

PROCEEDINGS OF SPIE

***Next Generation (Nano) Photonic
and Cell Technologies for Solar
Energy Conversion***

Loucas Tsakalacos
Editor

1–4 August 2010
San Diego, California, United States

Sponsored and Published by
SPIE

Volume 7772

Proceedings of SPIE, 0277-786X, v. 7772

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

The papers included in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. The papers published in these proceedings reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from this book:

Author(s), "Title of Paper," in *Next Generation (Nano) Photonic and Cell Technologies for Solar Energy Conversion*, edited by Loucas Tsakalacos, Proceedings of SPIE Vol. 7772 (SPIE, Bellingham, WA, 2010) Article CID Number.

ISSN 0277-786X
ISBN 9780819482686

Published by

SPIE

P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org

Copyright © 2010, Society of Photo-Optical Instrumentation Engineers

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of copying fees. The Transactional Reporting Service base fee for this volume is \$18.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923. Payment may also be made electronically through CCC Online at copyright.com. Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher. The CCC fee code is 0277-786X/10/\$18.00.

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.

SPIE 
Digital Library

SPIDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B ... 0Z, followed by 10-1Z, 20-2Z, etc.

The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.

Contents

vii	<i>Conference Committee</i>
ix	<i>Introduction</i>

NANOPHOTONICS FOR SOLAR ENERGY CONVERSION I

7772 02	Luminescence imaging: a powerful characterization tool for photovoltaic applications (Invited Paper) [7772-01] T. Trupke, J. W. Weber, BT Imaging Pty Ltd. (Australia)
7772 05	Design of photonic metamaterial multi-junction solar cells using rigorous coupled wave analysis [7772-04] E. Lansey, D. T. Crouse, The City College of New York (United States)

NANOPHOTONICS FOR SOLAR ENERGY CONVERSION II

7772 06	Nanoparticles for solar spectrum conversion (Invited Paper) [7772-05] W. G. J. H. M. van Sark, A. Meijerink, R. E. I. Schropp, Utrecht Univ. (Netherlands)
7772 07	Molecular approaches to third generation photovoltaics: photochemical up-conversion (Invited Paper) [7772-06] Y. Y. Cheng, B. Fückel, D. A. Roberts, T. Khoury, R. G. C. R. Clady, M. J. Y. Tayebjee, The Univ. of Sydney (Australia); R. Piper, N. J. Ekins-Daukes, Imperial College London (United Kingdom); M. J. Crossley, T. W. Schmidt, The Univ. of Sydney (Australia)
7772 08	Periodic arrays of ridge apertures as a high efficiency coupler for photovoltaic applications [7772-07] E. C. Kinzel, P. Srisungsitthisunti, X. Xu, Purdue Univ. (United States)
7772 09	Toward high-efficiency quantum dot solar cells: optimized gratings for ultrathin waveguide devices [7772-08] C. O. McPheeters, The Univ. of Texas at Austin (United States); C. J. Hill, Jet Propulsion Lab. (United States); D. Hu, Karlsruhe Institute of Technology (Germany); S. H. Lim, Arizona State Univ. (United States); D. Derkacs, Solar Junction Inc. (United States); D. Z. Ting, Jet Propulsion Lab. (United States); D. M. Schaad, Karlsruhe Institute of Technology (Germany); S. D. Gunapala, Jet Propulsion Lab. (United States); E. T. Yu, Univ. of Texas at Austin (United States)

7772 0A **Advances in up- and down-converted fluorescence for high efficiency solar cells using rare-earth doped fluorozirconate-based glasses and glass ceramics** [7772-09]
C. Paßlick, Martin-Luther-Univ. Halle-Wittenberg (Germany); B. Henke, Martin-Luther-Univ. Halle-Wittenberg (Germany) and Fraunhofer Ctr. for Silicon Photovoltaics (Germany); I. Császár, Martin-Luther-Univ. Halle-Wittenberg (Germany); B. Ahrens, Fraunhofer Ctr. for Silicon Photovoltaics (Germany); P.-T. Miclea, Fraunhofer Ctr. for Silicon Photovoltaics (Germany) and Martin-Luther-Univ. Halle-Wittenberg (Germany); J. A. Johnson, The Univ. of Tennessee Space Institute (United States); S. Schweizer, Martin-Luther-Univ. Halle-Wittenberg (Germany) and Fraunhofer Ctr. for Silicon Photovoltaics (Germany)

7772 0B **Silicon solar cells with nano-crystalline silicon down shifter: experiment and modeling** [7772-10]
Y. Jestin, G. Pucker, M. Ghulinyan, L. Ferrario, P. Bellutti, A. Picciotto, A. Collini, Bruno Kessler Foundation (Italy); A. Marconi, A. Anopchenko, Z. Yuan, L. Pavese, Univ. of Trento (Italy)

QUANTUM STRUCTURES FOR SOLAR ENERGY CONVERSION I

7772 0C **III-V quantum dot enhanced photovoltaic devices (Invited Paper)** [7772-11]
D. V. Forbes, S. M. Hubbard, C. Bailey, S. Polly, J. Andersen, Rochester Institute of Technology (United States); R. Raffaele, National Renewable Energy Lab. (United States)

7772 0G **Efficiency improvement by near infrared quantum dots for luminescent solar concentrators** [7772-15]
C. Wang, G. Shcherbatyuk, R. Inman, Univ. of California, Merced (United States); D. Pelka, Pelka & Associates Inc. (United States); W. Zhang, Univ. of California, Merced (United States); Y. Rodriguez, S. Carter, Univ. of California, Santa Cruz (United States); R. Winston, S. Ghosh, Univ. of California, Merced (United States)

QUANTUM STRUCTURES FOR SOLAR ENERGY CONVERSION II

7772 0J **Fabrication and characterisation of silicon quantum dots in SiO₂/Si₃N₄ hybrid matrix** [7772-18]
D. Di, I. Perez-Wurfl, G. Conibeer, M. A. Green, ARC Photovoltaics Ctr. of Excellence, Univ. of New South Wales (Australia)

NANO/MICRO WIRES & TUBES FOR SOLAR ENERGY CONVERSION I

7772 0M **Mimicking moth's eyes for photovoltaic applications with tapered GaP nanorods (Invited Paper)** [7772-28]
S. L. Diedenhofen, FOM Institute for Atomic and Molecular Physics (Netherlands); R. E. Algra, E. P. A. M. Bakkers, Philips Research Nederland B.V. (Netherlands); J. Gómez Rivas, FOM Institute for Atomic and Molecular Physics (Netherlands)

NANOSTRUCTURED ORGANIC SOLAR CELLS: JOINT SESSION WITH CONFERENCE 7777

- 7772 0P **Improving the photovoltaic properties of organic solar cells by structuring the P3HT:PCBM photoactive layer with functionalized SWCNTs** [7772-25]
H. Derbal-Habak, Univ. d'Angers (France) and Institut Matériaux Microélectronique Nanosciences de Provence, CNRS, Univ. Aix-Marseille (France); C. Bergeret, J. Cousseau, Lab. Moltech Anjou, CNRS, Univ. d'Angers (France); J. M. Nunzi, Queen's Univ. (Canada)

NANOPHOTONICS FOR SOLAR ENERGY CONVERSION III

- 7772 0Z **Fundamental limit of nanophotonic light-trapping in solar cells** [7772-33]
Z. Yu, A. Raman, S. Fan, Stanford Univ. (United States)
- 7772 11 **Quantifying intrinsic loss mechanisms in solar cells: Why is power efficiency fundamentally limited?** [7772-35]
L. C. Hirst, N. J. Ekins-Daukes, Imperial College London (United Kingdom)

ADVANCED PHOTOVOLTAIC TECHNOLOGIES

- 7772 12 **SLiM-cut thin silicon wafering with enhanced crack and stress control** [7772-36]
J. Vaes, A. Masolin, A. Pesquera, F. Dross, IMEC (Belgium)
- 7772 14 **Optical surface technologies: boosting efficiency from already present light** [7772-38]
M. A. Raymond, H. Lange, S. Weiss, M. A. Grossman, Genie Lens Technologies, LLC (United States)
- 7772 15 **Plasmonic field and efficiency enhancement in crystalline thin film photovoltaics** [7772-39]
D. Zhao, The Univ. of Texas at Arlington (United States); Z. Ma, Univ. of Wisconsin-Madison (United States); W. Zhou, The Univ. of Texas at Arlington (United States)

POSTER SESSION

- 7772 16 **Silicon nanowire/poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) heterojunction solar cells** [7772-40]
S.-C. Shiu, J.-J. Chao, S.-C. Hung, C.-L. Yeh, C.-F. Lin, National Taiwan Univ. (Taiwan)
- 7772 17 **Photovoltaic conversion enhancement of TiO₂ nanoparticles decorated with Au nanocrystals and sensitized with CdSe quantum dots and P3OT polymer** [7772-41]
I. Zarazúa, E. De la Rosa, T. López-Luke, Ctr. de Investigaciones en Óptica, A.P. (Mexico); J. Reyes, Univ. de Colima (Mexico); S. Ruiz, Ctr. de Investigaciones en Óptica, A.P. (Mexico)
- 7772 19 **Plasmonic structures integrated in organic solar cells** [7772-43]
S. Vedraïne, Ph. Torchio, H. Derbal-Habak, Institut Matériaux Microélectronique Nanosciences de Provence, CNRS, Univ. Aix-Marseille (France); F. Flory, Ecole Centrale Marseille, CNRS (France); V. Brissonneau, D. Duché, J. J. Simon, L. Escoubas, Institut Matériaux Microélectronique Nanosciences de Provence, CNRS, Univ. Aix-Marseille (France)

- 7772 1B **Photonic metamaterial absorber designs for infrared solar cell applications** [7772-45]
K. B. Alici, E. Ozbay, Bilkent Univ. (Turkey)
- 7772 1C **Optical properties of silicon nanowires array fabricated by metal-assisted electroless etching** [7772-46]
Z. Guo, J.-Y. Jung, K. Zhou, Y. Xiao, S. Jee, S. A. Moiz, J.-H. Lee, Hanyang Univ. (Korea, Republic of)
- 7772 1G **Optical absorption enhancement in silicon nanowire and nanohole arrays for photovoltaic applications** [7772-50]
C. Lin, M. L. Povinelli, The Univ. of Southern California (United States)
- 7772 1J **Optical properties of vertical silicon nanowire arrays with random position, diameter, or length** [7772-53]
H. Bao, X. Ruan, Purdue Univ. (United States)
- 7772 1K **Hybrid nanostructured solar cells based on the incorporation of inorganic nanoparticles in polymer-fullerene mixtures** [7772-54]
J. N. de Freitas, A. F. Nogueira, Univ. Estadual de Campinas (Brazil)
- 7772 1L **Nanophase semiconductors embedded within transparent conductive oxides matrices as optical sensitizers for photovoltaic applications** [7772-55]
C. G. Allen, G. H. Shih, R. J. Beal, B. G. Potter, Jr., The Univ. of Arizona (United States)

Author Index

Conference Committee

Symposium Chair

Martha Symko-Davies, National Renewable Energy Laboratory
(United States)

Conference Chair

Loucas Tsakalacos, GE Global Research (United States)

Program Committee

Amanda Chatten, Imperial College London (United Kingdom)
Gavin Conibeer, ARC Photovoltaics Center of Excellence, University of
New South Wales (Australia)
Alberto Salleo, Stanford University (United States)
Sean E. Shaheen, University of Denver (United States)
Wilfried G. J. H. M. van Sark, Utrecht Universiteit (Netherlands)
Deli Wang, University of California, San Diego (United States)
Xianfan Xu, Purdue University (United States)
Edward T. Yu, The University of Texas at Austin (United States)

Session Chairs

- 1 Nanophotonics for Solar Energy Conversion I
Xianfan Xu, Purdue University (United States)
- 2 Nanophotonics for Solar Energy Conversion II
Gavin Conibeer, ARC Photovoltaics Center of Excellence, University of
New South Wales (Australia)
- 3 Quantum Structures for Solar Energy Conversion I
Wilfried G. J. H. M. van Sark, Utrecht Universiteit (Netherlands)
- 4 Quantum Structures for Solar Energy Conversion II
Alberto Salleo, Stanford University (United States)
- 5 Nano/Micro Wires & Tubes for Solar Energy Conversion I
Loucas Tsakalacos, GE Global Research (United States)
- 6 Nanostructured Organic Solar Cells: Joint Session with
Conference 7777
Sean E. Shaheen, University of Denver (United States)

- 7 Nano/Micro Wires & Tubes for Solar Energy Conversion II
Deli Wang, University of California, San Diego (United States)
- 8 Nanophotonics for Solar Energy Conversion III
Gavin Conibeer, ARC Photovoltaics Center of Excellence, University of
New South Wales (Australia)
- 9 Advanced Photovoltaic Technologies
Joseph Luther, National Renewable Energy Laboratory (United States)

Introduction

The solar energy industry has seen strong growth in the last decade. While the recent Great Recession has certainly had an impact on the photovoltaics (PV) industry, this has not been as severe as feared and the industry is seeing promising growth levels. Conventional silicon and thin film PV technologies are well developed and capable of meeting the clean energy demands of many markets. They will have even more impact as cost reduction and manufacturing technologies improve. Nevertheless, there continues to be interest within the research community in developing technologies that can simultaneously reduce cost yet also provide breakthrough performance.

To this effect, research efforts in studying and applying the unique optical, electrical, and structural/architectural properties of micro and nanostructures to solar energy applications, either as novel photonic structures or as new solar cell device structures, continue to flourish. This year's third installment of the conference devoted to this topic, Next Generation (Nano) Photonic and Cell Technologies for Solar Energy Conversion, held at SPIE Optics + Photonics in 2010 as part of the Solar Energy + Technology Symposium, once again demonstrated the strong interest in this field of research. The conference's title was slightly modified this year to include a broader class of next generation concepts and other mechanisms of solar energy conversion.

The first two sessions of the conference were focused on Nanophotonics for Solar Energy Conversion, i.e., the use of novel layers and structures for light management in solar applications. After an overview of solar cell characterization using luminescent imaging, numerous presentations on up/down-conversion, plasmonics, light trapping, and photonic bandgap structures, among other topics, were given. The third and fourth sessions were devoted to Quantum Structures for Solar Energy Conversion, featuring talks on quantum dot solar cells, intermediate bands using highly mismatched alloys, and luminescent solar concentrators. A joint session (with the Organic Photovoltaics conference) on advances in Nanostructured Organic Solar Cells was held, followed by two sessions on Nano/Micro Wires & Tubes for Solar Energy Conversion. These included application of CdS/CdTe, α -Si:H, Si, and III-V wires and pillars in novel photovoltaic devices, and nanowire-based transparent conductors. Following a third session on Nanophotonics, the final session of the conference on Advanced Photovoltaic Technologies included presentations describing advanced thin silicon wafering, direct-write metallization, and other optical enhancing mechanisms for solar modules. A collection of excellent posters on various next generation PV topics further contributed to the conference.

The conference was also highlighted by the second year of a panel discussion moderated by Prof. Sean Shaheen (University of Denver) and myself on Commercialization of Emerging Photovoltaic Technologies, in which experts from academia and industry discussed the prospects and challenges in developing novel PV technologies based on organic and inorganic materials. This year's panelists were as follows:

Christoph J. Brabec, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)
Gavin Conibeer, ARC Photovoltaics Ctr. of Excellence, Univ. of New South Wales (Australia)
Gang Li, SOLARMER Energy, Inc. (USA)
Michael J. Naughton, Boston College (USA)
Kishore Kamath, Abound Solar, Inc. (USA)
John A. Rogers, Univ. of Illinois at Urbana-Champaign, for Semprius, Inc. (USA)
Tom Tibbits, QuantaSol Ltd. (United Kingdom).

Among the many interesting points raised by the panel, some noted that cost analysis is a critical component in analyzing the impact of a technology, though the general consensus was that this may be best left to those in business while those in research should focus on developing novel technologies through science and engineering. Some panelists argued that organic materials will play an increasing role in the future, whereas others felt that high efficiency III-V-based technologies will make an impact as new processing technologies are developed for low cost. Most agreed that crystalline silicon technology will continue be a major part of the solar market, as will thin film technologies based on CdTe and CIGS. The scale-up activities of several CdTe based companies were noted, as was the low cost position of this technology. Several members of the audience highlighted the potential for concentrator PV applications in the future.

Once again, the conference provided an excellent forum for the interchange of next generation photonic and device concepts in solar energy conversion. I would like to thank the conference program committee (Drs. A. Chatten, G. Conibeer, A. Salleo, S. E. Shaheen, W. G. J. H. M. van Sark, D. Wang, X. Xu, and E. T. Yu) for their great support, as well as the session chairs, authors, and SPIE staff for their help in making this a successful conference. The strong support of Dr. M. Symko-Davies, chair of the 2010 Solar Energy + Technology symposium, is also greatly appreciated.

Loucas Tsakalacos