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Editor-in-Chief

William T. Rhodes

Georgia Institute of Technology
School of Electrical and Computer Engineering
Atlanta, GA 30332-0250, USA
E-mail: bill.rhodes@ece.gatech.edu

Editorial Board

Ali Adibi

Georgia Institute of Technology
School of Electrical and Computer Engineering
Atlanta, GA 30332-0250, USA
E-mail: adibi@ee.gatech.edu

Toshimitsu Asakura

Hokkai-Gakuen University
Faculty of Engineering
1-1, Minami-26, Nishi 11, Chuo-ku
Sapporo, Hokkaido 064-0926, Japan
E-mail: asakura@eli.hokkai-s-u.ac.jp

Theodor W. Hänsch

Max-Planck-Institut für Quantenoptik
Hans-Kopfermann-Straße 1
85748 Garching, Germany
E-mail: t.w.haensch@physik.uni-muenchen.de

Takeshi Kamiya

Ministry of Education, Culture, Sports
Science and Technology
National Institution for Academic Degrees
3-29-1 Otsuka, Bunkyo-ku
Tokyo 112-0012, Japan
E-mail: kamiyatk@niad.ac.jp

Ferenc Krausz

Ludwig-Maximilians-Universität München
Lehrstuhl für Experimentelle Physik
Am Coulombwall 1
85748 Garching, Germany *and*
Max-Planck-Institut für Quantenoptik
Hans-Kopfermann-Straße 1
85748 Garching, Germany
E-mail: ferenc.krausz@mpq.mpg.de

Bo Monemar

Department of Physics
and Measurement Technology
Materials Science Division
Linköping University
58183 Linköping, Sweden
E-mail: bom@ifm.liu.se

Herbert Venghaus

Fraunhofer Institut für Nachrichtentechnik
Heinrich-Hertz-Institut
Einsteinufer 37
10587 Berlin, Germany
E-mail: venghaus@hhi.de

Horst Weber

Technische Universität Berlin
Optisches Institut
Straße des 17. Juni 135
10623 Berlin, Germany
E-mail: weber@physik.tu-berlin.de

Harald Weinfurter

Ludwig-Maximilians-Universität München
Sektion Physik
Schellingstraße 4/III
80799 München, Germany
E-mail: harald.weinfurter@physik.uni-muenchen.de

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Peter Seitz
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Editors

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Editors
Peter Seitz
CSEM SA
Bahnhofstraße 1, 7302 Landquart, Switzerland
E-mail: peter.seitz@csem.ch

Albert J.P. Theuwissen
Delft University of Technology
Mekelweg 4, 2628 CD Delft, The Netherlands
E-mail: a.j.p.theuwissen@tudelft.nl

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Preface

Dark clouds hung over physics toward the end of the nineteenth century, when physicists began to appreciate that their comprehension of the nature of light was critically incomplete. The classical description of light as an electromagnetic wave satisfying the beautiful equations of Maxwell obviously failed to explain significant optical effects: How is radiation absorbed by matter? How can light with such strange, narrow spectra be emitted by gases or solid materials? How can the nature of blackbody radiation be explained? In a radical step, Albert Einstein and Max Planck provided the key to this impasse by introducing the revolutionary notion that the energy states of the electromagnetic field are not continuous but rather quantized – they successfully imagined the photon. So, finally the clouds parted, opening vistas into the strange world of quantum physics.

A natural consequence of the concept of a photon is the existence of an ultimate detection limit of electromagnetic radiation. Once you can sense each individual photon (possibly gaining also information about its energy and polarization state), you know all about incident radiation that can be known. For this reason, the holy grail of photosensing is the spatially resolved detection of light with this ultimate precision, single photon imaging. The aim of this book is to provide a comprehensive and systematic overview of all relevant approaches currently in use to realize practical single photon imagers. In all of these devices, three major tasks have to be accomplished: (1) incoming photons must enter the detector, where they are converted into electronic charge; (2) this photogenerated charge must be collected and possibly amplified at the same time; and (3) the collected charge must be detected with suitable electronic circuitry.

In all these steps, one has to fight thermally generated noise: The photogeneration process competes with dark noise charge generation in the conversion layer; in the photocharge collection and amplification process, signal charges must be handled while avoiding the detrimental effects of thermally generated charge carriers; finally, the first stages of any electronic charge detection circuitry suffers from thermally generated Johnson noise in the channel of transistors or in resistors. Depending on the boundary conditions of a photodetection problem – for example, the photosensitive area, the response time, the mean detection rate, the exposure time, the frame rate, the spectral distribution of the radiation, the operating temperature, and the power consumption – a different technological approach will come out as an optimum. For this reason, the present book provides a theoretical and practical framework, where researchers and practitioners will find in condensed form all relevant information to resolve their particular single photon imaging solution.

In Chap. 1, relevant fundamental concepts for treating noise phenomena in optoelectronics are summarized, and a rigorous definition of the precise meaning of "single photon imaging" is given. State-of-the-art semiconductor technology especially suited for ultra-low-noise image sensing is presented in Chap. 2. The use of photocathodes in vacuum for single photon imaging is treated in several chapters: in Chap. 3, the charge multiplication processes is implemented with avalanche photodiode (APD) arrays; in Chap. 4, the photoelectrons are accelerated to a high voltage, and their bombardment of semiconductor imagers causes a large number of secondary electrons being created in the image sensor; in Chap. 5, a suitable geometry of several electrodes, each multiplying the incident electron packets by a factor, provides for photocharge multiplication of up to factor of one million. It is also possible to exploit the avalanche effect in semiconductors, without having to use vacuum devices. In Chap. 6, the avalanche effect is used in so-called electron-multiplying charge-coupled devices (EMCCDs), while Chap. 7 describes CMOS compatible semiconductor image sensors for single-photon avalanche detection (SPADs). In synchronous applications, where one samples the images at regular times while accumulating photogenerated charges between samples, it is possible to realize single photon CMOS imagers through systematic bandpass filtering, exploiting the parallelisms possible in CMOS imagers; this approach to single photon imaging is described in detail in Chap. 8, and the complementary Chap. 9 treats suitable architectures for the implementation of such single photon CMOS imagers. If one is not constrained to use standard CMOS processes, an interesting class of structures, called double-gate transistors and charge modulating devices (CMDs), make it possible to sense individual electrons with very high conversion gains of several 100 μV per electron, as described in Chap. 10. The case of high-energy photons (UV and X-ray radiation) arriving at arbitrary times is treated in Chap. 11, showing the way to efficient, energy-sensitive X-ray single photon imagers implemented with standard CMOS processes. Each of the last three chapters describes an important practical application in which single photon imaging is a key capability: in Chap. 12, optical time-of-flight range imaging is covered, with which complete 3D images of a scene can be acquired with millimeter resolution in real time. Astronomical and aerospace applications in which single photon imagers are essential are presented in Chap. 13. Finally, Chap. 14 describes a highly relevant application of gated ultra-low-noise imagers in the life sciences, namely very sensitive and highly specific pharmaceutical and medical diagnostics through time-resolved fluorescence imaging.

No panacea exists yet for the practical and economical solution of the many single photon imaging problems in the world, ranging from fundamental scientific research to the availability of cell phone cameras with which brilliant pictures can be taken also under extreme low-light conditions. Finding a solution still requires skillfully elaborating a good technological compromise. If the authors of this book have achieved their goal of providing a useful and powerful tool to many engineers and researchers in the wide field of image science, then our ambition has been fulfilled and the efforts of all involved colleagues have been worthwhile.

We would like to express our sincere thanks to the authors of the various chapters for their kindness and willingness to contribute to this book, for their hard work required in actually carrying through with the promise, and for their determination to meet all the deadlines revising and updating their chapters, with the goal to provide the most valuable and up-to-date contributions.

Landquart
Delft
March 2011

Peter Seitz
Albert Theuwissen

Contents

Contributors

Verle Aebi Intevac Photonics, Inc., 3560 Bassett Street, Santa Clara, CA 95054, USA, vaebi@intevac.com

Hiroaki Aihara Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
and
Institute for the Physics and Mathematics of the Universe (IPMU), The University of Tokyo, 5-1-5 Kashiwa-no-ha, Kashiwa-shi, Chiba 277-8568, Japan, aihara@phys.s.u-tokyo.ac.jp

Edoardo Charbon Technical University Delft, Mekelweg 4, 2628 CD Delft, The Netherlands, e.charbon@tudelft.nl

Kenneth Costello Intevac Photonics, Inc., 3560 Bassett Street, Santa Clara, CA 95054, USA, kcostello@intevac.com

Christof Fattinger F. Hoffmann-La Roche Ltd., Pharmaceutical Research and Early Development, Discovery Technologies, Grenzacherstrasse 124, 4070 Basel, Switzerland, christof.fattinger@roche.com

Matthew W. Fishburn Technical University Delft, Mekelweg 4, 2628 CD Delft, The Netherlands, m.w.fishburn@tudelft.nl

Boyd Fowler Fairchild Imaging, 1801 McCarthy Blvd., Milpitas, CA 95035, USA, boyd.fowler@fcimg.com

Shoji Kawahito Research Institute of Electronics, Shizuoka University, 3-5-1, Johoku, Naka-ku, Hamamatsu 432-8011, Japan, kawahito@idl.rie.shizuoka.ac.jp

Christian Lotto Heliotis AG, D4 Platz, 6039 Root Längenbold, Switzerland
and
CSEM SA, Photonics Division, Technopark, CH-8005 Zurich, Switzerland, christian.lotto@a3.epfl.ch

Yoshiyuki Matsunaga Image Sensor Business Unit, Semiconductor Company, Panasonic Co., Ltd., 1 Kotari-yakemachi, Nagaokakyo City, Kyoto 617-8520, Japan, matsunaga.yoshiyuki001@jp.panasonic.com

Pierre Magnan ISAE, 10 Av. E. Belin, 31055 Toulouse Cedex, France, Pierre.Magnan@isae.fr

R. Daniel McGrath Aptina Imaging, San Jose, CA 95134, USA, dmcgrath@ieee.org

Francis Müller F. Hoffmann-La Roche Ltd., Pharmaceutical Research and Early Development, Discovery Technologies, Grenzacherstrasse 124, 4070 Basel, Switzerland, francis.mueller@roche.com

Gert Nützel PHOTONIS Technologies S.A., Axis Business Park E, 18 Avenue de, Pythagore, 33700 Mérignac, France, g.nutzel@photonis.com

Mark Stanford Robbins e2v technologies Ltd, 106 Waterhouse Lane, Chelmsford, Essex CM1 2QU, UK, mark.robbins@physics.org

Peter Seitz CSEM SA, Nanomedicine Division, Bahnhofstrasse 1, 7302 Landquart, Switzerland
and
EPFL, STI-IMT-NE, Institute of Microengineering, Rue A.-L. Breguet 2, 2000 Neuchâtel, Switzerland, peter.seitz@csem.ch, peter.seitz@epfl.ch

Andrea Simoni Fondazione Bruno Kessler, Via Sommarive 18, 38123, Trento, Italy, simoni@fbk.eu

David Stoppa Fondazione Bruno Kessler, Via Sommarive 18, 38123 Trento, Italy, stoppa@fbk.eu

Albert J.P. Theuwissen Harvest Imaging and Delft University of Technology, Kleine Schoolstraat 9, 3960 Bree, Belgium, albert@harvestimaging.com, a.j.p.theuwissen@tudelft.nl