their conjugate dopant counterions. We show that these results can be generalized to many XSCs that are not purposely doped. A superlinear increase in conductivity with doping density is thus expected to be, and apparently is, a universal attribute of XSCs.

Solar Heating and Lighting (parallel)
Chair: Tim Merrigan
1:40–3:40 p.m.

1:40 - Low-Cost Solar Water Heating Systems

Jay D. Burch, Craig B. Christensen, and Tim J. Merrigan
National Renewable Energy Laboratory

In FY98, Solar Heating and Lighting set the goal to reduce the life-cycle cost of saved-energy for residential solar water heating systems by 50%, primarily through polymer technology. Focusing on passive systems in mild climates, two industry teams have developed integral-collector-storage (ICS) designs, currently in field testing phase. The DEG/SunEarth design is a single-glazed polymer ICS with rotomolded tank, and the FAFCO design is a double-glazed polymer ICS with extruded storage tubes. Both teams are revising designs addressing issues arising in monitoring. Support for the teams is being provided for materials testing, modeling and system testing. A suite of new ICS system models has been produced incorporating time-varying loss coefficients, immersed heat exchangers, and stratification, improving prediction accuracy by ~15%. A new SRCC ICS test procedure for the new ICS systems is undergoing testing and validation. Pipe freezing, freeze protection valves, and overheating have been tested and analyzed.

2:00 - Durability of Polymeric Glazing and Absorber Materials

Gary J. Jorgensen, Kent M. Terwilliger, Carl E. Bingham, and Michael J. Milbourne
National Renewable Energy Laboratory

The Solar Heating and Lighting Program has set the goal of reducing the cost of solar water heating systems by at least 50%. An attractive approach to such large cost reduction is to replace glass and metal parts with less-expensive, lighter-weight, more-integrated polymeric components. The key challenge with polymers is to maintain performance and assure requisite durability for extended lifetimes. The objective of this task is to quantify lifetimes through measurement of the optical and mechanical stability of candidate polymeric glazing and absorber materials. Polycarbonate sheet glazings, as proposed by two industry partners, have been tested for resistance to UV radiation with three complementary methods. Incorporation of a specific 2-mil thick UV-absorbing screening layer results in glazing lifetimes of at least 15 years; improved screens promise even longer lifetimes. Proposed absorber materials were tested for creep and embrittlement under high temperature, and appear adequate for planned ICS absorbers.

2:20 - Next-Generation Polymer Solar Heating Systems

Jane H. Davidson[1], Susan C. Mantell[1], Lorraine Francis[2], and Kelly Homan[3]
[1]Mechanical Engineering, University of Minnesota
[2]Chemical Engineering and Material Science, University of Minnesota
[3]Mechanical Engineering, University of Missouri-Rolla

The University of Minnesota is collaborating with NREL and industry to develop low-cost polymer based solar water heating systems. Our work addresses material and thermal performance issues related to polymer integral collector storage systems that use a load-side immersed heat exchanger. We have developed material selection criteria, tested candidate materials for compatibility and durability in hot chlorinated water, evaluated the growth of calcium carbonate (scale) on candidate polymers, developed empirical models to evaluate performance of immersed heat exchangers and tested prototype heat exchangers. On-going efforts focus on approaches to optimize heat exchanger performance, development of methods and testing to determine material durability and projected lifetime for heat exchanger materials, minimization of scale growth, and development of new concepts for lower cost solar heating.

2:40 - Overview of Solar Heating Industry Assistance Program
Greg J. Kolb and David F. Menicucci
Sandia National Laboratories

Sandia National Laboratories provides technical assistance to the solar thermal industry. Through it's Industry Assistance Program, Sandia follows a systems-driven approach to help manufacturers improve their products. In addition, the program helps potential technology users design their system to achieve maximum cost effectiveness. This assistance is often highly leveraged with funding from DoD and the utility industry. FY04 assistance projects are summarized. These include 1) an energy monitoring strategy to support the sale of green tags for solar hot water, 2) providing DoD options for providing hot water to troops in Iraq, 3) advising a green builder how to incorporate solar hot water systems into future housing projects, 4) developing a thermochromatic film to prevent overheat failure of the polymer collector, and 5) analysis of a design concept for a freeze-protected, passive thermosyphon collector system to meet near-term cost goals defined by DOE.

3:00 - Recent Advances in Hybrid Solar Lighting R&D
Jeff D. Muhs[1], Duncan D. Earl[1], David L. Beshears[1], L. Curt Maxey[1], and Byard Wood[2]
[1]Oak Ridge National Laboratory
[2]Utah State University

Electric lamps revolutionized the way buildings were designed during the first half of the 20th century, virtually eliminating the need for natural light. Paradoxically, much of the second half of the century was spent developing ways to convert sunlight into electricity, in large part to power electric lamps. Use of natural light in buildings is coming full circle as concerns over the sustainability of electric lighting systems grow, especially in commercial buildings where a third of the electricity is consumed by lights. However, future lighting systems incorporating sunlight must offer the features of flexibility, convenience, reliability, and control that are lacking in daylighting systems of today. Hybrid solar lighting systems have the unique potential to meet these requirements while providing value-propositions beyond energy-savings. This paper summarizes multidisciplinary R&D being conducted by several research organizations leading to the possible emergence of commercially viable HSL systems in the near future

3:20 - Solar Domestic Hot Water Systems Analysis
Jay D. Burch, Craig B. Christensen, and Tim J. Merrigan
National Renewable Energy Laboratory

The Solar Heating and Lighting goal is reducing the cost of saved-energy for solar domestic hot water systems (SDHW) by 50%. Systems analyses are underway supporting a cold-climate SDHW initiative in FY05. Systems under cost/performance analysis include: i) traditional systems: glycol and drainback systems; and ii) innovative system: freeze-protected thermosiphon. Options include lower-cost collectors (e.g. polymers) and storage (e.g. unpressurized). The thermosiphon system can meet the 50% reduction goal with lower-cost storage and collectors. It eliminates pump and controller cost and O&M, but places storage in the attic and subjecting potable water supply/return pipes to freezing conditions. Analysis and testing of pipe freezing and freeze prevention are ongoing, indicating multi-level freeze protection is practical and inexpensive. Additional analyses supporting a possible future space conditioning thrust indicates unglazed systems have potential in the southwest U.S. for cost-effective savings of space heating, cooling, and DHW loads.

Poster Session I
4:00–6:00 p.m.

Solar Heating and Lighting

P001 - SunCache Residential Solar Water Heating System – Phase V

Dick Bourne[1], Eric Lee[1], Duncan Callaway[1], Hugh Dwiggins[1], and Josh Plaisted[2]
[1]Davis Energy Group
[2]SunEarth, Inc.

In FY 2004, the team continued development of the SunCache low-cost ICS solar system. SunCache makes extensive use of polymer materials to lower material, labor and installation costs. The team is composed of Davis Energy Group, the primary subcontractor, and SunEarth, the manufacturing partner. SunEarth anticipates SunCache production beginning in late FY 2005. FY 2004 work was divided into the following tasks: 20 prototype systems were produced for use in the other Phase V tasks; complete systems and individual components were subjected to a wide variety of durability testing; applications were submitted for SRCC OG-300 and ICC-ES approval, and a packet of sample structural calculations and a manual were prepared; 12 units were field-tested in four climates; accessory components were developed for non-standard applications, and a new mold was purchased to address leaks in the water containment panel; multiple cost analyses were prepared; and a final report was prepared.

P003 - Polymer ICS System Development

Richard O. Rhodes and Josh Eaton
Fafco, Inc.

An unpressurized polymer integral-collector-storage collector has been designed and is being tested, with potential to reduce cost of saved energy by over 50%. Current objectives include to continue field testing, resolve technical issues, complete market research, fabricate pre-production polybutylene heat exchangers, and evaluate manufacturing and cost. Twelve field-test systems have been installed and have performed well, producing up to 19 kBTU per day, with lower outputs at small draw volumes. Technical issues have been identified and improvements made, including designing a finned copper heat exchanger with reduced cost, improving the water-make-up float valve design, adding a support bracket to the tank to eliminate creep failure, and increasing the tank size. Market research is nearing completion, and preliminary cost estimates at higher production rates show a need for additional cost reduction. The main technical focus is on further reducing system costs through redesign of the glazing and pan, and improving heat exchanger cost.

P005 - Quality Assurance via Certification; Development and Maintenance of Testing Standards for Solar Energy Systems

Byard Wood[1,3], Jim Huggins[1,4], and Jack Werner[1,2]
[1]Solar Rating & Certification Corporation
[2]Climate Institute
[3]Utah State University
[4]Florida Solar Energy Center

This project supports the SRCC certification programs and implements enhancements to certification procedures and test methods for increasing product durability and credibility of performance ratings. The following tasks will support the priority enhancements: (1) Inspection and evaluation of installed solar water heating systems; (2) Education and training outreach to utilities, state and federal agencies, building code jurisdictions, and trade organizations (education will emphasize the performance capabilities and advantages of solar water heating); (3) Modification of SRCC standards to accommodate advanced designs such as the polymer-based low cost solar water heaters being developed by DOE; (4) Continued monitoring of international activities and determination of the appropriateness of adopting ISO test methods that deal with solar water heating components and systems; (5) Expansion of the OG-300 certification to larger systems will be studied to determine how to certify and rate commercial systems; and (6) SRCC will continue working to bring its programs in compliance with national and international standards for third-party certification.

Exploratory PV

P007 – Coadsorbent-Induced Band Edge Shift in Dye-Sensitized TiO_2 Solar Cells

Nathan R. Neale, Nikos Kopidakis, Jao van de Lagemaat, and Arthur J. Frank
National Renewable Energy Laboratory

Adding the adsorbent chenodeoxycholate in conjunction with the sensitizing dye employed in high efficiency nanoparticle solar cells has been shown to increase the photovoltage. It is has been speculated that the increase in the photovoltage is due to the hydrophobic coadsorbent passivating surface states that mitigate the recombination of photoinjected electrons with redox species in the electrolyte. In collaboration with the DOE Office of Science Program, we are conducting transient photovoltage measurements to determine the mechanism for the improved photovoltage. Our initial results suggest that the coadsorbent has no significant effect on the recombination rate but instead causes the conduction band edge to move to negative potentials with respect to the Fermi level of the solution.

P009 - Effect of Nonideal Statistics on Electron Diffusion in Dye-Sensitized TiO_2 Solar Cells

Jao van de Lagemaat, Nikos Kopidakis, Nathan R. Neale, and Arthur J. Frank
National Renewable Energy Laboratory

Charge-extraction and time-resolved photocurrent measurements on sensitized electrolyte-infused porous nanocrystalline TiO_2 films show that the actual electronic charge in the films is significantly larger (2-17 times) than that estimated from small perturbation methods (collaboration with DOE Office of Science Program). This result has important implications for understanding the conversion efficiency of the cell. Continuous time random-walk simulations confirm that small perturbation techniques measure the chemical diffusion coefficient of electrons instead of the normally assumed tracer diffusion. The difference between the two diffusion coefficients is attributed to nonideal statistics, owing to the presence of an exponential density of states. The ratio of the two diffusion coefficients and therefore the ratio of the actual photoinjected charge in the nanoparticle film to the charge estimated from photocurrent measurements is shown to equal the inverse of the disorder parameter and therefore the slope of the exponential density of states.

P011 – Influence of the Electrolyte on the Performance of Dye-Sensitized TiO_2 Solar Cells: Band Edge Movement and Surface Shielding

Nikos Kopidakis, Nathan R. Neale, Jao van de Lagemaat, and Arthur J. Frank
National Renewable Energy Laboratory

State-of-the-art dye-sensitized nanocrystalline TiO_2 solar cells utilize liquid electrolytes containing several components. In collaboration with the DOE Office of Science Program, we are studying the effects of two of these components on the transport and recombination properties and cell performance. Transient photovoltage measurements indicate that one component strongly shields the TiO_2 surface against recombination, decreasing the rate of reaction by one order of magnitude, and shifting the conduction band edge toward positive potentials. This is the first clear evidence for reduction of the rate of recombination strictly by shielding. On the other hand, the other component was found to increase the recombination rate but to shift the band edges toward negative potentials. In combination, the two components caused a net positive potential shift of the band edges and a net reduction of the recombination rate resulting in an overall improvement in the photovoltage and cell efficiency.

P013 - Correlation of Morphology and Device Performance in Inorganic-Organic TiO_2-Polythiophene Hybrid Solid-State Solar Cells

Luke Robertson[1], Mark A. Poggi[1], Janusz Kowalik[1], Laren M. Tolbert[1], and Greg P. Smestad[2]
[1]School of Chemistry and Biochemistry, Georgia Institute of Technology
[2]Sol Ideas Technology Development

Flat solid-state polymer photovoltaic (PV) cells were constructed using poly(3-undecyl-2,2'-bithiophene) (P3UBT) and flat titanium dioxide (TiO_2) films prepared using sol-gel technique. Layers and interfaces were studied using AFM, SEM-EDX, and optical microscopy to determine the impact of the interfacial boundary morphology on the PV device performance. Friction mapping and surface roughness measurements of the fluorinated tin oxide (SnO_2:F) conductive glass, TiO_2, and P3UBT surfaces show a distinct difference in surface contours enabling a better understanding of light absorption as well as charge separation and injection by the polymer. The influence of varying experimental conditions was tested against the performance of the solar cell. The optimized spin- and cast-coated P3UBT layers were used with the best TiO_2 films to create flat solid-state photovoltaic inorganic-organic hybrid cells with J_{sc}= 80 µA/cm^2 and V_{oc} = 0.5 to 0.7 V. Films with fewer defects and aggregates yielded better PV device performance.

P015 - PV-Powered Hydrogen Production from the Electrolysis of Water

Douglas S. Ruby[1], F. Doug Wall[1], David Ingersoll[1], Greg J. Kolb[1], and Steven J. Cohen[2]
[1]Sandia National Laboratories
[2]Teledyne Energy Systems, Inc.

A systems analysis identified the technical advances that would reduce the cost of hydrogen produced by water electrolysis to that of the lowest cost approach, steam methane reforming. The cost of hydrogen generation is a strong function of electrolysis efficiency, with only a weak dependence on capital cost. A proposal was submitted to increase electrolyzer efficiency by increasing electrocatalyst activity and by lowering the resistance of electrolysis cell membranes. We partnered with Teledyne Energy Systems, the leading manufacturer of high-volume electrolysis equipment. Sandia will provide advanced membrane and electrochemical expertise. Teledyne will ensure that the advanced technology is both manufacturable and cost effective. Optimizing the interface between the PV power supply and the electrolyzer load will maximize overall system electrical efficiency. A computer model will simulate the alkaline electrolysis process and allow optimization of all important process parameters to achieve lowest overall hydrogen production cost.

P017 - Fabrication, Characterization, and Simulation of Solar Cells

Gregory B. Lush, David Zubia, Jorge Erives, Jorge Villasenor, and Oscar Quintero
Department of Electrical and Computer Engineering, University of Texas at El Paso (UTEP)

UTEP is working on fabrication, characterization, and simulation of solar cells. For fabrication we are investigating an ordered nanofabrication technique to overcome problems inherent with random polycrystalline thin films. This technique could advance the state-of-the-art in conversion efficiencies of CdS/CdTe solar cells. For characterization we are applying unique techniques to study the spatial non-uniformities of CdTe material quality and device performance. Previous studies of CdTe/CdS solar cells found that it is the weakest region of the solar cell that may determine the overall performance of a thin-film cell. We are observing the electroluminescence of CdTe-based solar cells using CCD camera and a thermal imaging system. For simulation we are developing an intelligent interface to a device simulator that allows the asking of more complex questions such as best efficiency. Genetic algorithms are used to provide the "intelligence," and a sophisticated modeler called STEBS2D will simulate the solar cells.

P019 – Development of Quantum Dot-Sensitized ZnO and TiO_2 Nanorod Array Solar Cells

Dawit Jowhar, Dionicia O'Berry, Esosa Ojomo, Olabode Ajiboye, and Richard Mu
Nanoscale Materials and Sensors Laboratory, Department of Physics, Fisk University

The Nano-PV Program at Fisk University, which recently gained support from REAP/NREL, focuses on both student research and education. From the research end, we proposed to develop an innovative solar cell structure based on the conventional Grätzel cell. Three undergraduate students and one graduate student have been advised to work on four major tasks that form the essential components of the cell: 1) to develop micro- and nanospheres based on the nano-patterning technique; 2) to fabricate spatially ordered 2D ZnO and TiO_2 nanorod structure on a substrate; 3) to optimize the experimental procedure for high-quality ITO thin-film, ZnO, and TiO_2 nanorod fabrication; and 4) to initiate new efforts for polymeric and flexible substrate development. In the past several months since the program's initiation, appreciable progress has been made in all four tasks. Highlights of the new results will be presented along with the status of both undergraduate and graduate student training.

P021 - DOE-NREL Minority University Research Associates Program

Fannie Posey-Eddy
National Renewable Energy Laboratory

The DOE-NREL Minority University Research Associates Program (MURA) encourages minority students to pursue careers in science and technology. In this program, undergraduate students perform renewable energy research projects during the academic year with principal investigators at their universities and are awarded summer internships in industry or at national laboratories such as NREL during the summer. Once accepted into the program, students can work on a research project for 1–3 years. By providing renewable energy research opportunities, the program has proven to be very successful in retention of Historically Black College and University (HBCU) students in the science and technology areas and helping many students reach their educational and career goals. Because of its success, the program has been expanded to include additional minority-serving colleges and universities and all solar energy technologies. Each university will conduct research in 1–3 areas: Basic Research, Photovoltaic Panel Measurement and Testing, and Solar Radiation Profile Study. This expansion will also add Tribal and Hispanic-, Alaska Native-, and Hawaiian Native-serving college and university students to the program along with the HBCU students.

P023 – PV Education and Research at Southern University

Kara Broussard, Olu Yurkfen, and Snowden India
Southern University and A&M College, Baton Rouge, Louisiana

Through the Minority University Research Associates Program and a prior similar program, DOE and NREL have provided funds to Southern University A&M College over a 5-year period to train selected African-American undergraduate students majoring in physics, chemistry, and engineering in the renewable energy sciences and introduce them to graduate education focusing on photovoltaics. Four undergraduates during the academic year and summer, and one or two graduate students exclusively during summer, have been supported every year since 1999. The students were involved in research on fuel cells, rechargeable batteries, electrochemical supercapacitors, and solar energy systems, with an emphasis on the development of new materials and analysis, testing, and design of components at both the microscale and system levels. The PV associates of this project authored 4 papers in refereed journals and 30 conference papers. More than 10 students graduated during the project duration: three of them are pursuing Ph.D. degrees, two were admitted to medical school, and the remaining five accepted employment in government and corporate sectors. This program has also provided the opportunity for our students to interact directly with NREL scientific staff via securing summer employment.

P025 – Generating Hydrogen through Water Electrolysis using Concentrator Photovoltaics

Robert McConnell[1] and Jamal Thompson[2]
[1]National Renewable Energy Laboratory
[2]Howard University

Hydrogen can be an important element in reducing global climate change if the feedstock and process to produce the hydrogen are carbon free. Using nuclear energy to power a high temperature water electrolysis process meets these constraints while another uses heat and electricity from solar electric concentrators. Nuclear researchers have estimated the cost of hydrogen generated in this fashion and we will compare their estimates with those we have made for generating hydrogen using electricity and waste heat from a dish concentrator photovoltaic system. The conclusion is that the costs are comparable and low enough to compete with gasoline costs in the not too distant future.

P027 - Exploratory Research for New Solar Electric Technologies

Robert McConnell and Rick Matson
National Renewable Energy Laboratory

We will describe highlights of exploratory research for new PV technologies funded by the United States Department of Energy (DOE) through its National Renewable Energy Laboratory (NREL). The most recent set of 14 exploratory research PV projects, termed Beyond the Horizon PV, completed their third and final year of research in FY2004. The projects tend to take two notably different approaches: high-efficiency solar cells that are presently too expensive, or organic solar cells having potential for low cost although efficiencies are currently too low. As prime examples of what these last projects have accomplished, researchers at Princeton University recently reported an organic solar cell with 5% efficiency (not yet NREL-verified). And Ohio State University scientists recently demonstrated an 18% (NREL-verified) single-junction GaAs solar cell grown on a low-cost silicon substrate for use in concentrator PV systems.

P029 – Modeling and Control of High-Concentrator Photovoltaics for Hydrogen Production for Fuels Cells

James A. Momoh and Robert A. Sowah
Center for Energy Systems and Controls, Howard University

The electrolytic process of cracking hydrogen from water involves intense energy utilization. This could be achieved by using a system that uses electricity and heat generated from high-concentrator photovoltaic cells to separate hydrogen from water molecules in a solid oxide electrolyzer.

This paper takes into account advanced modeling techniques and dynamic performance evaluation for both PV and hydrogen fuel cells and assesses their integration impacts and feasibility. System transients for both standalone and grid connected networks will be investigated. Development of computational tools for power management and distribution as well as energy efficiency evaluation, component level economic analysis and contingency studies for both standalone and grid connected systems will form the core of the proposed research paper.

High-Performance PV

P031 – Identification of Critical Paths in the Manufacturing of Low-Cost High-Efficiency CGS/CIS Two-Junction Tandem Cells

Oscar D. Crisalle[1], Sheng S. Li[2], and Timothy J. Anderson[1]
[1]Chemical Engineering Department, University of Florida
[2]Electrical and Computer Engineering Department, University of Florida

This project investigated critical issues in the growth of CGS and CIS thin-film absorber layers for their use in a bilayer tandem solar-cell device. The absorber growth was done using the University of Florida plasma-assisted migration-enhanced epitaxial reactor (PMEE), and functional cells were fabricated and evaluated. The CGS absorber films were grown under copper-rich and copper-poor conditions. The CIS absorbers were fabricated using two bilayer precursors, namely, a binary Cu-Se layer and a binary In-Se layer is first deposited on a Mo/glass substrate at low temperature. Then rapid thermal processing (RTP) under a controlled Se ambient is used to synthesize single-phase CIS film. The experimental studies were complemented by a simulation and analysis studies that led to a proposition of an optimally graded CGS bandgap, and to the identification of a tandem cell configuration that can realize a 25% energy-conversion efficiency. Finally, equipment suitable for supporting multi-step electrodeposition process for CGS was constructed and commissioned

P033 – Determining Hole Carrier Mobilities Directly in Working CIGS Photovoltaic Devices

J. David Cohen[1], JinWoo Lee[1], and William N. Shafarman[2]
[1]Materials Science Institute, University of Oregon
[2]Institute of Energy Conversion, University of Delaware

Hole mobilities in CIGS are generally determined using the Hall effect with DC electrical conductivity measurements on samples having insulating substrates and co-planar contacts. However, such mobilities may not accurately represent the electronic behavior of CIGS when it is incorporated into photovoltaic devices. To obtain carrier mobilities within working cells we have developed a new approach using ac admittance measurements at frequencies up to 100MHz. These measurements allow us to clearly identify the conductivity within the undepleted portion of the absorber layer itself. Hole carrier densities are then determined using drive-level capacitance profiling (DLCP) at frequencies just below dielectric carrier freeze-out. Using this method we typically find hole carrier mobilities near 10 $cm^2V^{-1}s^{-1}$ in polycrystalline CIGS samples with Ga fractions close to 30at.%. Hole mobilities have been determined in this fashion for CIGS sample devices with varying grain sizes, and also following long term light exposure.

P035 – Novel Polycrystalline Thin-Film Solar Cells

Eric Harmon[1], David Salzman[1], Jim Hyland[1], Robert Kouldelka[2], and Jerry Woodall[2]
[1]LightSpin Technologies, Inc.
[2]Yale University

LightSpin Technologies Inc, is developing new polycrystalline thin-film solar cells using compound III-V semiconductors. GaInP solar cells structures with a 1.6 eV band gap have demonstrated internal collection efficiencies in excess of 80% in spite of a high density of threading dislocations. No degradation in quantum efficiency was observed in solar cells made to simulate polycrystalline material by means of stars-and-stripes patterns etched lithographically with a very large fraction of mesa side-wall surface area and 6 μm grain sizes. The experimental results indicate that polycrystalline GaInP with average grain sizes as small as 5 μm can be used for high efficiency solar cells.

P037 – InGaP/InGaAs/Ge Triple Junction High Concentration Solar Cell Development at Emcore Photovolataics

Mark Stan, Daniel Aiken, Paul Sharps, Jen Hills, and John Doman
Emcore Photovoltaics

The goal of this project is to develop a high efficiency 3J solar cell as an enabling element for a 33% efficient receiver. The starting point of this cell development program was the Emcore production 3J space solar cell. This project has focussed on changes to the basic cell design that are necessary for high concentration applications. Characterization of the cell has been accomplished with the use of a high intensity pulsed solar simulator (HIPSS). Cell efficiencies as high as 33% at 350X (HIPSS measurement, 28C) have been observed for our 1.08cm^2. Outdoor measurements have been made with the use of a Fresnel lens-based receiver to geometrical concentrations of 522X. A discussion of the relationship between the 3J cell performances observed with the HIPSS and outdoor spectra will be presented. Finally, a discussion of potential modifications to the present cell design for still higher conversion efficiency will be presented.

P039 – InGaN Solar Cells

Christiana B. Honsberg[1], William A. Doolittle[2], Ian Ferguson[2], Omkar K. Jani[2], and Elaissa Trybus[2]
[1]Department of Electrical and Computer Engineering, University of Delaware
[2]School of Electrical and Computer Engineering, Georgia Institute of Technology

InGaN offers several advantages for solar cells, because of its wide band gap range and other unique properties such as strong polarization effects. The technology of InGaN material differentiates between the In-lean, high band gap alloys, which are commercially used for light emitting diodes grown using MOCVD, and the In-rich low band gap material grown primarily using MBE. This paper examines the critical material aspects in both the high and low band gap InGaN material. The paper presents analysis of p-i-n high band gap InGaN solar cells to determine key material parameters and the dominant loss mechanisms. The most important issue in the low band gap In-rich material is the analysis of the material quality and optimization of growth conditions, substrate and buffer layer. The paper presents experimental results that show InN growth on Ge, using AlN and Al as a buffer layer.

P041 – Toward-40% Efficient Mechanically Stacked III-V Terrestrial Concentrator Cells

Lewis M. Fraas[1], James E. Avery[1], Han-Xiang Huang[1], Keneth Edmondson[2], and Richard R. King[2]
[1]JX Crystals Inc.
[2]Spectrolab Inc.

Considerable progress has been made with monolithic multijunction cells based on InGaP-GaAs-Ge triple junction (3J) cells. However, the theoretical limit efficiency for this cell at 500 suns, 300 K, and AM1.5D is 42%. Meanwhile, the theoretical efficiency limit for a 3J cell consisting of an InGaP-GaAs 2J cell mechanically stacked on a GaSb cell is 46% because the lattice match and current match constraints are removed. Furthermore, the theoretical limit efficiency for a 4J mechanically stacked 2J+2J cell is 52%. This paper presents preliminary results using dual junction GaInP-GaAs cells mechanically stacked on GaSb as an alternative for high-efficiency concentrator devices. Experimental results are shown for a batch of GaSb single junction bottom cells. A description of the mechanical stack is given. The top two subcells will consist of GaInP-GaAs grown on GaAs substrates by MOVPE. Improvements of optical transmission through the anti-reflection coated GaAs substrate are discussed.

P043 – Advances in III-V Heterostructures and Solar Cells on SiGe/Si Substrates

Steven A Ringel[1], Carrie L. Andre[1], Eugene A. Fitzgerald[2], and David Isaacson[2]
[1]The Ohio State University
[2]Massachusetts Institute of Technology

We review research progress on III-V single and multi-junction materials and cells grown on Si using SiGe interlayers to engineer the substrate lattice constant. The first lattice-matched InGaP/GaAs dual junction cells were grown and processed on SiGe/Si substrates, yielding high open circuit voltages, in excess of 2 volts, on Si. Analysis shows that cell performance is limited by current mismatch in this first cell generation, with cell parameters retaining more than 92% of the values obtained for homoepitaxial control cells. Additionally, single junction GaAs cells on SiGe/Si have reached efficiencies in excess of 18% under AM1.5G conditions. This presentation will focus on the growth and properties of the novel dual junction on Si structures, key issues for next steps, and recent results of GaAs growth on a newly optimized SiGe substrate for which we have broken through the 10^6 cm^{-2} threading dislocation barrier for Ge on Si.

P045 - A Scaleable High-Concentration PV System

Stephen M. Kusek
Concentrating Technologies, LLC

Concentrating Technologies, LLC (CT) is developing a reflective optical system for use with high efficiency PV cells to create a high concentration PV (HCPV) system that has a "small" fundamental power conversion unit that can be combined to form single pedestal, two-axis tracking systems with ratings from tens of watts to over 70 kilowatts with current tracking system technology. CT has performed extensive work with Spectrolab to create a number of HCPV power conversion units. Under this development project, CT will enhance the design of their current prototype system to increase its efficiency, power, and reliability. A prototype unit will be installed at the Arizona Public Service Solar Test And Research (APS STAR) facility and undergo utility-type testing to uncover system characteristics that require further development before limited production of this type of multi-junction concentrator system can be considered.

P049 – Enhanced-Depletion-Width GaInNAs Solar Cells Grown by Molecular-Beam Epitaxy

A.J. Ptak and D.J. Friedman
National Renewable Energy Laboratory

The four-junction $GaInP_2$/GaAs/GaInNAs/Ge solar cell is capable of achieving greater than 40% efficiency, although these devices are presently current limited by the GaInNAs subcell. The highest QE values reported anywhere for GaInNAs are below 0.75. A p-i-n structure with a wide depletion width can greatly increase the current collection, and hence QE, from GaInNAs, but depletion widths are typically about 0.2 μm for as-grown MOCVD material. In this paper, we report on the molecular-beam epitaxy growth of GaInNAs with depletion widths greater than 3 μm and corresponding QEs greater than 0.9 for bandgaps approaching 1 eV. This represents significant progress towards a 1-eV junction usable in the four-junction structure.

P051 – An On-Sun Comparison of $GaInP_2$/GaAs Tandem Cells with Top Cell Thickness Varied

W.E. McMahon, K.E. Emery, D.J. Friedman, J.S. Ward, and Sarah Kurtz
National Renewable Energy Laboratory

To maximize the performance of $GaInP_2$/GaAs tandem cells and $GaInP_2$/GaAs/Ge triple-junction cells, the top $GaInP_2$ cell must be "thinned" slightly to allow some above-band-gap photons to pass through to the GaAs bottom cell. Because the solar spectrum changes throughout the day, different top cell thicknesses (t_{top}s) are optimal for different times of the day. Nonetheless, when tandem cells are manufactured for use in a concentrator system, a single t_{top} must be specified. This study is intended to aid in that selection. A set of $GaInP_2$/GaAs tandem cells with five different t_{top}s was mounted outdoors on a two-axis tracker for direct comparison. Incident sunlight was collimated to exclude all except the direct beam. Measurements made throughout a typical sunny day are summarized and compared to a cell performance model, which can then be used to guide cell design at other sites where the spectral variations may be different.

P053 – Integrating Deposition, Processing, and Characterization Equipment within the National Center for Photovoltaics

Brent P. Nelson, Steven Robbins, and Peter Sheldon
National Renewable Energy Laboratory

To gain important knowledge about process sequencing, growth chemistry and kinetics, interface characteristics, and an understanding of how these interfaces affect photovoltaic (PV) device performance, the National Center for Photovoltaics (NCPV) is developing new tools that will facilitate these investigations. The existing tool base in the NCPV cannot be integrated with other tools such that samples can be transferred between tools without contamination. Additionally, current NCPV tools use different substrate sizes, and lack the ability to be retrofitted with state-of-the-art in-situ or real-time analytical capabilities. The Process Integration Project will establish the infrastructure to overcome these shortcomings. Ultimately, the synergistic effort by NREL staff, universities, and the PV industry, working together around an integrated tool base, will add to the knowledge base, helping many PV technologies to advance. This paper is an overview of the project's status and direction.

P055 – Electron Microscopy Studies of GaP(NAs) Grown on Si

Andrew G. Norman, John F. Geisz, Jerry M. Olson, Kim M. Jones, and Mowafak M. Al-Jassim
National Renewable Energy Laboratory

GaP(NAs) grown lattice-matched on Si is of increasing interest for optoelectronic devices, e.g., LEDs and solar cells. High efficiency solar cells grown on Si substrates offer many advantages, including low cost, large area, robust substrates, and potential for integration with mature Si technology. GaP(NAs) alloys can be grown lattice-matched to Si with a direct energy gap in the optimum range for a high efficiency tandem solar cell. In this work, we report TEM studies of the defect structure and alloy homogeneity of GaP(NAs) alloys grown by MOCVD on Si substrates. Antiphase domains are generated at the GaP(NAs)/Si interface due to surface roughness. High threading dislocation densities can be observed, often associated with poor nucleation of the III-V layer. In addition, the GaP(NAs) alloys are found to atomically order during growth despite containing only a few percent of N.

P057 – **Electron Traps Detected in p-type GaAsN Using Deep Level Transient Spectroscopy**

Steven W. Johnston, Sarah R. Kurtz, Daniel J. Friedman, Aaron J. Ptak, and Richard K. Ahrenkiel
National Renewable Energy Laboratory

The GaAsN alloy can have a band gap as small as 1.0 eV when the nitrogen composition is about 2%. Indium can also be added to the alloy to increase lattice matching to GaAs and Ge. These properties are advantageous for developing a highly efficient, multi-junction solar cell. However, poor GaAsN cell properties, such as low open-circuit voltage, have led to inadequate performance. Deep-level transient spectroscopy data of p-type GaAsN has identified an electron trap having an activation energy near 0.2 eV and trap density up to 10^{16} cm^{-3}. This trap appears with the addition of small amounts of nitrogen to GaAs, which also corresponds to an increased drop in open-circuit voltage.

P059 – Correlation of DLTS and Performance of GaInNAs Cells

Sarah Kurtz and Steve Johnston
National Renewable Energy Laboratory

A four-junction GaInP/GaAs/GaInAsN/Ge solar cell should be able to reach 40% efficiency if each of the junctions can be made with a quality similar to that demonstrated for GaAs. However, the GaInAsN subcell has shown poor performance. Deep level transient spectroscopy (DLTS) can elucidate recombination centers in a material and could help identify the problem with the GaInAsN. DLTS studies of GaInAsN have shown many peaks. In this paper we compare the performance of the GaInAsN solar cells with the DLTS spectra to identify which DLTS peak is correlated with the device performance.

Thin Films: CIS and CdTe

PO61 – CdTe: How Thin Can It Be And How Does Chloride Activation Change Grain Boundaries?

Alvin D. Compaan, Akhlesh Gupta, and Xiangxin Liu
University of Toledo, Dept. of Physics and Astronomy

The thickness of CdTe cells is usually far greater than needed for optical absorption, and CdTe reduction has many advantages. We have used magnetron sputtering to prepare a series of CdS/CdTe cells on TEC-7 glass with CdTe thickness ranging from 2.5 to 0.5 µm. When all other processing parameters and cell components are held constant, the efficiency decreases only 25% at 0.68 μm of CdTe. Furthermore, the thin cells showed no greater degradation under stress than sputtered cells with 2.5-μm-thick layers. Optimization of processing and back contacting for the thinner layers improves these results. Good performance with thin, and therefore small-grained, CdTe implies excellent grain boundary passivation. Some indirect evidence of grain boundary chemistry has been obtained from x-ray fine structure at the Argonne APS. We find a transition from a Cu_2Te to a Cu_xO-like environment depending on the $CdCl_2$ treatment.

P063 – Impurity Effects in Two-Step Processing of CIGS Solar Cells

H. Sankaranarayanan, V. Mohanakrishnaswamy, S. Pethe, C. S. Ferekides, and D. L. Morel
Department of Electrical Engineering, University of South Florida

We have undertaken evaluation of the effect of impurities on CIGS device performance. With regard to impurities related to the vacuum ambient we find that residual air and moisture reduce the effective utilization of In and Ga, and that Cu deposited in a selenium-free environment does not allow adequate Ga bonding to increase the band gap. We also modulated the access of Na and other impurities from the soda lime glass substrate by use of Si_3N_4 blocking layers and by varying the Mo deposition conditions. Small changes in the back contact properties can have significant influence on device performance. Most of the observed changes are explainable in terms of Na. The model that seems most consistent with the observations is one in which Na acts as a catalyst to oxidation of V_{Se} changing them from donors to acceptors. In combination with V_{Cu} acceptors the resulting compensation level largely determines device performance.

P065 – Contact and Stability Studies of CdTe Solar Cells

Chris S. Ferekides, Krishnakanth Barri, Vijay Viswanath, Swetha Erra, and Don L. Morel
University of South Florida, Department of Electrical Engineering, Clean Energy Research Center

This paper reviews results related to the back contact process and the use of copper, two key factors that affect the performance and long-term stability of CdTe cells. A dry rf-sputter etch process has been developed as a cleaning step for the preparation of the CdTe surface prior to the back contact formation, therefore eliminating the use of wet chemistry, as well as the presence of excess Te on the CdTe surface or grain boundaries. A process where copper is introduced in the devices prior to all the high temperature process steps is also being developed. To-date results on device performance and stability are very encouraging, and this approach may provide a means of effectively controlling the amount of copper. CdTe cells with varying amounts of copper in the back contact are being light soaked in order to establish a correlation between the amount of copper and long-term stability.

P067 – CdTe and CIGS Numerical Simulations: When Are They Helpful?

James R. Sites and Markus Gloeckler
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Numerical simulations are extremely useful for the analysis of CdTe and CIGS thin-film solar cells, since these technologies often show irregular diode behavior that is difficult to evaluate analytically. The complexity of these devices also results in a number of difficult-to-measure parameters that complicate unique fitting of individual current-voltage curves. Several successful investigations, however, have focused on explanations for distinct features seen in the performance curves and on predictions that can assist with the design and prioritization of new experiments. The most frequently occurring irregularities in CdTe and CIGS cells are non-superposition due to photoconductivity in the buffer and window materials, the impact of band alignment on junction recombination, the band-gap grading common to CIGS solar cells, and secondary barriers at the front and back of CdTe devices. Examples of these features are used to demonstrate the explanatory and predictive capabilities of numerical simulations.

P069 – Local J-V Curves from LBIC Measurements

Tim J. Nagle and J.R. Sites
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LBIC (light-beam induced current) is routinely used to measure the local quantum efficiency of solar cells. Interpretation of forward-bias LBIC measurements as local light J-V data points is less straightforward, because the current and voltage effects of the non-illuminated portion of the cell must be assessed. By inclusion of the measured properties of the cell's dark diode curve, we approximate a light J-V curve at each point on the cell with spatial resolution as high as 1 μm. Since the dark diode curve itself is not spatially resolved, this technique is less sensitive to local effects than if the exact local dark curve were available. Conclusions can be drawn about series resistance, shunt resistance, and diode quality factor at specific points throughout a cell. These parameters can be traced to cell manufacturing processes, and therefore this technique has the potential to improve cell performance and stability.

P071 – Effect of CdTe and CIGS Thickness on Cell Efficiency: Experiment Versus Simulation

Alan L. Fahrenbruch
Colorado State University

For small absorber thickness (d), J_{sc} increases strongly with d as the integrated absorption increases (e.g., to ≅ 95% of its maximum value at d ≅ 0.8 micron of CdTe). However, CdTe and CIGS have small minority carrier diffusion lengths and field-aided collection is important so, for larger d, J_{sc} is expected to decrease with increasing d. The changes in cell output depend on a complex interplay among the optical absorption, carrier recombination, and the conduction band profiles, so modeling and simulation are valuable and can even be predictive in this case. The relationships between d and PV properties J_{sc}, V_{oc}, FF, Eff, and QE for several types of CdTe and CIGS devices will be shown, ranging from n/i/p devices in which the absorber layer is slightly n-type or insulating (junction barrier supported by the contacts), to appreciably p-type absorbers (junction barriers are supported by charge within the absorber).

P073 – Development of Large-Area CIGSS Thin-Film Solar Cells

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$CuIn_{1-x}Ga_xSe_{2-y}S_y$ (CIGSS) is a promising material for thin film PV cells. CIGSS/CdS solar cells are being prepared routinely on glass and metallic foil substrates for terrestrial and space applications. Earlier, the substrate size has been enhanced from 2.5 x 2.5 cm^2 to 15 x 10 cm^2. Best efficiency of 10.4% has been achieved on stainless steel substrate. During this year, a vacuum system was refurbished for evaporation of NaF by Joule heating prior to selenization. A setup has been developed for selenization of metallic precursors using diethylselenide as selenium source. Four-hearth electron-beam system was commissioned together with quartz crystal rate and thickness monitor for depositing Ni/Al contact fingers through mechanical mask. I-V and QE setups have been developed for cell characterization. The development of thin film deposition units and new characterization setups have facilitated research on large sizes comparable to those in PV industry.

P075 – Defect Physics and Chemistry in Thin-Film CdTe Solar Cells

Tim R. Ohno, Victor I. Kaydanov, Reuben T. Collins, Scott Feldman, and Fred Seymour
Colorado School of Mines

The presence of deep electronic states (DES) in excess of the apparent doping concentration has been reported for many polycrystalline photovoltaic devices. The origin of the defects has been associated with processing steps that introduce chemical defects and is also related to the polycrystallinity of the material. The impact of these DES on device performance is discussed based on modeling. In this paper we will report on measurements of these DES using luminescence techniques, photoluminescence (PL) and electroluminescence (EL), and impedance/transient studies for cells completed with different $CdCl_2$ and copper treatments. Spectral studies show that EL originates only from the CdTe absorber layer, and is more highly structured than PL, providing more insight into the DES. The primary goal is to determine the signatures of copper and chlorine that can be used to study degradation processes as well as the characteristics of high efficiency cells.

P077 – Study of Deep Electronic States in CdTe Solar Cells with Capacitance Transient Measurements

Fred H. Seymour and Victor Kaydanov
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In differently processed and stressed CdTe solar cells, numerous deep electronic states (DES) were detected and studied with admittance spectroscopy and capacitance transients (CTrs) measurements. Characteristic times of these DES range from microseconds to hundreds of seconds. Long-term (hours, days) transients with essentially non-exponential time dependencies have also been observed. Densities of some DES exceed the doping level, which creates misleading C-V doping profile results. In addition, CTrs induced by light with above- and sub-bandgap wavelengths have been detected and follow up photo-capacitance spectroscopy studies of DES are anticipated. Our system has a custom-built sample stage specifically designed to maintain stable temperatures for extended periods of time (drift $< 0.1K$ per minute) allowing for detection of subtle temperature dependencies with slow CTrs. Overall, the study of long-term transient effects in capacitance and photoelectric parameters will help reveal and characterize the processes behind CdTe solar cell degradation.

P079 – Defect Studies of CdTe Cells Using Spatially and Spectrally Resolved Electro-Optical Methods

S. D. Feldman, T. R. Ohno, R. T. Collins, and V. Kaydanov
Colorado School of Mines

Electroluminescence (EL) and Photoluminescence (PL) were studied on the exact same areas of a CdS/CdTe solar cell. The CdTe was non-uniformly doped with Cu evaporated through a shadow mask. EL emission was brighter over Cu doped regions at room temperature, while the pattern inverted at temperatures below 100 K. PL measurements showed no correlation with the Cu pattern when integrated over all energies. However, both PL and EL originating from Cu doped regions were more intense at lower energies, whereas undoped regions displayed more emission originating from shallower states. These small differences in spectra were discernible only with the patterned doping and spatially resolved characterization used here. Along with the inversion of the EL pattern at low temperature, the spectral data suggests a model in which Cu is most electrically active as a dopant in the form of Cd substitutionals, replacing Cd vacancies or a related complex.

P081 – Non-Uniformities in CdS/CdTe Cells Deposited on Buffer Layers

Joseph D. Beach, Lorelle M. Mansfield, Scott D. Feldman, Reuben T. Collins, and Timothy R. Ohno
Physics Department, Colorado School of Mines

CdS/CdTe "superstrate" solar cells were grown using chemical bath deposited CdS and gas jet deposited CdTe. One set of samples used a single layer of SnO_2:F, while the other used a bilayer of undoped SnO_2 on SnO_2:F. The highest efficiency single layer cell was 7.0%, while that for the bilayer was 11.4%. Electroluminescence images showed single layer cells were less uniform than bilayer cells. Optical and atomic force microscope studies of the CdS on similar samples showed bright raised spots in the CdS with the same density as the bright spots in electroluminsecence images. Ongoing work seeks to determine whether the raised spots in the CdS result in bright spots in the EL images.

P083 – Multiple-Wavelength Near-Field Scanning Optical Microscopy Study of Thin-Film Polycrystalline Solar Cells

J. M. Yarbrough, and R. T. Collins, J. D. Beach, V. Kaydanov, and T. R. Ohno
Colorado School of Mines

A near field scanning optical microscope (NSOM) has been built for use in characterization of polycrystalline thin film solar cells. The design goal is to house the microscope in a vacuum chamber, allowing measurements at low temperatures. The NSOM is presently being tested in air by performing spatially resolved photocurrent measurements on both planar and cross-sectional CdTe samples as well as planar measurements on CIGS samples. The optics allow multiple optical wavelengths ranging from blue to infrared to probe the device simultaneously. Preliminary results on planar samples show a contrast in photocurrent between the grains and grain boundaries in certain samples. Cross-sectional measurements show changes in photocurrent magnitude across the junctions of CdTe devices.

P085 – Advances in Continuous In-Line Processing of CdS/CdTe Devices: Stability and Scale-Up

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Materials Engineering Laboratory, Department of Mechanical Engineering

Utilizing a continuous, in-line pilot scale system, optimal process conditions for CdS/CdTe PV fabrication have been developed. It has been observed that small process changes (particularly the $CdCl_2$ process) can lead to significant differences in device stability. After nearly 3 years of outdoor exposure optimally processed devices show little or no efficiency change on average. Average efficiencies of devices remain over 10% after thousands of hours of accelerated stress. There is a leveling of efficiency loss for devices subjected to extremely long duration accelerated stress. An empirical factor correlating accelerated stress and outdoor exposure conditions is being developed. A quality control metric and defect analysis method have been developed for our process which enables the prediction of device stability without subjecting the devices to stress. The development of a joint venture with National Starch and Chemical has progressed. A 2 MW/year CdTe PV production prototype is currently under construction.

P087 – Large Area CIGS Films and Modules Produced by a Hybrid Process, and High-Performance TCOs

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Energy Photovoltaics, Inc.

We report process optimization resulting in high quality $Cu(In,Ga)Se_2$ (CIGS) films and high efficiency devices/modules using a hybrid process for CIGS formation. In the hybrid process, the Cu is supplied by magnetron sputtering, and the In, Ga, and Se are supplied by linear thermal sources. The advantages of sputtering the Cu include the ease and precision of thickness control, and good thickness uniformity. The investigation is conducted in a pilot-line system using 0.43 m^2 glass substrates. Among others, important parameters were found to be peak and final Cu/(In+Ga) ratios, selenization temperature, and Ga depth profile. Diagnostic cell efficiencies reaching 13% and module efficiencies of 7.5% (0.35 m^2, 26W) have been achieved. Continued improvement in module performance is expected. The use of reactive-environment, hollow cathode sputtering to produce transparent conductors having superior near-IR transmission (electron mobilities >80 cm^2/Vs) will also be described, together with first applications to the CIGS field.

P089 – Outdoor Monitoring of Thin-Film PV Modules in Hot and Humid Climate

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Energy Systems Laboratory, Texas A&M University

Research under this project is to install thin film PV modules in high voltage arrangements and monitor the performance of the arrays over time and under various conditions as determined by the weather in a hot and humid climate. Work during Phase I progressed in four major areas:

construction of the test stand, construction of the weather stand, construction of the data acquisition and reporting system, and the installation and monitoring of the PV arrays. The test stand construction has been completed. The weather station has been built and populated with sensors. All solar sensors are being calibrated by NREL. The construction of the data acquisition system has been completed. Modules have been received from two manufacturers and are being installed. Phase II work will focus on the monitoring of the PV arrays and the condition of the modules.

P091 – Fabrication of CIGS Solar Cells via Printing of Nanoparticle Precursor Inks
Vijay K. Kapur, Ashish Bansal, Omar Asensio, Neil Shigeoka, and Phucan Le
International Solar Electric Technology, Inc. (ISET)

ISET has been successfully fabricating CIGS solar cells using water based precursor inks to deposit the CIGS absorber layers. Precursor inks are water based colloidal suspensions of nanoparticles of mixed oxides of Cu, In and Ga and are called 'pigmented' inks. They can be printed on a variety of rigid and flexible substrates in any desired pattern by various printing techniques including inkjet printing. After drying they are annealed under an atmosphere of hydrogen gas to convert them into continuous films of Cu-In-Ga alloys which are further reacted under an atmosphere of H_2 Se gas to form the CIGS absorber layers. Solar cell fabrication is completed by depositing CdS via a CBD process followed by the deposition of ZnO layer via an OMCVD process. With this patented process we have fabricated CIGS solar cells with their efficiencies on glass (13.7%), on Mo foil (13.0%) and on polyimide (9.0%). The Cu/(In + Ga) ratio is fixed molecularly in the precursor ink which results in the CIGS absorber layer of uniform composition; the printing process is an 'additive' process with a materials utilization > 95% and the processing equipment for this non-vacuum process is generally inexpensive. Additionally, ISET fabricates CIGS solar cells in which the current collection is carried out with printed grids on top of the ZnO layer which allows us to vary the dimensions of the solar cells. These inherent features of ISET's process, help achieve high process yields and lower the costs of manufacturing CIGS solar cells. In this paper we will describe the successes and challenges of commercializing ISET's process.

P093 – Liquid-Phase Deposition of $CuInSe_2$ Thin Films
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CIS (α-$CuInSe_2$) is a leading candidate material for absorber layers in high-specific-power photovoltaic devices, e.g., for space applications. However, the routinely achieved conversion efficiency of CIS-based solar cells is much less than the theoretical conversion efficiency of 24%.[1] This has been attributed to current fabrication techniques, which usually generate a high density of structural defects (phase boundaries, grain boundaries, dislocations). Exploiting the newly established Cu–In–Se equilibrium phase diagram, we are investigating the feasibility of growing single-phase, coarse-grained, CIS films with low defect concentration from off-stoichiometric solutions.[2] We report first results of growth experiments and microcharacterization of these films.

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1. J. R. Sites: Separation of voltage loss mechanisms in polycrystalline solar cells, in: IEEE Photovoltaic Specialists Conference 06160-8371 (1988), IEEE, USA, pp. 1604-1607.
2. J. Cowen, L. Lucas, F. Ernst, P. Pirouz, A. Hepp, S. Bailey: Liquid-Phase Deposition of Single-phase Alpha-Copper-Indium-Diselenide, Materials Science and Engineering B, in press.

P095 - Formation of Chalcogen-Containing Plasmas and Their Use in Synthesis of Photovoltaic Absorber Layers

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The synthesis of copper chalcopyrite solar absorbers requires high temperature and excess chalcogen due to low chalcogen reactivity. This paper describes work aimed at addressing these issues through plasma processing. An inductively coupled plasma (ICP) source was used to activate both sulfur and selenium vapors into high-energy atomic and radical species. ICP processing configurations are described for both a flowtube geometry used for metal selenization and a high vacuum co-evaporation environment. The potential of this approach was demonstrated by converting indium and Cu/In/Ga films to chalcopyrites using the ICP source. It is shown that indium is readily converted to In_2Se_3 using argon/selenium plasma at room temperature. Similarly, Cu/In/Ga precursor thin films on a stainless steel substrate were exposed to plasma-activated selenium at 300^{o}C. The foils were converted into ternary and quaternary chalcopyrite compounds, and no crystalline binary phases (i.e. In_2Se_3/CuSe) were observed.

P097 – Nanostructure and Nanochemistry of Cu(In,Ga)Se_2 Materials

Changhui Lei, Chunming Li, Angus Rockett, and Ian Robertson
Department of Materials Science and Engineering, University of Illinois

The nanostructure and nanochemistry of semiconductors determines electronic device performances through effects on band structure and defect states. We performed atomic-resolution studies of chalcopyrite solar cell materials obtained from a wide variety of laboratories producing high-performance devices. We find no correlation between any of the common structural defects [twins, dislocations, stacking faults, or voids] on performance. However, evidence suggests that grain boundaries in lower-performance materials are significantly more disordered than in higher performance materials and the CIS/CdS heterojunction seems to vary significantly. There is no evidence of a change in nanochemistry at grain boundaries in measurements to date. Furthermore, there is no evidence of large quantities of Na in grain boundaries or in the heterojunction. The solar cell performance is probably determined by details of the heterojunction chemistry at the single-atomic layer scale and by the distribution of point defects in the materials.

P099 – Application of Combinatorial Tools for Solar Cell Improvement—New High-Performance Transparent Conducting Oxides

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Transparent conducting oxides (TCOs) can serve a variety of important functions in thin film photovoltaics such as transparent electrical contacts, antireflection coatings and chemical barriers. Two areas of particular interest are TCOs that can be deposited at low temperature and TCOs with high carrier mobilities. We have employed combinatorial high-throughput approaches to investigate both these areas. Conductivities of $\sigma = 2500\ \Omega^{-1}\text{-cm}^{-1}$ have been obtained for In-Zn-O (IZO) films deposited at 100°C and $\sigma > 5000\ \Omega^{-1}\text{-cm}^{-1}$ for In-Ti-O (ITiO) and In-Mo-O (IMO) films deposited at 550°C. The highest mobility obtained was 83 cm^2/V-sec for ITiO deposited at 550°C. Compositionally graded samples (“libraries”) are deposited by co-sputtering onto 2”x2” glass substrates. The libraries are characterized by automated combinatorial mapping tools including EPMA for metals stoichiometry, 4-pt. probe for sheet resistance, UV/VIS/NIR (200–2000 nm) reflection and transmission, FTIR optical reflection and transmission (1.8–25 μm) and x-ray diffraction (XRD) using a large-area 2D detector.

P101 – Barrier Coatings for Thin-Film Solar Cells

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Pacific Northwest National Laboratory

Barrier coatings for thin film solar cells may be very critical for achieving reliable and long lived devices. Coatings based on a multilayer polymer/oxide approach developed at PNNL for OLEDs are being investigated as effective moisture barriers for thin film solar cells. CIGSS circuits provided by Shell Solar Industries (SSI) and CdTe cells fabricated by the W.S. Sampath and coworkers at Colorado State University (CSU) are being utilized for the study. Barrier coatings involve deposition of a relatively thick polymer layer to establish a smooth surface for subsequent deposition of an oxide layer. Deposition of the first polymer/oxide dyad is followed by one or more additional pairs of polymer/oxide dyads. Coated devices have undergone accelerated testing in an environmental chamber set at 60ºC/90%RH. Whereas uncoated CIGSS circuits degrade very rapidly, the efficiency of circuits with barrier coatings decrease less than 10 % after 1800 hours. Work with CdTe cells was initiated only recently. The CSU has a relatively rough and thick back contact with a superstrate configuration. In order to have a relatively smooth surface for application of a barrier coating, the CSU back contact is removed and replaced by sputtered a sputtered contact at PNNL. Very encouraging results have been obtained for encapsulated CdTe cells based on this approach.

P103 – XPS and UPS Studies of Thin-Film PV Materials Modified by Reactions in Liquids

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Water-based processing steps are ubiquitous in the semiconductor industry, and the field of photovoltaics is no exception. Currently the best thin film $Cu(In,Ga)Se_2$-based solar cells use an n-type "buffer layer" of a sulfide, usually CdS, that is deposited on the p-type absorber via an aqueous chemical bath. Thin film devices based on CdTe are often subjected to an aqueous processing step to improve the performance of the back contact. The complex chemical reactions occurring both on the surface of the absorber and in solution are poorly understood, yet have been shown to have powerful effects on the performance in terms of reliability and efficiency of finished devices. In the past, electron spectroscopic studies of these reactions have been hampered by the conflicting requirements of ultra-high vacuum and exposure of samples to liquid water. In this paper we present initial results from a new tool at NREL that allows one to conduct atmospheric pressure, liquid phase chemical processes on thin film PV materials and subsequent examination via core and valence level electron spectroscopies without exposing samples to air contamination.

P105 – In-Situ Investigation on Reaction Mechanism and Kinetics of $CuInSe_2$ Formation from Cu-In/Mo/Glass Precursor during Selenization

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High-temperature X-ray diffraction (HT-XRD) was used to investigate the reaction mechanism and kinetics of $CuInSe_2$ formation from Cu-In/Mo/glass precursor during selenization. The Cu-In/Mo/glass precursor was prepared in a migration enhanced molecular beam epitaxial (MEE) reactor on Mo coated ultra thin glass substrates. The atomic composition (Cu/In atomic ratio ~ 1) and structure (Cu_2In, $Cu_{11}In_9$ and CuIn) of as-deposited precursor were determined by ICP and XRD, respectively. Selenium powder was placed in the XRD sample holder chamber with the precursor sample. During the selenization of Cu-In/Mo, the generation of CuSe followed by transformation of CuSe to $CuSe_2$ at higher temperature was observed. The formation of $CuInSe_2$ was observed to be initiated at a temperature between 250 and 300^{o}C. Additionally, the production of $MoSe_2$ was clearly detected at a temperature above 400^{o}C. The reaction kinetics was investigated based on the analysis of the time-resolved XRD data.

P107 – Pulsed-Laser Annealing and Rapid Thermal Annealing on CIGS Solar Cells

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The effects of Pulsed Laser Annealing (PLA) treatment using a specially designed, long pulse Excimer laser on the film properties and the performance of CIGS solar cells have been studied under various irradiation conditions. SEM surface feature size increase suggests near surface structure changes upon laser annealing treatment. Dark- and photo- J-V, and QE results show explicit improvement on diode quality factor, cell performance, and spectral response. Deep- level transient spectroscopy (DLTS) results show a 50% reduction of a shallow-level defect density after low power PLA. The laser energy density and pulse number used were found to play a key role in modifying the optical and electrical properties of the CIGS films and hence the cell performance. In addition, progressive rapid thermal annealing (RTA) was performed on NREL CIGS cells, and photo- J-V results reveal that RTA treatment can greatly improve the overall uniformity and performance of CIGS cells.

P109 – Growth and Characterization of $Zn_xCd_{1-x}S$ Buffer Layers by Chemical Bath Deposition for $CuGaSe_2$ and $Cu(In,Ga)Se_2$ Solar Cells

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$Zn_xCd_{1-x}S$ films were deposited on the SLG substrates by CBD process. As- deposited $Zn_xCd_{1-x}S$ films with x = 0.3 and 0.5 were characterized by SEM and spectrophotometer to analyze the surface morphology and optical transmission spectral characteristics. ZnCdS films may be used as buffer layers for $CuGaSe_2$ or $Cu(In,Ga)Se_2$ solar cells. The deposition rate decreased with increasing mixture ratio of $x = [ZnCl_2]/([ZnCl_2]+[CdCl_2])$ in the solution. The results showed that grain size on the film surface grew larger with increasing Zn content. It showed more than 70% transmittance at wavelengths longer than 600 nm. For $Zn_{0.3}Cd_{0.7}S$ films with thickness in the range of 10 to 20 nm, over 80% transmittance at shorter and longer wavelengths were obtained, while films with thickness of 80 nm has a 70% transmittance at wavelengths longer than 600 nm. The results of CBD ZnCdS buffers deposited on CGS and CIGS cells will be given in this paper.

P110 – Spatially Resolved Studies of Grain-Boundary Effects in Polycrystalline Solar Cells Using Micro-Photoluminescence and Near-Field Microscopy

S. Smith, R. Dhere, T. Gessert, P. Stradins, and A. Mascarenhas
National Renewable Energy Laboratory

Photoluminescence and photocurrent spectroscopies combined with diffraction-limited and sub-diffraction-limited spatial resolution are achieved via micro-photoluminescence (μ-PL) and near-field microscopy (NSOM). These methods are used to examine the photo-response of individual grain boundaries in thin-film, polycrystalline solar cells at room and cryogenic temperatures. A systematic μ-PL study of the effect of $CdCl_2$-treatment on recombination in CdTe/CdS solar cell structures of varying thickness directly reveals the grain-boundary and surface passivation action of this important post-growth processing step. We achieve 50nm (λ/10) spatial resolution in near-field Optical Beam Induced Current imaging (n-OBIC) of polycrystalline silicon solar cells using NSOM, at varying stages of silicon nitride grain-boundary passivation, and measure lateral variations in photo-response of CdTe/CdS solar cells with subwavelength spatial resolution.

P111 – Non-Vacuum Processing of CIGS Solar Cells

Chris Eberspacher, Karen L. Pauls, and John P. Serra
Unisun

This project is directed at developing low-cost, non-vacuum techniques for fabricating photovoltaic (PV) solar cells based on thin-film $Cu(In,Ga)Se_2$ (CIGS). Processes for forming both CIGS optical absorber films and metal oxide transparent conducting electrode coatings are being developed. The aim is to accelerate the commercialization of thin-film PV technology by reducing the cost and complexity of fabricating efficient CIGS solar cells. To date CIGS films formed by non-vacuum techniques based on nanoparticle technologies have yielded 11.7% individual cells and 7% monolithic multi-cell submodules when combined with vacuum-deposited transparent conductor coatings. Solar cells incorporating vacuum-deposited CIGS films and transparent conductor coatings formed by non-vacuum techniques have yielded 8.7% efficiencies, and solar cells incorporating both CIGS films and transparent conductor coatings formed by non-vacuum techniques have yielded 6.3% efficiencies.

P112 – **Conductive Atomic Force Microscopy of CdTe/CdS Solar Cells**

Helio Moutinho, Ramesh Dhere, Chun-Sheng Jiang, Mowafak Al-Jassim, and Larry Kazmerski
National Renewable Energy Laboratory

Conductive atomic force microscopy (C-AFM) is a recently developed technique that applies a voltage between a very sharp tip and the sample, permitting the study of the electrical properties of the sample with very high spatial resolution. It also provides current vs. voltage curves at well-define spots. C-AFM is applied simultaneously with atomic force microscopy, providing topographic and current images of the same region. In this work, we analyze CdTe/CdS samples, before and after $CdCl_2$ treatment, and after bromine/methanol and nitric/phosphoric etch. The as-deposited samples show grains with different contrasts, indicating that the material is not uniform. The $CdCl_2$ treatment results in less conductive grain boundaries, suggesting a decrease in the conductivity at these locations. After the bromine/methanol etch, the conductivity at grains boundaries is higher than inside the grains, whereas for the nitric/phosphoric etch the conductivity increases over the entire surface.

P113 – Raman Studies of Nanocrystalline CdS:O Film

Yong Zhang, Xuanzhi Wu, Ramesh Dhere, Yanfa Yan, and Angelo Mascarenhas
National Renewable Energy Laboratory

Oxygenated nanocrystalline CdS films show improved solar cell performance, but the physics and mechanism underlying this is not yet clearly understood. On one hand, x-ray diffraction (XRD) measurements have indicated that the (0002) peak of the crystalline CdS quickly disappears leaving a broad band near the (0002) position, on increasing [O]. In conjunction with the blue shift in the absorption edge, XRD results seem to suggest a polycrystalline to amorphous phase transition. On the other hand, transmission electron microscopy (TEM) studies have indicated the formation of CdS related nano-particles with their sizes varying from a few hundred Å to a few tenths Å, on increasing [O]. Raman scattering is used to probe the effects due to the structural changes induced by oxygen incorporation, and to obtain insights for the physics underlying the above mentioned phenomena.

P114 – Study of Potential Cost Reductions Resulting from Super-Large-Scale Manufacturing of PV Modules

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We have studied the design for "A Solar City Factory" that will produce 2–3.5 GW of solar panels per year at a single factory site—100x the volume of a typical, thin-film, solar panel manufacturer in 2003, and more than 4x the volume of the entire solar panel industry in 2003. We have shown that with a reasonable selection of materials, and conservative assumptions, this “Solar City Factory” can hit a price target of $1.00 per watt as the total price for a complete, installed solar energy system (6.5x–8.5x lower than prices in 2003). This breakthrough in the price of solar energy comes without the need for any significant new innovation. It comes entirely from the design of a very large, dedicated and optimized factory, the design of manufacturing equipment for a very large factory and the cost savings resulting from operating at such a large manufacturing scale.

P115 – Sensitivities in Roll-to-Roll Processing of CIGS-Based Photovoltaics on Flexible Metal Foils

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Co-evaporation of $CuIn_xGa_{1-x}Se_2$ (CIGS) via two-stage and three-stage processes has been used in a variety of laboratories throughout the world to produce small-area devices with efficiencies greater than 15%. Thus, the two-stage and three-stage processes have come to be viewed as laboratory standards for the deposition of CIGS devices. However, a number of conditions are encountered during continuous manufacturing that differ from the laboratory processes. Such differences include both those imposed by continuous processing of moving substrates, and those implemented to decrease costs and increase throughput. This study describes the quantification of the impact of several variations in laboratory processing on device performance and the associated implications for roll-to-roll manufacturing on thin metal foils. Variations described here include split of group III atoms between first and third stages, CIGS cool-down and venting procedures, surface sulfurization, and Mo morphology.

Solar Resource Characterization

P116 – Progress Toward an Updated National Solar Radiation Data Base

Steve Wilcox and David S. Renné
National Renewable Energy Laboratory

In 1992, NREL released the 1961-1990 National Solar Radiation Data Base (NSRDB), a 30-year set of hourly solar radiation data. In April 2003, NREL convened a meeting of experts to investigate issues concerning a proposed update of the NSRDB to include more recent data. The panel determined that an important difficulty posed by the update was the shift from manual to automated cloud observations at National Weather Service stations in the United States in the 1990s. The solar model used in the original NSRDB relied heavily on manual cloud observations, and the meeting participants recommended that NREL produce a plan for creating an update using currently available meteorological observations and satellite imagery. In FY04 a two-year test data set was produced using new and modified models, providing a basis for evaluating methods for producing an updated NSRDB. This paper describes current progress toward a plan for an updated NSRDB.

P117 – Workplan and Annex: "Solar Resource Knowledge Management"

David S. Renné
National Renewable Energy Laboratory

"Solar Resource Knowledge Management" will be a new task under the International Energy Agency's Solar Heating and Cooling Programme. The task development has involved researchers from Germany, France, Switzerland, Spain, Portugal, Italy, Canada, the U.S. that have been engaged in the use of satellite imagery to develop solar resource maps and datasets around the world. The task will address three major areas: 1) "Benchmarking” of satellite-based solar resource methods so that resource information derived from approaches developed in one country or based on a specific satellite can be quantitatively intercompared with methods from other countries using different satellites, as well as with ground data; 2) Data archiving and dissemination procedures, especially focusing on access to the data by end users; and 3) basic R&D for improving the reliability and usability of the data, and for examining new types of products important to the solar industry, such as solar resource forecasts.

Communications

P118 – Planning Strategic Communications and Outreach for the Solar Program

Susannah Pedigo[1], Don Gwinner[1], Ruby Nahan[1], Connie Brooks[2], Wendy Butler Burt[3]
[1]*National Renewable Energy Laboratory*
[2]*Sandia National Laboratories*
[3]*U.S Department of Energy*

Advances made through the Solar Program in photovoltaic and solar thermal technologies must be well communicated to appropriate audiences if further technical and market growth will occur. As the Program's communications team, we developed a plan to: 1) integrate communications across the various solar technologies and reduce redundancy; 2) better target audiences and messages; 3) respond better to changes in markets, technology perceptions, audiences, and funding; 4) develop communication projects within the context of other relevant plans; 5) leverage limited resources; and 6) cultivate a multiyear mentality. Our approach included profiling eight key audiences, including their perceptions of solar technologies; formulating audience-specific messages and communication objectives and strategies; and proposing communications tactics to reinforce the objectives. Next, we will conduct a gap analysis, prioritize projects, complete high-priority projects, measure effectiveness of projects and the plan, and find strategic connections with other activities and programs.

Measurements and Characterization

P119 – The FTIR Laboratory in Support of the PV Program

B.M. Keyes, L.M. Gedvilas, R. Bhattacharya, Y. Xu, X. Li, and Q. Wang
National Renewable Energy Laboratory

The Fourier Transform Infrared (FTIR) Laboratory supports the PV Program through the measurement and analysis of infrared transmittance, refletance, and absorbance data. These results are an integral part of several research projects involving material systems ranging from amorphous and crystalline silicon to transparent conducting oxides. This review poster will briefly describe the capabilities of the lab and highlight a few of the research projects supported during the past year.

Electrochromic Films

P120 – The Ion Transport and Storage Characteristics of Tungsten and Vanadium Oxide Films Deposited by PECVD for Electrochromic Applications

Mike Seman, Joey Marino, and Colin A. Wolden
Dept. of Chemical Engineering, Colorado School of Mines

Films like tungsten and vanadium oxide are often deposited by physical vapor deposition (PVD) technique, while plasma enhanced chemical vapor deposition (PECVD) has received little attention. PECVD offers a number of advantages including high rate, uniformity, and control over film properties. Here we report our findings on PECVD synthesis of tungsten and vanadium oxide thin films. Tungsten oxide was synthesized by PECVD using mixtures of WF_6, H_2, and O_2. Similarly, vanadium oxide thin film synthesis was accomplished by PECVD using mixtures of $VOCl_3$, O_2, and H_2. Rates are an order of magnitude greater than with PVD. A quantitative evaluation of PECVD WO_3 and V_2O_5 was carried out using potentiostatic intermittent titration technique in concert with optical transmission to determine diffusion and absorption coefficients using both H^+ and Li^+ containing electrolytes. Optimized tungsten and vanadium oxide films were combined with an organic electrolyte to form complete electrochromic devices.

Focus Session: Recombination in Photovoltaic Materials

Chairs: Brian Keyes, Dean Levi

7:00–9:00 p.m.

7:00 – Ribbon Lifetime Issues—Application of Photoluminescence Diagnostics

Juris P. Kalejs
RWE SCHOTT Solar Inc.

Bulk electronic lifetime of typical as-grown crystalline silicon ribbon is low in comparison to other multicrystalline wafers, but is upgraded substantially with optimized solar cell processing, often by as much as up to two orders of magnitude. These large changes make it difficult to find a suitable as-grown material lifetime measurement technique for wafers which can be used as a predictor of solar cell performance in a manufacturing line environment. I will discuss in this paper our efforts to apply photoluminescence spectroscopy to tracking of lifetime during upgrading of EFG silicon ribbon in solar cell processing, and examine the approaches we are taking to calibrate a photoluminescence method for use in our high-speed solar cell manufacturing line.

7:20 – On the Use of Minority-Carrier Lifetime Measurements: Applying R&D Device-Physics Results into Crystalline Si Manufacturing Lines

Ronald A. Sinton[1], Tanaya Mankad[2], and Stuart Bowden[3]
[1]Sinton Consulting, Inc.
[2]Consultant
[3]Institute for Energy Conversion, University of Delaware

During this last decade, contactless minority-carrier lifetime measurements have become a primary tool for the R&D optimization of dopant diffusions, bulk lifetime preservation during processing, grown or deposited surface passivations, trapping defects, bulk and hydrogen passivation, metallic contamination in multi-crystalline materials, gettering, and studies of light degradation due to B:O pairs. The key enabling feature that has been critical to these studies is the absolute calibration of both the lifetime results and the photogenerated excess carrier densities. Recently, several new instruments have been developed to allow these calibrated lifetime measurements to be done extremely quickly on both individual wafers and entire blocks or boules of Si. This allows for the use of device-physics-quality data and analysis for routine process control in the production line. This talk will present several instruments and applications that promise significant improvements in yields and cell performance in crystalline silicon production lines.

8:00 – Time-Resolved Photoluminescence and Photovoltaics

Wyatt K. Metzger, Richard K. Ahrenkiel, Sarah Kurtz, John F. Geisz, and Mark W. Wanlass
National Renewable Energy Laboratory

The time-resolved photoluminescence technique and its ability to characterize recombination in bulk photovoltaic semiconductor materials are reviewed. Results from recent studies and a variety of materials are summarized and compared.

8:20 – Recombination Lifetimes Using the RCPCD Technique: Comparison with Other Methods

Richard Ahrenkiel[1,2], Steven Johnston[1], and Jamayana Dashdorj[1,2]
[1]National Renewable Energy Laboratory
[2]Department of Physics, Colorado School of Mines

The resonance-coupled photoconductive decay (RCPCD) technique is based on the electromagnetic coupling of the sample under test (SUT) to a resonant antenna-enclosure system (400 to 1000 Mhz) with a very high quality factor (Q), and has been described in the literature. We have three other lifetime techniques available in our laboratory; these are time-resolved photoluminescence (TRPL), microwave reflection (mR), and the quasistatic (QS- Sinton) technique. We will describe the RCPCD measurements on both direct bandgap materials (such as GaAs) and on indirect bandgap silicon. We will compare the RCPCD data with that obtained by the μR technique (GaAs and silicon), TRPL (GaAs), and the QS technique (silicon). All four methods measure slightly different parameters, which enable one to extract lifetime data. For example, RCPCD measures the transient photoconductivity, whereas QS measures steady-state photoconductivity. We will discuss the major attributes and limitations of RCPCD as compared to alternative methods.

8:40 – Photoexcited Charge Carrier Lifetime Measurements by Time-Resolved Photoluminescence Upconversion
Randy J. Ellingson
National Renewable Energy Laboratory

Photoluminescence (PL) lifetime measurement techniques exhibit limitations on time resolution, wavelength detectivity, and sensitivity. The technique known as time-resolved PL by upconversion (TRPL upconversion) relies on an optical gating method in which sample luminescence is mixed with a strong laser pulse in a nonlinear crystal to generate the sum-frequency wavelength; the sum-frequency light is then detected in steady-state. The strengths of the TRPL upconversion technique include broad wavelength detectivity and excellent time resolution. On the other hand, the difficulty in measuring lifetimes for weakly-emitting samples represents a weakness for this technique. We will describe the measurement system, and its ability to measure time-dependent data at single emission wavelengths as well as emission spectra at fixed delays. Measurement of the emission spectrum at multiple delays allows one to track the evolution of the thermalized carrier distribution temperature.

Tuesday, October 26, 2004

<u>Plenary Session II: Managing the Solar R&D Portfolio—DOE's Systems-Driven Approach</u>
Chair: Christopher Cameron
8:30–10:10 a.m.

8:30 – Systems-Driven Approach: What Is It and Why Do It?
Christopher P. Cameron
Sandia National Laboratories, on detail to DOE

The Department of Energy's Solar Energy Technologies Program began the formulation of a Systems-Driven Approach (SDA) to R&D portfolio management and prioritization with a workshop held in December 2002. This paper will introduce a session on the Systems-Driven Approach by seeking to answer the questions: What is SDA and Why do SDA? SDA begins with analysis supporting definition of market requirements and translation of those requirements to research and development needs for systems, components, and materials. Current cost and performance are benchmarked, and parametric models are developed to permit identification and prioritization of opportunities to improve cost and performance. Modeling is also used to evaluate the potential impact of proposed research, including new concepts resulting from basic research. In this session, the approaches to analysis, benchmarking, and modeling will be described, and examples of application of the systems-driven philosophy will be presented for inverters and thin-films.

8:40 – Benchmarking of Solar Technologies for the Systems-Driven Approach
Charles J. Hanley
Sandia National Laboratories

There are two essential elements to benchmarking within the Systems-Driven Approach (SDA) of the DOE Solar Energy Technologies Programs. These are: (1) to validate and update the present performance and cost figures for the various program technologies in the Multi-Year Technical Plan (MYTP); and (2) to provide default "real world" parameters to the models being developed for the SDA. By achieving these objectives in the near term, the benchmarking process will then continue over time to measure and track progress in terms of several measurable parameters, as stipulated in the MYTP. Presently, benchmarking focuses on photovoltaic systems in residential, commercial, and utility-scale applications, in concert with the model development and the SDA analysis to date. This paper discusses the status of this PV benchmarking and outlines future activities.

9:00 – Performance and Cost Model for Solar Energy Technologies in Support of the Systems-Driven Approach
G. David Mooney, Mark Mehos, Craig Christensen, and Nate Blair
National Renewable Energy Laboratory

A key element to the successful development and implementation of the Systems Driven Approach to R&D portfolio management and prioritization is the development of a comprehensive, integrated systems performance and financial model. Such models are currently under development. The models are being developed to allow solar program management, researchers, and industry partners to evaluate PV, CSP, and SHW systems performance through parametric analysis from the whole-system level down to the component and sub-component level. Additionally, cost and financial variables will be able to be investigated from a variety of perspectives (residential, commercial, utility, etc.), with the financial and performance data integrated to yield the cost of energy generated from a given system configuration and cost/financing scenario.

9:20 – Solar Technology and Policy Analysis to Support the Systems-Driven Approach
Robert M. Margolis
National Renewable Energy Laboratory

The primary focus of the Systems-Driven Approach (SDA) Analysis Team is to improve the analytical basis for understanding the system and policy drivers of solar technologies in various markets. Analysis activities during the past year have been focused in three interrelated areas: (1) developing long-term market-penetration projections for the full set of technologies funded within the DOE Solar Energy Technologies Program, (2) reviewing the Program's out-year cost and performance targets for photovoltaic (PV) technology, and (3) evaluating policies as well as other factors that impact the value of solar energy technologies in various markets. This paper will summarize the results of these activities and describe how they relate to the overall SDA effort.

9:40 – The Systems-Driven Approach to Inverter R&D
Ward I. Bower
Sandia National Laboratories

A broad perspective on inverter research and development is part of the U.S. DOE Solar Program and Sandia National Laboratories' emphasis on the systems-driven approach to understanding the challenges facing the solar inverter industry. The approach focuses on identifying the most important research needed to create reliable hardware to assure effective power transfer. It emphasizes the importance of materials/processes, components, products, applications and markets for the technology are related to each other. It emphasizes how changes in an inverter affect the market or how changes in the market affect component cost and performance. Each inverter approach has unique attributes and specific technical challenges. The DOE Solar Program is focusing its resources on the most critical challenges as determined in the first "DOE Workshop for a Systems-driven Approach To Inverter Research and Development." Inverter reliability was identified as one of the most critical areas requiring R&D that folds into production advancements. The systems-driven approach, backed by inverter modeling and analysis tools capable of illuminating full systems issues provides the means to explore all of the implications of research goals and objectives in a systems context.

9:55 – Analyzing Thin-Film Technologies: A Concrete Example Using the Systems-Driven Approach

Ken Zweibel
National Renewable Energy Laboratory

Thin film PV devices are a challenging part of the module, but not the only part. In addition, they must: be protected by encapsulation that allows sunlight in; be made on a substrate (which can double as encapsulation); have an interface with the external circuit; have a mounting scheme. Each functional subsystem can be analyzed for: technical options, performance, reliability, and cost. By analyzing the functional subsystems, one can come to a basic understanding of the opportunities and challenges facing thin film module development. This is the aim of the system driven approach; and this paper is an attempt to derive the implications. All known thin film technologies (including multijunctions); and various combinations of substrates and superstrates (glass, stainless steel, plastic) will be examined.

<u>**High-Performance PV II: III-Vs and Concentrators (parallel)**</u>
Chairs: Martha Symko-Davies and Robert McConnell
10:30 a.m.–12:10 p.m.

10:30 – Development of High-Efficiency GaInP/GaInAs/Ge Concentrator Cells and Robust Receiver Packages for High-Concentration Photovoltaic Terrestrial Modules

Raed A. Sherif, Richard R. King, Hector L. Cotal, Chris M. Fetzer, and Nasser H. Karam
Spectrolab, Inc.

This paper presents an overview of the advances made by Spectrolab in the NREL High-Performance PV program Phase 1A, as well as plans for continuous development in Phase 1B. In this program, Spectrolab investigated two different approaches to realize high efficiency cells with a target 41% conversion efficiency. In the first approach, a lattice-match or metamorphic GaInP/GaInAs/Ge cell structure was considered. In the second approach, a mechanical–stack cell structure was considered. In the course of this work, special emphasis was placed on demonstrating robustness of multi-junction cells under continuous illumination at high concentration. To this end, we investigated different receiver package designs and assembly processes used to mount concentrator cells on heat sinks. The above effort has led to demonstration of 37.3% concentrator cell efficiency. It has also led to the development of a robust receiver package design that can be used for long-term outdoor high concentration tests.

10:50 – Wafer-Scale Fabrication of Ge/Si and InP/Si for Multijunction Solar Cell Applications

Harry Atwater[1], Katsuaki Tanabe[1], Melissa Griggs[1], James Zahler[2], and Anna Morral[2]
[1]California Institute of Technology
[2]Aonex Technologies Corporation

We describe advances in both the science and technology of ion-implantation induced layer transfer processes for compound semiconductor heterostructure solar cell applications. Wafer-scale fabrication of Ge/Si and InP/Si with Ohmic contacts to the substrate has been achieved for the first time. The 50 mm diameter Ge/Si and InP/Si wafers were fabricated using ion implantation-induced layer transfer, and approaches to removal of roughness and implantation damage using chemical, plasma and chemo-mechanical etching have been investigated. The Ge layer splitting kinetics have also been investigated in detail using multiple internal reflection

Fourier transform infrared spectroscopy and transmission electron microscopy, which reveals the changes in chemical bonding state of hydrogen that occur during the splitting phase of the layer transfer process. The picture that emerges for Ge layer splitting is consistent with formation of two H-passivated internal surface during the moment of layer splitting. Similar results have also been obtained for InP layer splitting.

11:10 – III-V/Si Lattice-Matched Tandem Solar Cells
John F. Geisz, Jerry M. Olson, Daniel J. Friedman, and Sarah R. Kurtz
National Renewable Energy Laboratory

A two-junction device consisting of a 1.7-eV GaNPAs junction on a 1.1-eV silicon junction has the theoretical potential to achieve nearly optimal efficiency for a two-junction tandem cell. We have demonstrated some of the key components toward realizing such a cell, including GaNPAs top cells grown on silicon substrates, GaP-based tunnel junctions grown on silicon substrates, and diffused silicon junctions formed during the epitaxial growth of GaNP on silicon. To accomplish this, we have developed techniques for the growth of high crystalline quality lattice-matched GaNPAs on silicon by metal-organic vapor-phase epitaxy.

11:30 – Report on Year 1: Design and Demonstration of a >33% Efficiency High-Concentration Module Using >40% III-V Multijunction Devices
Vahan Garboushian, Ken Stone, Jerry Turner, Alex Slade, and Robert Gordon
Amonix, Inc.

This paper covers the first phase of a three-phase project to integrate III-V high-performance multijunction solar cells into a proven, large-scale Fresnel lens concentrating system. Areas investigated in this phase include: development of a 'waterfall' Table of potential performance losses, verification of the 'waterfall' Table by test and analysis, design of an optimal optical path including secondary optical elements, cell packaging, cell package thermal analysis, cell package and cell encapsulation, a study of cell combining losses, package interconnects, testing performance of multiple cell design options as a function of insolation and temperature. The goal of this project is to field a complete module in Phase three.

11:50 – Characterization of PV Concentrators at NREL
Keith Emery, Tom Moriarty, and James Kiehl
National Renewable Energy Laboratory

The Photovoltaic High-Performance Project has a goal of a 40%-efficient solar cell under concentrated sunlight. At present our estimated 95% confidence uncertainty for these high efficiency structures is +/- 5% of the reported efficiency. This estimated uncertainty is higher than desirable because a 38% cell and 42% cell are within this uncertainty range. This paper documents the efforts to achieve this estimated uncertainty and the justification for it. The 2-axis test bed for continuously monitoring small concentrator modules will be discussed. Also efforts to reduce the uncertainty in the efficiency even further will be discussed.

<u>**Polycrystalline Thin Films I: CdTe (parallel)**</u>
Chair: Ken Zweibel
10:30 a.m.–12:10 p.m.

10:30 – XPS and AES Studies of Cu/CdTe(111)-B
Glenn Teeter, Tim Gessert, and Sally Asher
National Renewable Energy Laboratory

Copper is frequently incorporated at the back contacts of CdTe-based thin film photovoltaic devices, where it is believed to dope the CdTe p-type and aid in the formation of a pseudo-ohmic contact. In the present study, surface analysis techniques including X-ray Photoelectron Spectroscopy (XPS), Auger Electron Spectroscopy (AES) and Temperature Programmed

Desorption (TPD) have been used to probe some of the fundamental properties of this system. TPD measurements demonstrate that the reaction of Cu thin films with the CdTe(111)-B surface proceeds via zero order kinetics. Temperature-resolved XPS measurements have been used to probe a surface segregation phenomenon, in which Cu reversibly segregates to the CdTe(111)-B surface as a function of temperature. AES mapping measurements demonstrate changes in surface composition and morphology that accompany the reaction of Cu thin films with the CdTe(111)-B surface. In particular, AES maps provide evidence that Cu stabilizes this surface with respect to faceting.

10:50 – Advances in the In-House CdTe Research Activities at NREL

Timothy A. Gessert, Xuanzhi Wu, and Ramesh Dhere
National Renewable Energy Laboratory

NREL in-house CdTe research activities have impacted a broad range of recent program priorities. Foundational studies have yielded improved understanding of how various process steps may combine to affect the radiatiative recombination in CdTe. Similarly, controlled studies of impurity diffusion from typical contacts continue to show links to acceptor activation, and have provided potential insight into device formation and stability. Recently, electro- and nano-probe techniques have been used successfully to assess the strength and spatial distribution of the resulting electric field within the devices. Studies aimed at industrially relevant applications have produced new materials and processes that enhance the performance of devices based on present commercial materials (i.e., soda-lime glass, SnO_2:F, etc.). Preliminary tests of the effectiveness of these novel components using large-scale processes have been encouraging.

11:10 – Physics of Large-Area, Thin-Film Devices: Nonuniformities, Interfacial Layers, and Reach-Through Effects

Victor G. Karpov
Department of Physics and Astronomy, University of Toledo

Three major factors specific to large-area thin-film PV are discussed: (1) *Lateral nonuniformities* originate from the film non-crystalline structure. They noticeably affect both the device efficiency and stability. Microscopic nonuniformities span macroscopic scales, causing losses of up to one-third of a typical module's efficiency and inducing local instabilities such as shunting, metal delamination, and arcing. Recently suggested successful remedies are interfacial layers based on electro-chemical treatments. (2) *Interface states* have extremely strong impact on device parameters and compete with bulk doping effects when the film thickness is small. This understanding leads to new approaches in the buffer layer design and device doping. (3) *Reach-through effects* make it possible for the electric field to act through a thin-film, which paves a way to novel back contact schemes. As an example, taking the above factors into account results in a simple recipe of Cu-free CdTe device that demonstrates 13% efficiency and a superior stability.

11:30 – High-Throughput Processing of Stable CdTe/CdS Solar Cells

Brian E. McCandless, Kevin D. Dobson, Steven S. Hegedus, Robert W. Birkmire, and Wayne A. Buchanan
Institute of Energy Conversion, University of Delaware

Processing options for increasing throughput, and diagnostic tools for assessing film properties, are being developed for CdTe/CdS thin film solar cells. High CdTe deposition rate, up to 20 µm/min, is demonstrated for vapor transport deposition on moving substrates at ~550°C. Factors controlling deposition rate, gas phase utilization, and CdTe growth habit are evaluated. Reduced post-deposition treatment time is demonstrated for vapor treatment using a remote $CdCl_2$ generator. The effects of treatments on film conductivity, surface composition and device stability are shown. Contact wetting angle measurement allows rapid determination of CdS and CdTe surface energy before and after treatment and is correlated with other measurements to demonstrate potential as a processing diagnostic tool. Low temperature V_{oc} measurements of devices made by three deposition methods show that the maximum V_{oc} for CdTe/CdS is ~1 V.

Bifacial quantum efficiency using transparent ZnTe contacts is being used to probe bulk and junction properties.

11:50 – The Improved Intrinsic Stability of CdTe and Cu(In,Ga)Se_2 Polycrystalline Thin-Film Devices

David S. Albin, Tracie J. Berniard, Samuel H. Demtsu, and Rommel Noufi
National Renewable Energy Laboratory

A systems-driven approach linking upstream solar cell device fabrication history (e.g. temperatures, times, pressures) with downstream, performance and stability is demonstrated. Surface treatments immediately preceding the final backcontact deposition distinguish different modes of degradation with NREL-made CdTe devices. These treatments include pre-contact etches as well as oxygen ambient conditions during the vapor $CdCl_2$ treatment. When Te is absent, the particular degradation mode observed more closely follows what has been observed in similar tests performed with First Solar devices. We also demonstrate how cell perimeter effects may have dominated stress testing performed on these devices in the past. A "margined" contact approach significantly reduces the contribution of edge-shunting to overall device degradation, and thus, yields a more stable construct by which "intrinsic" stability can be measured. Finally, we will present stability data for CdTe and Cu(In,Ga)Se_2 devices tested simultaneously under open-circuit, 85°C, 1-sun accelerated stress conditions.

Technology Adoption I (parallel)
Chairs: John Thornton, Charles Hanley
10:30 a.m.–12:10 p.m.

10:30 – The Role of Technology Adoption within the Department of Energy's Solar Energy Technologies Program

Charles J Hanley[1] and John Thornton[2]
[1]Sandia National Laboratories
[2]National Renewable Energy Laboratory

Several technical activities are undertaken on behalf of DOE’s Solar Energy Technologies Program in the interests of increasing the broader adoption of solar technologies in the marketplace. Included in these activities are technical support to the development of electrical codes and standards; installer and hardware certification programs; domestic and international technical support activities with leveraged partners; developing new systems configurations, such as building-integrated systems; and studies on environmental, safety, and health related aspects of production. These technology adoption (TA) activities serve several valuable purposes to the DOE program, and provide a valuable link to the fundamental and applied R&D within the program. Through TA support, the DOE program is able to identify market-based needs through data gathering and analysis and communicate these needs to program researchers. In addition, TA activities maintain the role of the DOE and the labs as impartial brokers of information as the markets for these products continue to grow.

10:50 – The Million Solar Roofs Initiative: A Solar Deployment Strategy

Heather Mulligan
U.S. DOE, Western Regional Office

DOE's Million Solar Roofs Initiative is a unique public-private partnership, aimed at overcoming barriers to market entry for photovoltaic, solar hot water, and solar pool heating technologies. The goal of the Initiative is to facilitate the sale and installation of one million "solar roofs" by the year 2010. The Initiative is among the portfolio of deployment activities implemented by the Office of Solar Energy Technologies. It offers an opportunity to provide valuable feedback to the program's R&D activities on market drivers, issues, and performance of systems. The Initiative works through a nationwide network of over 89 State and local Partnerships, comprised of over 800 participating members. Over the past year, this growing network of partnerships worked to build markets in their local communities, through a variety of means including: identifying and addressing local barriers; using solar technologies to meet important public policy goals; leveraging state and local incentives for solar; and educating the next generation of consumers, and their parents.

11:10 – Moving Markets with Education & Outreach Strategies: IREC's Results with Getting the Right Information to the Right People

Jane M. Weissman
Interstate Renewable Energy Council

As part of the outreach and educational deployment activities for the Department of Energy, the Interstate Renewable Energy Council (IREC) tackles some of the difficult issues impacting expanded renewable energy use. This presentation will focus on some of the results that IREC has accomplished regarding rules that support connecting solar electric photovoltaics to the utility grid, setting competency and content standards for practitioners and education programs, and getting the right information to the right people. In the past year, IREC released two model rules for use as guidance by state policymakers considering net metering or interconnection rules. This presentation will review the rules and the results to date and will include a summary of state activity. This presentation will also show how IREC has addressed the workforce development framework by implementing steps that connect labor market needs with occupational and training standards, educational providers, and third-party programs that verify competencies.

11:30 – Native American EmPowerment: Solar Electric Initiatives

Jennifer J. Coots, Benjamin Mar, and Sandra K. Begay-Campbell
Sandia National Laboratories

Since 1993, the Navajo Tribal Utility Authority (NTUA) has installed stand-alone photovoltaic (PV) systems on the Navajo Reservation to provide some of its most remote customers with electricity. Sandia National Laboratories student interns' case study summarizes the rural utility's experience over the last decade with solar electric power. In particular, it examines the technical and economic drivers that led to four generational changes of their PV systems. The sustainable renewable energy program at the NTUA could not have happened without taking from the many lessons learned over the course of the program. Starting small and working toward ever-larger energy producing systems has been key, as has the passion, dedication, and partnering of the NTUA staff and all those with whom they have interacted, including ongoing technical assistance from Sandia National Laboratories.

11:50 – Optimization of Cadmium Telluride Photovoltaic Module Recycling

Vasilis Fthenakis and Wenming Wang
Brookhaven National Laboratory

This paper presents the latest experimental results on CdTe PV module recycling obtained at Brookhaven National Laboratory. Hydrometallurgical processing technologies, namely, H_2SO_4/H_2O_2 leaching,cation exchange separation and electrowinning, were investigated. The stripping of both cadmium and tellurium from PV module substrates was achieved using hydrogen peroxide leaching in dilute sulfuric acid. Both cadmium and tellurium were readily solubilized in 30 minutes with low strength of acid at ambient temperature. Leaching the PV module scraps yielded complete extraction of both cadmium and tellurium. Cation exchange resin was then used to remove and separate cadmium completely from tellurium-rich leach liquor of 0.5 M H_2SO_4. Through this procedure, cadmium was exchanged to the resin, whereas tellurium remained in the leach liquor for the recovery. Complete elution of the resin with high strength H_2SO_4 was successful and further studies are in progress to recover cadmium by optimizing electrolytic separation.

12:10 – Tandem, Planar, Bulk and Mixed Heterojunction Solar Cells: Achieving High Efficiencies Using Small Molecular Weight Organic Photovoltaics

Stephen Forrest[1], Jiangeng Xue[1], Barry Rand[1], and Soichi Uchida[1,2]
[1]*Department of Electrical Engineering, Princeton University*
[2]*Nippon Oil Company*

We discuss the fundamental limitations to solar cell efficiencies employing organic thin films. To support our analysis, several strategies for optimizing the power conversion efficiency of small molecular weight organic PV cells. Conversion efficiencies approaching 6% at 1 sun, AM1.5G simulated illumination are observed employing thin film cells consisting of CuPc and C60 as the active region materials. The influence of structural morphology in high efficiency bulk heterojunction and mixed molecular heterojunction cells is considered, as well as that of surface plasmons in tandem cell architectures containing metallic nanoparticle layers separating each sub-cell in a multilayer stack. Surface plasmons are shown to increase the efficiency by a significant fraction in these tandem cells, suggesting that this particular approach has the highest potential for resulting in solar power conversion efficiencies >10%.

PV Manufacturing R&D I: Manufacturing Support, BOS, and Systems Integration (parallel)

Chairs: Kathryn Brown and Richard Mitchell
1:40–3:40 p.m.

1:40 – PV Manufacturing R&D Project—Trends in the U.S. PV Industry

Kathryn E. Brown[1], Richard L. Mitchell[1], Ward I. Bower[2], and Richard King[3]
[1]*National Renewable Energy Laboratory*
[2]*Sandia National Laboratories*
[3]*U.S. Department of Energy*

To foster continued growth in the U.S. photovoltaic (PV) industry, the U.S. Department of Energy initiated the PV Manufacturing R&D (PVMR&D) Project – a partnership with U.S. PV industry participants to perform cost-shared manufacturing research and development. Throughout FY2004, PVMR&D managed fourteen subcontracts across the industry. The impact of PVMR&D is quantified by reductions in direct module manufacturing costs, scale-up of existing PV production capacity, and accrual of cost savings to the public and industry. An analysis of public and industry investment shows that both recaptured funds by mid-1998 based on estimated manufacturing cost savings from PVMR&D participation. Since project inception, total PV manufacturing capacity has increased from 13 MW to 201 MW at the close of 2003 while direct manufacturing costs reduced from $5.55/W to $2.49/W. These results demonstrate continued progress toward the overriding goals of the PVMR&D Project.

2:00 – Development of an In-line Minority-Carrier Lifetime Monitoring Tool for Process Control during Fabrication of Crystalline Silicon Solar Cells

R. A. Sinton[1], Tanaya Mankad[2], and Stuart Bowden[3]
[1]*Sinton Consulting, Inc.*
[2]*Consultants*
[3]*Institute for Energy Conversion, University of Delaware*

As the production volumes of crystalline silicon manufacturing lines continue to grow, the demand for improved process control and process monitoring in manufacturing has increased. Sinton Consulting has developed several new instruments for use in the manufacture of silicon solar cells. Four instruments have now been extensively tested through collaborations with industry. For each instrument and application, substantial R&D work was required to develop the device physics and analysis in addition to the hardware. Of particular importance was the development of methodologies to calibrate lifetime measurements for use on industrial samples, including the measurement of unpassivated wafers as they exist in the production line and the measurement of multicrystalline bricks to determine lifetime, trapping, and iron concentration as a function of position. While providing the documentation necessary for industrial applications of the instruments, these results have also been widely presented at technical conferences as contributions to silicon photovoltaics R&D.

2:20 – Interfacial Characterization of Glass Surfaces and Encapsulant Bonding in Thin-Film Photovoltaic Modules

Hardial S. Dewan[1], Edward A. Kurz[1], Susan C. Agro[2], and Ryan T. Tucker[2]
[1]Institute of Materials Science, University of Connecticut
[2]Specialized Technology Resources, Inc.

Bulk glass chemistry and EVA as well as their interface in thin-film modules have been examined by FTIR, SEM/EDX, XPS, and TD/GC/MS. No differences were noted by FTIR between unexposed EVA and that examined from several modules both with normal appearance and with corrosion. TD/GC/MS revealed differences between unexposed EVA and EVA from various module regions of normal and corroded appearance. A small amount of water was occasionally found in corroded regions, but not in unexposed or non-corroded samples. Acetic acid and other organics were found in all device areas but not in unexposed EVA. XPS revealed the presence of slight EVA oxidation (initially not in unexposed EVA) in all regions examined. SEM/EDX of fractured EVA cross-sections within a module revealed the presence of numerous inorganic contaminants (Ca, Na, S, K, excess Si). These contaminants were most likely due to two causes - glass degradation and water ingression.

2:40 – PV Inverter Products Manufacturing and Design Improvements for Cost Reduction and Performance Enhancements

Ray Hudson[1] and Rick West[2]
[1]Xantrex Technology, Inc.
[2]Distributed Power, Inc.

The contract goals were to achieve an overall cost reduction of 20% for three photovoltaic inverters and with no compromise in performance. The costs of two 3-phase inverter products with 10kW and 25kW ratings were both reduced substantially. Not only were the contract cost reduction goals exceeded by a wide margin but the performance and reliability of the products were also enhanced. Conversion losses in the three-phase inverters were reduced, improving efficiency. Size and weight were also reduced. The third product, a single-phase, 2.5kW inverter, was also designed and tested. The 2.5kW inverter benefits equally from the overall design approach where highly integrated PCB power assemblies under Digital Signal Processor (DSP) control are used to achieve streamlined product architectures.

3:00 – The Development and Testing of an AC Module

Miles C. Russell
RWE Schott Solar, Inc.

With support from the PV Manufacturing R&D Project, RWE Schott Solar, Inc., is developing innovative products for its PV system offerings. The most significant of these is an AC module, based on the company's standard 300-watt PV module. The AC module comes with a factory-integrated dc-to-ac inverter on the back, and proprietary 3-pin quick connectors to carry the AC output. Prototypes will be installed and operated in late summer. Specifications and test results will be reported as available. In the mid-1990s an early version of an AC module was produced with the company's 300-watt module. That AC module was high in cost and only a few hundred units were built. The new AC module will address cost and provide features to enhance the user interface and facilitate troubleshooting. Also in this project, the company is evolving its line of PV array wiring junction boxes, to simplify the wiring of conventional dc arrays in both residential and commercial-scale PV systems. Finally the company is also developing an innovative package to simplify the wiring of a PV system's ac output to the utility service in a residence. The status and performance of these product developments will be presented. Test results and specifications will also be reported.

3:20 – PowerLight Lean Manufacturing—Project Accomplishments
Jonathan D. Botkin and Larry N. Hargis
PowerLight Corp.

This paper describes the advances made by PowerLight under the PV Manufacturing R&D subcontract. The goal of this project was to reduce the cost of PowerGuard manufacturing while simultaneously improving product quality. By implementing lean manufacturing techniques, PowerLight worked to eliminate waste in the manufacture of PowerGuard tiles. Changes included design-for-manufacturability improvements of the PowerGuard product and enhancements of the manufacturing process. Changes were made to the PowerGuard product to eliminate curing steps. Parts were designed as much as possible to allow workers to assemble them quickly and reliably. Batch processing of PowerGuard was replaced with continuous flow and a pull system to minimize the amount of work-in-process. Error proofing was used to improve quality. Dark current/voltage testing was used on photovoltaic modules before integration into PowerGuard tiles. The factory was rearranged to optimize the flow of materials. The overall result of this work was an 18% reduction in cost of PowerGuard backerboards.

Polycrystalline Thin Films II: CIS (parallel)
Chair: Rommel Noufi
1:40–3:40 p.m.

1:40 – Properties of High-Efficiency CIGS Thin-Film Solar Cells Properties of High Efficiency CIGS Thin Film Solar Cells
Kannan Ramanathan
National Renewable Energy Laboratory

This paper will review the recent progress in the fabrication and characterization of high efficiency CIGS thin film solar cells. At the time of writing this abstract, we are investigating the properties of solar cells as a function of Ga content. Ga/(Ga+In) ratio has been varied in the range 0.25–0.31 and the Cu/(In+Ga) ratio is controlled by thermocouple end point detection. We are able to consistently fabricate solar cells with efficiencies near 19% with high open circuit voltages and fill factors. A summary of this work will be given. Some aspects of the device structure are re-examined. Properties of CIGS solar cells with and without the undoped ZnO layer will be presented. Results of experiments performed to date suggest that high efficiency cells can be fabricated without the undoped layer. This is a surprising result and has the potential to simplify the device processing. It also sheds new light on our view of how the ZnO/CdS/CIGS works. A brief summary of accomplishments in the alternative buffer layer research will also be given.

2:00 – CIS Product Line Expansion and Production Scale-up at SSI
Dale E. Tarrant, Rob A. Steeman, Robert D. Wieting, and Robert R. Gay
Shell Solar Industries (SS I)

SSI has made outstanding progress in the initial commercialization of high performance thin film $Cu(In,Ga)(S,Se)_2$ (CIS) technology. Predictability of SSI's CIS process has been demonstrated using statistical process control. Process R&D at successive levels of CIS production has led to high yield production while increasing product efficiency. These major accomplishments support attractive cost projections for CIS and have demonstrated the prerequisites for large-scale commercialization. Device and production R&D will lead to further product and production improvements. Remaining R&D challenges are to scale the processes to even larger areas, to reach higher production capacity, to demonstrate extended in-service durability, and to advance the fundamental understanding of CIS-based materials and devices with the goal of improvement for future products. This paper highlights progress with early commercialization and plans for CIS development at SSI and in conjunction with NREL National CIS R&D Team activities.

2:20 – Processing Improvements for Roll-to-Roll Deposition of Cu(InGa)Se_2

Robert Birkmire, Erten Eser, Shannon Fields, William Shafarman
Institute of Energy Conversion, University of Delaware

A number of process and system improvements, driven by the need for a reproducible and robust reactor, have been implemented in the roll-to-roll Cu(InGa)Se_2 web deposition system operating at the Institute of Energy Conversion, University of Delaware. Initially, the metal evaporation sources were controlled by Atomic Absorption Spectroscopy (AAS) directly measuring effusion rates. However, the AAS approach was discontinued due to instability and maintenance issues in favor of temperature control via thermocouples located in the sources. Also, sources have been redesigned to avoid sharp internal lines and corners acting as stress concentrators resulting in the breakage of the boron nitride boat. Se source control and operation has been greatly improved by controlling the surface temperature of the molten Se using a thermocouple attached to a graphite float. Control of web temperature and web/Mo cracking and adhesion will be discussed.

2:40 – Solid State Theory of PV Materials: Nanoscale Grain Boundaries and Doping CIGS

Alex Zunger
National Renewable Energy Laboratory

Modern advances in Quantum-Mechanical, "first-principles" simulations of PV materials have provided guidelines for experimentation, as well as a clear physical context for analysis of observations. I will review a few such recent cases, where theoretical predictions and experimental work led to advances that were not possible without both components: (1) Theory shows that Grain-Boundaries in CIGS are heavily Cu-deficient, and hence pose a repulsive potential toward holes, thus limiting recombination and improving cell performance (Persson and Zunger, PRL, 91,266401, 2004). (2) Practical "doping Rules" are distilled from First-Principles Calculations, permitting rational design of doping strategies (A. Zunger, APL, 83, 57, 2003). Application to n-type doping of CIS and CGS were considered (in collaboration with S. Lany, Y.J. Zhao and C. Persson), showing how cation-doping (Cd,Zn) and anion-doping-(Cl, Br) work for CIS and fail for CGS.

3:00 – Local Built-in Potential on Grain Boundary of Cu(In,Ga)Se_2 Thin Films

C.-S. Jiang, R. Noufi, K. Ramanathan, H. R. Moutinho, and M. M. Al-Jassim
National Renewable Energy Laboratory

We report on a direct measurement of two-dimensional potential distribution on the surface of photovoltaic Cu(In,Ga)Se_2 thin films using a nanoscale electrical characterization of scanning Kelvin probe microscopy. The potential measurement reveals a higher surface potential or a smaller work function on grain boundaries (GBs) of the film than on the grain surfaces. This demonstrates the existence of a local built-in potential on GBs, and the GB is positively charged. This built-in potential can be expected to increase minority-carrier collection area or probability. Role of the built-in potential in device performance was further demonstrated to be positive by tuning Ga content or band gap of the film. With increasing the Ga content, the potential drops sharply in a Ga range of 28~38%. Comparing the change in the built-in potential to the theoretical and experimental photoconversion efficiencies, we conclude that the potential plays a significant role in the device conversion efficiency of NREL's three-stage Cu(In,Ga)Se_2 device.

3:20 – Scanning Tunneling Luminescence and Cathodoluminescence of Grain Boundaries in Cu(In,Ga)Se_2

Manuel J Romero, Chung-Sheng Jiang, Rommel Noufi, and Mowafak Al-Jassim
National Renewable Energy Laboratory

Grain boundaries in Cu(In,Ga)Se_2 (CIGS) are attracting the interest of the thin-film photovoltaic community because of their anomalous, and potentially beneficial, behavior. We performed simultaneous imaging of cathodoluminescence (CL) and scanning tunneling luminescence (STL) on grain boundaries in CIGS. In cathodoluminescence, photons are emitted by recombination of electrons and holes, previously excited by primary electrons. Recombination is thus *bipolar* and does not depend on the carrier densities in the semiconductor under observation. In STL, which is based on scanning tunneling microscopy (STM), photons are emitted by recombination of tunneling electrons. Recombination is thus *unipolar* and does depend on the carrier densities in CIGS. Combining our findings from CL and STL with those by scanning Kelvin probe microscopy (SKPM), a model for carrier recombination at grain boundaries is further discussed.

Technology Adoption II (parallel)
Chairs: Charles Hanley and John Thornton
1:40–3:40 p.m.

1:40 – Overview of the Sandia/NREL PV International Activities for the DOE Solar Energy Technologies Program

Vipin Gupta[1], Warren Cox[1], Debra Lew[2], and William Wallace[3]
[1]International Sustainable Engineering Group, Sandia National Laboratories
[2]Energy and Environmental Applications Center, National Renewable Energy Laboratory
[3]National Center for Photovoltaics, National Renewable Energy Laboratory

One of the primary goals of Department of Energy's Solar Energy Technologies Program is to make solar energy systems an accepted and easily integrated option for distributed-energy generation both on and off the electric utility grid. The Sandia/NREL international activities contribute to this goal by developing off-grid PV systems and applications as well as overcoming PV technology adoption barriers through international collaborations. Collaborations and leveraging include support of bilateral agreements through the U.S. Department of Energy, Environmental Protection Administration, and Agency for International Development. Strategic targets include Central America, Mexico, China, India, Brazil, and others. The international program also works through such multilateral forums as the International Energy Agency (IEA), the World Bank, and the United Nations. Global off-grid markets are forecast to continue growing at 15%–18% per year, and German and Japanese markets represent a substantial portion of near-term and long-term U.S. industry sales. This paper details how present and future international activities at Sandia and NREL contribute to the PV tasks and R&D milestones in the DOE Solar Program Multi-Year Technical Plan. The paper also summarizes key capacity building and policy successes achieved in strategic partnerships with high potential developing countries for national program and market development, especially for rural electrification.

2:00 – Ten-Year Reliability Assessment of Photovoltaic Water Pumping Systems in Mexico

Robert Foster[1], Martin Gomez[1], Michael Ross[2], Charles Hanley[3], and Vipin Gupta[2]
[1]Southwest Technology Development Institute, New Mexico State University
[2]International Sustainable Engineering Group, Sandia National Laboratories
[3]Solar Systems, Sandia National Laboratories

Between 1994 and 2000, 206 photovoltaic (PV) water pumping pilot systems were installed in Mexico as part of the Mexican Renewable Energy Program (MREP). MREP is a collaborative program sponsored by the U.S. Agency for International Development (USAID) and U.S. Department of Energy (DOE). Various Mexican program partners have collaborated with MREP, including the Fideicomiso de Riesgo Compartido (FIRCO) for the deployment of PV systems for agriculture. After ten years of MREP PV system implementation, systems benchmarking was conducted of 52 installed systems. The evaluations revealed that over 3/5 of the surveyed systems were operating appropriately after as much as 10 years of operation. This paper details the technical analysis of 52 PV water pumping systems assessed in the Mexican states of Baja California Sur, Chihuahua, Sonora, and Quintana Roo and characterizes technology reliability. The results provide documentation for MYTP Milestone 50 on PV rural utility applications.

2:20 – Development of a Federal Agency List of Accepted PV Systems for Rural Coops

Larry M Moore[1], Harold N Post[1], Kevin Lynn[2], George Bagnall[3], and Harvey Bowles[3]
[1]Sandia National Laboratories
[2]Florida Solar Energy Center
[3]USDA, Rural Utilities Service

The U.S. Department of Energy, Sandia National Laboratories, and U.S. Department of Agriculture Rural Utilities Service (RUS) have developed a partnership to expand the use of photovoltaic (PV) energy systems as an additional customer service option for the nation's rural electric utilities. A key partnership objective is to simplify rural utility access to accepted PV systems and RUS funding to purchase these systems via the RUS List of Materials. Many of the system acceptance and design review processes developed through the Florida PV Buildings Program are being utilized in the listing of accepted packaged PV systems by the RUS. The first PV systems for listing will focus on water pumping and on-grid residential applications. This paper will review the acceptance criteria, listing processes, and use of the RUS list to better serve the nation's rural coops.

2:40 – Technical Support for Standards and Certification

Charles M. Whitaker[1,2], William F. Brooks[1], Jeffrey, D. Newmiller[1], William L. Erdman[2], and Michael R. Behnke[2]
[1]Endecon Engineering
[2]BEW Engineering, Inc.

The authors have been providing support to the DOE program, through Sandia National Laboratories, in the following areas:

Device Certification – To develop a comprehensive set of test procedures for evaluating the performance of grid connected PV inverters. These tests will ultimately be used in an inverter certification program.

Practitioner Certification – To work with the National Board of Certified Energy Practitioners (NABCEP) to establish the requirements, test content, and guides for the national certification program for PV system installers.

Domestic and International Standards – To support the on-going development of domestic PV System Standards (IEEE Standards Coordinating Committee 21) and international standards (IEC TC82) for photovoltaics systems (WG 3) and Balance of System Components (WG6).

The presentation will provide details and accomplishments in each of these areas.

3:00 – The National Impact of Zero Energy Homes

Thomas Kenney[1], Philip Davis[1], Robert Margolis[2], Craig Christensen[2], and Tim Merrigan[2]
[1]National Association of Home Builders Research Center
[2]National Renewable Energy Laboratory

In FY 2004, the Solar Energy Technologies Program began a study to assess the potential impact of Zero Energy Homes (ZEH) on reducing U.S. energy consumption. Working collaboratively with the Building Technologies Program, the National Association of Home Builders (NAHB) Research Center conducted a market-based assessment of the adoption rate for ZEH technologies in the new home construction industry. Through a combination of focus groups and home buyer surveys, market penetration rates were established for homes that produce as much energy from solar electric and solar thermal systems as they use. Then, using housing sector forecasts and energy consumption characteristics for the four U.S. census regions, the potential energy savings due to the construction of Zero Energy Homes was determined. In addition, a regional optimization analysis was conducted in order to determine the necessary technology advancements and R&D required to achieve DOE's goal of 100% Zero Energy Homes.

3:20 – NABCEP Solar PV Installer Certification Program
Peter Sheehan
North American Board of Certified Energy Practitioners

The NABCEP Solar PV Installer Certification Program has created realistic installation standards for PV practitioners through its transparent and inclusive process of garnering input from a wide variety of industry stakeholders. These standards are included in the NABCEP Task Analysis, the core document utilized as the basis for the Program Exam and, by trainers and educators in creating meaningful curricula and training programs in PV design, installation and troubleshooting/maintenance. The Program now has certified over 100 practitioners throughout the United States in 27 states through two national exam administrations. Demand for certification by practitioners remains high. PV and BOS manufacturers, distributors, dealers, state energy offices, utilities and other stakeholders recognize the value of national standards and best practices inherent in NABCEP certification. Accordingly, these groups have offered an array of incentives for NABCEP certificants. Work on a knowledge-based only, entry a-level certificate for those interested in pursuing careers in PV has recently begun.

PV Manufacturing R&D II: Manufacturing (parallel)
Chairs: Richard Mitchell and Kathryn Brown
4:00–6:00 p.m.

4:00 – Large-Scale PV Module Manufacturing Using Ultra-thin Polycrystalline Silicon Solar Cells
John H. Wohlgemuth, Mohan Narayanan, Roger Clark, Tim Koval, Joseph Creager
BP Solar International

This paper will report on the work performed by BP Solar during the first two years of NREL PV Manufacturing R&D subcontract #ZDO-2-30628-03. The major objectives of this program are to advance BP Solar’s multicrystalline silicon manufacturing technology to: increase ingot size; improve ingot material quality; develop wire saws to slice 100-µm-thick silicon wafers; develop equipment for demounting and handling of ultra-thin wafers; develop cell processes that produce cells with efficiencies of 15.4% at an overall yield exceeding 95%; expand existing in-line manufacturing data reporting systems; and facilitate an increase in the availability of lower-cost solar grade silicon feedstock. Specific accomplishments include casting of larger ingots, sawing of 125 µm thick multicrystalline Si wafers, process improvements to increase cell and module efficiency, identification of handling and process changes necessary to product ultra-thin cells and process them into modules, and development of tests to identify micro-cracks in wafers and cells.

4:20 – EFG Technology and Diagnostic R&D for Large-Scale PV Manufacturing
Juris P. Kalejs
RWE SCHOTT Solar, Inc.

We report here on R&D on technology being developed for processing cells and modules based on silicon ribbon wafers produced by the Edge-defined Film-fed growth (EFG) technique. Manufacturing of EFG wafers has matured at RWE SCHOTT Solar in the past 10 years and ribbon growth capacity has expanded to over 40 MW. We are developing cell manufacturing methods for EFG wafers with areas up to 12.5 cm x 12.5 cm, and will discuss R&D on implementing process control and diagnostics improvements for a 12-MW cell line in Billerica which is currently being upgraded in capacity. Current priorities in our NREL program that will also be examined in the talk include: automating EFG wafer and cell production, diagnostics and sensor development in wafer production, evaluating improved laser cutting technology, and improving properties of 250-micron-thick, large-area EFG wafers.

4:40 – Advances in String Ribbon Silicon Technology

Jack I. Hanoka
Evergreen Solar

Under the auspices of an NREL-funded PV Manufacturing Research and Development subcontract, dual ribbon growth from a single crucible (Gemini) and subsequent cell processing have advanced. Gemini is now the basis for a 15 MW expansion at Evergreen Solar. This expansion has been fueled by exploiting a deeper understanding of String Ribbon crystal growth. Controls and instrumentation have been refined with improved software algorithms and their use in more accurate measurements. This has resulted in improvements of anywhere from 10% to 30% in the measurement and control of key growth parameters such as temperature, silicon melt depth, and ribbon thickness. The result has been the flattest ribbon and the highest production yields ever achieved on String Ribbon. With these Gemini advances, down stream processing has been developed to result in in-line, high yield processes in cell and module making.

5:00 - ECD's PV Manufacturing R&D Program: The Implementation of a Comprehensive Online Diagnostic System for Roll-to-Roll a-Si Solar Cell Production

Tim Ellison[1], Jeff Karn[1], Genady Bondarenko[1], Rujiang Liu[2], and David Dodge[3]
[1]Energy Conversion Devices, Inc.
[2]United Solar Ovonic
[3]Focus Software

Energy Conversion Devices has developed a comprehensive set of online diagnostic systems that allow real-time measurement of PV device characteristics in-situ during a-Si deposition, prior to application ITO. Device characteristics measured include open-circuit voltage, charging rate, and thickness of each cell in the trip-junction device. Measurements are made with a precision of about 0.1%, and at rates of 0.02 to 1 Hz. The information from theses systems is displayed real-time in the control room for online quality assurance and trouble-shooting. The systems have also begun to be incorporated into software feedback loops to control deposition processes. In this paper we describe the performance of these detector systems, their use in operations, and plans for future continuous online optimization. We also discuss how the PV Manufacturing R&D program enables the possibility of continuous significant improvement in this manufacturing technology.

5:20 – Recent a-Si Manufacturing Developments at Energy Photovoltaics, Inc.

Hermann N. Volltrauer and Kai W. Jansen
Energy Photovoltaics, Inc.

The objective of our PV Manufacturing R&D contract was to advance our a-Si production technology, thereby reducing manufacturing costs and increasing module output, throughput and yield. One major area of focus has been on streamlining the process to reduce the complexity and time needed to manufacture a module by eliminating or combining process steps. Cost reductions were also achieved with the use of lower cost raw materials. In addition, significant effort has been put into improving the performance of the standard a-Si tandem module. This work has identified and developed process changes that have lead to a near 20% increase in module power, with the largest contributors being the implementation of a zinc oxide/aluminum back reflector and significant increases of active area. As a result of these productivity and process improvements, the direct manufacturing cost per watt of an EPV module in the NJ facility has decreased by nearly 30%.

5:40 – Manufacturing Process Advancements for Flexible CIGS PV on Stainless Foi

Lin J Simpson[1], Scott Wiedeman[2], Tyrone L. Vincent[3], Bharat S. Joshi[1], and Nicolas B. Gomez[1]
[1]ITN Energy Systems, Inc.
[2]Global Solar Energy, Inc.
[3]Colorado School of Mines

Substantial increases in efficiency and yield have resulted for roll-to-roll CIGS PV on stainless foil at GSE. Large area cells (68.8 cm^2) have advanced beyond 12.5% efficiency, (10% average efficiency in manufacturing lots); yield has improved from 20% to 90%, by using designed experiments to optimize deposition. These successes were enabled by process control and reliability improvements under programs including the NREL-PVMR&D ITN Energy Systems subcontract. Improved cell integration, module construction and cell efficiency have led to modules with greater than 40W/kg (11.3% efficiency) in fully flexible, lightweight formats. ITN Energy Systems' PV Manufacturing R&D subcontract has advanced CIGS technology by development of predictive control models, fault tolerance, in-situ sensors, and process improvements. Physics-based models for deposition processes were developed to improve process control, redesign hardware and implement fault tolerance. With fault prevention strategies, sensor/hardware failure detection, and real-time reconfiguration of systems to operate despite sensor/hardware failures, process reliability and reproducibility have increased greatly.

Balance of Systems (parallel)
Chair: Ward Bower
4:00–6:00 p.m.

4:00 – Progress of Photovoltaic BOS R&D and Related Electronic Hardware Analysis
Ward I. Bower
Sandia National Laboratories

The "Balance of System" (BOS) generally includes everything except the photovoltaic module when applied to photovoltaic systems. A complete BOS session would take several days to include all mechanical and electrical aspects of installing, sizing, component compatibility, performance matching and operating windows. This session will focus primarily on the electronic aspect of the balance of system. The session will contain three speakers that provide an overview of ongoing advanced inverter development intent upon improving the reliability of this critical component. Speakers will also present papers describing related benchmarking, long-term testing and analysis of the process of providing valuable feedback to the inverter industry as well as validation of the characterization process.

4:20 – High-Reliability Inverter Project
Ray Hudson and Mark Edmunds
Xantrex Technology, Inc.

As the usable life of PV modules has grown to over 20 years, the life span of one of the key distributed energy system components, the inverter, has not kept pace. This work focuses on the development of a high reliability inverter and supporting MPPT charge controller that can operate effectively for many years, while meeting state-of-the-art performance levels for efficiency and flexibility. The key design goal is to achieve a mean time before failure (MTBF) in excess of 10 years through the choice of components, their mounting, and designed in operating margins as well as the manufacturing process. Extensive verification and "highly accelerated life testing" (HALT) will be carried out to uncover any design defects that might limit operating life, and to ensure the goal of a highly reliable design has been met.

4:40 – General Electric's High-Reliability Photovoltaic Inverter Program
Joseph L. Smolenski
GE Global Research

GE is developing a highly reliable inverter for residential photovoltaic system applications. This presentation will discuss the current status of the Phase II portion of this competitively bid high-reliability inverter initiative, cost shared with the US Department of Energy's Solar Program through Sandia National Laboratories. The main objectives of the high reliability initiative are to improve photovoltaic inverter reliability while keeping cost low, and to obtain sales volumes of at least 10,000 units per year in the near term. Circuit topology, design margins, thermal management, materials and component selection, and packaging all lead to an improved product for the photovoltaic industry. Technology improvements and potential development areas for inverter will be discussed.

5:00 – SatCon's High-Reliability Inverter Initiative
Leo F. Casey
SatCon Technology Corporation

SatCon is under contract to Sandia National Laboratories for the US Department of Energy's Solar Program to produce a highly reliable inverter for photovoltaic applications. SatCon produces a full line of inverters rated up to 3MW. The high-reliability project has allowed SatCon to extend some of the key elements of high reliability "Industrial Inverter" design into lower powered commercial product. Examples of key design elements are the elimination of electrolytic capacitors (the Achilles heel of power electronics), elimination of optical components (particularly unreliable at elevated temperatures), and applications of voltage, power, and device temperature deratings used in industrial design practices. Another area that benefits from industrial inverter practice is the suppression of Voltage surges and spikes. The presentation will discuss key elements of our conceptual design, the status of design and verification, and our plans for proof of design and proof of manufacturing. It will also provide a discussion of new opportunities for "Dramatic Advances in Reliability" that are based on SatCon's experience in packaging, manufacturing processes, materials, and device developments.

5:20 – Coordination of Long-Term Inverter Testing
Jerry W. Ginn
Sandia National Laboratories

Efforts are underway to characterize the performance of photovoltaic inverters operating over extended periods of time. This information is needed in order to predict the efficiency, energy production and overall performance of PV systems that may be expected to operate in excess of twenty years. Models resulting from these long-term evaluations will provide information for system integrators and input to the performance module of the DOE systems-driven approach model PVSAM. Long-term data that have been acquired for fielded PV systems have not been specific to inverter performance, and detailed laboratory inverter evaluations do not assess long-term environmental or aging effects. A combination of these two approaches is indicated. To acquire the necessary data requires a team approach that includes multiple facilities. Basic parameters affecting inverter performance are postulated

5:40 – Inverter Testing and Analysis at Sandia National Laboratories
Sigifredo Gonzalez, Chris Beauchamp, Jerry Ginn
Sandia National Laboratories

Utility interconnected inverters are subjected to detailed evaluations at Sandia's Distributed Energy Technologies Laboratory (DETL). There are several purposes for these evaluations. First, they assist manufacturers to achieve the performance and reliability that are required to sustain the present high level of implementation of photovoltaics. Additionally, test information is being used in the development of an inverter performance model for the DOE system-driven approach model PVSAM. Laboratory testing will also validate inverter simulations being performed cooperatively with South Dakota State University. Finally, DETL is verifying test procedures for an inverter performance certification test protocol being developed by Sandia in collaboration with the California Energy Commission. Recently a number of new utility-interconnected photovoltaic inverters have been evaluated. Laboratory evaluations of prototype and production indicate that today's designs have shown a significant increase in performance and are meeting utility interconnection requirements.

PV Systems Engineering and Reliability (parallel)
Chair: Michael Quintana
4:00–5:40 p.m.

4:00 – Photovoltaic Systems Engineering and Reliability; Overview
Michael A. Quintana, David L. King, Charles J. Hanley, and Larry M. Moore
Sandia National Laboratories

An ever-increasing need for technical information on photovoltaic systems is being fueled by market growth. Competition has spurred a demand for information that photovoltaic system integrators can use to sell value propositions to their customers. Likewise, customers are becoming more sophisticated in their analysis of whether or not to purchase photovoltaics systems. Finally, some state financial incentives are requiring certain system conditions/metrics be met in order for incentives to be disbursed. Requests for information fall primarily into the categories of system cost, system reliability and system performance. The objective of this paper and this session is to examine informational needs of the industry, customers, and the states and describe recent work funded by the DOE Solar Program addressing the increasing demand for technical information.

4:05 – NREL PV System Performance and Standards Technical Progress
C.R. Osterwald, J. del Cueto, J. Pruett, D. Trudell, and W. Marion
National Renewable Energy Laboratory

This paper presents an overview of the status and accomplishments of the PV Module Reliability and Performance R&D task, under the PV Module Reliability R&D Project. During FY04, the thin film module hot & humid exposure subcontracts (part of the Thin Film PV Partnership) were supported through extensive baseline testing, data archiving, and site visits. A new solar weathering test has been initiated in the recently refurbished Outdoor Accelerated-weathering Test System (OATS). We completed a test plan with First Solar on CdTe modules involving indoor stress testing and outdoor testing in the Performance and Energy Ratings Testbed (PERT). Damp heat and thermal cycling tests were done on crystalline-Si prototype modules from SBM Solar.

4:20 – Changes in the 2005 National Electrical Code and Their Impact on the PV Industry
John C. Wiles
Southwest Technology Development Institute

The PV Industry Forum submitted more that 30 proposals for revising the 2005 National Electrical Code (NEC) to the National Fire Protection Association (NFPA). These proposals, and the 2005 code in general, will directly affect the safety of installed PV systems. They will positively impact the cost and performance of PV systems. Most of the submitted proposals were accepted (some with minor revisions). A few were rejected. Several of the accepted changes will clarify the code and simplify the work of both PV installers and electrical inspectors. Some of the accepted changes will allow simplified installations and reduced material and labor costs, while others will allow installations that have previously been prohibited. Ultimately, these proposals will allow newer technology to be used, thereby increasing system efficiencies while reducing equipment costs.

4:40 – Photovoltaic Power Plant Experience at Arizona Public Service—A 5-Year Assessment
Larry M. Moore[1], Harold N. Post[1], Bryan Scott Canada[2], and Herb Hayden[2]
[1]Sandia National Laboratories
[2]Arizona Public Service

Arizona Public Service (APS) currently has over 4.3 MWdc of grid-connected flat-plate photovoltaic systems including 21 tracking horizontal flat-plate systems greater than 90 kWdc each that have been installed in its service territory over the past five years. Most of this installed PV capacity is in support of the Arizona Corporation Commission Environmental Portfolio

Standard goal that encourages APS to generate 1.1% of its energy generation through renewable resources by 2007, with 60% of that amount from solar. During this time, much has been learned regarding performance, cost, maintenance, installation and design. This paper presents an assessment of these topics and including baseline cost, performance and operation and maintenance data and a perspective associated with this PV experience.

5:00 – Benchmarking Results for Utility-Scale PV Systems
Andrew L. Rosenthal
Southwest Technology Development Institute

Benchmarking is the process of documenting first costs, recurring and non-recurring costs, reliability, and performance of fielded PV systems. Accurate benchmarking data are a fundamental component of DOE's Systems Driven Approach (SDA) required for the completion of three DOE milestones related to development of PV analysis tools, revision and refinement of the SDA process, and the establishment of a useful performance and reliability database. In conjunction with SNL and NREL, the Southwest Region Experiment Station (SWRES) has been defining the suite of benchmarking parameters and then providing the qualified data necessary to document these parameters for utility-scale and large, grid-connected commercial PV systems. The first sets of benchmarking data are now available for use by DOE, the national laboratories, policy makers, and the PV community.

5:20 – Recent and Planned Enhancements for PVWATTS
B. Marion, M. Anderberg, and P. Gray-Hann
National Renewable Energy Laboratory

PVWATTS is an Internet-accessible software program that allows the user to easily calculate the energy production and cost savings for photovoltaic (PV) systems located throughout the United States. Recent enhancements have been made to allow the user to define the system location by the use of zip code or latitude and longitude coordinates, and to receive more detailed performance information by providing a.c. energy production for each hour of the year, as well as average hourly a.c. energy profiles by month. Future enhancements under consideration are also discussed. They include more flexibility for the user in defining system losses from soiling and in the conversion from d.c. to a.c. power, an option for international locations, and accounting for PV module shading.

Wednesday, October 27, 2004

Plenary Session III: Program Highlights
Chairs: Tom Surek, Joe Tillerson
8:30–10:10 a.m.

8:30 - Photovoltaics R&D: at the Tipping Point
Lawrence L. Kazmerski
National Renewable Energy Laboratory

*"... with robust investments in research and market development, the picture changes dramatically."** Thus, the realigned U.S. PV Industry Roadmap highlights R&D as critical to the tipping point that will make solar PV significant in the U.S. energy portfolio—part of a well-designed plan that would bring "2034 expectations" to reality by 2020. Technology improvement and introduction depend on key, focused, and pertinent research contributions, ranging from the most fundamental through the applied. In this presentation, the successes and relevance of our current PV R&D program are underscored, built on integrated capabilities spanning atomic-level characterization, nanotechnology and new materials design, interface and device engineering, theoretical guidance and modeling, processing, measurements and analysis, through process integration. This presentation identifies and provides examples of critical research tipping points

needed to foster *now and near technologies* (primarily crystalline silicon and thin films) and to introduce *coming generations of solar PV* that provide options to push us to the next performance levels (devices with ultra-high efficiencies and with ultra-low cost). The serious importance of science and creativity to U.S. PV technology ownership—and the increased focus on accelerating the time from laboratory discovery to industry adoption—are emphasized at this *"tipping point"* for solar PV.

** Our Solar Power Future: The U.S. Photovoltaics Industry Roadmap Through 2030 and Beyond (SEIA, Washington, DC, 2004).*

8:50 - From Microscale to Macroscale: PV Systems of the Future
Jeffrey S. Nelson
Sandia National Laboratories, Solar Technologies Division

This presentation will discuss the opportunities and requirements of future PV systems from the microscale (milliwatts) to the macroscale (gigawatts). Particular focus will be given to technologies and applications with the potential for near-term (<10 years) impact on PV manufacturing volumes and installations.

9:10 - Progress in Thin-Film CdTe Module Manufacturing
Rick C. Powell and Peter V. Meyers
First Solar

Steady progress has been made in the manufacture of thin film CdTe-based photovoltaic modules at First Solar. Average module performance (total area) has increased from 7.1% in 2002 to 8.6% in 2004. Our current champion module has an NREL-confirmed performance of 9.4%. Production volume has increased from 1.5 MW in 2002 to 2.5 MW in 2003. Approximately 6 MW will be produced in 2004. An upgraded and fully automated 25MW/yr production line is currently being qualified and full operation is expected in early 2005. Sales, primarily into Europe, have kept pace with the production volume increase. Market demand continues to grow and is expected to readily accommodate production volume from the new manufacturing line. Support from the Thin Film Photovoltaic Partnership Program has leveraged technology development of advanced front contacts, semiconductor deposition, accelerated life testing and waste reduction/recycling. An overview of the progress in manufacturing and technology improvement will be presented.

9:30 - A Vision for Crystalline Silicon Solar Cells
Richard M. Swanson
SunPower Corporation

The intent of this paper is to present a vision for crystalline silicon solar cells that details a possible set of technical, financial and political requirements to enable their ultimate success as a significant source of renewable energy. Historically, solar cell module prices have been decreasing roughly 50 percent per decade. We will show how crystalline silicon solar cells can continue this trend over the next decade, thus becoming cost-competitive without subsidies in many distributed grid-connected applications. Significantly no "big breakthroughs" are needed for this to happen. An evolutionary development of existing silicon technology is shown to be all that is necessary, and indeed all that is likely. The total required subsidy in order to "buy down" this market is roughly $25 billion. Projections beyond ten years become problematic. It is here that breakthrough photovoltaic technologies now in the laboratory can be expected to contribute.

9:50 - Approaches for Ultra-High-Efficiency Solar Cells
Christiana B. Honsberg
Department of Electrical and Computer Engineering, University of Delaware

As existing photovoltaic devices approach their material-imposed efficiency limits, new approaches are being developed that can circumvent the efficiency limits imposed by presently used materials. One approach is to use new materials, such as the InGaN material system, that allow tandem structures with a large number of junctions. The InGaN material system is an ideal candidate for high-performance photovoltaics since it has an ideal band gap range, it is relatively insensitive to dislocations, and its piezoelectric properties offer a new design parameter for high efficiency devices. A different class of approaches involves the design of new band structures, using nanostructures and quantum confinement, to design solar cells that efficiently convert photons with energy below that of the Fermi-level separation at the contacts. Such devices require that new physical mechanisms, such as intra- or inter-band transitions, two-photon absorption that occur in quantum wells and quantum dots, are optimized for efficient energy conversion.

Silicon I: Crystalline (parallel)

Chair: Howard Branz

10:30 a.m.–12:10 p.m.

10:30 - a-Si:H Emitter and Back-Surface-Field Contact for Crystalline Silicon Solar Cells

Tihu Wang, Eugene Iwaniczko, Qi Wang, Matthew R. Page, and Dean H. Levi
National Renewable Energy Laboratory

Thin intrinsic and doped hydrogenated amorphous silicon (a-Si:H) double layers by hot-wire chemical vapor deposition (HWCVD) are investigated as emitters and back-surface-field (BSF) contacts to both p- and n-type crystalline silicon wafers. Passivation quality is studied by characterizing the finished solar cells and by photoconductive decay lifetime measurements. The crystal-amorphous heterointerface is studied with real-time spectroscopic ellipsometry and high-resolution transmission electron microscopy to detect phase change and material evolution. A common requirement in excellent emitter and BSF is minimization of interface recombination which is obtained with immediate a-Si:H deposition and an abrupt and flat interface to the c-Si substrate. We obtain open-circuit voltage greater than 640 mV, interface recombination velocity less than 15 cm/sec, and efficiency of 14.8% on polished p-type Czochralski-grown Si wafers. Collaboration between NREL and Georgia Tech resulted in a 15.7%-efficient HWCVD-deposited a-Si emitter on non-textured FZ-Si with a Georgia Tech screen-printed Al-BSF.

10:50 - Development of High-Efficiency Solar Cells on Low-Cost Silicon Materials

Ajeet Rohatgi, Vijay Yelundur, and Abasifreke Ebong
University Center of Excellence for Photovoltaics Research and Education, School of Electrical and Computer Engineering, Georgia Institute of Technology

This paper reports on five record-high-efficiency 4 cm^2 solar cells on three different multicrystalline silicon materials achieved through effective hydrogen passivation of bulk defects during cell processing. Silicon ribbon solar cell efficiencies of 18.2% and 17.9% were achieved on EFG and String Ribbon Si cells fabricated with photolithography front contacts, screen-printed Al-doped back surface field, and double layer anti-reflection coating. In addition, high-efficiency, screen-printed cells were achieved on HEM (16.9%), EFG (16.1%), and String Ribbon (15.9%) Si. Proper implementation of fast co-firing of screen-printed contacts in a belt furnace significantly enhanced the bulk lifetime to ~100 µs, produced high quality contacts, and improved the quality of the Al back surface field. It is found that the back surface recombination velocity obtained on float zone cells cannot be used to predict the performance of Cz or mc-Si cells. A roadmap for achieving 18-19%-efficient screen-printed cells on low-cost materials is presented.

11:10 - The Impact of Metal Impurity Clusters on Solar Cell Performance in Multicrystalline Silicon

Tonio Buonassisi, Andrei A. Istratov, and Eicke R. Weber
University of California, Berkeley

Synchrotron-based analytical microprobe techniques were employed to investigate metal precipitates in mc-Si. X-ray fluorescence microscopy was used to study the elemental nature and location of nanometer-sized metal-rich particles in mc-Si solar cells, X-ray absorption microspectroscopy was used to determine the chemical phase of metals within the precipitates, and the X-ray beam induced current technique was used for in-situ mapping the recombination-activity of the precipitates. Transition metal precipitates were found both at grain boundaries and within intragranular defect clusters. The majority of metal clusters were small metal-silicide precipitates, but a few large oxidized particles were also observed. The collected database on morphology, chemical state, and density of metal precipitates allowed us to suggest mechanisms of their formation in solar cells and propose approaches how to reduce the metal content in solar cells or how to reduce the impact of metals on degradation of minority carrier diffusion length.

11:30 - Effect of Grown-in Light Element Impurities on PV Silicon Mechanical Properties
Abdennaceur Karoui, F. Sahtout Karoui, and George Rozgonyi
Dept. of Materials Science and Engineering., North Carolina state University

Oxygen and nitrogen effects on dislocation motion have been studied in relation to the mechanical properties of Czochralski and float zone silicon. Nitrogen related chemical complexes (i.e., N-O-Si_V), in regions with known extended defects in annealed N doped CZ and FZ Si wafers were analyzed by high resolution synchrotron Fourier transform IR spectroscopy. A strong correlation was observed between the depth dependent FTIR absorption variations, the defect distributions, and the local hardness. Large observed differences in hardness were explained in terms of dislocation-impurity interactions. In close correlation with measured hardness, atomistic calculations showed that there are three groups of impurities that produce distinct dislocation locking effects in silicon. The model used, developed by Johnson et al., incorporates impurity size effects with the continuum theory of elasticity and explains how light elements will bind strongly with edge dislocations, in line with the observed hardness enhancement. For a local atomic fraction of 10^{-4} the impurity-dislocation binding energy varies from 0.008 eV/Å for P to 1.7eV/Å and 1.8 eV/Å for N and O, respectively.

11:50 – Residual Stress Measurements as Related to Solar Cell Processing
S. Danyluk, S. He, A. Rohatgi, A. Upadhyaya, and V. Yelundur
Georgia Institute of Technology

It is well known that residual stresses in silicon are insidious and their magnitude, sign and spatial distribution can lead to a degradation of electrical properties and fracture. It is also well known that processing of silicon into photovoltaic cells can modify, redistribute and exacerbate the residual stresses. Our work has involved the development of an optical polariscopy technique (near infrared wavelength light transmission) that maps out the residual stresses in typical dimension silicon wafers. New methods of transmitted optical signal processing taking into effect the crystallographic anisotropy of the especially thin (<250) silicon have been developed and full-field mapping of stresses has been achieved. This polariscopy technique and analysis has been applied to Cz, cast, EFG and ribbon wafers at various stages of PV cell processing. Measurements of residual stress have been made after etching, diffusion and AR-coating. The relationship of these stresses to photoluminescence and photovoltage will also be presented.

Exploratory PV II: Advanced Solar Conversion Processes (parallel)
Chair: Robert McConnell
10:30 a.m.–12:10 p.m.

10:30 - DOE Office of Science Funded Basic Research at NREL that Impacts Photovoltaic Technologies
Satyen K. Deb
National Renewable Energy Laboratory

The DOE Office of Science, Basic Energy Sciences, supports a number of basic research projects in materials, chemicals, and biosciences at NREL that impact several renewable energy technologies, including photovoltaics. The goal of the Material Sciences projects is to study the structural, optical, electrical, and defect properties of semiconductors and related materials using state-of-the-art experimental and theoretical techniques. Specific projects involving photovoltaics include: ordering in III-V semiconductors, isoelectronic co-doping, doping bottlenecks in semiconductors, solid state theory, and computational science. The objective of the Chemical Sciences program is to advance the fundamental understanding of the relevant science involving materials, photochemistry, photoelectrochemistry, nanoscale chemistry, and catalysis that support solar photochemical conversion technologies. Specific projects relating to photovoltaics include: dye-sensitized TiO_2 solar cells, semiconductor nanostructures, and molecular semiconductors. This presentation will give an overview of some of the major accomplishments of these projects.

10:50 – High-Efficiency Solar Cell Concepts: Physics, Materials, and Devices

Angelo Mascarenhas and Mark Wanlass
National Renewable Energy Laboratory

Over the past three decades significant progress has been made in the area of high-efficiency multijunction solar cells, where the effort has primarily been directed at current-matched solar cells in tandem. The key materials issues here have been obtaining semiconductors with the required band gaps for sequential absorption of light in the solar spectrum and that are lattice matched to readily available substrates. The GaInP/GaAs/Ge cell is a striking example of success achieved in this area. In this talk, I will discuss several new approaches for high-efficiency solar cell design that involve novel methods for tailoring alloy bandgaps, alternate technologies for hetero-epitaxy of III-Vs on Si, and finally, new device architectures. The advantages and difficulties expected to be encountered with each approach will be discussed, addressing both the materials issues and device physics whilst contrasting them with other fourth--generation solar cell concepts.

11:10 – Theoretical and Experimental Investigation of Approaches to >50%-Efficient Solar Cells

Christiana B. Honsberg[1] and Michael Levy[2]
[1]Department of Electrical and Computer Engineering, University of Delaware
[2]School of Electrical and Computer Engineering, Georgia Institute of Technology

Solar cell device modeling based on generalized efficiency-limit modeling shows that a variety of new approaches can achieve efficiencies over 50%. Many of the suggested approaches for ultra-high efficiency, including intermediate band, quantum well, and quantum dot devices, rely on the ability to have multiple quasi-Fermi levels in a single structure. In order to design solar cells and test structures, device simulations, which include multiple Fermi level calculations, are required. This paper presents models for processes that give rise to multiple Fermi levels or multiple quasi-Fermi levels. One set of models focuses on calculating band structures for multiple Fermi levels in quantum dot devices, in order to determine material, device, and doping constraints. The second model focuses on transport processes that can give rise to multiple quasi-Fermi levels. The key transport processes are those unique to quantum-based devices, such as thermal and optical capture and escape mechanisms and tunneling.

11:30 – Quantum Dot Solar Cells: High Efficiency through Impact Ionization

Mark Hanna, Randy J. Ellingson, Matt Beard, Pingrong Yu, and Arthur J. Nozik
National Renewable Energy Laboratory, Center for Basic Sciences

Impact ionization (I.I.) is a process where absorbed photons that are at least twice the bandgap can produce multiple electron-hole pairs. For single-bandgap PV devices, this effect produces greatly enhanced theoretical thermodynamic conversion efficiencies that range from 45%–85%, depending on solar concentration, cell temperature, and the number of electron-hole pairs produced per photon (1); in principle N electron-hole pairs can be produced from photons with energy N x E_g. In bulk semiconductors, the requirement that crystal momentum needs to be conserved in addition to energy, leads to thresholds for I.I. that are typically 3-4 times the bandgap. This greatly limits the application of I.I. in p-n PV cells, since the threshold is driven to the UV. However, for quantum dots (QDs), crystal momentum is not a good quantum number and need not be conserved; this means the threshold may occur at only 2 x E_g. We have observed astoundingly efficient impact ionization in QDs of PbSe (bulk E_g = 0.28 eV). The threshold for I.I. occurs at 3 times the QD HOMO-LUMO transition (its "bandgap") because of the unusual electronic structure of PbSe. However, the quantum yield rises quickly after the threshold and reaches 300% at 4 x E_g; this means that every QD in the sample produces 3 electrons/photon. Future work will explore the dependence of size, electronic structure, and related semiconductor properties on I.I., and will also model the performance of quantum dot solar cells that are based on I.I. This work was done in collaboration with NREL's research program supported by the DOE Office of Science, Office of Basic Energy Sciences.

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1. P.T. Landsberg and V. Badescu, J. Phys. D: Appl. Phys. 35, 1236 (2002).

11:50 - Quantum Dots for PV: Theory
Alex Zunger
National Renewable Energy Laboratory

Quantum dots have been studied for PV applications (Nozik et al.) with considerable promise. There are two basic properties of such systems that form the basis for this promise. We will examine these theoretically: (a) Whereas in "bulk" solids or thin films, electrons excited above the conduction band minimum (CBM) decay rapidly to the CBM (and thus their energy is lost), in quantum dots this decay may be slowed down, to the benefit of greater efficiency. Furthermore (b) in dots, a high-energy (larger than twice the bandgap) exciton may decay to the CBM while giving up its energy to create another exciton, rather than losing its energy to heat. This (impact ionization) would thus create two excitons from one. Using state-of-the-art atomistic quantum theory, we have computed quantitatively the probability of these two events for CdSe quantum dots, identifying the conditions needed for their success.

Concentrating Solar Power I (parallel)
Chair: Thomas Mancini
10:30 a.m.–12:10 p.m.

10:30 - Development and Testing of High-Temperature Solar Selective Coatings
Cheryl E. Kennedy and Henry Price
National Renewable Energy Laboratory

The solar energy technology program is working to reduce the cost of parabolic trough solar power technology. System studies show that increasing the operating temperature of the solar field from 390ºC to >450ºC will result in improved performance and significant cost reductions. This requires the development of new more efficient selective coatings that have both high solar absorptance (>0.96) and low thermal emittance (<0.07) and are thermally stable above 450ºC, ideally in air. Potential selective coatings were modeled, identified for laboratory prototyping, and manufactured at NREL. Optimization of the samples and high temperature durability testing will be performed. Development of spectrally selective materials depends on reliable characterization of their optical properties. Protocols for testing the thermal/optic properties of selective coating were developed and a round robin experiment conducted to verify and document the high-temperature emittance measurements. The development, performance, and durability of these materials and future work will be described.

10:50 - Development and Testing of Solar Reflectors
Cheryl E. Kennedy, Kent Terwilliger, and Michael J. Milbourne
National Renewable Energy Laboratory

To make concentrating solar power technologies more cost competitive, it is necessary to develop advanced reflector materials that are low in cost and maintain high reflectance for extended lifetimes under severe outdoor environments. The Advanced Materials team performs durability testing of candidate solar reflectors at outdoor test sites and in accelerated weathering chambers.

Several materials being developed by industry have been submitted for evaluation. These include silvered glass mirrors, aluminized reflectors, and front-surface mirrors. In addition to industry-supplied materials, NREL is funding the development of new, innovative reflectors, including a new commercial laminate reflector and a super thin glass mirror. To help commercialize the super thin glass technology, a cost analysis was performed which shows the total production cost could meet the goal. The development, performance, and durability of these candidate solar reflectors and the results of the cost analysis will be described.

11:10 - Advanced Heat Transfer and Thermal Storage Fluids

Daniel M. Blake and Luc Moens
National Renewable Energy Laboratory

The next-generation solar parabolic trough system with direct thermal storage will require a heat transfer fluid with a liquid range from near 0°C to over 400°C. The vapor pressure must be below 1 atm. Other considerations are heat capacity, environment and safety, materials compatibility, and cost. We are investigating a wide range of organic liquid materials that could meet these specifications. One group comprises modifications of Therminol-VP1Ô (biphenyl and diphenyl oxide mixture), whereby we are searching for derivatives that remain liquid over a wider temperature range and have a lower vapor pressure. A second group is liquid esters that are produced for the lubricant and polymer industry where they are used for their high thermal stabilities and excellent cold flow characteristics under extreme temperature conditions. Our work involves the synthesis of such liquids and the determination of their thermal properties using Thermogravimetric Analysis and Differential Scanning Calorimetry.

11:30 – Concentrator Optical Characterization

Timothy J. Wendelin
National Renewable Energy Laboratory

Solar parabolic trough power plant projects are soon to be implemented both in the U.S. and internationally. In addition to these new projects, parabolic trough power plants totaling approximately 350 MW already exist within the United States and have operated for close to 20 years. As such, the status of the technology exists within several different phases. Theses phases include R&D, manufacturing/installation, and operations/maintenance. One aspect of successful deployment of this technology is achieving and maintaining optical performance. Different optical tools are needed to assist in improving initial designs, provide quality control during manufacture/assembly and help maintain performance during operation. This paper discusses several such tools developed at Sun♦Lab for these purposes. Preliminary testing results are presented. Finally, plans for further tool development are discussed.

11:50 – Economics of CSP Deployment

Henry Price[1] and Scott Jones[2]
[1]National Renewable Energy Laboratory
[2]Sandia National Laboratories

If solar technology is ever to be a significant contributor to the United States primary energy supply, large-scale solar energy systems must be developed. Currently, and for the foreseeable future, concentrating solar power (CSP) systems represent the lowest cost solar option for large-scale solar energy systems. Unfortunately, CSP systems are still too expensive to compete with conventional power technologies in the power market. However, rising natural gas prices and increased price volatility have helped close the cost gap with conventional power technologies. This paper evaluates the cost of power in the Southwest from conventional fossil-fuel plants and compares that with an estimate of the cost of power from new parabolic trough power plants. The paper discusses how the cost of solar electricity can achieve parity with that of electricity generated from natural gas power plants through development of solar power parks, expanded incentives or access to lower cost financing.

Silicon II: Thin Films (parallel)
Chair: J. David Cohen
1:40–3:40 p.m.

1:40 - Amorphous and Nanocrystalline Silicon PV Technology

Jeffrey Yang, Baojie Yan, and Subhendu Guha
United Solar Ovonic Corporation

Thin-film photovoltaic technology based on amorphous silicon (a-Si) and silicon germanium (a-SiGe) alloys has been the foundation for the triple-junction spectrum-splitting structure used in our roll-to-roll manufacturing plants. The annual capacity of our plants has increased from 5 MW in 1997 to 30 MW in 2003, and is expected to increase further in the near future. R&D efforts to improve stable module efficiency have also resulted in higher product rating from our new 30 MW plant. In recent years, hydrogenated nanocrystalline silicon (nc-Si) materials and solar cells have shown remarkable progress. In our laboratory, an initial active-area cell efficiency of 14.6% has been achieved using an a-Si/a-SiGe/nc-Si structure. This value is similar to that achieved previously for the a-Si/a-SiGe/a-SiGe configuration. Status and challenges associated with nc-Si solar cells will be discussed.

2:00 – Fabrication, Analysis, and Modeling of High-Efficiency a-Si-Based Solar Cells

Xunming Deng
Department of Physics and Astronomy, University of Toledo

In this presentation, I will give an overview of the recent research activities at the University of Toledo in the fabrication, analysis and modeling of a-Si:H based solar cells. This overview will include the fabrication of triple (a-Si/a-SiGe/a-SiGe), tandem (a-Si/a-SiGe) and single-junction (a-SiGe) solar cells, all with initial efficiencies above 12.5%, and the new processes that were used to obtain these high-efficiency devices. For example, the high efficiency for single-junction a-SiGe:H cells was achieved using a nc-Si:H p-layer prepared under carefully controlled conditions so that the quantum size effect for these nanocrystalline grains lead to an ideal bandgap match between the p- and i-layers. Second, I will provide an overview of the development of a special technique for measuring the component-cell I-V characteristics in a multi-junction, two-terminal device structure. Third, a modeling study on the performance of triple-junction cells using ASA program (by TU Delft) will be described.

2:20 – Insights from Modeling and Mobility Measurements in Amorphous and Microcrystalline Silicon Solar Cells

Steluta Dinca[1], Thorsten Dylla[2,1], Jianjun Liang[1], Eric A. Schiff[1], and Baojie Yan[3]
[1]Syracuse University
[2]Forschungszentrum Juelich
[3]United Solar Ovonic LLC

Low photocarrier mobilities limit solar cell conversion efficiencies. We present measurements and modeling for amorphous silicon (a-Si:H) and microcrystalline Si solar cells. These indicate that the as-deposited efficiencies of a-Si:H cells from United Solar Ovonic Corp. are close to the limit determined by the hole drift-mobility. For microcrystalline silicon cells from Forschungszentrum Julich, the hole drift-mobility is also roughly consistent with hole mobility-limitation—albeit with larger mobilities and absorber layer thicknesses than for a-Si:H. One implication of this work is thus that increasing the hole mobilities in these disordered materials is a potentially important pathway to improving cell efficiencies. For a-Si:H, this implication is tempered by the fact that cells degrade below the mobility-limit in sunlight. We describe possible models for the apparent coincidence that the solar conversion efficiencies in the mobility-limited state and the degraded state have similar magnitudes.

2:40 – Lowgap Hot-Wire a-SiGe:H Materials and Devices

A.H. Mahan[1], Y. Xu[1], L.M. Gedvilas[1], and B. Yan[2]
[1]National Renewable Energy Laboratory
[2]United Solar Ovonic Corporation

The incorporation of high Ge content a-SiGe:H into a low bandgap solar cell commonly involves the use of bandgap (Ge) profiling, where the lowest bandgap (highest Ge content) material is placed near the middle of the i-layer to avoid abrupt bandgap transitions at the interfaces. Since in this approach the material must be profiled over a wide range of Ge content, all i-layer alloy compositions, including that of a-Si:H (no Ge), must be of device quality and be deposited using similar process conditions. This work explores deposition of optimum quality low bandgap a-SiGe:H as well as optimum quality a-Si:H by the HWCVD technique using a tantalum filament operating at low temperature. We gauge the material quality by comparing infrared, film bandgap, SIMS, and conductivity results to those presented elsewhere, and fabricate single junction as well as tandem n-i-p solar cell devices using these i-layers.

3:00 – Phase Engineering of High-Efficiency a-Si:H Solar Cells

Christopher R. Wronski[1] and Robert W. Collins[2]
[1]Center for Thin Film Devices, Pennsylvania State University
[2]Department of Physics and Astronomy, University of Toledo

In this research program, systematic optimization has been undertaken for protocrystalline Si:H deposited using hydrogen dilution of silane. This approach was guided by deposition phase diagrams obtained by real time spectroscopic ellipsometry. These diagrams describe the microstructural and phase evolution with thickness for the protocrystalline Si:H during its growth with different hydrogen dilutions. Systematic optimization was also guided by the measured characteristics of carrier recombination that reveal clearly transitions of the films with thickness from purely amorphous to an amorphous + (nanocrystalline/microcrystalline) mixed-phase. Results of a “two-step” process are presented and discussed. In this process, systematic improvements are obtained for the intrinsic layers, consisting of two purely amorphous-protocrystalline phases, which are fabricated with controlled thicknesses and hydrogen dilutions. Results are presented on the detailed characterization of such phase engineered cell structures that offer new insights into the various mechanisms limiting the performances of highest quality cells.

3:20 – Tritiated Amorphous Silicon: Insights into the Staebler-Wronski Mechanism

Paul Stradins[1], Janica Whitaker[2], Stefan Zukotynski[3], and P. Craig Taylor[2]
[1]National Renewable Energy Laboratory
[2]University of Utah
[3]University of Toronto

Hydrogen, though essential for device-quality amorphous silicon, likely contributes to the light-induced degradation process (Staebler-Wronski effect) that reduces the solar cell efficiency by about 4 absolute percent. We are testing the role of hydrogen by using its isotope tritium. When tritium bonded to Si spontaneously decays into inert helium-3, it should leave behind the Si dangling bond defect. We have studied degradation due to tritium and note its resemblance to Staebler-Wronski effect. Surprisingly, 100x fewer defects are created than expected from tritium decay, suggesting a mechanism that heals most of the defects, even at temperatures down to 4 K. We consider different mechanisms for the thermal and athermal healing processes (motion of hydrogen, effect of beta-electrons, decay of hydrogen-tritium molecules etc.). Our findings might shed new light on the degradation mechanism in a-Si:H and help reveal the role of hydrogen and structural rearrangements near a newly created defect.

PV Module Reliability (parallel)
Chair: Roland Hulstrom
1:40–3:40 p.m.

1:40 - PV Module Reliability R&D Project Overview

Roland L. Hulstrom[1] and Michael Quintana[2]
[1]National Renewable Energy Laboratory
[2]Sandia National Laboratories

The DOE Solar Energy Technologies Program includes a project entitled "Photovoltaic Module Reliability R&D." This project has been in existence for several years to help ensure that the PV technologies that advance to the commercial module stage have acceptable service lifetimes and annual performance degradation rates. The long-term goal is to assist industry with the development of PV modules that have 20- to 30-year service lifetimes with less than 1% annual performance degradation rates. The approach includes: (1) accelerated indoor and outdoor, and long-term outdoor exposure testing; (2) advanced diagnostics; (3) failure and degradation discovery, identification, analysis, and mitigation; (4) characterization and modeling; and (5)module packaging and design R&D. The project is a team effort including the National Renewable Energy Lab, Sandia National Labs, the Florida Solar Energy Center, the Southwest Technology Development Institute, Arizona State University, and many PV industry partners.

2:00 – Performance Degradation Rates in Commercial Modules

David L. King, Jay A. Kratochvil, Barry R. Hansen, and William E. Boyson
Sandia National Laboratories

The electrical performance of all commercial photovoltaic modules degrades as a function of time spent outdoors. Depending on the rate of degradation, the associated performance loss can be a significant factor influencing the reliability and ultimately the commercial viability of photovoltaic power systems. Accurately quantifying degradation rates is difficult because results are influenced by module production variability, testing and analysis procedures, and the exposure environment. Addressing system reliability, Sandia initiated an effort that has continued since 1991 to investigate performance degradation rates in commercial modules subject to real-time outdoor exposure. Extensive test data for a wide variety of commercial modules have been recorded using consistent and tightly controlled measurement procedures, providing both degradation rates and an estimate of their associated uncertainty. This paper highlights results for selected modules (without identifying manufacturers) and defines the extent of analyses yet to be completed for a more comprehensive report on module degradation rates.

2:20 – Outdoor Monitoring and High-Voltage Bias Testing of Thin-Film PV Modules

Neelkanth G. Dhere, Vinaykumar V. Hadagali, Jyoti S. Shirolikar, and Sachin M. Bet
Florida Solar Energy Center

Grid-connected photovoltaic systems must withstand high voltage bias in addition to harsh environmental conditions. The objective of this research is to test the performance of thin-film PV module arrays in hot and humid climate under high-voltage bias and understand reliability issues to lay scientific basis for improved manufacturing technology. Modules of each U.S. thin-film PV company are connected in series to reach the maximum V_{oc} of up to +600 V and –600 V. Measurements are carried out across a small resistors connected in series with the load resistors. Each array voltage output, back of module temperatures, relative humidity, solar irradiance, UV irradiance and wind speed and leakage currents from modules individually biased to +600 V and –600 V are monitored regularly. Parameters are measured at 15-second intervals and averages over 2-minute periods are recorded. Visual and IR images are also taken to monitor any changes in modules.

2:40 – Module Design, Materials, and Packaging Research Team: Activities and Capabilities
T.J. McMahon, Joe delCueto, Gary Jorgensen, Mike Kempe, and Kent Terwilliger
National Renewable Energy Laboratory

Our team activities are directed at improving PV module reliability by incorporating new, more effective and less expensive packaging materials and techniques. Characterization of new and existing materials or designs are evaluated before and during accelerated environmental exposure for the following properties: (1) Adhesion and cohesion; peel strength and lap shear. (2) Electrical conductivity; surface, bulk, interface and transients. (3) Water vapor transmission; solubility and diffusivity. (4) Accelerated weathering; UV, temperature, and damp heat tests. (5) Module and cell failure diagnostics; IR imaging, individual cell shunt, coring. (6) Fabrication improvements; SiONC barrier coatings and enhanced wet adhesion. (7) Modeling; Moisture ingress/egress and cell-to-frame leakage current. And (8) Rheological properties of polymer encapsulant and sheeting materials. Specific examples will be described.

3:00 – Packaging Materials and Design for Improved Module Reliability
Gary J. Jorgensen, Kent M. Terwilliger, Michael D. Kempe, and Tom J. McMahon
National Renewable Energy Laboratory

A number of candidate alternative encapsulant and soft backsheet materials have been evaluated in terms of their suitability for PV module packaging applications. Relevant properties including peel strength as a function of damp heat exposure and permeability have been measured. Based on these tests, promising new encapsulants with adhesion-promoting primers that result in improved properties have been identified. Test results for backsheets provided by industry and prepared at NREL have suggested strategies to achieve significantly improved products. The ability of glass/glass and glass/breathable backsheet constructions laminated with various encapsulant and/or edge seal materials to protect thin-film aluminum coatings deposited onto glass substrates was assessed. Glass/glass laminate constructions can trap harmful compounds that catalyze moisture-driven corrosion of the aluminum. Constructions with breathable backsheets allow higher rates of moisture ingress but also allow egress of deleterious substances that can result in decreased corrosion.

3:20 – Module Encapsulant Diagnostic and Modeling
Michael D. Kempe
National Renewable Energy Laboratory

Encapsulant materials are used in photovoltaic devices for mechanical support, electrical isolation, and protection against corrosion. The ability of an encapsulant to protect against surface corrosion is related to its adhesional strength. The adhesion of an encapsulant under accelerated environmental stress was examined to determine what materials have the best hydrolytic stability and are more likely to reduce corrosion rates. Under environmental exposure the ingress of water has been correlated with increased corrosion rates. The diffusivity of different encapsulants has been measured to determine how long it takes for water to enter a module. The high diffusivity of ethylene vinyl acetate indicates that even with the use of an impermeable back-sheet, moisture from the sides will diffuse throughout the entire module. To significantly reduce moisture ingress requires a true hermetic seal, the use of an encapsulant loaded with desiccant, or the use of a very low diffusivity encapsulant.

Concentrating Solar Power II (parallel)
Chair: Mark Mehos
1:40–3:40 p.m.

1:40 – Advanced Trough Concentrator Design

Randy Gee[1] *and Allan Lewandowski*[2]
[1]*Solargenix Energy*
[2] *National Renewable Energy Laboratory*

The USA Trough Initiative has been supporting the development of advanced parabolic trough designs for several years. This initiative will expand U.S. industry involvement and competitiveness in worldwide trough development activities. Specific activities will reduce cost, improve performance, improve reliability, reduce commercial risk, or affect other factors to improve the competitiveness of trough technology. This paper will describe activities at Solargenix Energy to achieve the goals of the USA Trough Initiative. In previous efforts, they used wind tunnel test data to design a lightweight and easily transportable space frame trough structure. In addition, a new controller has been designed to operate and control the collectors. Current work will focus on lighter weight space frame designs with prototypes to be installed in Nevada and at NREL, continued development of the local controller; development of a field controller and finally full-scale wind load experiments to validate wind tunnel test results.

2:00 – Parabolic Trough Organic Rankine Cycle Solar Power Plant

Scott Canada[1]*, Robert Cable*[2]*, Gilbert Cohen*[2]*, Henry Price*[3]*, and Doug Brosseau*[4]
[1]*Arizona Public Service*
[2]*Solargenix Energy*
[3]*National Renewable Energy Laboratory*
[4]*Sandia National Laboratories*

Arizona Public Service (APS) is required to generate a portion of its electricity from solar resources in order to satisfy its obligation under the Arizona Environmental Portfolio Standard. In recent years, APS has procured a number of fixed, tracking, and concentrating photovoltaic systems to help meet the solar portion of this obligation and to develop an understanding of which solar technologies provide the best cost and performance to meet the utility's needs. During FY 2004, APS began construction of a 1-MWe parabolic trough concentrating solar power plant. This plant represents the first parabolic trough plant to begin construction since 1991. The plant will be the first commercial deployment of the Solargenix parabolic trough collector technology developed under contract to NREL. The plant will use an Ormat organic Rankine cycle power plant. The power plant is much simpler than a steam plant and will allow for unattended operation of the plant.

2:20 – Rotating Platform Testing Development

Timothy A. Moss and Doug A. Brosseau
Sandia National Laboratories

The main focus of effort for this year has been to upgrade the facilities and equipment, and training new personnel for testing. The LS2 concentrator used to test HCEs (heat collecting elements) was found to deviate from design specifications and was corrected. This has made it easier to install the HCEs and to accomplish mirror alignment. The rotating platform has been extensively rewired by replacing sun rotted wiring, removing wiring used from past tests, and cleaning up the interconnect boxes. The computers and software have been upgraded and the customary problems of software upgrades have been solved. A great deal of time has been spent tracing wiring since documentation has not been kept current for some time. A benefit from this work has been a better method of reading thermocouples that lowered signal noise about 30%. These improvements will be used to test the Solel and the new Schott HCEs.

2:40 – Trough Thermal Storage Developments

Doug A Brosseau[1], David W Kearney[2], Henry Price[3], and Bruce Kelly[4]
[1]Sandia National Laboratories
[2]Kearney & Associates
[3]National Renewable Energy Laboratory
[4]Nexant Company, Inc.

Parabolic trough power systems that use solar energy to generate electricity are a proven technology. Integration of thermal energy storage (TES) is a logical development that increases the value and enhances the dispatchability of concentrated solar energy. One option to significantly reduce costs is to use thermocline-based TES, low-cost filler materials as the primary thermal storage medium, and molten nitrate salts as the direct heat transfer fluid. Tests and experiments conducted at Sandia during FYs 2001 through 2004 have demonstrated the feasibility of the thermocline concept, investigated potential salt-oil interactions, identified molten salt issues and solutions, and demonstrated the durability of selected thermocline filler materials in molten salt operational environments over extended time frames. SunLab supports Arizona Public Service through a CRADA for the design, construction, and eventual operation and performance evaluation of a 1-MWe parabolic trough power plant now under construction near Tucson, Arizona. Sun♦Lab is also developing the design of a thermocline-based cost-shared TES that will be installed and evaluated at this plant during FYs 2005 and 2006.

3:00 – Dish Stirling Development

Charles Andraka[1], Robert Liden[2], and Bruce Osborne[2]
[1]Sandia National Laboratories
[2]Stirling Energy Systems

Stirling Energy Systems (SES) is pursuing and aggressive deployment of many 25-kW dish-Stirling systems for bulk power generation. Their hardware is based on the tried-and-true McDonnell Douglas design, with enhancements for reducing manufacturing costs. SES is working closely with Sandia's engineering team in order to maximize the possibility of success. This year, SES deployed a first prototype of the upgraded system at Sandia. SES has a significant engineering presence at Sandia in order to enhance technology transfer and support. Sandia engineers provided critical development support to resolve structural and optical issues with the prototype, resulting in successful operation within SES's aggressive schedule. The prototype success has led to the start of manufacture of five more units, also to be installed at Sandia. These will form a "mini power plant," scheduled for operation in 2005, for demonstration, exploration of field operation issues, and reliability improvement.

3:20 – Siting Utility-Scale CSP Projects

Mark S. Mehos[1] and Brandon Owens[2]
[1]National Renewable Energy Laboratory
[2]Platts Research and Consulting

In 2002, Congress asked the U.S. Department of Energy to "develop and scope out an initiative to fulfill the goal of having 1000 megawatts (MW) of new parabolic trough, power tower, and dish engine solar capacity supplying the southwestern United States." The major purpose of a large solar installation initiative would be to accelerate the transition of concentrating solar power (CSP) generation technologies to a point where they could establish sustainable markets. In this paper, we present a review of the solar resource for Arizona, California, Nevada, and New Mexico. These four states have the greatest number of "premium" solar sites in the country and each has a renewable portfolio standard. In addition, we present information on the generation potential of the solar resources in these states, and present regions within each state that may be ideally suited for developing large-scale CSP plants because of their proximity to load and access to unconstrained transmission.

Poster Session II
4:00–6:00 p.m.

Technology Adoption

P002 – 21-kW Thin-Film PV Technology Validation—An NREL-Solar Energy Center Cooperative Project
Peter McNutt and Harin Ullal
National Center for Photovoltaics, National Renewable Energy Laboratory

This poster summarizes findings during a one-week (27-31 October 2003) site visit to the Thin-Film Technology Test Bed at India's Solar Energy Center (SEC) near New Delhi. The U.S. and Indian governments signed a Memorandum of Understanding in March 2000 to undertake a 50-50 cost-shared 21-kW thin-film photovoltaic (PV) technology validation project to evaluate the performance of thin-film PV modules under Indian climatic conditions. This project benefits India by giving them experience with cost-effective PV materials, and provides benefits to the United States because data will be sent to the appropriate U.S. thin-film PV manufacturers for evaluation and analysis. During the mission, NREL personnel pursued technical discussions for thin-film PV technology with the Ministry of Non Conventional Energy Sources engineers and scientists. Issues included inspecting the newly constructed arrays, discussing better methods of electrically loading the PV arrays and taking I-V traces, and gathering baseline I-V data.

P004 – The Design of a Net-Metering and PV Exhibit for the 2005 Solar Decathlon
Michael R. Wassmer and Cecile L. Warner
National Renewable Energy Laboratory

In the 2005 Solar Decathlon competition, 19 collegiate teams will design, build, and operate grid-independent homes powered by photovoltaic (PV) arrays on the National Mall. The prominence of grid-interconnected systems in the marketplace has provided the impetus for the development of a net-metering exhibit to be installed and operated during the competition. The exhibit will inform the visiting public about PV basics and appropriate alternatives to grid-independent systems. It will consist of four interactive components. One will be designed to educate people about the principles of net metering using a small PV array, a grid-interactive inverter, and a variable load. Additional components of the exhibit will demonstrate the effects of orientation, cloud cover, and nighttime on performance. The nighttime component will discuss appropriate storage options for different applications.

P006 – Cooperation with Brazil for Sustainable Rural Development
Alia Ghandour
Energy and Environmental Applications Office, National Renewable Energy Laboratory

Under the Luz Para Todas ("Lights for All") Program, the Government of Brazil (GOB) seeks to provide basic electricity services to all of its citizens by 2008. An estimated 2.5 million rural households (12 million Brazilians) currently lack electric service, with approximately 80% of them located in rural areas. Since many of these households are too geographically isolated to be connected to the national grid, they will receive distributed energy systems, and the government intends to maximize the use of local renewable resources to service them. The National Renewable Energy Laboratory (NREL) is working with the GOB and a variety of local partners to identify and implement sustainable off-grid solutions to meet these rural energy needs. Focused in the Amazon region, these collaborative activities on the one hand are using field-based activities to build local technical capacity and design replicable models for rural energy development, while on the other hand, they are helping to develop the policy and institutional structures that will be necessary to sustain distributed renewable energy development on a large scale in Brazil.

P008 – Cooperation with China for Sustainable Rural Energy Development

Ian Baring-Gould and Jean Ku
Energy and Environmental Applications Office, National Renewable Energy Laboratory

The National Renewable Energy Laboratory (NREL), under the Department of Energy's Solar Energy Technologies Program and the Office of Weatherization and Intergovernmental Programs, works with existing and evolving Chinese rural energy programs to promote policy development, training, quality system design, technical monitoring, and productive use applications for renewable energy-based village power systems. The main objective of the cooperative activities is to examine and address issues of long-term sustainability and both "hard" and "soft" infrastructure development. NREL accomplishments to date include establishing an accredited training center for village power technicians in China, developing a standard technical training manual, providing sustainability training to provincial program administrators, and advancing technology transfer and business development opportunities to U.S. and Chinese companies manufacturing village power components. With China's goal of 1 GW of installed solar PV by 2020 and the upcoming Chinese renewable energy law, these activities are timely and significant.

P010 – Environmental Impact Assessment for Materials in the Production of $Cu(InGa)Se_2$ Photovoltaics

Vasilis Fthenakis and Wenming Wang
Brookhaven National Laboratory

Potential environmental effects from the production of materials used in manufacturing CIGS photovoltaic cells are examined for the purpose of Life Cycle Analysis. Material flows and emissions during mining, extraction, and purification of indium, gallium, selenium, and copper, are investigated. Indium is recovered from zinc ore processing via roasting, leaching and electrolysis or cementation. Gallium is extracted mainly as a byproduct of bauxite ore processing via fractional precipitation, electrolysis, and solvent extraction or ion exchange. Selenium is extracted from electrolytic copper refinery slimes as a byproduct of copper production. Copper is a primary metal produced by various pyrometallurgical and hydrometallurgical operations. These metals are further purified to semiconductor/PV grades. The emissions associated with their production are assessed and allocated between products according to ISO guidelines. The impact of very large scales of CIGS PV implementation to the availability of materials, and allocation of emissions is discussed.

P012 – Development of a Home Energy Monitor

Robb A. Aldrich[1], Jay McLellan[2], Srikanth Puttagunta[1], Ron Gumina[2], and Douglas K Owens[1]
[1]Steven Winter Associates, Inc.
[2]Home Automation, Inc.

Most efforts to improve home energy efficiency have focused on standard systems (envelope, HVAC, water heating, lighting, etc.) and on improving the performance of renewable energy systems. Steven Winter Associates, Inc. (SWA) and Home Automation, Inc. (HAI) have partnered to address often-overlooked aspects: homeowner behavior and awareness. HAI is a leader in "smart home" systems incorporating security, lighting, and HVAC. Using HAI's existing products, SWA and HAI are developing systems that will monitor and display: home electricity use, PV production, hot water use, solar hot water performance, space conditioning, and environmental conditions. Making this information available to home residents in a clear, accessible display will empower them to make great strides toward the "zero energy" goal. The product will also offer energy-saving control of home systems. During 2004, SWA and HAI have completed plans for the system and new products required. Prototypes are planned for 2005.

P014 – Complementing Energy Efficiency with PV
Gabriela Cisneros, Luis Estrada, and Corey Asbill
Southwest Technology Development Institute

DOE and other federal agencies promote conservation and energy efficiency, but neither the DOE/EPA Energy Star Buildings program nor the Leadership in Energy and Environmental Design (LEED) program provide decision-making support for the analysis of the potential benefits of adopting renewable energy technologies, such as photovoltaics (PV). In some settings, complementing energy efficiency improvements with PV can offer a positive economic solution to reducing a building's total energy costs. This paper presents decision support rules for determining the favorability of including PV in an energy efficiency upgrade program based on topics such as time-of-use rates, seasonal rates, peak shaving, and demand changes. This work directly addresses tasks outlined in the DOE Solar Program Multi-Year Technical Plan calling for development of modeling and analysis tools that define optimal systems configurations.

P016 – Rural Energy Options Analysis Training Development and Implementation at NREL
Paul Gilman and Peter Lilienthal
Energy and Environmental Applications Office, National Renewable Energy Laboratory

The National Renewable Energy Laboratory has developed presentation and training materials on rural energy topics for rural energy planners and project managers in developing countries. NREL supports regional, national, and sub-national rural energy programs. NREL is contributing to meeting the USAID initiative SARI/E goal of creating linkages among the countries of South Asia by training engineers and decision makers in Sri Lanka and the Maldives. NREL trains program managers and system designers for China's National Township Electrification Program and Brazil's Light for All Program. In Mexico, NREL trains state rural energy stakeholders to support the Mexico Secretariat of Energy's efforts to promote the use of renewable energy technologies for rural development. NREL's rural energy training topics include renewable energy technology overviews, approaches to rural energy planning and program design, analysis of resources and technology options, and the use of HOMER and other rural energy software tools.

P018 – Solar Decathlon 2005
Cecile Warner[1], Mike Wassmer[1], Ruby Nahan[1], and Richard King[2]
[1]National Renewable Energy Laboratory
[2]U.S. Department of Energy

Solar Decathlon 2005 is a DOE/NREL competition involving 19 colleges and universities from the United States, Canada, and Spain. These teams will compete to design, build, and demonstrate solar homes. In fall 2005, teams will transport their competition solar houses to Washington, D.C., where they will construct a solar village on the National Mall. Once the houses are assembled, the teams will compete against each other in 10 contests (hence, a decathlon) for about a week. The contests range from design to comfort to energy performance. Each team must provide an aesthetically pleasing entry that produces sufficient solar energy for space conditioning, hot water, lighting, appliances, and an electric car. The Solar Decathlon is co-sponsored by BP Solar, The Home Depot, the American Institute of Architects, and the National Association of Home Builders. For more information, visit the Web site (www.solardecathlon.org).

P020 – Outreach Is Serious Fun!
Wendy M. Larsen
Photovoltaic Applications Development, National Renewable Energy Laboratory

This paper outlines the planning and effort that goes into a successful, and inexpensive, outreach project. Since 1996, the National Renewable Energy Laboratory has had an educational exhibit booth and has also presented workshops on renewable energy at the two-week long National Western Stock Show, held each January in Denver, Colorado. In our exhibit booth and workshops, farmers, ranchers, and homeowners learn how solar, wind, and biomass energy systems can provide economical electricity within the agricultural community. We show how this outreach has grown to include the presentation of renewable energy exhibits at events in South Dakota and Illinois at the request of the Deputy Secretary for Energy of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, and our support of the U.S. Department of Agriculture in Kansas and Nebraska on the issuance of the 2004 Farm Bill.

P022 – Using NREL's HOMER Micropower Optimization Model to Compare Solar, Diesel, and Hybrid Off-Grid Power Systems

Peter Lilienthal[1] and Tom Lambert[2]
[1]Energy and Environmental Applications Office, National Renewable Energy Laboratory
[2]Mistaya Engineering Company

Simple photovoltaic/battery systems are a cost-effective alternative to the grid for small loads in remote areas. As load requirements increase, incorporating a diesel generator reduces the storage requirement, making a hybrid system more cost-effective. NREL has developed a Micropower Optimization Model, HOMER, that designs least cost systems and illustrates their sensitivity to design conditions. This study used HOMER to explore how the relative role of PV and diesel in a least-cost design changes with load size, fuel price, solar resource, and reliability requirements.

P024 – IEA-PV Power Systems Task 10–Urban-Scale PV Applications, Urban Energy Solutions for the Emerging Global Market

Christy Herig
Seque Energy Consulting

As the global market finds definition, PV is poised to provide urban energy solutions. Whether a newly planned community targeting an environmentally and socially conscious market or an existing high-density, built-out urban area, PV can meet the needs. The newest PVPS task, Task 10–Urban Scale PV Applications, is an international team bringing together the expertise of architects, builders, municipal planners, financiers, utilities, solar industries and educators. The Task will build on existing market development success stories from participating countries to establish a sustainable global urban market. The United States will benefit from participation in Task 10 through coordination and enhancement of existing US DOE activities such as the Systems Driven Approach, Zero Energy Buildings, and the Million Solar Roofs Initiative. A strong industry and utility focus is envisioned for the task. However, information dissemination will be targeted for all stakeholders positioned to influence the market transitions and technical integration required for urban scale PV applications. PV, as a mainstream element of urban buildings, integrates well into whole building design and energy conscious urban planning.

P026 – Small Hybrid Systems and Applications Testing at NREL's Outdoor Test Facility

Lorenzo Roybal
National Center for Photovoltaics, National Renewable Energy Laboratory

The PV International Program at the National Renewable Energy Laboratory recently installed a small off grid PV/Wind hybrid system. The solar system provides 2,800 watts of power and the wind turbine is rated at 900 watts at 28 miles per hour with a 48-volt, 390 Ah battery storage bank. The turbine is mounted on a tilt-down, guyless 30-foot tower that allows one person to easily lower and raise the machine for maintenance. The PV International Test Building (ITB) contains equipment to provide "load" for the system such as a refrigerator, radio, lights, computers, telephone, space heating, and data acquisition. Other tests being conducted at the facility include solar lanterns, water purification, water pumping, battery charging, and air conditioning. The data acquisition will monitor the individual outputs, then download the live data on to the PV International website for public viewing.

P028 – Five-Year Reliability Assessment of SunWize PV Systems in Mexico

Robert E. Foster[1], Luis Estrada[1], Vipin Gupta[2], and Charles Hanley[2]
[1]*Southwest Technology Development Institute*
[2]*Sandia National Laboratories*

In 1999, innovative photovoltaic (PV) lighting systems were installed on 145 homes in Moris, Chihuahua, Mexico, by SunWize, a New York company, and its local partner (ENSO) as part of the Mexican Renewable Energy Program (MREP). After nearly five years of operation, random field surveys were conducted at 35 homes. The SunWize PV systems and components have performed well and are meeting or exceeding design and life criteria. The PV systems have saved users an average of U.S. $300 over five years in lieu of previous gas and dry cell battery options. Based on these results, the State of Chihuahua has expanded this PV program with over 1,200 more installations by 2004. These field tests are providing valuable data for benchmarking the cost and reliability of fielded systems (Solar Program Multi-Year Technical Plan [MYTP] Table 4.1.1-6, Tasks 7-9). In addition, these data will help meet 2006 MYTP milestone #35 to document progress towards 25-year system lifetimes.

P030 – Identifying Key Issues in Implementing a Quality Solar for Schools Program

Jennifer S. Szaro and Kevin W. Lynn
Florida Solar Energy Center

In January of 2003, the Florida Department of Environmental Protection/Florida Energy Office (DEP/FEO) allocated $600,000 in hardware funds toward the installation of photovoltaic (PV) solar systems on Florida schools. This project, known as the SunSmart Schools Program, provided rebates of $5 per watt, based on system nameplate rating, up to $25,000 for systems without batteries. An additional rebate of $1 per watt was offered for systems that include a battery back up component and can be used to provide electricity to a school disaster relief shelter. The purpose of the program was to encourage the installation of grid-connected PV systems on schools through partnerships with the local school districts and communities, the state's electric utilities, corporate sponsors, and solar industry. This will increase public awareness of the benefits of this technology and provide an excellent educational opportunity to Florida's future leaders. As a result of this program, PV systems were installed on 29 schools, each of which has incorporated a solar educational program into their curriculum. The Florida Solar Energy Center (FSEC) monitors these systems and provides this real-world data to students via the Internet. Although a good deal of effort and planning went into the design of this program, problems occurred on several different levels during its implementation. The purpose of this paper is to review these issues so others can benefit from this experience.

PV Manufacturing R&D

P032 – Manufacturing Process Advancements for Flexible CIGS PV on Stainless Foil

Lin J Simpson[1], Scott Wiedeman[2], Tyrone L. Vincent[3], Bharat S. Joshi[1], and Nicolas B. Gomez[1]
[1]*ITN Energy Systems, Inc.*
[2]*Global Solar Energy, Inc.*
[3]*Colorado School of Mines*

Substantial increases in efficiency and yield have resulted for roll-to-roll CIGS PV on stainless foil at GSE. Large-area cells (68.8 cm^2) have advanced beyond 12.5% efficiency, (10% average efficiency in manufacturing lots); yield has improved from 20% to 90%, by using designed experiments to optimize deposition. These successes were enabled by process control and reliability improvements under programs including the NREL-PVMR&D ITN Energy Systems subcontract. Improved cell integration, module construction and cell efficiency have led to modules with greater than 40W/kg (11.3% efficiency) in fully flexible, lightweight formats. ITN Energy Systems-PVMR&D has advanced CIGS technology by development of predictive control models, fault tolerance, in-situ sensors, and process improvements. Physics-based models for deposition processes were developed to improve process control, redesign hardware and implement fault tolerance. With fault prevention strategies, sensor/hardware failure detection, and real-time reconfiguration of systems to operate despite sensor/hardware failures, process reliability and reproducibility have increased greatly.

P034 – Enhanced CIS Production Using XRF for PVD Process Control
Dale E. Tarrant, Robert D. Wieting, and Robert R. Gay
Shell Solar Industries

Shell Solar Industries (SSI) has made outstanding progress in the initial commercialization of thin-film CIS technology and is poised to make significant contributions to EERE Solar Program Multi-Year Technical Plan goals. Predictability of SSI's process has been demonstrated using statistical process control. Process R&D at successive levels of CIS production has led to high yield while increasing product efficiency. These major accomplishments support attractive cost projections for CIS and have demonstrated the prerequisites for large-scale commercialization. PV Manufacturing R&D Project subcontract work allowed SSI to address several production bottlenecks thereby allowing SSI to exercise the overall process at higher production rates and to lay the groundwork for evaluation of near-term and long-term manufacturing scale-up options. This paper will highlight implementation of XRF measurements as process control for both precursors and the base electrode sputter deposition, which has practically eliminated system time used for diagnostics instead of part production.

P036 – Development of Automated Production Line Processes for Solar Brightfield Modules
Michael Nowlan, John Murach, Scot Sutherland, David Miller, and Stephen Hogan
Spire Corporation

A program is underway for developing automated systems for fabricating large photovoltaic modules for multi-megawatt grid-connected applications. We designed an 800 W module with emphasis on minimizing installed systems costs for utility-scale arrays. Unique module features include laminated by-pass diodes, which simplify internal busing and output terminals, and a cantilevered superstrate that allows for reduced glass thickness. We are designing automated tools for producing these modules in multi-megawatt per year quantities. A cell string inspection system with machine vision and infrared microcrack detection was developed. An advanced lamination process was developed with a faster-curing EVA encapsulant for increased laminator throughput. Automated systems are being designed for laying up module sheet materials and for installing bus ribbons and diodes. Our remaining work includes the development of an improved large area laminator and sun simulator, and a computer integrated manufacturing system for module line supervisory control and data acquisition.

P038 – Silicon-Film Sheet Material
James A. Rand and Ralf Jonczyk
GE Energy

GE Energy plans to continue the development of Silicon-Film sheet material begun by AstroPower. Plans call for operating the process in a pilot scale to focus on two critical technical issues. The first technical issue is determining the silicon feedstock purity levels required by the process. The second is increasing solar cell conversion efficiency by improvements in the solar cell device. The Silicon-Film process has already demonstrated the capability to make wafers with good material utilization and at very low cost, both in terms of capital equipment expense and direct material consumption. The final hurdle for Silicon-Film is the demonstration of efficiencies comparable to those generated by cast multicrystalline wafers in the market place today. The poster will outline the efforts underway at GE Energy to realize this commercial product.

P040 – PV Manufacturing R&D Project—Trends in the U.S. PV Industry

Kathryn E Brown[1], Richard L Mitchell[1], Ward I Bower[2], and Richard King[3]
[1]*National Renewable Energy Laboratory*
[2]*Sandia National Laboratories*
[3]*U.S. Department of Energy*

To foster continued growth in the U.S. photovoltaic (PV) industry, the U.S. Department of Energy initiated the PV Manufacturing R&D (PVMR&D) Project – a partnership with U.S. PV industry participants to perform cost-shared manufacturing research and development. Throughout FY2004, PVMR&D managed fourteen subcontracts across the industry. The impact of PVMR&D is quantified by reductions in direct module manufacturing costs, scale-up of existing PV production capacity, and accrual of cost savings to the public and industry. An analysis of public and industry investment shows that both recaptured funds by mid-1998 based on estimated manufacturing cost savings from PVMR&D participation. Since project inception, total PV manufacturing capacity has increased from 13 MW to 201 MW at the close of 2003 while direct manufacturing costs reduced from $5.55/W to $2.49/W. These results demonstrate continued progress toward the overriding goals of the PVMR&D Project.

Balance of Systems

P042 – Outdoor Performance Characterization of Residential Grid-Connected Inverters

Kevin W. Lynn
Florida Solar Energy Center

In order to achieve the goal of sustainable markets, PV systems need to have at least 20-year lifetimes. One of the most important components in a PV system is the inverter, which converts the electrical energy produced by the PV array into energy that is compatible with the utility grid. Because there have been performance and reliability problems with utility-interactive inverters in the past, many have determined a need to characterize the performance of these systems. The Florida Solar Energy Center, in collaboration with Sandia National Laboratories and the Southwest Technical Development Institute, is developing a protocol and a test facility for characterizing the performance of these inverters up to a maximum of 5-kW AC output. The following performance parameters will be documented as a result of this test: inverter efficiency, maximum power point tracking, tare losses, and power foldback.

P044 – Inverter Long-Term Test Facility—Early Results

Corey D. Asbill
Southwest Technology Development Institute

This poster presents early results obtained from the Inverter Long-term Test Facility (ILTF) at the Southwest Region Experiment Station. Details of installation, configuration and early test procedures are presented. The ILTF was designed and is being operated to answer recurring questions regarding inverter performance and reliability as well as to support DOE efforts to develop standard inverter test procedures. This reconfigurable facility and its data will contribute to the completion of two milestones defined in the Solar Program Multi-Year Technical Plan related to developing inverter test protocols and accurate inverter modeling. The ILTF, capable of high data rate testing, system test development and verification, and long-term continuous inverter monitoring, is a unique facility within the DOE national PV Subprogram

PV Systems Engineering and Reliability

P046 – Advances in Solar Radiometry and Metrology

Daryl R. Myers, Afshin A. Andreas, Ibrahim M. Reda, and Stephen M. Wilcox
National Renewable Energy Laboratory

The Solar Radiometry and Metrology Task at the National Renewable Energy Laboratory (NREL) provides traceable optical radiometric measurements and calibrations to photovoltaic (PV) researchers and the PV industry. Traceability of NREL solar radiometer calibrations to the World Radiometric Reference was accomplished during the NREL Pyrheliometer Comparison in October 2003. The task has calibrated 10 spectral and over 100 broadband instruments for solar measurements. Other accomplishments include: characterization of pyranometer thermal offset errors with laboratory and spectral modeling tools; developing a simple scheme for correcting pyranometer data for known responsivity variations; measuring detailed spectra distributions of the NREL High Intensity Pulsed Solar Simulator (HIPSS) as a function of lamp voltage and time. The optical metrology functions support the NREL Measurement and Characterization Task effort for ISO 17025 accreditation of NREL Solar Reference Cell Calibrations. Optical metrology functions have been integrated into the NREL quality system and audited for ISO17025 compliance.

P048 – Certification of PV Modules and Systems and IEC Participation

Steven Chalmers
PowerMark

PowerMark is funded as the result of an NREL contract to develop PV certification in the United States. Arizona State University Photovoltaic Testing Laboratory has been approved for modules and Florida Solar Energy Center for balance of systems. The poster will indicate the accomplishments to date and the status of International Electrotechnical Commission (IEC) participation for international PV systems standards development. The roll of IEC/PV-GAP for international certification is being developed and the transition and impacts will be indicated.

P050 – Management and Administration of IEC TC-82 Secretariat

Howard O. Barikmo
Sunset Technology, Inc.

Standards are a strategic business tool that help develop new global markets. U.S. participation ensures foreign market access to US technology. Participants help eliminate non-tariff trade barriers. Participation keeps one on the cutting edge of current technology and market trends. This paper describes the organization of Technical Committee 82, Photovoltaics, of the International Electrotechnical Commission (IEC) and its various working groups that write standards for the international photovoltaic industry. Briefly examines the standards published to date and lists those that are being worked on.

PV Module Reliability

P052 – Alternative Approaches to Buss Bars for PV Modules

Joel W. Pankow
National Renewable Energy Laboratory

Metal foil coated with metal loaded pressure sensitive adhesive has been used on PV modules as buss bars for current collection. Modules employing this type of buss bar have often been noted to develop hot spots in the field. Examination of these modules as well as various sample test coupons by a variety of physical and chemical characterization techniques has resulted in the development of a failure mechanism which culminates in localized buss bar delamination followed by the appearance of hot spots and/or actual arcing. A variety of alternative buss bar options were evaluated including conductive epoxies, alternative curing schedules, low temperature solders and ultrasonic bonding. The most promising approach to date has been the direct application of metal buss bars via various electrochemical approaches which offers a variety of distinct advantages including intimate electrical contact, minimal residual stress, user-controllable variables and a wide choice of metals.

P054 – NREL PV Module Reliability and Performance R&D Status and Accomplishments

C.R. Osterwald, J. del Cueto, J. Pruett, D. Trudell, and W. Marion
National Renewable Energy Laboratory

This paper presents an overview of the status and accomplishments of the PV Module Reliability and Performance R&D task, under the PV Module Reliability R&D Project. During FY 2004, the thin-film module hot & humid exposure subcontracts (part of the Thin Film PV Partnership) were supported through extensive baseline testing, data archiving, and site visits. A new solar weathering test has been initiated in the recently refurbished Outdoor Accelerated-weathering Test System (OATS). We completed a test plan with First Solar on CdTe modules involving indoor stress testing and outdoor testing in the Performance and Energy Ratings Testbed (PERT). Damp heat and thermal cycling tests were done on crystalline-Si prototype modules from SBM Solar.

P056 – Advanced Indoor Module Light-Soaking Facility

J.A. del Cueto and Carl Osterwald
National Renewable Energy Laboratory (NREL)

The Outdoor Test Facility at NREL hosts a gamut of indoor accelerated stress tests that are useful in assessing the reliability and qualifications of photovoltaic (PV) modules intended for long-term energy production and deployment. One of these is the Indoor Light-Soaking Exposure Station, comprising a programmable climate-controlled chamber equipped with a solar simulator that allows high-intensity light exposure. Concurrently, we can monitor the electrical characteristics of multiple PV modules and exercise active control over their electrical bias using programmable electronic loads, interfaced to a data acquisition system, thereby acquiring power tracking and current-voltage data. This active loading capability allows us to the test different bias conditions and to cyclically alternate between them. Additionally, we can vary the light intensity or module temperatures and garner realistic temperature coefficients of module performance. We present some of the results obtained so far on amorphous silicon and cadmium telluride modules.

P058 – Outdoor Energy Rating Measurements of PV Modules

Yingtang Tang[1], Govindasamy TamizhMani[1], Liang Ji[1], and Carl Osterwald[2]
[1]Arizona State University East, Photovoltaic Testing Laboratory
[2]National Renewable Energy Laboratory

Photovoltaic (PV) modules are currently rated for power (W) under standard test conditions (STC). The overall objective of this work is to rate the PV modules for the energy (Wh) production per IEEE1479 and IEC61853 draft standards, and per user defined site-specific conditions. The primary difference between the previous works and this work is the use of outdoor (natural sunlight) based equipment rather than the indoor (solar simulator) based equipment. This paper will present key information on this outdoor equipment including: the design characteristics of thermal test bed (TTB) installed on a 2-axis tracker outdoor; the capability of this TTB to control the module temperatures between 5ºC and 60ºC; the means to change the irradiance level on the test module; and the technique to carry out spectral mismatch measurements. The results obtained from these measurements, on a typical PV module, will be analyzed and presented.

P060 – PV Module Durability Research and Module Long-Term Exposure

Neelkanth G. Dhere, Vinaykumar V. Hadagali, Parag S. Vasekar, Matthew W. Nugent, and Sachin M. Bet
Florida Solar Energy Center (FSEC)

The FSEC PV Materials Laboratory has been carrying out a systematic and detailed study of module durability and long-term exposure concentrating on the solar cell/encapsulant composite with an objective to improve the manufacturing technology of PV modules. Samples are extracted and analyzed from so as to understand solder bond degradation in c-Si commercial modules supplied by Sandia. Leakage currents in high-voltage-biased encapsulated Glass/TCO/EVA/Glass composite mini-modules specially prepared by EPV with improved SnO_2:F TCO are being monitored in hot and humid climate in Florida. Adhesional strength is being measured and and surface analysis is being carried out on samples extracted from First Solar CdTe PV modules so as to serve as a baseline for future studies. PV modules from various U.S. manufacturers are being are being tested under Module Long Term Exposure project. I-V measurements and visual inspections are carried out, spreadsheets are prepared and submitted to Sandia on monthly basis.

Silicon

P062 – Inkjet-Based Metallizations for Solar Cells

Tanya Kaydanova, Maikel F.A.M van Hest, Calvin J. Curtis, Alex Miedaner, and David S. Ginley
National Renewable Energy Laboratory

Inkjet printing is rapidly becoming a viable alternative to the existing deposition approaches for a variety of inorganic and organic electronic materials. We report here on an ink-based approach to printing Ag, Cu, and Ni metallizations with near-vacuum deposition quality. The approach developed can be easily extended to other conductors such as Pt, Pd, and Au. Thick highly conducting lines of Ag and Cu demonstrating good adhesion to glass, Si and PCB have been printed at 100^o–200^oC in air and N_2, respectively. Si solar cells with 8% efficiencies were produced using inkjet-printed Ag grids. Next generation multicomponent inks have been developed with improved fire through contacts leading to higher cell efficiencies. Also we have successfully applied inkjet to printing electrically conducting polymers for contacts in polymer solar cells. Inkjet-printed PEDOT lines and layers with the conductivity as good or better than those of spin-coated films will be discussed.

P064 – Growth of High Minority Lifetime Epitaxial and Polycrystalline Silicon by Hot Wire Chemical Vapor Deposition

Harry Atwater, Christine Richardson, and Maribeth Swiatek
California Institute of Technology

We have investigated the low-temperature epitaxial growth of thin silicon films by hot-wire chemical vapor deposition (HWCVD)on Si(100) substrates and on large-grained polycrystalline template layers formed by selective nucleation and solid phase epitaxy(SNSPE). Using reflection high energy electron diffraction and transmission electron microscopy, we have derived a phase diagram for Si epitaxy on Si(100). Twinned epitaxial films were grown to over 1 micron thickness with R=50 and substrate temperature of 300ºC. Although nickel is a known lifetime killer even in small concentrations, the lifetimes of films on SNSPE templates are comparable to the lifetimes of films on Si(100). Under low level injection conditions, the minority carrier lifetimes for films on Si(100) range from 5.7 to 7.5 microseconds, and the minority carrier lifetimes for films on SNSPE templates range from 5.9 to 19.3 microseconds. This suggests that the growth of epitaxial films by HWCVD on SNSPE templates is a viable strategy for the fabrication of thin-film photovoltaics.

P066 – Acoustical Diagnostics of Residual Stress in EFG Silicon Wafers

A. Belyaev[1], S. R. Best[1], D. P. Hess[1], S. Ostapenko[1], and J. P. Kalejs[2]
[1]University of South Florida
[2]RWE Schott Solar, Inc.

This paper presents acoustical study of residual stress in Edge-defined Film-fed Growth (EFG) silicon wafers. Audible and ultrasonic vibratory approach had been employed to evaluate the effect of thermo-elastic residual stress on acoustical characteristics of the set of EFG-Si wafers. The set of twelve 100mm by 100mm as-grown EFG silicon wafers with nominal 340 micron thickness was used in this study. All wafers were initially screened using a high resolution Scanning Acoustic Microscopy (SAM) to check no micro-cracks over 10 microns length were present at the periphery. Following SAM inspection, the wafers were measured with scanning infrared polariscopy to assess the level and distribution of in-plane stress. The vibratory experiments have been carried out along with finite element analysis (FEA). The FEA modal shapes were validated through classic Chladni type patterns. The vibratory data is found to correlate very reasonably with residual stress infrared polariscopy measurements. These results may be useful for solar cell industry to assess mechanical quality control and breakage inspection.

P068 – Hydrogenation Methods and Passivation Mechanisms for c-Si Photovoltaics

Stefan K. Estreicher[1] and Michael Stavola[2]
[1]Physics Department, Texas Tech University
[2]Physics Department, Lehigh University

The identification, characterization, and passivation (by hydrogen) of lifetime-reducing defects in solar-grade Si are critical to the optimization of PV devices. First-principles theory and microscopic experiment are used to investigate these issues quantitatively. The theoretical work involves (1) calculating the ground-state properties of H-impurity and H-defect complexes, including their vibrational properties for IR identification, (2) predicting the basic properties of lifetime-reducing defects, such as transition metal impurities and boron-oxygen complexes, (3) extending first-principles theory to finite temperatures to understand defect behavior under operating conditions. The experimental work involves IR studies of hydrogenation from a nitride layer or a hydrogen plasma for samples specially prepared with Pt markers. The formation of {Pt,H} and vacancy-H complexes can be monitored as a function of depth. The goals are to quantify how much hydrogen diffuses into the sample, its depth of penetration, and how many native defects are generated during the hydrogenation process.

P070 – Hydrogen-Defect Interaction Phenomena in Si

S. Ashok[1], Aniruddha R. Vengurlekar[1], Bhushan Sopori[2], and Esidor Ntsoenzok[3]
[1]Pennsylvania State University
[2]National Renewable Energy Laboratory
[3]CNRS-CERI

Interaction of atomic hydrogen with defects, its trapping and migration, and formation of complexes have been studied in order to understand the mechanisms of defect passivation and activation in crystalline Si. The first experimental study focused on the creation of buried cavity layers in Si by He implantation and thermal anneal, followed by ECR plasma hydrogenation. The ultimate aim here is to evaluate the gettering ability of these nanocavities while simultaneously using the hydrogen-soaked cavities as a source of atomic hydrogen for passivation of defects elsewhere in the structure. This technique should be particularly effective for the emergent thin c-Si technologies. We have found that hydrogenation is also effective in controlling the cavity size and distribution. A second set of studies deals with another catalytic effect of H where its presence in the lattice lowers the anneal temperature for thermal activation of ion implanted dopants.

P072 – The Role of Hydrogen in Metastable Defect Formation in a-Si:H and a-Ge:H

P. C. Taylor, T. Su, and J. Whitaker
University of Utah, Department of Physics

About 30 years ago, Staebler and Wronski discovered that irradiation of hydrogenated amorphous Silicon (a-Si:H) with light of band-gap energy produces a metastable decrease in both the photo- and dark conductivities. From electron spin resonance (ESR) measurements, the defects responsible for the decreases in conductivity are known to be silicon dangling bonds. Hydrogen has long been invoked as important in stabilizing these dangling-bond defects, but the experimental proof of this conjecture has been elusive. We discuss recent advances in understanding the role of hydrogen in the production and annealing of defects that contribute to the Staebler-Wronski effect in a-Si:H. Specifically, we discuss (1) the observation by nuclear magnetic resonance of a paired hydrogen site that stabilizes the silicon dangling bond defects that produce the Staebler-Wronski effect, (2) the observation of the Staebler-Wronski effect in a-Ge:H, and (3) the production of neutral silicon dangling bonds in tritiated a-Si:H.

P074 – Electronic Properties of RF Glow Discharge Microcrystalline Silicon Near the Amorphous Silicon Phase Boundary

J. David Cohen[1], James J. Gutierrez[1], Baojie Yan[2], Jeffrey C. Yang[2], and Subhendu Guha[2]
[1]Materials Science Institute, University of Oregon
[2]United Solar Ovonic Corporation

Work at United Solar to develop high-efficiency a-Si:H/μc-Si:H tandem cells have recently been showing a considerable degree of success. To aid in this effort we have begun studying the electronic properties of their microcrystalline silicon material using transient photocapacitance spectroscopy (TPC) and drive-level capacitance profiling (DLCP). The DLCP method has allowed the shallow doping density to be profiled and the deep defect densities to be estimated. The TPC spectra reveal that *both* a microcrystalline *and* an amorphous component are present in these samples. By varying the measurement temperature, these TPC spectra have allowed us to directly monitor the degree of minority carrier collection in these films. Significant effects due to light soaking were observed which indicate a reduction in this minority carrier collection. These results may help account for the degradation in the microcrystalline cell performance with light soaking that has been observed.

P076 – Species Responsible for Amorphous Silicon Growth and Properties in Photovoltaics

Alan Gallagher, Peter Horvath, and Wengang Zheng
University of Colorado

The experimental design uses threshold ionization mass spectroscopy to detect the chemically active (radical) species at the substrate surface, in an a-Si:H PECVD deposition chamber. Most of the contract activities have involved apparatus construction and testing, and obtaining and understanding the radical signals under conditions used for device quality film production. Major issues solved recently include minimizing particle size, as particles can easily clog sampling orifices, extension of the mass spectroscopy to H-atom detection, and computer control of mass spectrometer, discharge switching and RF power. The high H_2 pressures (~ 1 Torr) typical in current device deposition also requires several stages of differential pumping between substrate and the mass spectrometer. Data from SiH_4/H_2 mixtures shows several types of radicals, as will be described. This work is supported by DOE contract De-AC36-02G010244.

P078 – Correlation of Material Properties and nc-Si:H Solar Cell Performance Studied by Raman and Photoluminescence Spectroscopies

Keda Wang[1], Daxing Han[1], Baojie Yan[2], Jeffrey Yang[2], and Subhendu Guha[2]
[1]Department of Physics & Astronomy, University of North Carolina at Chapel Hill
[2]United Solar Ovonic Corporation

We used Raman and photoluminescence (PL) to study nc-Si:H intrinsic layer properties in solar cell structures. The crystalline volume fraction (fc) was deduced from the Raman spectrum. Generally, a high fc leads to a high J_{sc} and a low V_{oc}. PL spectra were measured using 632.8-nm and 442-nm laser lines. There are two distinguished PL peaks at 80 K, one a-Si peak at ~1.4 eV, the other at ~ 0.9 eV from the crystalline regions. Generally, the relative intensity of the low energy PL peak (I_{gb}) was larger for 442-nm than 632.8-nm excitation, indicating an increase in crystallinity along the growth direction. However, I_{gb} decreased from the bulk to the top layer for the best performance cells obtained using H_2 dilution profiling and i/p buffer layer. The results verified that properly controlled crystallinity in the intrinsic layer and the buffer layer are important for optimizing nc-Si:H solar cells.

P080 – Physics of Nanocrystalline Si Solar Cells

Vikram L. Dalal and Puneet Sharma
Iowa State University

Nanocrystalline Si:H is an important photovotlaic material. It consists of small grains of crystalline Si, with amorphous tissue and H surrounding the grains. The electronic properties depend critically upon the grain size and the degree of passivation by the amorphous phase. The optical absorption coefficient is larger than in c-Si with large grains. In this paper, we discuss the optical properties, doping characteristics, defect densities and minority carrier transport in this material. It will be shown that the transport is by holes and that the material is generally n type, probably because of accidental doping by oxygen. The mid-level defects are localized in energy between 0.5 eV and 0.35 eV below the conduction band. The diffusion length is controlled by the mid-level defects through a Shockley-Read-Hall recombination mechanism. The transport of minority carriers is by diffusion and not by drift. Device I-V curves follow the crystalline Si model.

P082 – Four-Terminal Solar Cells Using Ultra-Thin Amorphous Silicon and Nanocrystalline Silicon

Jian Hu[1], Dalong Zhong[2], and Arun Madan[1]
[1]MVSystems, Inc.
[2]Advanced Coatings & Surface Engineering Laboratory, Colorado School of Mines

We report on our recent progress in the development of stable amorphous Si and nano-crystalline Silicon tandem junction solar cell constructed as a four-terminal (4-T) device, in which the current matching constraint is released from each constituent cell. This allows the use of ultra-thin (<1000 A) a-Si:H solar cell where instability is no longer an issue. We report that by merely joining two cells constructed on separate pieces of glass, we have achieved conversion efficiency, η, >9%. We show that by constructing the 4-T device on either side of the glass, and by the use of optimizing procedures, stable device with η >12% can be achieved. With an expected improvement of the open circuit voltage >650 mV in nc-SiH device, η>16% should be possible.

P084 – Structure of HWCVD Amorphous-SiGe:H Thin Films

D.L. Williamson[1], G. Goerigk[2], Y. Xu[3], and A.H. Mahan[3]
[1]Physics Department, Colorado School of Mines
[2]Institut fuer Festkoerperforschung, Forschungszentrum Juelich
[3]National Renewable Energy Laboratory

Hot-wire chemical-vapor-deposition (HWCVD) is being investigated by NREL as an alternative to the industry standard plasma-enhanced CVD (PECVD) method for fabrication of low bandgap

amorphous SiGe alloys for use in multi-junction solar cells. Recent progress indicates better photoconductivity for HWCVD films with low bandgaps near 1.3 eV so it is of interest to determine whether structural improvements are correlated with the improved photoresponse. Small-angle X-ray scattering (SAXS) experiments are being used to probe the nanoscale heterogeneity and there is evidence of significant improvements in homogeneity for the alloys optimized by lowering the filament and substrate temperatures. Ge non-uniformity is being probed by anomalous SAXS, which employs X-rays near the Ge edge to specifically isolate Ge composition fluctuations. Both microvoid volume fractions and Ge non-uniformity have been reduced compared to PECVD and earlier HWCVD materials with similar low bandgaps.

P086 – Thin-Film Si Solar Cells and Materials by Single-Chamber PECVD and HWCVD

Yuan-Min Li[1], John A. Anna Selvan[1], J. Liang[2], and A. Rafik Middya[2]
[1]Energy Photovoltaics, Inc., [2]Department of Physics, Syracuse University

We report progress in preparation of nanocrystalline silicon (nc-Si) solar cells and films, respectively, using RF-PECVD and hot-wire CVD (HWCVD) in single chamber systems. We describe the novel "static seeding" (closed-chamber plasma) technique in comparison with conventional nucleation method for p-i-n type nc-Si solar cells. We discuss device performance issues including cross-contamination, alternative TCO front contacts to SnO_2 superstrates, and the tunnel junction for a-Si/nc-Si stacked cells. Excellent stability is seen for single junction nc-Si cells of over 6% efficiency using ZnO/Al back contact. For a-Si/nc-Si tandem cells (8-9% initial efficiencies), larger degradation is observed under one-sun light soaking than 47 suns. We developed a ceramics HWCVD technique and fabricated small grain (10–30 nm) polycrystalline silicon thin films at low temperature (250°C) with a growth rate ~8 Å/s. The ceramic filament holder can minimize film impurity and reduce substrate temperature by confining thermal radiation from the filament.

P088 – Transparent Conductive Oxide Materials for Improved Back Reflector Performance for Amorphous Silicon-Based Solar Cells

Scott J. Jones, Joe Doehler, David Tsu, Tongyu Liu, and Masat Izu
Energy Conversion Devices, Inc.

A back reflector comprising an Al/(multi-layered stack)/ZnO structure is being developed to replace Al/ZnO used in manufacturing and boost conversion efficiencies. The results from studies of different transparent conductive oxides (TCOs) that comprise the multi-layered stack are reported. Alloying ZnO with Si or MgF_2, TCOs with low indices of refraction between 1.5 and 1.6 have been fabricated. Using these materials in a multi-layer stack with Si to create Al(specular)/ZnO/ZnOSi/Si/ZnOSi/ZnO back reflectors, reflectance values in the 600–1000-nm portion of the light spectrum are similar to those obtained for Ag/ZnO back reflectors. With the Al/multi-layer/ZnO back reflector stacks, a 7% improvement in the short-circuit currents has been obtained for a-SiGe:H cells. However, the gain in current is offset by to higher series resistances and lower fill factors. Studies are now ongoing to reduce the series resistances, raise the fill factors, and improve the cell efficiencies.

P090 – Real-Time Spectroscopic Ellipsometry as an In-Situ Diagnostic for HWCVD Growth of Amorphous and Epitaxial Si

Dean H. Levi, Charles W. Teplin, Eugene Iwanczko, Tihu Wang, and Howard M. Branz
National Renewable Energy Laboratory

In this paper we report on our work using real-time spectroscopic ellipsometry (RTSE) to optimize hot wire chemical vapor deposition (HWCVD) growth of amorphous hydrogenated silicon (a-Si:H) and epitaxial crystal silicon (epi-Si). Heterojunction a-Si:H crystal-silicon solar cells require extremely thin layers of intrinsic and doped a-Si:H for best performance. We have used RTSE to provide real time thickness feedback to optimize the i- and n-layers in these devices, achieving efficiencies as high as 15.7% on p-type float zone crystal silicon wafers. We have also applied RTSE as a rapid diagnostic for HWCVD epitaxial growth of crystal silicon. Evaluation of the dielectric function versus time provides immediate feedback on the crystallinity and thickness of the epi-Si. The only other means of obtaining this information is through TEM analysis, which normally requires several weeks to obtain the same information. Using the rapid RTSE feedback we have achieved epi-Si growth up to 400nm.

P092 – Reflectance Spectroscopy: Rapid Quantitative Measurements in Commercial Production of Si Solar Cells

Bhushan Sopori
National Renewable Energy Laboratory

We have developed a very versatile technique involving reflectance spectroscopy for measuring a host of physical parameters of wafers and solar cells. The reflectance spectrum (R vs. λ) of an entire wafer or solar cell is measured very rapidly (typically < 40 ms), which is then deconvolved to provide average values of parameters that characterize each surface and the bulk of the wafer or cell. Differential illumination is used to identify and characterize lateral nonuniformities. Our reflectometer uses reciprocal optics to enable large-area measurements; it operates in either spectral mode (to generate R vs. λ) or in imaging mode (to provide spatial maps of the desired parameter). The applications developed to date consist of characterizing surface roughness and sawing irregularities, surface film parameters, wafer thickness, and backside reflectance. This paper will describe applications for monitoring solar cell processing steps—sawing and wafering, texturing etching, AR coating, front metallization, and backside contact.

P096 – Photovoltaic Properties Of Nanocrystalline Germanium-Carbon:H alloys

Xuejun Niu and Vikram Dalal
Iowa State University

Nanocrystalline (Ge,C):H is a potentially new material for photovoltaic energy conversion. While Ge and C are not miscible in thermal equilibrium, using plasma CVD, one can make this new material. As C is added to the material, the bandgap shifts to higher values. In this paper, we report on the photovoltaic device properties of this material. It is shown that as C is added, the open circuit voltage increases and the quantum efficiency in the infrared decreases. Subgap absorption in devices shows that the bandgap has increased with increasing C content. Midgap defect densities were measured using multi-frequency capacitance and were in the 1016/cm^3 range. Mobility measurements were made using Hall measurements, and they show mobilities as large as 5 cm^2/V-sec. Diffusion length of holes was measured using quantum efficiency, and they are in the range of 0.5 micrometer.

P098 – High-Rate Deposition of Hydrogenated Nanocrystalline Silicon Solar Cells

Baojie Yan, Guozhen Yue, Jeffrey Yang, and Subhendu Guha
United Solar Ovonic Corporation

Modified very-high-frequency (MVHF) glow discharge, RF glow discharge under high pressure depleting regime (RF-HPD), and microwave glow discharge have been used for high rate deposition of hydrogenated nanocrystalline silicon (nc-Si:H) solar cells. We compare the advantage and disadvantage of the three deposition techniques. The MVHF and RF-HPD produce reasonably good nc-Si:H solar cells at a deposition rate of ~5 Å/s. nc-Si:H single-junction and a-Si:H/nc-Si:H double-junction cells made with these two methods show initial active active-area efficiencies of ~7%–8% and ~12%–13%, respectively. At this rate, the intrinsic nc-Si:H layer is deposited in around one hour. Microwave glow discharge can deposit nc-Si:H at a very high rate ~20–30 Å/s, but the cell performance is poorer. We will present recent progress made using each deposition method and discuss challenges related to the nc-Si:H technology.

P100 – Nanocrystalline and Microcrystalline Silicon—Simulations of Improved Material Properties

Rana Biswas[1], Bicai Pan[1,2] and Venkatesh Selvaraj[1]
[1]*Dept. of Physics and Microelectronics Research Center, Iowa State University*
[2]*Dept. of Physics, University of Science and Technology of China*

Materials grown close to the phase boundary of amorphous and microcrystalline growth have superior electronic properties for solar cells. These include nanocrystalline materials grown in the amorphous region of the phase diagram with nanometer size crystallites, and microcrystalline materials where crystallites have coalesced. We investigate the improved properties of these materials through atomistic simulations. Nanocrystalline and microcrystalline silicon have been simulated for varying crystallite volume fractions. Nanocrystalline materials have unstrained nanocrystallites and an improved order of the amorphous host— which leads to the improved stability of nc-Si. There is an excess density of H at the nanocrystallite boundary, which leads to a low temperature (250º–400ºC) H-evolution peak. H evolution simulations show both lower and higher temperature evolution peaks in good agreement with experiment. We have simulated mixed phases similar to μc-Si and find no well-defined boundary between the crystallite and the amorphous matrix.

P102 – Three-Dimensional Void Array Photonic Crystal Backside Reflector for Efficient Light Trapping in Thin-Film Crystalline Silicon Solar Cells

David T. Danielson, Luca Dal Negro, Yasha Yi, Tongyan Lin, and Lionel C. Kimerling
Massachusetts Institute of Technology

The continued decrease of crystalline silicon (Si) solar cell cost per watt requires the development of low-cost, high-efficiency thin-film Si technologies. In transitioning from substrate-based to thin-film cells, the importance of "photon lifetime" supersedes that of minority carrier lifetime due to dramatically decreased photon absorption and charge collection lengths. In this work, we apply low fabrication cost photonic crystal concepts to the development of highly efficient backside light trapping structures for thin-film Si solar cells. Our approach uses electrochemical etching to fabricate a regular array of cylindrical pores in p-type Si that serves as a template for the formation of a three-dimensional void array, with periodicity on the order of the critical wavelength range (800–1200 nm) for light trapping in thin-film Si, via capillarity-driven hydrogen annealing-induced surface migration. We report here on the successful fabrication of regular arrays of high aspect ratio cylindrical pores in p-type Si via electrochemical etching.

P104 – Metallo-Dielectric Photonic Crystal Tunable Narrowband Infrared Sources

Irina Puscasu[1], Martin Pralle[1], Mark McNeal[1], Ed Johnson[1], and Rana Biswas[2]
[1]*Ion Optics, Inc.*
[2]*Iowa State University*

Metallo-dielectric photonic crystals lay the foundation for a new class of infrared light sources. Exploiting Si-based suspended micro-bridge structures, these devices consist of a metal film perforated by a periodic array of apertures extending into a dielectric substrate. Heated by a thermal source, a resonant coupling occurs between metal surface plasmons and the underlying dielectric photonic crystals. This produces a strong narrowband emission behavior at wavelengths commensurate with the lattice parameter of the photonic crystal. The coupling provides for unusually high optical emission efficiencies when the structure is thermally excited. Theoretical analysis of the spectral response using electromagnetic simulation methods shows good agreement with the experimental data and gives insight into the physical mechanisms responsible. We envision applying this technology to modify the thermal emission of hot bodies into narrowband light of optimum solar cell wavelength, maximizing the thermal photovoltaic energy conversion.

P106 – Stress-Induced Lifetime Variations In Rapid Thermal Processed Silicon Wafers
A. Karoui and G.A. Rozgonyi
North Carolina State University

Post-anneal carrier lifetime of silicon wafers processed in RTP systems are examined and discussed in the context of stress induced during processing. Minority carrier recombination lifetime maps were obtained using µPCD. Lifetime depth profiles were constructed for the region extending from the surface to the center of the wafer by acquiring consecutive minority carrier lifetime maps after each 100-µm material removal step. Each lifetime map provides the lifetime in the top 20 µm of the remaining material, which corresponds to the minority carrier generation volume. Correlation of structural defects with lifetime was also undertaken for a few spots. A number of phenomena were observed, including stress induced lifetime rings, lifetime enhancement rings, and anisotropies in lifetime distributions. These apparent features share common characteristics that is the stress wave and impurity gettering induced by non-steady state contact events that occur at high temperature between the wafer and the point supports.

P108 – Hot-Wire Chemical Vapor Deposition of Silicon Nitride for Photovoltaic Applications
Harry Atwater, Christine Richardson, and Youngbae Park
California Institute of Technology

Silicon nitride films have been grown by hot-wire chemical vapor deposition and film properties have been characterized as a function of SiH_4/NH_3 flow ratio. Silicon nitride films were produced with refractive indices ranging from 1.8–2.5 and H-content from 9–18 atomic % as the flow ratio increased from 1% to 8%. Fourier Transform Infrared Spectroscopy revealed a change from predominantly N-H to Si-H bonding as the flow ratio increases to beyond 6%. Subsequent annealing studies showed different kinetics for H release from Si versus N. Films grown with a low SiH_4/NH_3 ratio were found to oxidize readily (23 atomic %), while larger ratios yielded no oxygen incorporation. H outdiffusion and capture by Pt-vacancy sites indicated a higher hydrogen release in Si-rich silicon nitride films grown by hot-wire chemical vapor deposition relative to those grown by plasma-enhanced chemical vapor deposition.

Thursday, October 28, 2004

Plenary Session IV-A and B: Solar Future
Chair: Robert Margolis
8:30–10:00 a.m. (A); 10:20–11:50 a.m. (B)

8:30 a.m. – The Solar Future for the United States—How Do We Get There?
Robert Margolis (NREL) and panelists: Allen Barnett, Claudine Schneider, Bill Guiney, Tom Starrs, Michael Rogol, and Daniel Kammen

This session will focus on how to achieve a solar future for the United States. It will examine three key questions: Where are we? Where are we going? And how can we accelerate the growth of solar technologies in the United States in the future? The panel will open with an overview presentation exploring the potential for central and distributed solar energy technologies in the United States over the long-term, i.e., through 2050. It will then include presentations on each of the major categories of solar technologies: photovoltaics, concentrating solar power, and solar hot water. These technology-specific presentations will discuss the current status and potential for growth of each technology. After a short break, the session will include three additional presentations. The first will examine the regulatory and policy context for moving solar into the mainstream, the second will explore how to engage the financial community in this process, and the third will describe the potential.

9:00 a.m. – The New U.S. PV Industry Roadmap

Allen Barnett
University of Delaware

The U.S. photovoltaic industry released the new *U.S. PV Industry Roadmap* on October 20, 2004, at the Solar Power 2004 Conference in San Francisco. This Roadmap calls for an increase in research funding to $250 million per year by 2010 and national market incentives. This combined approach can lead to electricity costs to the consumer that are less than 6 cents per kWh within ten years. These end-user costs can be below 4 cents per kWh by 2030. The economic benefits of this program can be greater than its costs. The Roadmap, its goals for the federal research support, and an overview of the cost and benefits of a robust solar program will be presented.

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Mark your calendars for next year's meeting!

2005 DOE Solar Energy Technologies Program Review Meeting

November 7–10, 2005

Denver Marriott City Center

17th and California (downtown)

Denver, Colorado

Web site: www.eere.energy.gov/solar/review_meeting

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NREL/BR-520-36821, October 2004

Produced by the National Renewable Energy Laboratory, a DOE national laboratory.