

PROCEEDINGS OF SPIE

Solar Hydrogen and Nanotechnology II

Jinghua Guo
Editor

27–30 August 2007
San Diego, California, USA

Sponsored by
SPIE

Cosponsored by
Varian, Inc. (USA)

Published by
SPIE

Volume 6650

Proceedings of SPIE, 0277-786X, v. 6650

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 *Solar Hydrogen and Nanotechnology II*, edited by Jinghua Guo, Proceedings of SPIE Vol. 6650 (SPIE, Bellingham, WA, 2007) Article CID Number.

ISSN 0277-786X

ISBN 9780819467980

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 © 2007, 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/07/\$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>

PLENARY SESSION

- 6650 02 **The solar-hydrogen economy: an analysis (Plenary Paper)** [6650-101]
W. D. Reynolds, Eco-Engineers, Inc. (USA)
- 6650 03 **Solar hydrogen production by tandem cell system composed of metal oxide semiconductor film photoelectrode and dye-sensitized solar cell (Plenary Paper)** [6650-102]
H. Arakawa, C. Shiraishi, M. Tatamoto, H. Kishida, D. Usui, A. Suma, A. Takamisawa, T. Yamaguchi, Tokyo Univ. of Science (Japan)

SESSION 1 SYNTHESIS OF ADVANCED NANOSTRUCTURES AND SEMICONDUCTOR I

- 6650 06 **Copper gallium diselenide photocathodes for solar photoelectrolysis** [6650-03]
B. Marsen, B. Cole, S. Dorn, R. E. Rocheleau, E. L. Miller, Univ. of Hawaii at Manoa (USA)

SESSION 2 SYNTHESIS OF ADVANCED NANOSTRUCTURES AND SEMICONDUCTOR II

- 6650 08 **Effects of doping on photocatalytic activity for water splitting of metal oxides and nitrides (Invited Paper)** [6650-05]
N. Arai, N. Saito, H. Nishiyama, H. Kadowaki, Nagaoka Univ. of Technology (Japan); H. Kobayashi, Kyoto Institute of Technology (Japan); K. Sato, Y. Inoue, Nagaoka Univ. of Technology (Japan)
- 6650 09 **Nanostructured ZnO films electrodeposited using monosaccharide molecules as templates (Invited Paper)** [6650-06]
C. Boeckler, A. Feldhoff, T. Oekermann, Leibniz Univ. Hannover (Germany)
- 6650 0A **Electrodeposition of ZnO nanowire arrays with tailored dimensions: building blocks for photoelectrochemical devices (Invited Paper)** [6650-07]
R. Tena-Zaera, J. Elias, C. Lévy-Clément, Institut de Chimie et Matériaux de Paris-Est, CNRS (France)

SESSION 3 SOLAR HYDROGEN AND WATER SPLITTING

- 6650 0C **Nanowires for solar energy and hydrogen production (Invited Paper)** [6650-10]
Y. Qu, A. M. Sutherland, T. Guo, Univ. of California, Davis (USA)
- 6650 0D **Metal oxide semiconductors in PEC splitting of water (Invited Paper)** [6650-11]
V. R. Satsangi, Dayalbagh Educational Institute (India)

SESSION 4 BANDGAP ENGINEERING OF SOLAR HYDROGEN MATERIALS

- 6650 OE **Hydrogen production using metal nanoparticle modified silicon thin film photoelectrode (Invited Paper)** [6650-12]
S. Yae, Univ. of Hyogo (Japan) and CREST, Japan Science and Technology Agency (Japan); A. Onaka, M. Abe, N. Fukumuro, Univ. of Hyogo (Japan); S. Ogawa, Gifu Univ. (Japan); N. Yoshida, S. Nonomura, Gifu Univ. (Japan) and CREST, Japan Science and Technology Agency (Japan); Y. Nakato, Kwansai Gakuin Univ. (Japan) and CREST, Japan Science and Technology Agency (Japan); H. Matsuda, Univ. of Hyogo (Japan)
- 6650 OF **Electronic structure characterization and bandgap engineering of solar hydrogen materials (Invited Paper)** [6650-13]
J. Guo, Lawrence Berkeley National Lab. (USA)
- 6650 OG **Rapid synthesis of nanostructured metal-oxide films for solar energy applications by a flame aerosol reactor (FLAR)** [6650-14]
E. Thimsen, N. Rastgar, P. Biswas, Washington Univ. in St. Louis (USA)
- 6650 OH **Band gap reduction of ZnO for photoelectrochemical splitting of water** [6650-15]
Y. Yan, K.-S. Ahn, S. Shet, T. Deutsch, M. Huda, S. H. Wei, J. Turner, M. M. Al-Jassim, National Renewable Energy Lab. (USA)

SESSION 5 SOLAR HYDROGEN AT BIOHYBRID AND ORGANIC CATALYSTS

- 6650 OI **Ultrafast structural dynamics of photoactive metal complexes in solar hydrogen generation (Invited Paper)** [6650-28]
L. X. Chen, D. Liu, E. C. Wasinger, X. Zhang, K. Attenkofer, G. Jennings, Argonne National Lab. (USA)
- 6650 OJ **Merging [FeFe]-hydrogenases with materials and nanomaterials as biohybrid catalysts for solar H₂ production (Invited Paper)** [6650-16]
P. W. King, D. Svedruzic, National Renewable Energy Lab. (USA); M. Hambourger, M. Gervaldo, Arizona State Univ. (USA); T. McDonald, J. Blackburn, M. Heben, National Renewable Energy Lab. (USA); D. Gust, A. L. Moore, T. A. Moore, Arizona State Univ. (USA); M. L. Ghirardi, National Renewable Energy Lab. (USA)
- 6650 OK **Sonoelectrochemical synthesis of low band gap titania nanotubes for photoelectrochemical generation of hydrogen (Invited Paper)** [6650-17]
Y. S. Sohn, Y. Smith, K. S. Raja, V. Subramanian, M. Misra, Univ. of Nevada, Reno (USA)
- 6650 OL **Photocatalytic hydrogen production using surface-modified titania nanoparticles** [6650-18]
W. Choi, Pohang Univ. of Science and Technology (South Korea)

SESSION 6 HYDROGEN GENERATION AND STORAGE MATERIALS

- 6650 ON **Temperature-dependent Raman scattering study of LiAlH₄ and Li₃AlH₆ (Invited Paper)** [6650-20]
L. Seballos, R. Newhouse, J. Z. Zhang, Univ. of California, Santa Cruz (USA); E. Majzoub, Sandia National Labs. (USA) and Univ. of Missouri, St. Louis (USA); E. Rönnebro, Sandia National Labs. (USA)

SESSION 7 SOLAR HYDROGEN DEVICES AND APPLICATIONS

- 6650 OS **α -SiC:H films used as photoelectrodes in a hybrid, thin-film silicon photoelectrochemical (PEC) cell for progress toward 10% solar-to hydrogen efficiency** [6650-25]
F. Zhu, MVSystems, Inc. (USA) and Colorado School of Mines (USA); J. Hu, A. Kunrath, MVSystems, Inc. (USA); I. Matulionis, Colorado School of Mines (USA); B. Marsen, B. Cole, E. Miller, Univ. of Hawaii at Manoa (USA); A. Madan, MVSystems, Inc. (USA) and Colorado School of Mines (USA)
- 6650 OT **Photoelectrochemical and photocatalytic properties of nanocrystalline TiO₂ electrodes** [6650-26]
H. G. Oliveira, D. C. Nery, M. P. Paschoalino, W. F. Jardim, C. Longo, Univ. Estadual de Campinas (Brazil)

SESSION 8 PHOTO-CATALYSIS AT TITANIUM OXIDES

- 6650 OW **Slow photons in TiO₂ inverse opals: optical amplification and effect of disorder on the photocatalytic efficiency** [6650-29]
J. I. L. Chen, Univ. of Toronto (Canada); G. von Freymann, Forschungszentrum Karlsruhe (Germany); S. Y. Choi, Univ. of Toronto (Canada); V. Kitaev, Wilfrid Laurier Univ. (Canada); G. A. Ozin, Univ. of Toronto (Canada)
- 6650 OX **Synthesis and characterization of TiO₂ nanoparticles: anatase, brookite, and rutile** [6650-30]
D. Reyes-Coronado, G. Rodriguez-Gattorno, CINVESTAV-IPN (Mexico);
M. Espinosa-Pesqueira, Instituto Nacional de Investigaciones Nucleares (Mexico);
J. M. Gardner, G. J. Meyer, Johns Hopkins Univ. (USA); G. Oskam, CINVESTAV-IPN (Mexico)

POSTER SESSION

- 6650 OY **Photocatalytic hydrogen production over CdS/titania-nanotube composite films** [6650-31]
S.-J. Moon, H.-M. Lee, W.-W. So, J.-O. Baeg, K. Kong, Korea Research Institute of Chemical Technology (South Korea)
- 6650 OZ **A solar photobioreactor for the production of biohydrogen from microalgae** [6650-32]
L. Pantí, P. Chávez, D. Robledo, R. Patiño, CINVESTAV-Mérida (Mexico)
- 6650 10 **Preparation of high efficiency visible light activated Pt/CdS photocatalyst for solar hydrogen production** [6650-33]
C. Huang, B. Illiassou, A. T-Raissi, N. Muradov, Univ. of Central Florida (USA)
- 6650 11 **Interaction of [FeFe]-hydrogenases with single-walled carbon nanotubes (Best Poster Paper Award)** [6650-34]
D. Svedruzic Chang, T. J. McDonald, Y.-H. Kim, J. L. Blackburn, M. J. Heben, P. W. King, National Renewable Energy Lab. (USA)

Author Index

Conference Committee

Symposium Chair

Ravi Durvasula, Lightfleet Corporation (USA)

Conference Chair

Jinghua Guo, Lawrence Berkeley National Laboratory (USA)

Program Committee

Hironori Arakawa, Tokyo University of Science (Japan)

Jan Augustynski, Université de Genève (Switzerland)

Joe da Costa, The University of Queensland (Australia)

Maria L. Ghirardi, National Renewable Energy Laboratory (USA)

Michael Graetzel, École Polytechnique Fédérale de Lausanne
(Switzerland)

Ting Guo, University of California, Davis (USA)

Claude Lévy-Clément, Institut de Chimie et Matériaux de Paris-Est,
CNRS (France)

Yoshihiro Nakato, Osaka University (Japan), Kwansai Gakuin University
(Japan), and CREST, Japan Science and Technology Agency
(Japan)

Janusz Nowotny, University of New South Wales (Australia)

Ian C. Plumb, Commonwealth Scientific and Industrial Research
Organisation (Australia)

Pathiyamattom J. Sebastian, Universidad Nacional Autónoma de
México (Mexico)

John A. Turner, National Renewable Energy Laboratory (USA)

Lionel Vayssieres, National Institute for Materials Science (Japan)

T. Nejat Veziroglu, The International Centre for Hydrogen Energy
Technologies (Turkey)

Gunnar Westin, Uppsala Universitet (Sweden)

Upul Wijayantha, Loughborough University (United Kingdom)

Jin Z. Zhang, University of California, Santa Cruz (USA)

Session Chairs

1 Synthesis of Advanced Nanostructures and Semiconductor I

Jinghua Guo, Lawrence Berkeley National Laboratory (USA)

2 Synthesis of Advanced Nanostructures and Semiconductor II

Lionel Vayssieres, National Institute for Materials Science (Japan)

- 3 Solar Hydrogen and Water Splitting
Jin Z. Zhang, University of California, Santa Cruz (USA)
- 4 Bandgap Engineering of Solar Hydrogen Materials
Gunnar Westin, Uppsala Universitet (Sweden)
- 5 Solar Hydrogen at Biohybrid and Organic Catalysts
Ting Guo, University of California, Davis (USA)
- 6 Hydrogen Generation and Storage Materials
James K. McCusker, Michigan State University (USA)
- 7 Solar Hydrogen Devices and Applications
Lionel Vayssieres, National Institute for Materials Science (Japan)
- 8 Photo-Catalysis at Titanium Oxides
Hironori Arakawa, Tokyo University of Science (Japan)

Introduction

Solar energy can be converted to heat for warming space and water, to electricity and chemical fuels for energy use and storage [1-4]. However, the cost and conversion efficiency have hampered the potential use of solar energy. There are the emerging technologies using semiconductors for light harvesting assemblies, and processes for charge transfer to solar cells. Sunlight in the near infrared, visible, and near ultraviolet regions has considerable energy (about 0.9 to 3.2 electron volts per photon) and intensity. It could provide a significant contribution to our electrical and chemical resources if efficient and inexpensive systems utilizing readily available materials could be devised for the conversion process.

The electron-hole pair formation that occurs at the interface between a semiconductor and a solution upon absorption of light leads to oxidation or reduction of solution species. The fabrication of artificial photosynthetic systems for the conversion of H_2O and CO_2 to fuels (like H_2 and CH_3OH) has become a field of much current research interest and has encouraged new fundamental investigations of the interactions of light, electron flow, and chemical reactions.

Bandgap, band edge positions, as well as the overall band structure of semiconductors are of crucial importance in photoelectrochemical and photocatalytic applications. The energy position of the band edge level can be controlled by the electronegativity of the dopants, solution pH (for example, flatband potential variation of 60 mV per pH unit), as well as by quantum confinement effects. Accordingly, the band edges and bandgap can be tailored to achieve specific electronic, optical, or photocatalytic properties in nanostructure semiconductors.

The aim of this conference is to offer a forum of discussion for scientists, engineers, and members of industry involved in photoelectrochemical systems and nanotechnology for solar generation of hydrogen. The technical program will address the current status and prospects of solar hydrogen R&D activities, major achievements and latest performances, technological limitations and crucial remaining challenges, latest advances in fundamental understanding and development in semiconductor nanostructures, devices fabrication, modeling, simulation and characterization techniques as well as assessing and establishing the role and contribution of solar hydrogen in the hydrogen economy.

Interested and committed individuals from academia, national laboratories, industries and start-ups are kindly invited to contribute to future conferences by submitting their abstract on the following relevant topics:

- Fundamentals of photoelectrochemical water splitting
- Modeling and simulation of photocatalytic reactions
- Energetics and electronic structure of photocatalysts and semiconductor nanostructures

- Electron and hole transport in large bandgap semiconductors
- Surface and interface properties of photocatalysts/electrolyte junctions
- Optical, electrical, mechanical, chemical, and physical properties of photo-anodes
- Long term aqueous stability, corrosion, and photocorrosion of semiconductors
- Recent advances in nano-structural analysis of photocatalysts
- New approaches to bandgap profiling and engineering
- Development of advanced photocatalysts for efficient solar hydrogen production
- New morphology of classical metal oxide semiconductors
- Large bandgap semiconductors of low dimensionality
- Combinatorial chemistry approach to photocatalysts
- Spectroscopic and photoelectrochemical characterization
- New devices, methods, and apparatus for solar hydrogen generation
- Solar hydrogen generation from sea water
- Solar thermal water splitting
- Photo-biological generation of hydrogen
- National and international solar hydrogen energy systems, projects, and networks
- Societal, educational, environmental, and economic aspects of solar hydrogen.

This year, we had 2 plenary talks, 21 invited talks and 8 contributed talks. For the poster competition, Drazenka Svedruzic Chang, et al., received the Best Poster Paper Award for the poster entitled "Interaction of [FeFe] hydrogenases with single-walled carbon nanotubes." The current proceedings volume includes 25 papers.

Finally, I would to acknowledge the support of SPIE staff for assistance throughout the preparation of the conference and in editing the proceedings. I would like to acknowledge the committee members for their strong support. And also I would like to thank all speakers and attendees who made the conference successful.

Jinghua Guo

References

1. "Solar Energy Conversion", George W. Crabtree and Nathan S. Lewis, Physics Today, March 2007. [doi:10.1063/1.2718755](https://doi.org/10.1063/1.2718755)
2. "Limiting and realizable efficiencies of solar photolysis of water", James R. Bolton, Stewart J. Strickler, and John S. Connolly, Nature **316**, 495 (1985). [doi:10.1038/316495a0](https://doi.org/10.1038/316495a0)
3. "Photoelectrochemistry", Allen J. Bard, Science **207**, 139 (1980). [doi:10.1126/science.207.4427.139](https://doi.org/10.1126/science.207.4427.139)
4. "Solar Fuels", James R. Bolton, Science **202**, 705 (1978). [doi:10.1126/science.202.4369.705](https://doi.org/10.1126/science.202.4369.705)