

PROCEEDINGS OF SPIE

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

**Loucas Tsakalacos**

*Editor*

**21–23 August 2011**

**San Diego, California, United States**

*Sponsored and Published by*  
SPIE

**Volume 8111**

Proceedings of SPIE, 0277-786X, v. 8111

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 II*, edited by Loucas Tsakalakos, Proceedings of SPIE Vol. 8111 (SPIE, Bellingham, WA, 2011) Article CID Number.

ISSN 0277-786X  
ISBN 9780819487216

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 © 2011, 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](http://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/11/\$18.00.

Printed in the United States of America.

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

The logo for SPIE Digital Library features the word "SPIE" in a bold, sans-serif font above the words "Digital Library" in a smaller, sans-serif font. To the right of the text is a stylized graphic consisting of three vertical bars of increasing height, resembling a barcode or a signal waveform.

[SPIDigitalLibrary.org](http://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 as 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 *Conference Committee*
- ix *Introduction*
- xi *Solar Energy Grid Integration Systems (SEGIS): adding functionality while maintaining reliability and economics (Plenary Paper) [811202]*  
W. Bower, Sandia National Labs. (United States)

---

## NANOPHOTONICS FOR PHOTOVOLTAICS I

---

- 8111 02 **Advances in spectral conversion for photovoltaics: up-converting Er<sup>3+</sup> doped YF<sub>3</sub> nano-crystals in transparent glass ceramic (Invited Paper) [8111-01]**  
J. Marques-Hueso, Heriot-Watt Univ. (United Kingdom); D. Chen, Fujian Institute of Research on the Structure of Matter (China); S. K. W. MacDougall, Heriot-Watt Univ. (United Kingdom); Y. Wang, Fujian Institute of Research on the Structure of Matter (China); B. S. Richards, Heriot-Watt Univ. (United Kingdom)
- 8111 03 **Embedded metallic nanopatterns for enhanced optical absorption [8111-03]**  
F. Ye, M. J. Burns, M. J. Naughton, Boston College (United States)
- 8111 04 **Visible to infrared down conversion in rare-earth doped fluorides for luminescent solar converters [8111-04]**  
D. Serrano, A. Braud, J.-L. Doualan, P. Camy, R. Moncorgé, CIMAP, CNRS, ENSICAEN, Univ. de Caen (France)

---

## NANOPHOTONICS FOR PHOTOVOLTAICS II

---

- 8111 06 **Plasmonic enhancement of thin-film solar cells using gold-black coatings [8111-06]**  
C. J. Fredricksen, LRC Engineering Inc. (United States); D. R. Panjwani, J. P. Arnold, P. N. Figueiredo, F. K. Rezaie, J. Colwell, K. Baillie, Univ. of Central Florida (United States); S. J. Peppernick, A. G. Joly, K. M. Beck, W. P. Hess, Pacific Northwest National Lab. (United States); R. E. Peale, Univ. of Central Florida (United States)
- 8111 07 **Optical simulations and prototyping of microcrystalline silicon solar cells with integrated plasmonic reflection grating back contacts [8111-07]**  
U. W. Paetzold, E. Moulin, B. E. Pieters, U. Rau, R. Carius, Forschungszentrum Jülich GmbH (Germany)
- 8111 08 **Self-assembly as a design tool for the integration of photonic structures into excitonic solar cells [8111-08]**  
S. Guldin, Univ. of Cambridge (United Kingdom); P. Docampo, Univ. of Oxford (United Kingdom); S. Hüttner, P. Kohn, Univ. of Cambridge (United Kingdom); M. Stefik, Cornell Univ. (United States); H. J. Snaith, Univ. of Oxford (United Kingdom); U. Wiesner, Cornell Univ. (United States); U. Steiner, Univ. of Cambridge (United Kingdom)

---

## QUANTUM DOT SOLAR CELLS

---

- 8111 OH **High-efficiency quantum dot solar cells due to inter-dot n-doping** [8111-16]  
K. A. Sablon, J. W. Little, U.S. Army Research Lab. (United States); V. Mitin, A. Sergeev, N. Vagidov, Univ. at Buffalo (United States); K. Reinhardt, Air Force Office of Scientific Research (United States)
- 8111 OI **High-voltage quantum well waveguide solar cells** [8111-17]  
R. E. Welsler, G. G. Pethuraja, A. K. Sood, Magnolia Solar, Inc. (United States); O. A. Laboutin, M. Chaplin, V. Un, W. Johnson, Kopin Corp. (United States); A. W. Sood, D. J. Poxson, J. Cho, E. F. Schubert, Rensselaer Polytechnic Institute (United States); P. Haldar, College of Nanoscale Science & Engineering (United States); J. L. Harvey, New York State Energy Research and Development Authority (United States)

---

## ADVANCED SOLAR ENERGY CONVERSION MECHANISMS I

---

- 8111 OK **Towards photonic luminescent solar concentrators** [8111-20]  
J. Gutmann, M. Peters, B. Bläsi, M. Hermle, Fraunhofer-Institut für Solare Energiesysteme (Germany); H. Zappe, Albert-Ludwigs-Univ. Freiburg (Germany); J. C. Goldschmidt, Fraunhofer-Institut für Solare Energiesysteme (Germany)

---

## ADVANCED SOLAR ENERGY CONVERSION MECHANISMS II

---

- 8111 OO **Theoretical analysis of hot electron collection in metal-insulator-metal devices** [8111-24]  
F. Wang, N. A. Melosh, Stanford Univ. (United States)

---

## WIRE-BASED INORGANIC SOLAR CELLS

---

- 8111 OQ **Silicon nanowire solar cells with a-Si heterojunction showing 7.3% efficiency (Invited Paper)** [8111-26]  
F. Falk, G. Jia, G. Andrä, I. Sill, Institut für Photonische Technologien e.V. (Germany); N. Petkov, Tyndall National Institute (Ireland)
- 8111 OR **Optical response of 3D nano-architecture solar cells and integration with 3D device physics** [8111-27]  
A. Wangperawong, C. Hägglund, S. F. Bent, Stanford Univ. (United States)
- 8111 OU **Detailed balance limit of silicon nanowire and nanohole array solar cells** [8111-30]  
C. Lin, M. L. Povinelli, The Univ. of Southern California (United States)

---

## NANOSCALE AND HYBRID SYSTEMS: JOINT SESSION WITH CONFERENCE 8116

---

- 8111 OV **GaAs nanowire/PEDOT:PSS hybrid solar cells: the relationship between nanowire morphology and device performance** [8111-31]  
J.-J. Chao, S.-C. Shiu, S.-C. Hung, C.-F. Lin, National Taiwan Univ. (Taiwan)

- 8111 OW **Si/silicon nanowire/poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) heterojunction solar cells** [8111-32]  
H.-J. Syu, S.-C. Shiu, C.-F. Lin, National Taiwan Univ. (Taiwan)

---

**POSTER SESSION**

- 8111 OY **Embedded silver nanoparticle fabrication for surface plasmon-enhanced silicon photovoltaics** [8111-34]  
N. Kadakia, M. Huang, H. Bakhru, Univ. at Albany, SUNY (United States)
- 8111 OZ **Optical and electrical properties of crystalline silicon wire arrays** [8111-36]  
Y.-P. Pai, B. Simonds, J. Fields, R. Collins, P. C. Taylor, Colorado School of Mines (United States)
- 8111 10 **Optical absorption in vertical silicon nanowires for solar cell applications** [8111-37]  
M. Foldyna, L. Yu, B. O'Donnell, P. Roca i Cabarrocas, LPICM, CNRS, Ecole Polytechnique (France)
- 8111 11 **Improvement of solar cell efficiency using nano-scale top and bottom grating** [8111-38]  
X. Jin, A. Ellaboudy, G. Chavoor, California Polytechnic State Univ. (United States)
- 8111 16 **Fine tuning the structure of unsymmetrical squaraine dyes towards the development of efficient dye-sensitized solar cells** [8111-44]  
S. S. Pandey, R. Watanabe, N. Fujikawa, Y. Ogomi, Kyushu Institute of Technology (Japan); Y. Yamaguchi, Nippon Steel Chemical Co., Ltd. (Japan); S. Hayase, Kyushu Institute of Technology (Japan)
- 8111 17 **Aluminum nanoparticles for improved OPV devices** [8111-45]  
V. Kochergin, L. N. Neely, MicroXact, Inc. (United States); S. Wi, C.-Y. Jao, H. D. Robinson, Virginia Polytechnic Institute and State Univ. (United States)
- 8111 18 **Device properties of nanopore PN junction Si for photovoltaic application** [8111-46]  
H. Jin, T. W. Chang, L. G. Liu, Univ. of Illinois at Urbana-Champaign (United States)
- 8111 1D **Properties of Si/SiO<sub>x</sub> quantum well structure for solar cells applications** [8111-51]  
K.-H. Kim, J.-H. Kim, P. Jang, C. Jung, K. Seomoon, Cheongju Univ. (Korea, Republic of)

*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 J. Chatten**, Imperial College London (United Kingdom)  
**Gavin J. Conibeer**, ARC Photovoltaics Center of Excellence (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 Photovoltaics I  
**Loucas Tsakalacos**, GE Global Research (United States)
- 2 Nanophotonics for Photovoltaics II  
**Loucas Tsakalacos**, GE Global Research (United States)
- 3 Nanophotonics for Photovoltaics III  
**Loucas Tsakalacos**, GE Global Research (United States)
- 4 Quantum Dot Solar Cells  
**Sean E. Shaheen**, University of Denver (United States)
- 5 Advanced Solar Energy Conversion Mechanisms I  
**Alberto Salleo**, Stanford University (United States)
- 6 Advanced Solar Energy Conversion Mechanisms II  
**Xianfan Xu**, Purdue University (United States)
- 7 Wire-Based Inorganic Solar Cells  
**Loucas Tsakalacos**, GE Global Research (United States)
- 8 Nanoscale and Hybrid Systems: Joint Session with Conference 8116  
**Alberto Salleo**, Stanford University (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. Furthermore, the industry is beginning what appears to be a process of consolidation that may be representative of maturity, particularly as competition from low-cost Si manufacturers continues to provide price pressure on modules and ultimately on PV systems. Nevertheless, there continues to be interest within the research community in developing technologies that can simultaneously reduce cost yet also provide breakthrough performance. Today solar technologies that simultaneously provide high performance yet low cost and reliability are not well established or non-existent.

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 fourth installment of the conference devoted to this topic (8111: Next Generation (Nano) Photonic and Cell Technologies for Solar Energy Conversion II), held at SPIE Optics & Photonics in 2011 as part of the Solar Energy + Technology track, once again demonstrated the strong interest in this field of research.

There were many significant advances presented at the conference, including 7% efficient Si nanowire solar cells, new designs for light trapping and waveguiding in PV devices, improved materials and structures for up and down conversion, demonstration of hot carrier extraction from quantum dot monolayers, high efficiency quantum dot devices, application of metamaterials to PV, use of self-assembly to create photonic structures, and novel organic and hybrid devices (joint session with OPV conference).

The conference was also highlighted by the third year of a panel discussion 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:

**Martha Symko-Davies**, National Renewable Energy Lab. (USA)

**Dana Olsen**, National Renewable Energy Lab. (USA)

**Louay A. Eldada**, SunEdison (USA)

**Frank van Mierlo**, 1366 Technologies, Inc. (USA)

Among the topics discussed by the panel included vertical integration of solar companies, the role of silicon in the future of the PV industry, the effect of Si feedstock impurities, the future of organic PV in the market, cost and reliability of concentrator PV, and next generation concepts.

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 (J. Lowell in particular) for their help in making this a successful conference.

**Loucas Tsakalacos**