
founded by H.K.V. Lotsch

Editor-in-Chief: W. T. Rhodes, Atlanta

Editorial Board: A. Adibi, Atlanta
T. Asakura, Sapporo
T. W. Hänsch, Garching
T. Kamiya, Tokyo
F. Krausz, Garching
B. Monemar, Linköping
H. Venghaus, Berlin
H. Weber, Berlin
H. Weinfurter, München

Springer Series in OPTICAL SCIENCES

The Springer Series in Optical Sciences, under the leadership of Editor-in-Chief *William T. Rhodes*, Georgia Institute of Technology, USA, provides an expanding selection of research monographs in all major areas of optics: lasers and quantum optics, ultrafast phenomena, optical spectroscopy techniques, optoelectronics, quantum information, information optics, applied laser technology, industrial applications, and other topics of contemporary interest.

With this broad coverage of topics, the series is of use to all research scientists and engineers who need up-to-date reference books.

The editors encourage prospective authors to correspond with them in advance of submitting a manuscript. Submission of manuscripts should be made to the Editor-in-Chief or one of the Editors. See also www.springer.com/series/624

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: kamiyat@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

For further volumes:

<http://www.springer.com/series/624>

Peter Seitz
Albert J.P. Theuwissen
Editors

Single-Photon Imaging

With 250 Figures

 Springer

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

Springer Series in Optical Sciences ISSN 0342-4111 e-ISSN 1556-1534

ISBN 978-3-642-18442-0 e-ISBN 978-3-642-18443-7

DOI 10.1007/978-3-642-18443-7

Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2011934863

© Springer-Verlag Berlin Heidelberg 2011

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: eStudio Calamar Steinen

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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 $100\ \mu\text{V}$ 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

1	Fundamentals of Noise in Optoelectronics	1
	Peter Seitz	
1.1	Introduction	1
1.2	Quantization of Electromagnetic Radiation, Electrical Charge, and Energy States in Bound Systems	2
1.3	Basic Properties of the Poisson Distribution	3
1.4	Interaction of Radiation and Matter	5
1.5	Noise Properties of Light Sources	6
1.5.1	Coherent Light (Single-Mode Lasers)	6
1.5.2	Thermal (Incandescent) Light Sources	6
1.5.3	Partially Coherent Light (Discharge Lamps)	7
1.5.4	Light Emitting Diodes	8
1.6	The Meaning of “Single-Photon Imaging”	9
1.7	Energy Band Model of Solid State Matter	11
1.8	Detection of Electromagnetic Radiation with Semiconductors	12
1.8.1	Quantum Efficiency and Band Structure	12
1.8.2	Thermal Equilibrium and Nonequilibrium Carrier Concentrations	13
1.8.3	Dark Current	14
1.8.4	Avalanche Effect and Excess Noise Factor	15
1.9	Electronic Detection of Charge	16
1.9.1	Basic Components of Electronics and their Noise Properties	17
1.9.2	Basic Circuits for Electronic Charge Detection	20
1.9.3	Conclusions for Single-Electron Charge Detection	21
1.10	Summary: Physical Limits of the Detection of Light	23
1.10.1	Sensitive Wavelength Range	23
1.10.2	Dark Current and Quantum Efficiency	24
1.10.3	Electronic Charge Detection	24
	References	25

2	Image Sensor Technology	27
	R. Daniel McGrath	
2.1	Program and a Brief History of Solid-State Image Sensors	27
2.2	Anatomy of an Image Sensor	28
2.3	Operation	33
2.4	Image Sensor Devices	35
2.5	Image Sensor Process Technology	39
2.6	Outlook for a Single Photon Process Technology	46
	References	47
3	Hybrid Avalanche Photodiode Array Imaging	49
	Hiroaki Aihara	
3.1	Introduction	49
3.2	Principle of Hybrid APD Operation	50
3.3	Single-pixel Large Format Hybrid APD	51
	3.3.1 Device Description	51
	3.3.2 Performance	53
	3.3.3 Application	55
3.4	Multipixel Hybrid APD Array	56
	3.4.1 Device Description	56
	3.4.2 Performance	60
	3.4.3 Application	61
3.5	Conclusions and Remaining Issues	62
	References	62
4	Electron Bombarded Semiconductor Image Sensors	63
	Verle Aebi and Kenneth Costello	
4.1	Introduction	63
4.2	Electron Bombarded Semiconductor Gain Process	65
4.3	Hybrid Photomultiplier EBS Image Sensors	66
	4.3.1 Hybrid Photomultiplier Gain and Noise Analysis	66
	4.3.2 Hybrid Photomultiplier Time Response	67
	4.3.3 Hybrid Photomultiplier Imagers	67
4.4	EBCCD and EBCMOS EBS Image Sensors	69
	References	71
5	Single-Photon Imaging Using Electron Multiplication in Vacuum ...	73
	Gert Nützel	
5.1	Introduction	73
5.2	The Photocathode	75
	5.2.1 The Working Principle of Photocathodes	75
	5.2.2 Multialkali Photocathodes	77
	5.2.3 III–V Photocathodes	79
5.3	Image Intensifiers	80
	5.3.1 Working Principle	80
	5.3.2 Applications	82

5.3.3	The Components of an Image Intensifier	83
5.3.4	Performance Characteristics	87
5.3.5	Special Image Intensifiers	94
5.4	Photomultiplier Tube	95
5.4.1	Working Principle	96
5.4.2	Applications.....	96
5.4.3	The Components of a PMT	97
5.4.4	Performance Characteristics	99
5.5	Conclusions and Outlook	102
	References.....	102
6	Electron-Multiplying Charge Coupled Devices – EMCCDs	103
	Mark Stanford Robbins	
6.1	Introduction.....	103
6.2	Harnessing Impact Ionisation for Ultra Sensitive CCD Imaging	104
6.3	The Electron Multiplying CCD Concept.....	104
6.3.1	Output Amplifier Noise	104
6.3.2	The Use of Multiplication Gain	106
6.3.3	Noise and Signal-to-Noise Ratio.....	109
6.3.4	Output Signal Distributions	110
6.4	Photon Counting with the EMCCD	112
6.5	Background Signal Generation	114
6.5.1	Dark Signal	114
6.5.2	Statistics of Dark Signal Generation.....	117
6.5.3	Spurious Charge Generation	117
6.6	Improving the Efficiency of Signal Generation	118
6.7	Concluding Comments	119
	References.....	120
7	Monolithic Single-Photon Avalanche Diodes: SPADs	123
	Edoardo Charbon and Matthew W. Fishburn	
7.1	A Brief Historical Perspective	123
7.2	Fundamental Mechanisms	124
7.2.1	SPAD Structure and Operation.....	124
7.2.2	Idle State and Avalanche Buildup.....	126
7.2.3	Quench, Spread, and Recharge	129
7.2.4	Example Waveforms.....	131
7.2.5	Pulse-Shaping	134
7.2.6	Uncorrelated Noise: Dark Counts.....	135
7.2.7	Correlated Noise: Afterpulsing and Other Time Uncertainties	136
7.2.8	Sensitivity: Photon Detection Probability	138
7.2.9	Wavelength Discrimination	141
7.3	Fabricating Monolithic SPADs	141
7.3.1	Vertical Versus Planar SPADs.....	141

7.3.2	Implementation in Planar Processes	142
7.3.3	SPAD Nonidealities	146
7.3.4	SPAD Array Nonidealities	146
7.4	Architecting SPAD Arrays	148
7.4.1	Basic Architectures	148
7.4.2	On-Chip Architecture	149
7.4.3	In-Column Architecture	150
7.4.4	In-Pixel Architecture	151
7.5	Trends in Monolithic Array Designs	153
7.6	Conclusions.....	154
	References.....	154
8	Single Photon CMOS Imaging Through Noise Minimization	159
	Boyd Fowler	
8.1	Introduction.....	159
8.2	Theory	161
8.2.1	QE and MTF	161
8.2.2	Photo-carrier Detection Probability.....	167
8.2.3	Additive Temporal Noise Systems.....	168
8.2.4	Uncorrelated Temporal Noise Sources	170
8.2.5	Correlated Temporal Noise Sources	174
8.3	Amplification and Bandwidth Control	175
8.3.1	Amplification	175
8.3.2	Bandwidth Control	179
8.4	Architectures	181
8.4.1	4T Pixel with Pinned Photodiode Column Level Amplification and CDS.....	181
8.4.2	4T CTIA Pixel with Pinned Photo Diode Column Level Amplification and CDS	184
8.4.3	Architecture Comparison.....	188
8.5	Low-Noise CMOS Image Sensor Optimization	189
8.5.1	Electrical	189
8.5.2	Optical.....	192
8.6	Conclusion.....	193
	References.....	194
9	Architectures for Low-noise CMOS Electronic Imaging.....	197
	Shoji Kawahito	
9.1	Introduction.....	197
9.2	Signal Readout Architectures.....	198
9.3	Correlated Samplings and their Noise Responses	201
9.3.1	Correlated Double Sampling and Correlated Multiple Sampling	201
9.3.2	Response of CDS and CMS to Thermal and 1/f Noises.....	203

- 9.4 Noise in Active-pixel CMOS Image Sensors Using Column CMS Circuits 207
- 9.5 Possibility of Single Photon Detection 211
 - 9.5.1 Single Photon Detection Using Quantization 211
 - 9.5.2 Condition for Single Photon Detection 214
- References 216
- 10 Low-Noise Electronic Imaging with Double-Gate FETs and Charge-Modulation Devices 219**

Yoshiyuki Matsunaga

 - 10.1 Introduction 219
 - 10.2 Double-Gate FET Charge Detector 220
 - 10.2.1 Floating Well Type 220
 - 10.2.2 Floating Surface Type 226
 - 10.3 CCD Image Sensor with Double-Gate FET Charge Detector 233
 - 10.3.1 Sensor Construction 233
 - 10.3.2 Feedback Charge Detector 234
 - 10.3.3 Evaluation 236
 - 10.3.4 Signal Processing 237
 - 10.4 Charge-Modulation Image Pixel Application 239
 - 10.4.1 Pixel Construction 242
 - 10.4.2 Operation 243
 - 10.4.3 Simulation 245
 - 10.4.4 Results 245
 - 10.4.5 Applications of Area Sensor 246
 - 10.5 Conclusions 248
 - References 248
- 11 Energy-Sensitive Single-Photon X-ray and Particle Imaging 249**

Christian Lotto

 - 11.1 Introduction 249
 - 11.1.1 Applications 250
 - 11.1.2 Basic Topology 251
 - 11.2 Particle Sensing Devices 251
 - 11.2.1 Direct Conversion Sensing Devices 252
 - 11.2.2 Scintillators Coupled to Sensing Devices for Visible Light 253
 - 11.3 Asynchronous Charge Pulse Detecting Circuits 254
 - 11.3.1 Charge Sensitive Amplifier 255
 - 11.3.2 Charge Sensitive Amplifier with Shaper 261
 - 11.3.3 Voltage Buffer with Shaper 269
 - 11.4 Voltage Pulse Processing Circuits 271
 - 11.4.1 Energy Discrimination Methods 272
 - 11.4.2 Information Readout 272
 - References 273

12	Single-Photon Detectors for Time-of-Flight Range Imaging	275
	David Stoppa and Andrea Simoni	
12.1	Introduction	275
12.2	Time-of-Flight Measuring Techniques and Systems	278
12.2.1	Time-of-flight System	278
12.2.2	Direct and Indirect Time Measuring Techniques	279
12.2.3	Optical Power Budget	281
12.2.4	D-TOF and I-TOF Noise Considerations	284
12.3	Single-Photon Sensors for 3D-TOF Imaging	286
12.3.1	Single-photon Detectors	286
12.3.2	Pixel Architectures for Single-photon TOF Imaging	288
12.3.3	Circuit Implementations for I-TOF Pixels	289
12.3.4	Circuit Implementations for D-TOF Pixels	291
12.3.5	State-of-the-art Time-resolved CMOS SPAD Pixel-array	293
12.4	Challenges and Future Perspectives	294
12.5	Conclusions	297
	References	298
13	Single-Photon Imaging for Astronomy and Aerospace Applications	301
	Pierre Magnan	
13.1	Introduction	301
13.2	Scientific Detectors in Astronomy and Space Applications	303
13.2.1	Scientific CCDs	303
13.3	Imaging Through the Atmosphere	309
13.4	Lucky Imaging Technique	311
13.5	Adaptive Optics	313
13.5.1	Principles	313
13.5.2	Wavefront Sensor Requirements and Detector Implementations	315
13.5.3	Infrared Detectors for Wavefront Sensor	319
13.6	Space LIDAR Applications	321
13.7	Concluding Remarks	324
	References	325
14	Exploiting Molecular Biology by Time-Resolved Fluorescence Imaging	329
	Francis Müller and Christof Fattinger	
14.1	Introduction: Time-Resolved Fluorescence as a Uniquely Sensitive Detection Method for the Analysis of Molecular Biology	329
14.1.1	Labeling of Specific Molecules by a Long- Lifetime Fluorophore	330

14.1.2	Integration of the Investigated Specimens in a Planar Array: Homogeneous and Heterogeneous Assays.....	331
14.1.3	Excitation of Multiple Specimens in the Array by Intense Light Pulses and Imaging of the Arrayed Specimens on an Image Sensor conceived for Time-Gated Readout of the Fluorescence Signal	332
14.1.4	Microarray Assays.....	333
14.2	Properties of the Ideal Fluorophore for Ultra-Sensitive Fluorescence Detection	334
14.3	Ruthenium Complexes	336
14.4	Applications in the Life Sciences.....	338
14.4.1	Assay for Drug Discovery.....	338
14.4.2	Assay for Point of Care Testing.....	341
14.5	Prospective Use of Ultra-Low-Noise CMOS Image Sensors for Time-Resolved Fluorescence Imaging	342
	References.....	344
	Index	345

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