June 2004 • NREL/CP-520-35347

# Next-Generation Photovoltaic Technologies in the United States

## Preprint

R. McConnell and R. Matson

*To be presented at the 19th European PV Solar Energy Conference and Exhibition*
*Paris, France*
*June 7–11, 2004*

**National Renewable Energy Laboratory**
**1617 Cole Boulevard, Golden, Colorado 80401-3393**
**303-275-3000 • www.nrel.gov**

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
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Contract No. DE-AC36-99-GO10337

Conference Paper

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# NEXT-GENERATION PHOTOVOLTAIC TECHNOLOGIES IN THE UNITED STATES

Robert McConnell and Richard Matson
NREL, 1617 Cole Boulevard, Golden, CO 80401-3393, USA, Tel: 303-384-6419 and 303-384-6431, Fax: 303-384-6481 and 303-384-6430, e-mail: robert_mcconnell@nrel.gov and mailto:rick_matson@nrel.gov

ABSTRACT: This paper describes highlights of exploratory research into next-generation photovoltaic (PV) technologies funded by the United States Department of Energy (DOE) through its National Renewable Energy Laboratory (NREL) for the purpose of finding disruptive or "leap frog" technologies that may leap ahead of conventional PV in energy markets. The most recent set of 14 next-generation PV projects, termed Beyond the Horizon PV, will complete their third year of research this year. 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. We will describe accomplishments for several of these projects. 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. We also completed an evaluation of proposals for the newest set of exploratory research projects, but we are unable to describe them in detail until funding becomes available to complete the award process.
Keywords: Organic Solar Cell – 1, Multijunction Solar Cell – 2, Fundamentals – 3

## 1 BACKGROUND

Next-generation PV technologies are defined as those not in production or in limited production of less than 1% of the conventional PV market sales. Exploratory research into these next-generation technologies sprang from a consensus at a 1997 conference often referred to as "The Leap Frog Conference." This international conference was convened to review the viability of conventional PV technologies and to present and discuss next-generation PV technologies that might conceivably leap ahead of present-generation solar cells, either in terms of higher efficiency, lower cost, or both [1]. The consensus of conference participants was that the present generation, typically using crystalline silicon, was exhibiting incremental performance increases and cost decreases, with diminishing hope for a dramatic breakthrough that would lead to a much more commercially viable position in the energy marketplace.

In 1998, DOE, through NREL and its Exploratory Research Project, issued a request for proposals for next-generation PV concepts and conducted a rigorous competition leading to the selection of 18 university groups solely on the basis of the quality of the research proposed and the capabilities of the researchers. Each award, funded for 3 years, was to conduct exploratory research into a next-generation PV topic. This set of projects—called Future-Generation PV—explored many PV ideas, including nanoparticles in polymers, new III-V materials for higher-efficiency multijunction solar cells, porous silicon cells, nanorod solar cells, new transparent conducting oxides, and several studies of the Staebler-Wronski effect in amorphous silicon. Early results from some of the projects appeared at a second conference, entitled "Photovoltaics for the 21st Century," along with an identification of exploratory research opportunities in conventional PV technologies [2]. A third conference in 2001, called "Photovoltaics for the 21st Century II," highlighted presentations from all of the principal investigators who documented their major results at the end of their 3-year Future Generation projects [3].

A second request for proposals—called Beyond the Horizon PV—yielded 15 new 3-year projects beginning in 2001 and working on dye solar cells, molecular-chromophore cells, liquid-crystal cells, multijunction small-molecule cells, polymer cells, nanocrystalline silicon cells, lower-cost substrates for III-V multijunction cells, nonvacuum processing for CIGS thin-film cells, rectenna cells, and a novel solar concentrator cavity whose interior is covered with multiple single-junction solar cells with complementary broadband rugate filters. Some of these projects encountered significant obstacles, whereas others achieved some very good results. In 2002, we presented preliminary results for these projects, including references to key articles [4]. Because these projects are finishing this year, we will present preliminary highlights from some of them in this paper.

Over the years, these projects have self-ordered into two notably different approaches—"the high road and the low road." One involves high-efficiency solar cells that as of yet are too high in cost. The other focuses on low-cost devices whose conversion efficiencies at the moment are too low to be practical. The former approach includes high-efficiency III-V multijunction solar cells and, more recently, "Third Generation" concepts that have yet to be demonstrated [5,6]. The latter approach is mostly based on materials that absorb photons by creating excitons and includes a variety of organic solar cells. The goal for both approaches is the same: the production of significant amounts of low-cost solar electricity that is competitive in the world's energy markets. We recently described these two approaches and earlier Exploratory Research Project accomplishments in a paper prepared for the 2003 EU-Russian Workshop entitled "Efficient Use of the Solar Spectrum in Photovoltaics" that suggested future PV technologies should make better use of the solar spectrum [7].

In 2003, we conducted a third solicitation for exploratory research proposals for next-generation PV technologies and received many strong, intriguing proposals. However, at the time of writing this manuscript, budget uncertainties have delayed the announcement of any new awards.

## 2 LEAP-FROG TECHNOLOGIES

### 2.1 Multijunction solar cells for solar concentrators

High-efficiency III-V multijunction solar cells for use in solar electric concentrators appear likely to become a "leap frog" technology, with the distinct possibility of jumping ahead of existing technologies, rather than taking the more characteristic development time of 10 to 20 years (Fig. 2, next page). Concentrating sunlight is a technology as old as Archimedes, and focusing sunlight onto solar cells has been explored since the 1970s, so it is not a new technology. However, as noted in the preface of the "Leap Frog" conference [1]: "Indeed, many of these presentations referenced a long history for their ideas. What has changed, perhaps, is the availability of new technologies and discoveries that might make some of these concepts realistic." In the case of solar electric concentrators, the development of high-efficiency crystalline silicon solar cells (now at 26% efficiency under concentration) in the 1980s and the subsequent development of high-efficiency multijunction III-V solar cells (now at 37% efficiency) in the 1990s have led to an increased possibility that this technology will become a "leap frog" technology [8]. Both the first set of Future Generation and the second set of Beyond the Horizon projects included exploratory research into materials for higher-efficiency III-V multijunction cells and low-cost substrates for them. However, in addition to early funding for NREL's landmark in-house research on III-V solar cells (Fig. 2), there was significant early funding from the DOE's Office of Science and later funding provided by other U.S. government agencies (principally the U.S. Air Force within the U.S. Department of Defense) to develop manufacturing facilities for III-V solar cells used for powering various communications and defense satellites. The manufacturing capacity of these facilities is of the order of several megawatts (MW) worldwide, with the potential for quickly supplying hundreds of MW of concentrators if the early high-value space markets diminish.

In 2000, DOE, through NREL, initiated the High-Performance PV Project, whose goal was to double sunlight-to-electricity conversion efficiencies for thin films and concentrators by developing multijunction cells, one of the few Third-Generation concepts with demonstrated high efficiencies [5]. In the case of concentrators, the goal is to develop 41% cells and 33% solar concentrators. The project is beginning its second 3-year round of projects exploring pathways to achieve these goals through research at NREL, companies, and universities. The high-performance research on polycrystalline tandem cells is conducted predominantly at NREL and at universities. Recent achievements are reported elsewhere at this conference [9]. By contrast, high-performance research on multijunction solar cells for concentrators is performed at NREL, four companies, and three universities. Although it may be difficult to estimate the importance of company involvement, it accelerates the technology transfer process for taking new developments into production and commercialization.

### 2.2 Exploratory research successes in multijunctions

Two of the new universities in the High-Performance Project—California Institute of Technology and Ohio State University—are completing recent Exploratory Research Projects on innovative ways to fabricate multijunction cells on low-cost substrates. As their exploratory research projects near completion, they are just beginning new 3-year projects awarded by the High-Performance PV Project. Both of these projects can be said to have successfully "graduated" into the next phase of development for their technologies.

Harry Atwater's exploratory research project at Caltech is entitled "Layer Transfer Fabrication of High-Efficiency Solar Cells." His team developed methods for fabricating large-area InP/Si and Ge/Si films and grew InP/InGaAs/InP and InGaP/GaAs/InGaP double heterostructures by metal-organic chemical-vapor deposition on these InP/Si bonded template films. Values of photoluminescence yields for band-edge luminescence and photoluminescence decay lifetime from the GaAs layer on Ge/Si were comparable to those on bulk substrates. Electrical measurements of bonded Ge/Si and InP/Si interfaces indicate that low interfacial resistances (< 0.1 ohm-cm$^2$) can be obtained for heavily doped $p^+$ Ge/$p^+$ Si and $n^+$ Ge/$p^+$ Si, indicating that bonded interfaces can enable high-quality tunnel-junction interfaces in tandem solar cells made by layer-transfer fabrication. Fundamental studies of electronic transport at lightly doped bonded interfaces indicate that the Schottky barrier height decreases as hydrogen diffuses out of the bonded interface during annealing.

A new start-up company, Aonexx Corporation, was recently formed out of the Atwater group and obtained funding to commercialize bonded engineered substrates for high-efficiency PV and optoelectronics applications. Active research projects are in place with Spectrolab and Emcore to develop layer-transfer fabrication processes for triple-junction and 4-junction solar cell applications (Fig. 1). Spectrolab will be a subcontractor to Caltech's new High-Performance PV work.

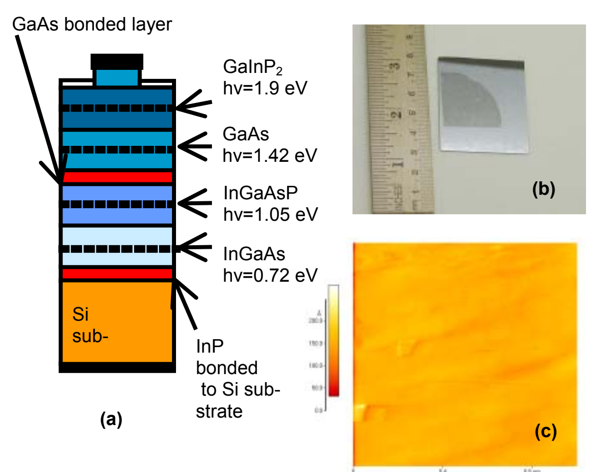


**Figure 1:** (a) Schematic of four junction solar cell with bonded layers. (b) Bonded InP/Si film. (c) AFM scan demonstrating 0.9 nm surface roughness.

Steven Ringel at Ohio State University is completing his exploratory research project, entitled "III-V Solar Cells on Si Substrates Using GeSi Buffer Layers." His group has been developing the substrate engineering expertise necessary to use SiGe metamorphic buffer layers to achieve integrated high-performance III-V solar cells on Si. Their significant results include the highest-performance single-junction GaAs solar cell grown on Si with 18% AM1.5 at 1-sun (NREL-verified) with 10.5%

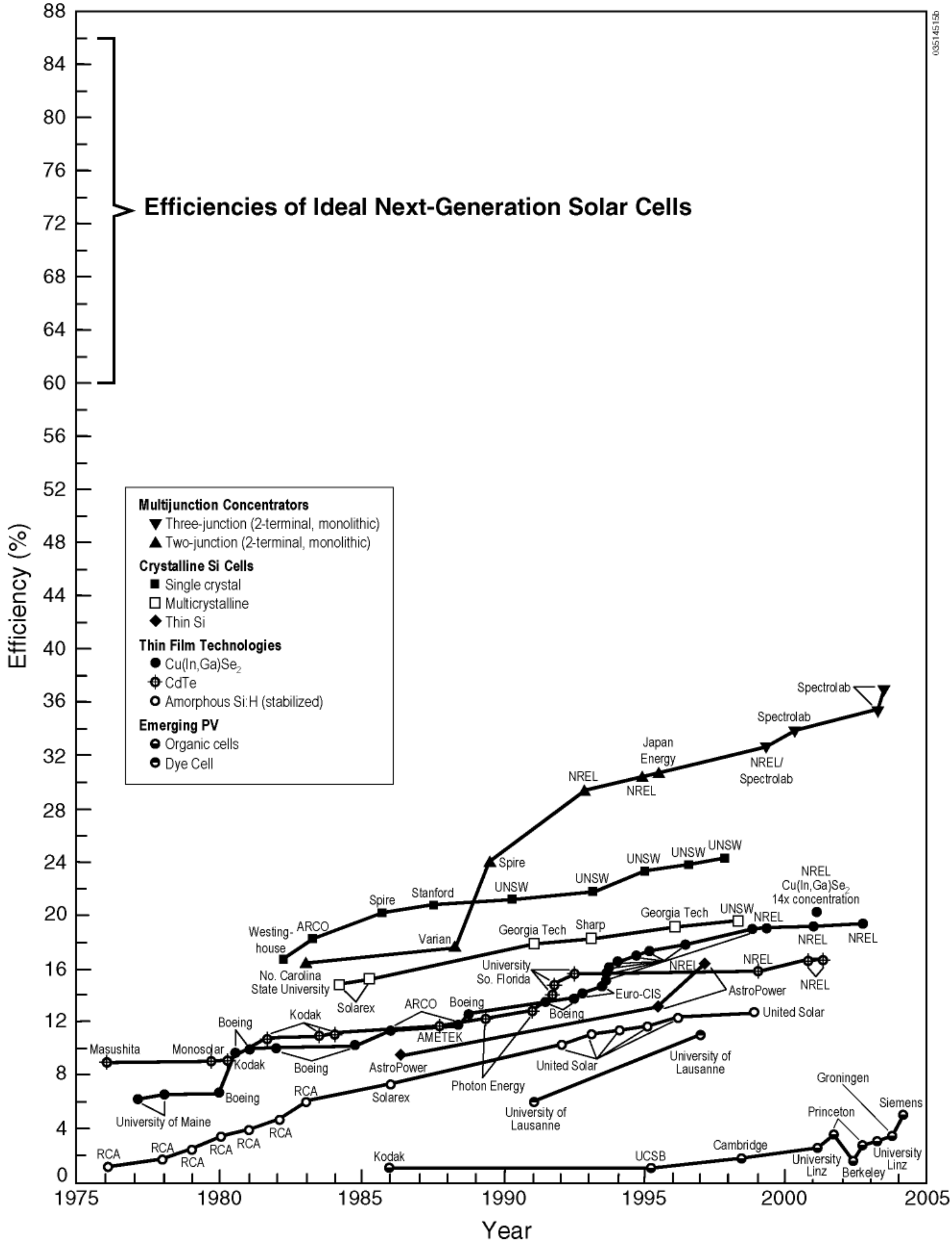


**Figure 2:** Highest conversion efficiencies of present and next-generation solar cells measured at NREL.

grid coverage. Very recently, they demonstrated their first III-V dual junction cell on Si. These are excellent results for their new work to begin within the High-Performance PV Project.

2.3 Organic solar cells

Organic solar cell technology is another likely candidate to become a "leap frog" technology. Organic materials absorb sunlight and create charge carriers through a different process than that occurring in almost all the inorganic solar cells, whether conventional or next generation. Photon absorption in almost all inorganic solar cell materials leads to the creation of independent electrons and holes that move by means of potential gradients within the solar cells. The photon absorption process in organic materials creates excitons—bound pairs of electrons and holes—which diffuse to a nearby internal boundary with another material where they dissociate into separate charge carriers at the boundary [10]. This fundamentally different photovoltaic process leads to much different length scales: the diffusion lengths for excitons are typically 10 nm, so that the required thicknesses of organic solar cells are measured in 10s of nanometers, instead of microns, for thin films, or in 100s of microns for crystalline silicon solar cells. Organic solar cells have been demonstrated for a variety of organic materials, including organic dyes, polymers, small molecules, and hybrids of polymers containing inorganic nanoparticles. Inorganic nanoparticles are another breeding ground for exciton creation by photon absorption. The efficiencies of organic solar cells are still quite low, but there is another application having a higher-value market than energy service that is spurring research and development. The leveraging of engineering development costs—usually an order of magnitude more expensive than exploratory research efforts—is critical to bringing a new solar technology to market. This scenario has been true with crystalline silicon (the integrated-circuit industry), amorphous silicon thin films (thin-film transistors for displays), and III-V solar cells (satellite power for defense and commercial applications). Without this leveraging, the time it takes to get to market is measured in decades, instead of years. One such organic semiconductor application is the organic light-emitting diode (organic LED), which appears today in high-value display applications such as cellular phones. Equally relevant may be the recent interest of the U.S. Defense Advanced Research Projects Agency (DARPA) in developing portable organic solar cells for battery charging that would reduce battery weight by a factor of two for special operations teams. These solar cells are expected to weigh considerably less and bend without breaking, and they are showing improving efficiencies. Further, low cost is eventually expected because these organic semiconductors don't use scarce, expensive, or toxic elements and their manufacture typically involves room-temperature substrates and, sometimes, no vacuum. Long-term reliability is slowly being demonstrated for organic LEDs through the development of effective encapsulation technologies, but this is certainly an important issue remaining for organic solar cells. DARPA is believed to be negotiating four multimillion-dollar, multiyear, multiteam awards to develop organic solar cells with dramatically higher efficiencies; NREL researchers will be working on two of the awards. Because of these additional market opportunities for organic solar cell materials, relatively small exploratory research projects can leverage knowledge and "know how" acquired in larger development programs.

2.4 Exploratory research successes in organic cells

Stephen Forrest's exploratory research project at Princeton University is entitled "Very High Efficiency Double Heterostructure and Tandem Organic PV Cells with Integrated Solar Concentrators." His team's focus has primarily been on developing new strategies to apply to small-molecular-weight organic PV cells that can lead ultimately to very high power conversion efficiencies (>10%) for reliable cells on flexible substrates. They are exploring several different approaches that result in a "tool box" of techniques leading to higher efficiencies. One strategy involves a novel, double-heterostructure PV cell, using the donor/acceptor materials pair, CuPc/$C_{60}$, along with another technique (an exciton-blocking layer of bathocuproine (BCP)) for minimizing losses at the cell's metallic contact [11]. The team more recently achieved 4.2% with the same materials through a layer-thinning process that lowered resistance. They also discovered another technique whereby a layer of Ag nanoparticles placed between cells results in a plasmon optical field enhancement of the incident light by reradiating the light and concentrating it in the thin sub-cell active regions [12].

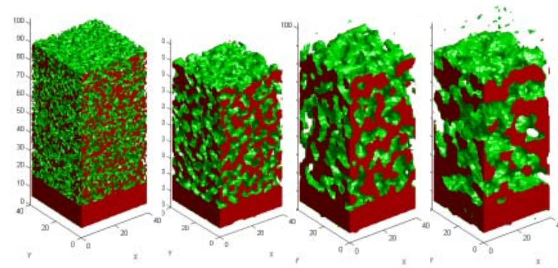

**Figure 3:** Formation of a bulk heterojunction by thermal annealing of small molecules (Peumans et al., Nature 425, 158 (2003)).

Simultaneously they have been investigating a new approach for bulk heterojunction solar cells. First experiments annealing mixed layers of CuPc and PTCBI exposed some severe obstacles [13], but recent, not-yet-published annealing investigations of mixed CuPc/$C_{60}$ layer cells resulted in 5% efficiency (Fig. 3). The Princeton team has made its own efficiency measurements (STC AM1.5, 1-sun) to monitor their progress. Princeton scientists are preparing to send samples to NREL for efficiency verification. A recent article by Forrest reviews the progress and potential of organic electronic devices, including organic LEDs and solar cells [14]. The Princeton team is currently working with a start-up company, Global Photonic Energy Corporation, to find partners for producing and commercializing their 5% efficient cells on low cost plastic substrates.

Arizona State University is completing their exploratory research project entitled "Liquid-Crystal-Based Photovoltaic Technologies" under Neal Armstrong. While Armstrong's group has developed promising new self-organizing phthalocyanines, another Arizona investigator, Bernard Kippelen, recently moved to the Georgia Institute of Technology to continue his line of research on the project. In completing their research effort, the Kippelen research group has fabricated CuPc/$C_{60}$/BCP/Al devices on bare ITO, similar to some Princeton cells. Four cells showed good reproducibility, with an efficiency of 1.85% under AM 1.5 and one sun. Further optimization of these cells is in progress.

Sometimes the successes of these projects are more than efficiency increases. Sue Carter at the University of California, Santa Cruz, is finishing a challenging exploratory research project entitled "Polymer Hybrid PV for Inexpensive Electricity Generation." Her team's interactions with Add-vision, Inc., resulted in the fabrication of a fully printed flexible polymer blend PV cell with efficiencies comparable to vacuum-processed polymer PV cells. A complete code for modeling the performance of a polymer hybrid PV cell was done in collaboration with IBM. And so as not to forget the importance of people in technology transfer, Carter's former students involved in the project are currently working with start-up companies to develop polymer hybrid PV technology.

Several other exploratory research projects are completing their work this year. Some of the teams are completing their work consistent with earlier plans, whereas others have made some dramatic changes in their research directions. We plan to report more fully on the results as all of the projects finish.

## 3 CONCLUSION

This brief paper mentions only a handful of the overall set of 58 projects falling under the Exploratory Research Project since its inception in 1998. Our desire was to provide a sense of the overall direction, although we cannot adequately describe here the wide spectrum of investigations into next-generation PV technologies. The Exploratory Research Project consists of a set of basic research efforts with the goal of producing low-cost solar electricity and representing work performed in concert with other university groups and industry researchers, wherever possible. These efforts are much more than a number of isolated scientific investigations; rather, they include all of NREL's activities in its National Center for Photovoltaics, and can be viewed as one network, one effort, one ensemble—all directed to finding solar cells that can make a significant and timely contribution to the world's need for clean energy.

## ACKNOWLEDGEMENT

We wish to acknowledge the efforts of the many research teams supported by DOE and NREL through the Exploratory Research Project. We have visited most of the universities and companies working on these projects and talked with dozens of graduate students and professional researchers over the years. Their excitement, enthusiasm, and dedication to photovoltaics technologies have inspired us and been important in achieving so many of the contributions to science and to the future of photovoltaics. None of this work would have been possible without the support of DOE under Contract No. DE-AC399GO10337 and more specifically, the DOE Solar Energy Technologies Program within its Office of Energy Efficiency and Renewable Energy.

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# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
June 2004

**2. REPORT TYPE**
Conference paper

**3. DATES COVERED** *(From - To)*

**4. TITLE AND SUBTITLE**
Next-Generation Photovoltaic Technologies in the United States: Preprint

**5a. CONTRACT NUMBER**
DE-AC36-99-GO10337

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
R. McConnell and R. Matson

**5d. PROJECT NUMBER**
NREL/CP-520-35347

**5e. TASK NUMBER**
PVP40100

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

**8. PERFORMING ORGANIZATION REPORT NUMBER**
NREL/CP-520-35347

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSOR/MONITOR'S ACRONYM(S)**
NREL

**11. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**12. DISTRIBUTION AVAILABILITY STATEMENT**
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT** *(Maximum 200 Words)*

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**15. SUBJECT TERMS**
PV; organic solar cell; multijunction solar cell; fundamentals

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| Unclassified | Unclassified | Unclassified | UL | | |
| | | | | | **19b. TELEPONE NUMBER** (*Include area code*) |

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F1147-E(05/2004)