

PROCEEDINGS OF SPIE

Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XVIII

**Klaus P. Streubel
Heonsu Jeon
Li-Wei Tu
Martin Strassburg**
Editors

**4–6 February 2014
San Francisco, California, United States**

Sponsored and Published by
SPIE

Volume 9003

Proceedings of SPIE 0277-786X, V. 9003

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

Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XVIII, edited by
Klaus P. Streubel, Heonsu Jeon, Li-Wei Tu, Martin Strassburg, Proc. of SPIE Vol. 9003, 900301
© 2014 SPIE · CCC code: 0277-786X/14/\$18 · doi: 10.1117/12.2063883

Proc. of SPIE Vol. 9003 900301-1

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 *Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XVIII*, edited by Klaus P. Streubel, Heonsu Jeon, Li-Wei Tu, Martin Strassburg, Proceedings of SPIE Vol. 9003 (SPIE, Bellingham, WA, 2014) Article CID Number.

ISSN: 0277-786X

ISBN: 9780819499165

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 © 2014, 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/14/\$18.00.

Printed in the United States of America.

Publication of record for individual papers is online in the 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 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

ix *Conference Committee*

SESSION 1 SOLID STATE LIGHTING I

- 9003 03 **Merit function for the evaluation of color uniformity in the far field of LED spot lights (Invited Paper) [9003-2]**
A. Teupner, Technical Univ. of Madrid (Spain); K. Bergenek, R. Wirth, Osram GmbH (Germany); J. C. Miñano, P. Benítez, Technical Univ. of Madrid (Spain)
- 9003 04 **Dual phosphors-converted white LEDs modeling by using near-field chromatic luminance data [9003-3]**
B. Q. Chen, Philips Group Innovation (Netherlands) and National Taiwan Univ. of Science and Technology (Taiwan); H. J. Cornelissen, Philips Group Innovation (Netherlands); N. C. Hu, National Taiwan Univ. of Science and Technology (Taiwan)

SESSION 2 NANOTECHNOLOGIES FOR LEDs I

- 9003 06 **Phosphor-free InGaN/GaN/AlGaN core-shell dot-in-a-wire white light-emitting diodes (Invited Paper) [9003-5]**
Z. Mi, H. P. T. Nguyen, S. Zhang, A. T. Connie, Md. G. Kibria, Q. Wang, I. Shih, McGill Univ. (Canada)

SESSION 3 HIGH-CURRENT LED PERFORMANCE

- 9003 0D **Comprehensive study of internal quantum efficiency of high-brightness GaN-based light-emitting diodes by temperature-dependent electroluminescence method [9003-13]**
Y. Wang, M. Pan, T. Li, Lightera Corp. (United States)
- 9003 0E **Reduction of efficiency droop in InGaN light-emitting diodes on low dislocation density GaN substrate [9003-14]**
K. Yamashita, Nagoya Univ. (Japan); T. Sugiyama, M. Iwai, NGK Insulators, Ltd. (Japan); Y. Honda, Nagoya Univ. (Japan); T. Yoshino, NGK Insulators, Ltd. (Japan); H. Amano, Nagoya Univ. (Japan)
- 9003 0F **Improvement of carrier distribution by using thinner quantum well with different location [9003-15]**
S.-W. Wang, D.-W. Lin, C.-Y. Lee, C.-C. Lin, H.-C. Kuo, National Chiao Tung Univ. (Taiwan)

SESSION 4 NANOTECHNOLOGIES FOR LEDs II

9003 0H **Long wavelength nanowire light emitting diodes (Invited Paper)** [9003-17]
P. Bhattacharya, S. Jahangir, E. Stark, Univ. of Michigan (United States); M. Mandl,
T. Schimpke, M. Strassburg, OSRAM Opto Semiconductors GmbH (Germany)

9003 0I **Nanorod-structured flip-chip GaN-based white light-emitting diodes (Invited Paper)**
[9003-18]
C.-T. Lee, Y.-T. Su, H.-Y. Lee, National Cheng Kung Univ. (Taiwan)

SESSION 5 LED FABRICATION

9003 0L **New developments on high-efficiency infrared and InGaAlP light-emitting diodes at OSRAM Opto Semiconductors** [9003-21]
M. Broell, P. Sundgren, A. Rudolph, W. Schmid, A. Vogl, M. Behringer, OSRAM Opto Semiconductors GmbH (Germany)

9003 0M **Advanced packaging methods for high-power LED modules** [9003-22]
R. C. Jordan, C. Weber, C. Ehrhardt, M. Wilke, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany)

9003 0O **The performance of GaN LEDs using an embedded finger-type contact** [9003-24]
R.-H. Horng, K.-C. Shen, C.-Y. Pai, National Chung Hsing Univ. (Taiwan); D.-S. Wu, National Chung Hsing Univ. (Taiwan) and Da-Yeh Univ. (Taiwan)

SESSION 6 UV LEDs

9003 0S **Enhancing carrier injection in the active region of a 280nm emission wavelength LED using graded hole and electron blocking layers** [9003-28]
B. Janjua, T. K. Ng, King Abdullah Univ. of Science and Technology (Saudi Arabia);
A. Y. Alyamani, M. M. El-Desouki, King Abdulaziz City for Science and Technology (Saudi Arabia); B. S. Ooi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

SESSION 7 NOVEL LED TECHNOLOGIES

9003 0W **High-efficiency green light-emitting diodes based on InGaN-ZnGeN₂ type-II quantum wells**
[9003-32]
L. Han, K. Kash, H. Zhao, Case Western Reserve Univ. (United States)

SESSION 8 LED EFFICIENCY DROOP I: JOINT SESSION WITH CONFERENCE 8986

- 9003 0Z **Identification of Auger effect as the dominant mechanism for efficiency droop of LEDs (Invited Paper)** [9003-35]
J. Peretti, Lab. de Physique de la Matière Condensée, CNRS, Ecole Polytechnique (France); C. Weisbuch, Lab. de Physique de la Matière Condensée, CNRS, Ecole Polytechnique (France) and Univ. of California, Santa Barbara (United States); J. Iveland, Univ. of California, Santa Barbara (United States); M. Piccardo, Lab. de Physique de la Matière Condensée, CNRS, Ecole Polytechnique (France) and Univ. of California, Santa Barbara (United States); L. Martinelli, Lab. de Physique de la Matière Condensée, CNRS, Ecole Polytechnique (France); J. S. Speck, Univ. of California, Santa Barbara (United States)
- 9003 10 **Microscopic models of non-radiative and high-current effects in LEDs: state of the art and future developments (Invited Paper)** [9003-36]
F. Bertazzi, M. Goano, Politecnico di Torino (Italy) and IEIT-CNR (Italy); M. Calciati, X. Zhou, G. Ghione, Politecnico di Torino (Italy); E. Bellotti, Boston Univ. (United States)

SESSION 9 LED EFFICIENCY DROOP II: JOINT SESSION WITH CONFERENCE 8986

- 9003 11 **Microscopic many-body investigation of the efficiency droop in GaN based light emitting devices (Invited Paper)** [9003-37]
J. Hader, J. V. Moloney, Nonlinear Control Strategies, Inc. (United States) and College of Optical Sciences, The Univ. of Arizona (United States); S. W. Koch, College of Optical Sciences, The Univ. of Arizona (United States) and Philipps-Univ. Marburg (Germany)

SESSION 10 NOVEL SUBSTRATES FOR LEDs

- 9003 13 **Ammonothermal bulk GaN substrates for LEDs (Invited Paper)** [9003-39]
W. Jiang, D. Ehrentraut, D. S. Kamber, B. C. Downey, J. Cook, M. Grundmann, R. T. Pakalapati, H. Yoo, M. P. D'Evelyn, Sora, Inc. (United States)
- 9003 16 **Extremely high current density over 1000 A/cm² operation in M-GaN LEDs on bulk GaN substrates with low-efficiency droop (Invited Paper)** [9003-42]
T. Yokogawa, A. Inoue, Panasonic Corp. (Japan)

SESSION 11 SOLID STATE LIGHTING II

- 9003 17 **Adjustable spectrum LED solar simulator** [9003-43]
K. J. Linden, W. R. Neal, H. B. Serreze, Spire Corp. (United States)
- 9003 18 **Spectral behavior and coherence length of GaN- and AlGaInP-based light-emitting diodes** [9003-45]
R. Hetzel, Technische Univ. Graz (Austria) and Lumitech Produktions und Entwicklungs GmbH (Austria); G. Leising, Technische Univ. Graz (Austria)

- 9003 19 **Permanent transparent color-warming glazes for dimmable and non-dimmable LED bulbs** [9003-46]
J.-M. A. Spanard, Spanard Studio (United States)
- 9003 1B **Thermal, optical, and electrical engineering of an innovative tunable white LED light engine** [9003-48]
N. Trivellin, LightCube SRL (Italy) and Univ. degli Studi di Padova (Italy); M. Meneghini, M. Ferretti, D. Barbisan, M. Dal Lago, G. Meneghesso, E. Zanoni, Univ. degli Studi di Padova (Italy)

POSTER SESSION

- 9003 1F **A NO_x and SO₂ gas analyzer using deep-UV and violet light-emitting diodes for continuous emissions monitoring systems** [9003-52]
R. Higashi, Fuji Electric Co., Ltd. (Japan) and The Univ. of Tokyo (Japan); Y. Taniguchi, K. Akao, K. Koizumi, N. Hirayama, Fuji Electric Co., Ltd. (Japan); Y. Nakano, The Univ. of Tokyo (Japan)
- 9003 1G **Novel samarium/erbium and samarium/terbium codoped glass phosphor for application in warm white light-emitting-diode** [9003-53]
C. M. da Silva Jr., A. S. Gouveia-Neto, L. A. Bueno, Univ. Federal Rural de Pernambuco (Brazil)
- 9003 1J **Study of grating layer location of a GaN nano-grated LED for improvement of transmission efficiency** [9003-57]
A. Behill, G. Aleman, California Polytechnic State Univ., San Luis Obispo (United States); X. Jin, California Polytechnic State Univ., San Luis Obispo (United States) and Peking Univ. (China); X.-N. Kang, G.-Y. Zhang, Peking Univ. (China)
- 9003 1K **High-color rendering indices performance of glass based phosphor-converted white light-emitting diodes for solid state lighting** [9003-58]
C.-C. Tsai, Far East Univ. (Taiwan) and National Sun Yat-Sen Univ. (Taiwan); W.-C. Cheng, National Sun Yat-Sen Univ. (Taiwan); G.-H. Chen, Far East Univ. (Taiwan); Y.-C. Lee, C.-T. Kuo, Lextar Electronics Corp. (Taiwan); W.-H. Cheng, National Sun Yat-Sen Univ. (Taiwan)
- 9003 1N **Multicolor upconversion luminescence of rare-earth doped Y₂CaZnO₅ nanophosphors for white lighting-emitting diodes** [9003-61]
R. Rajeswari, Sri Venkateswara Univ. (India); S. Surendra Babu, Research Ctr. Imarat (India); C. K. Jayasankar, Sri Venkateswara Univ. (India)
- 9003 1O **Classification evaluation of tobaccos using LED-induced fluorescence spectroscopy** [9003-62]
W. Zhong, Y. Dong, X. Liu, H. Lin, Zhejiang Univ. (China) and Joint Research Ctr. of Photonics (China); L. Mei, Zhejiang Univ. (China), Joint Research Ctr. of Photonics (China), and Lund Univ. (Sweden); C. Yan, Zhejiang Univ. (China) and Joint Research Ctr. of Photonics (China)

- 9003 1P **Real-time monitoring of sulfur dioxide using ultraviolet light-emitting diode** [9003-63]
W. Zhong, H. Lin, Zhejiang Univ. (China) and Joint Research Ctr. of Photonics (China);
X. Lou, Harbin Institute of Technology (China); C. Yan, Zhejiang Univ. (China) and Joint
Research Ctr. of Photonics (China); L. Mei, Zhejiang Univ. (China), Joint Research Ctr. of
Photonics (China), and Lund Univ. (Sweden)
- 9003 1R **Estimation of carrier leakage in InGaN light emitting diodes from photocurrent
measurements** [9003-65]
S. Hafiz, F. Zhang, M. Monavarian, S. Okur, V. Avrutin, H. Morkoç, Ü. Özgür, Virginia
Commonwealth Univ. (United States)
- 9003 1S **Microscope investigation and electrical conductivity of Si-doped n-type Al_{0.45}Ga_{0.55}N layer
grown on AlGaN/AlN superlattices** [9003-66]
S. R. Jeon, Korea Photonics Technology Institute (Korea, Republic of); S. J. Son, LG Innotek
(Korea, Republic of); S.-H. Park, Yeungnam Univ. (Korea, Republic of)
- 9003 1T **Electrical efficiency and droop in MQW LEDs** [9003-67]
V. K. Malyutenko, V.E. Lashkaryov Institute of Semiconductor Physics (Ukraine)
- 9003 1U **Portable fluorescence spectroscopy platform for Huanglongbing (HLB) citrus disease in situ
detection** [9003-68]
A. D. Mota, G. Rossi, G. C. de Castro, AgriOS (Brazil); T. A. Ortega, Univ. de São Paulo
(Brazil) and AgriOS (Brazil); J. C. de Castro N., Univ. de São Paulo (Brazil)

Author Index

Conference Committee

Symposium Chairs

David L. Andrews, University of East Anglia Norwich (United Kingdom)
Alexei L. Glebov, OptiGrate Corporation (United States)

Symposium Co-chairs

Jean Emmanuel Broquin, IMEP-LAHC (France)
Shibin Jiang, AdValue Photonics, Inc. (United States)

Program Track Chair

Klaus P. Streubel, OSRAM AG (Germany)

Conference Chairs

Klaus P. Streubel, OSRAM AG (Germany)
Heonsu Jeon, Seoul National University (Korea, Republic of)
Li-Wei Tu, National Sun Yat-Sen University (Taiwan)

Conference Co-chair

Martin Strassburg, OSRAM Opto Semiconductors GmbH (Germany)

Conference Program Committee

Gerd Bacher, Universität Duisburg-Essen (Germany)
Ray-Hua Horng, National Chung Hsing University (Taiwan)
Mitch M. C. Chou, National Sun Yat-Sen University (Taiwan)
Michael Heuken, AIXTRON SE (Germany)
Satoshi Kamiyama, Meijo University (Japan)
Jong Kyu Kim, Pohang University of Science and Technology
(Korea, Republic of)
Markus Klein, OSRAM Opto Semiconductors GmbH (Germany)
Mike Krames, Soraa, Inc. (United States)
Hao-Chung Kuo, National Chiao Tung University (Taiwan)
Kei May Lau, Hong Kong University of Science and Technology
(Hong Kong, China)
Kurt J. Linden, Spire Corporation (United States)
Hans Nikol, Philips Lighting B.V. (Netherlands)
Joongseo Park, LG Electronics Inc. (Korea, Republic of)
E. Fred Schubert, Rensselaer Polytechnic Institute (United States)
Ross P. Stanley, Centre Suisse d'Electronique et de Microtechnique SA
(Switzerland)

Session Chairs

- 1 Solid State Lighting I
Michael R. Krames, Soraa, Inc. (United States)
- 2 Nanotechnologies for LEDs I
Michael R. Krames, Soraa, Inc. (United States)
- 3 High-Current LED Performance
E. Fred Schubert, Rensselaer Polytechnic Institute (United States)
- 4 Nanotechnologies for LEDs II
Gerd Bacher, Universität Duisburg-Essen (Germany)
- 5 LED Fabrication
Ray-Hua Horng, National Chung Hsing University (Taiwan)
- 6 UV LEDs
Satoshi Kamiyama, Meijo University (Japan)
- 7 Novel LED Technologies
Jong Kyu Kim, Pohang University of Science and Technology
(Korea, Republic of)
- 8 LED Efficiency Droop I: Joint Session with Conference 8986
Joachim Piprek, NUSOD Institute LLC (United States)
- 9 LED Efficiency Droop II: Joint Session with Conference 8986
Klaus P. Streubel, OSRAM AG (Germany)
- 10 Novel Substrates for LEDs
Dong-Sing Wu, National Chung Hsing University (Taiwan)
- 11 Solid State Lighting II
Ross P. Stanley, Centre Suisse d'Electronique et de Microtechnique
SA (Switzerland)