THE UNIVERSITY of EDINBURGH

ISSW2020

INTERNATIONAL IMAGE SENSOR SOCIETY

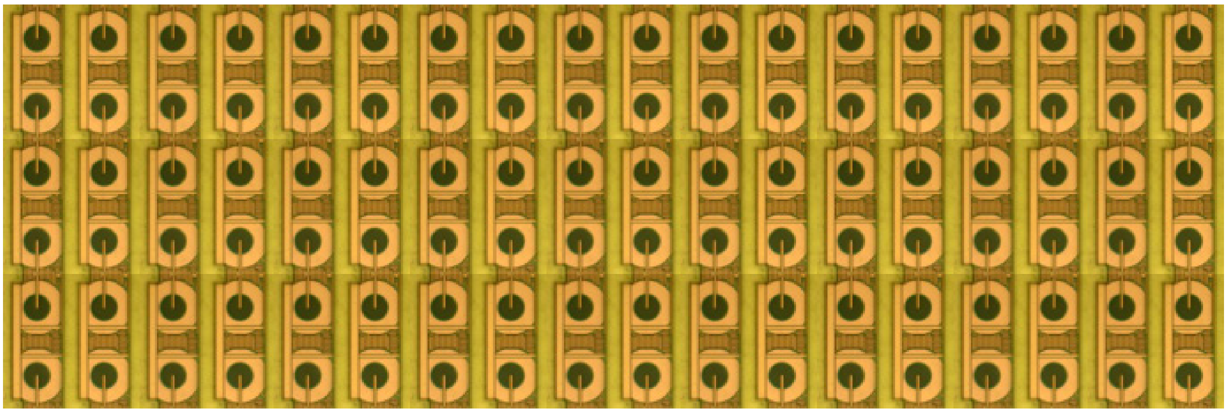
Welcome to

The International SPAD Sensor Workshop

Edinburgh, Scotland (UK)
8-10 June 2020

Photograph by Kim Traynor

Focused on the study, modeling, design, fabrication, and characterization of SPAD sensors.



Facilitated by The University of Edinburgh School of Engineering.

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Contents

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Welcome

It is my pleasure to welcome you to the 2nd International SPAD Sensor Workshop being held virtually from Edinburgh Scotland. This follows on from a very successful event hosted by Prof. Charbon in beautiful surroundings of Les Diablerets in Switzerland in February 2018. We had hoped to stage our own event in a lovely Victorian Hydro Hotel in the Highlands of Scotland at this special time of year with long evenings and warm weather. It became very clear in March 2020 that this was no longer tenable due to the COVID-19 pandemic and we took the heart-breaking decision to cancel our booking and move to a virtual format. At the time this seemed a very unsatisfactory substitute for the original in-person event with its rich opportunities for interaction but we were encouraged by the support of our speakers and sponsors who were still on-board with the new format. It is a testimony to the quality of those speakers and the associated technical programme that there has been such an encouraging level of attendance at the virtual ISSW. We are very grateful to them for their willingness to engage with the new IT-intensive arrangements.

As we have come closer to the date of the event and many of us have endured months of self-isolation and working from home, the value of providing a community event to engineers and researchers worldwide has become clearer. Recent developments in CMOS SPAD sensors have been rapid, spurred by large investments in LIDAR and industrialised SPAD device development by the semiconductor companies. The announcements of widefield LIDAR sensors moving from research labs into products and the first megapixel SPAD imagers have generated considerable excitement. It therefore feels timely for us all to take this opportunity to update on latest developments in the SPAD field and to inspire the next wave of innovations.

On proud display at the workshop, are the diversity of applications enabled by SPADs; quantum, biomedical, 3D ToF imaging, LIDAR, Raman spectroscopy, microscopy to optical communications. Further evidence of our vibrant technical field is that the last few years have also seen considerable growth in the number of companies, research institutes and Universities engaging with SPAD technology. We have sought to represent this wider participation in the new names in our technical programme. A free postgraduate entry program has been made possible by the generosity of our sponsors. A poster session has also been instituted to include new concepts and encourage discussion.

I would like to thank our technical committee for putting together this varied and topical programme and chairing the sessions. I thank our enthusiastic and hardworking team of moderators for their tremendous effort in the preparation and daily organisation of the workshop. We are all grateful to our sponsors for generous funding, active participation in the technical sessions and contribution of talks. Special thanks go to our core organisational team of Katrina Saridakis, Neil Finlayson, Danial Chitnis, Eddie Dubourg and Emily Martin without whose hard work, strong IT and organisational skills the event would not have been possible.

Robert K Henderson
Professor of Electronic Imaging
The University of Edinburgh

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Steering Committee

Robert Henderson is a Professor in the School of Engineering at the University of Edinburgh. He obtained his PhD in 1990 from the University of Glasgow. From 1991, he was a research engineer at the Swiss Centre for Microelectronics, Neuchatel, Switzerland. In 1996, he was appointed senior VLSI engineer at VLSI Vision Ltd, Edinburgh, UK where he worked on the world's first single chip video camera. From 2000, as principal VLSI engineer in STMicroelectronics Imaging Division he developed image sensors for mobile phone applications.

He joined Edinburgh University in 2005, designing the first SPAD image sensors in nanometer CMOS technologies in MegaFrame and SPADnet EU projects. In 2014, he was awarded a prestigious ERC advanced fellowship.

Sara Pelligrini
Advanced Photonics Pixel Architect
Imaging Sub-Group, Analog, MEMS and Sensors Group
STMicroelectronics

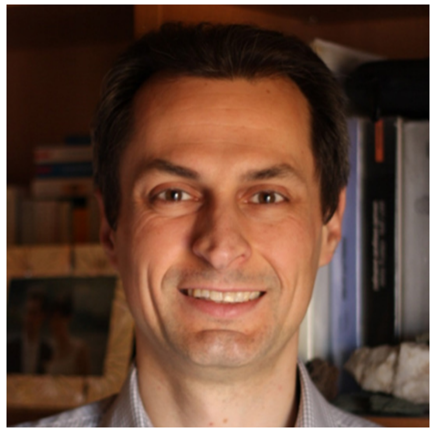
Sara Pellegrini is Advanced Photonics Pixel Architect at the Imaging subgroup within ST's Analog, MEMS and Sensors Group and has held this position since December 2017.

Pellegrini joined ST as Characterization and Modelling Engineer in 2006 and has progressed to the role of Session Manager and later to Pixel Architect. In her current role, she leads the advanced photonics sensor technology development, working in close collaboration with the silicon, process, module, and system R&D teams to define and develop ST's imaging photonics pixel roadmap and specification. Pellegrini also works with external collaborators on several R&D projects within ST's Imaging PhD Programme.

Pellegrini holds several patents and authored and presented papers on SPAD (Single-Photon Avalanche Diode) and SPAD-based systems and applications.

Sara Pellegrini was born in Bergamo, Italy, in 1972. She graduated with a degree in Electronic Engineering from the Politecnico di Milano in 1999 and received her PhD in Physics from Heriot-Watt University in 2006.

David Stoppa (SM'12-M'97) received the Laurea degree in Electronics Engineering from Politecnico of Milan, Italy, in 1998, and the Ph.D. degree in Microelectronics from the University of Trento, Italy, in 2002. In 2017 he joined AMS where he is in charge of the development of next generation 3D imaging sensors and systems. From 2014 to 2017 he has been the head of the Integrated Radiation and Image Sensors research unit at FBK where he has been working as a research scientist since 2002 and as group leader of the Smart Optical Sensors and Interfaces group from 2010 to 2013. From 2002 to 2012 he has been teaching at the Telecommunications Engineering faculty of the University of Trento, courses of Analogue Electronics and Microelectronics. His research interests are mainly in the field of CMOS integrated circuits design, image sensors and biosensors. He has authored or co-authored more than 120 papers in international journals and presentations at international conferences, and holds several patents in the field of image sensors. Since 2011 he served as program committee member of the 'International Solid-State Circuits Conference' (ISSCC) and the SPIE 'Videometrics, Range Imaging and Applications' conference, and was technical committee member of 'International Image Sensors Workshop' (IISW) in 2009, 2013, 2015 and 2017. He was a Guest Editor for IEEE Journal of Solid-State Circuits special issues on ISSCC'14 in 2015 and he is serving as Associate Editor since 2017. Dr. Stoppa received the 2006 European Solid-State Circuits Conference Best Paper Award.



Alberto Tosi, Associate Professor at Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB). He received his Master's degree in electronics engineering and his PhD degree in information technology engineering from Politecnico di Milano in 2001 and 2005, respectively and has been an Associate Professor of Electronics since 2014. In 2004, he was a Student with the IBM T. J. Watson Research Center, Yorktown Heights, NY, working on optical testing of CMOS circuits.

He designs, develops and exploits silicon, InGaAs/InP and Ge-on-Si Single-Photon Avalanche Diodes (SPADs). He works on arrays of SPADs for 2D and 3D applications, on silicon photomultipliers and on time-correlated single-photon counting electronics. He develops single-photon counting modules and time-to-digital converters for high-resolution high-throughput applications. In collaboration with other research groups, he develops new applications of single-photon counting in various fields, from biomedicine to secure communications, from material science to LIDAR.

He has been the principal investigator for POLIMI – DEIB in four EC funded projects, one DARPA funded project and one ESA funded project. He is co-author of more than 240 papers on peer-reviewed journals and conference proceedings, and he is the co-inventor of 3 patents and 2 patent applications. His H-index is 35 (according to Scopus, author ID 35499994500).

Edoardo Charbon (SM’00 F’17) received the Diploma from ETH Zurich, the M.S. from the University of California at San Diego, and the Ph.D. from the University of California at Berkeley in 1988, 1991, and 1995, respectively, all in electrical engineering and EECS. He has consulted with numerous organizations, including Bosch, X-Fab, Texas Instruments, Maxim, Sony, Agilent, and the Carlyle Group. He was with Cadence Design Systems from 1995 to 2000, where he was the Architect of the company's initiative on information hiding for intellectual property protection. In 2000, he joined Canesta Inc., as the Chief Architect, where he led the development of wireless 3-D CMOS image sensors. Since 2002 he has been a member of the faculty of EPFL, where is a full professor since 2015. From 2008 to 2016 he was with Delft University of Technology’s as Chair of VLSI design. He has been the driving force behind the creation of deep-submicron CMOS SPAD technology, which is mass-produced since 2015. His interests span from 3-D vision, LiDAR, FLIM, FCS, NIROT to super-resolution microscopy, time-resolved Raman spectroscopy, and cryo-CMOS circuits and systems for quantum computing. He has authored or co-authored over 350 papers and two books, and he holds 22 patents. Dr. Charbon is a distinguished visiting scholar of the W. M. Keck Institute for Space at Caltech, a fellow of the Kavli Institute of Nanoscience Delft, a distinguished lecturer of the IEEE Photonics Society, and a fellow of the IEEE.

Claudio Bruschini received the Laurea degree in physics from the University of Genoa, Genoa, Italy, in 1992, and the Ph.D. degree in applied sciences from Vrije Universiteit Brussel, Brussels, Belgium, in 2002.

He is currently a Scientist and Lab Deputy with EPFL’s Advanced Quantum Architecture Laboratory. His scientific interests have spanned from high energy physics and parallel computing in the early days, to challenging sensor applications in humanitarian demining, concentrating since 2003 on quantum photonic devices, high-speed and time-resolved 2D/3D optical sensing, as well as applications thereof (biophotonics, nuclear medicine, basic sciences, security, ranging).

He is an IEEE Senior Member and co-founder of one start-up commercialising selected AQUA lab SPAD designs.

Programme

MONDAY 8TH JUNE 2020

08:45-09:00	Welcome and Introduction	Robert Henderson, The University of Edinburgh

TECHNOLOGY

SESSION Chair: Sara Pellegrini from STMicroelectronics, United Kingdom

09:00-9:40	Charge-Focusing SPAD Image Sensors for Low Light Imaging Applications	Kazuhiro Morimoto, Canon
09:40-10:20	Charge-Focusing SPAD Image Sensors for Low Light Imaging Applications	Angelo Gulinatti, Politecnico di Milano
10:20-11:00	LFoundry: SPAD, status and perspective	Giovanni Margutti, LFoundry
11:00-11:15	Break	

SESSION Chair: Sara Pellegrini, STMicroelectronics, United Kingdom

11:15-11:55	Device and method for a precise breakdown voltage detection of APD/SPAD in a dark environment	Alexander Zimmer, XFAB
11:55-12:35	Ge on Si SPADs for LIDAR and Quantum Technology Applications	Douglas Paul, University of Glasgow
12:35-13:30	Lunch	

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12:35-13:00	Photon Force - Timing is Everything.	Richard Walker Photon Force
13:00-13:25	The Great Wavelength Debate: Which Will Prevail for Automotive LIDAR?	Bahman Hadji, OnSemiconductor

SESSION Chair: Edoardo Charbon, EPFL AQUA, Switzerland

13:30-14:10	3D-Stacked SPAD in 40/45nm BSI Technology	Georg Rohrer, AMS
14:10-14:50	SPAD arrays based on wafer bond technology	Werner Brockherde, Fraunhofer
14:50-15:30	Planar Microlenses for SPAD sensors	Norbert Moussy, CEA-LETI
15:30-15:45	Break	

PIXELS

SESSION Chair: Edoardo Charbon, EPFL AQUA, Switzerland

15:45-16:25	3D Integrated Frontside Illuminated Photon-to-Digital Converters: Status and Applications	Jean-Francois Pratte, University of Sherbrooke
16:25-17:05	Combining linear and SPAD-mode diode operation in pixel for wide dynamic range CMOS optical sensing	Matthew Johnston, Oregon State University
17:05-18:00	PhD Poster Session	
	Monday workshop close	

TUESDAY 9TH JUNE 2020

LIDAR AND TOF

SESSION Chair: David Stoppa, AMS, Switzerland

08:00-08:40	ToF Image Sensor Systems using SPADs and Photodiodes	Simon Kennedy, Monash University
08:40-09:20	A 1.1 mega-pixels vertical avalanche photodiode (VAPD) CMOS image sensor for a long range time-of-flight (TOF) system	Yukata Hirose, Panasonic
09:20-10:00	Single photon detector for space active debris removal and exploration	Alexandre Pollini, Csem
10:00-10:15	Break	

LIDAR

SESSION Chair: David Stoppa, AMS, Switzerland

10:15-10:55	4D solid state LIDAR – NEXT Generation NOW	Unsal Kabuk, Ibeo
10:55-11:35	Depth and Intensity LiDAR imaging with Pandion SPAD array	Salvatore Gnecchi, Onsemi
11:35-12:15	256 x 16 SPAD Array and 16-Channel Ultrashort Pulsed Laser Driver for Automotive LIDAR	André Srowig, Elmos
12:15-13:30	Lunch	

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12:15-12:40	Image Sensors: technologies and applications	Sara Pellegrini, Stmicroelectronics
12:40-13:05	From device to systems: 3D sensing solutions at AMS	David Stoppa, Ams
13:05-13:20	Next-generation technologies to enable high-performance, low-cost LIDAR	Hod Finekelstein, Sense Photonics

SWIR LIDAR

SESSION Chair: Alberto Tosi, Politecnico di Milano, Italy

13:30-14:10	LIDAR using SPADs in the visible and short-wave infrared	Gerald Buller, Heriot-Watt University
14:10-14:50	InP-based SPADs for Automotive LIDAR	Mark Itzler, Argo AI
14:50-15:30	Custom Focal Plane Arrays of SWIR SPADs	Erik Duerr, MIT Lincoln Labs
15:30-15:45	BREAK	

SENSOR ARCHITECTURES

SESSION Chair: Alberto Tosi, Politecnico di Milano, Italy

15:45-16:25	Cmos Spad Sensors With Embedded Smartness	Vornicu, University Of Seville
16:25-17:05	Modelling TDC Circuit Performance for SPAD Sensor Arrays	Daniel Van Blerkom, Ametek (Forza)
17:05-18:00	PhD Poster Session	
	Tuesday Workshop Close	

WEDNESDAY 10TH JUNE 2020

IMAGING APPLICATIONS

SESSION Chair: Robert Henderson, The University of Edinburgh, United Kingdom

9:00-9:40	Data processing of SPAD sensors for high quality imaging	Chao Zhang, Adaps Photonics
09:40-10:20	Scalable, Multi-functional CMOS SPAD arrays for Scientific Imaging	Leonardo Gasparini, FBK
10:20-11:00	Small and Smart SPAD Pixels	Edoardo Charbon, EPFL
11:00-11:15	Break	

MICROSCOPY APPLICATIONS

SESSION Chair: Robert Henderson, The University of Edinburgh, United Kingdom

11:15-11:55	High-resolution imaging of the spatio-temporal dynamics of protein interactions via fluorescence lifetime imaging with SPAD arrays	Simon Ameer-Beg, King's College
11:55-12:35	Image scanning microscopy with classical and quantum correlation contrasts	Ron Tenne, Weizmann Institute
12:35-13:00	Lunch	
12:35-13:00	SPAD Arrays for Brain-Computer Interface Applications	Francesco Marsili, Facebook

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SPECTROSCOPY AND TOMOGRAPHY APPLICATIONS

SESSION Chair: Claudio Bruschini, EPFL AQUA, Switzerland

13:30-14:00	Imaging oxygenation by near-infrared optical tomography based on SPAD image sensors	Martin Wolf, ETH Zurich
14:10-14:50	Raman spectroscopy utilizing a time resolving CMOS SPAD line sensor with a pulsed laser excitation	Ilkka Nissinen, University of Oulu
14:50-15:05	Break	

EMERGING APPLICATIONS

SESSION Chair: Claudio Bruschini, EPFL AQUA, Switzerland

15:05-15:45	Optical wireless communication with SPAD receivers	Horst Zimmermann, Tu Wien
15:45-16:25	SPAD Arrays for Non-Line-of-Sight Imaging	Andreas Velten, University Of Wisconsin
16:25-16:30	Workshop closing remarks	Robert Henderson, The University of Edinburgh

Day 1 - Abstract Presentations

Charge-Focusing SPAD Image Sensors for Low Light Imaging Applications

Kazuhiro Morimoto, Junji Iwata, Yukihiro Kuroda, Tatsuhito Goden, Tomoya Sasago, Yasuharu Ota, Keisuke Ota, Mahito Shinohara, Yusuke Fukuchi, Ayako Chiba, Mariko Furuta, Fumihiro Inui, Yasushi Matsuno, Hidekazu Takahashi, Katsuhito Sakurai, Takeshi Ichikawa

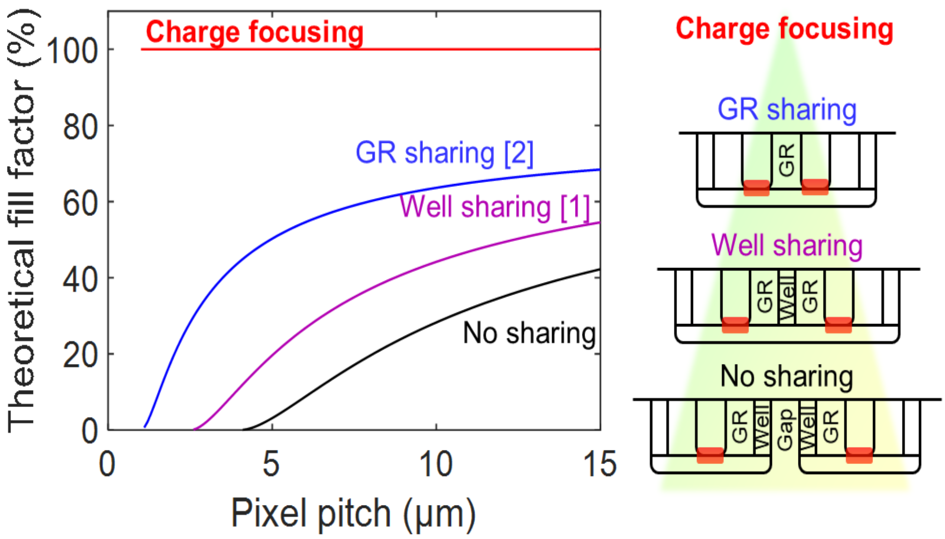

Fig. 1 Theoretical fill factor of SPAD arrays as a function of pixel pitch. Guard-ring (GR) width, well width, well-to-well distance are assumed to be 1 μm, 0.5 μm, and 1 μm, respectively. 3D-stacked configuration with circular-shaped multiplication region is assumed.

Growing demands for compact and high-resolution SPAD arrays in science and industry have motivated researchers towards aggressive miniaturization of SPAD pixels below 10 μm-pitch. 3D-stacking process has enabled to spatially separate the SPADs from pixel circuits, while ensuring electrical connections via pixel-level bonding. In such a configuration, a major limiting factor of the miniaturization is the reduced fill factor (FF). Several techniques have been proposed to enhance FF in small pixels [1,2], however, achieving FF > 50% in the miniaturized SPADs has been a challenge.

Here we propose a novel charge-focusing SPAD device to push the fundamental limit of the SPAD miniaturization, thereby potentially achieving 100% FF with the pixel pitch below 6 μm. The proposed device overcomes the native trade-off between PDE and DCR, while minimizing afterpulsing, crosstalk, power consumption and dead time. A proof-of-concept 128×128 SPAD image sensor demonstrates ultralow DCR (0.015 Hz/μm2), 40% PDP, and best-in-class performance for hot pixel population and afterpulsing probability. On-chip color filter array and all-digital readout ensure the single-photon-sensitive global shutter RGB imaging for extremely low light conditions.

Combining this technology with BSI 3D-stacking will pave the way to the next-generation multi-megapixel photon counting imagers, as well as high near-infrared-PDE megapixel time-of-flight sensors for 3D-LiDAR applications.

[1] T. Al Abbas, et al. Int. Image Sensor Workshop (2017).
[2] K. Morimoto, et al. Opt. Express 28(9), 13068-13080 (2020).

Kazuhiro Morimoto received the B.S. and M.S. degree in applied physics from the University of Tokyo, Japan, in 2011 and 2013, respectively. Since 2013, he has been working for Canon Inc., Japan, as a semiconductor device engineer. He engaged in pixel design of image sensors including 250 Mpixel CMOS image sensors. In 2017 he started working towards the PhD degree in AQUALab, École Polytechnique Fédérale de Lausanne, Neuchâtel, Switzerland. His interests include multi-megapixel SPAD image sensors for low light imaging applications, and for time-resolved applications such as LiDAR, fluorescence lifetime imaging microscopy, medical imaging, and light-in-flight imaging.
Major achievements:
- Demonstrated the world's first megapixel SPAD imager (K. Morimoto et al. Optica, 2020)
- Demonstrated the world's smallest 2.2 μm-pitch SPAD pixel array (K. Morimoto et al.)

THE UNIVERSITY of EDINBURGH ISSW2020 Day 1 - 8th June

Custom Silicon Technologies for High Detection Efficiency SPAD Arrays

Angelo Gulinatti[1], Francesco Ceccarelli[2], Giulia Acconcia[1], Massimo Ghioni[1], Ivan Rech[1]

[1] Dipartimento di Elettronica, Informazione e Bioingegneria – Politecnico di Milano, piazza Leonardo da Vinci 32, 20133 Milano, Italy.
[2] Istituto di Fotonica e Nanotecnologie – Consiglio Nazionale delle Ricerche (IFN-CNR), piazza Leonardo da Vinci 32, 20133 Milano, Italy.

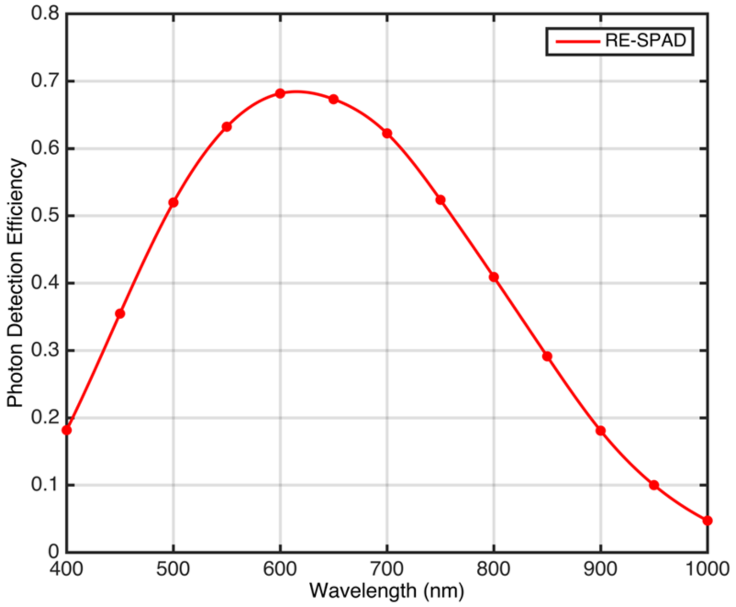

Fig. 1 Photon detection efficiency as a function of the wavelength for a typical Red-Enhanced SPAD. The measurement has been performed on a 50 µm diameter detector at an overvoltage VOV = 20V.

Growing demands for compact and high-resolution SPAD arrays in science and industry have motivated researchers towards aggressive miniaturization of SPAD pixels below 10 µm-pitch. 3D-stacking process has enabled to spatially separate the SPADs from pixel circuits, while ensuring electrical connections via pixel-level bonding. In such a configuration, a major limiting factor of the miniaturization is the reduced fill factor (FF). Several techniques have been proposed to enhance FF in small pixels [1,2], however, achieving FF > 50% in the miniaturized SPADs has been a challenge.

Here we propose a novel charge-focusing SPAD device to push the fundamental limit of the SPAD miniaturization, thereby potentially achieving 100% FF with the pixel pitch below 6 µm. The proposed device overcomes the native trade-off between PDE and DCR, while minimizing afterpulsing, crosstalk, power consumption and dead time. A proof-of-concept 128×128 SPAD image sensor demonstrates ultralow DCR (0.015 Hz/µm2), 40% PDP, and best-in-class performance for hot pixel population and afterpulsing probability. On-chip color filter array and all-digital readout ensure the single-photon-sensitive global shutter RGB imaging for extremely low light conditions.
Combining this technology with BSI 3D-stacking will pave the way to the next-generation multi-megapixel photon counting imagers, as well as high near-infrared-PDE megapixel time-of-flight sensors for 3D-LiDAR applications.

Many applications with a potentially disruptive impact in science and technology rely on the detection of single photons in the red and in the near infrared range (e.g. 600 – 950 nm). The capability of detecting such photons with high detection efficiency, low timing jitter and high throughput is a key requirement for the successful implementation of applications ranging from single-molecule spectroscopy to quantum information processing. CMOS and BCD technologies, with small modifications to their standard process flow, allowed designers to attain remarkable results in terms of detection efficiency. However, these solutions are always forced to move in the tight boundaries set by transistors fabrication. On the contrary, technologies entirely dedicated to the fabrication of the detectors can be fully customized and allow for the free exploration of new SPAD structures.

We will present our progress in developing a custom technology for the fabrication of SPAD arrays with high detection efficiency and low timing jitter. With such Red-Enhanced technology we demonstrated a peak detection efficiency of about 70% at 600 nm (40% at 800 nm) combined with a low timing jitter of less than 90 ps FWHM. This technology allows for the fabrication of SPAD arrays, but only with low fill-factor. Therefore, we will discuss also our work to make this technology suitable for high density SPAD array with even higher detection efficiency.

Angelo Gulinatti received the Laurea degree in Electronics Engineering and the Ph.D. degree in Information Technology (both summa cum laude) from Politecnico di Milano, Italy, in 2003 and 2007 respectively. He is currently Associate Professor at Politecnico vge area, high detection efficiency and low noise SPADs including the ones now commercialized by Micro Photon Devices. Currently, he works at the development of arrays of detectors with low timing jitter and improved photon detection efficiency. He has co-authored over 100 papers on both international peer-reviewed journals and conference proceedings.

LFoundry: SPAD, status and perspective

G. Margutti[1]

1. LFoundry, Avezzano, Italy.

The first part of the presentation briefly introduces LFoundry company.

A short history of the Introduction of SiPM is given in the second part, followed by a description of the different flavors of the product and their main characteristics.

The following section is dedicated to the integration of the SPAD cell in the LFoundry CMOS process flow (0.15 um and 0.11 um technology nodes) . The main figures of merit of the cells implemented in the LFoundry PDK are reported. The presentation provides a summary of the results obtained by customers who designed and produced their SPAD cells using LFoundry PDK.

Lastly, the presentation ends with a summary of the current and future activities regarding the development of SPAD and SiPM.

Giovanni Margutti
After the degree (Laurea) in Physics and a two years fellowship at INFN (Istituto Nazionale Fisica Nucleare) Giovanni joined Texas Instruments in 1995 in the Avezzano plant (Italy). Following the "fate" of the Fab, Giovanni joined Micron Technology first (1998) and LFoundry (2013 covering several positions. He has been working on CIS since 2005 (in the process integration department first and later on in the R/D department).
He actually covers the position of SMTS in the LFoundry R/D department as SiPM/SPAD SME (subject matter expert).
Giovanni is author or coauthor of more 20 scientific publications on peer reviewed journals. He is also author/co-author of six patents filed in the USPT, Europe, Korea.

THE UNIVERSITY of EDINBURGH ISSW2020 Day 1 - 8th June

Device and method for a precise breakdown voltage detection of APD/SPAD in a dark environment

Alexander Zimmer, Daniel Gäbler

1. X-FAB Global Services GmbH

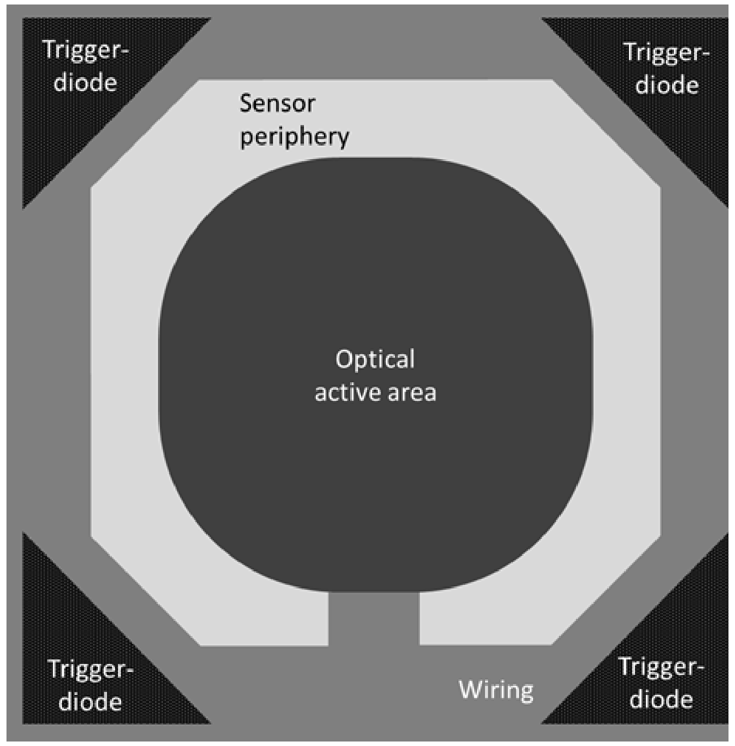

Figure 1: Sketch of an avalanche photodiode/single photon avalanche diode with a trigger diode to enhance the detection of the breakdown voltage.

The determination and characterization of the breakdown voltage is mandatory for the application of an avalanche photodiode (operation just below the breakdown). For single photon avalanche diode (SPAD) the operating condition starts with reaching the breakdown voltage. However, it is a common problem to trigger the breakdown and determine the voltage at this point [1].

A fundamental condition for an avalanche breakdown is, to have at least one carrier in the junction to trigger this event. For some applications under dark or low light environment this condition might not be given, so that the avalanche is not triggered. The detected breakdown voltage could shift to higher voltages. Because of such misinformation, the wrong reverse biasing on the APD/SPAD disturbs the functionality or lowers the performance.
To overcome this problem several possibilities are conceivable (shine some light on the junction, increase the temperature, measure with very slow ramp, use high dark count devices, ...).
We propose an integrated solution within the sensor itself, to open the possibility for a reliable and very fast measurement. In addition to that, the new method is independent of environmental factors e.g. temperature, time delay during the measurement, intensity of light sources and is implemented without increasing the fill factor of the device.

[1] G. Röher, et al. "SPAD device for excess bias monitoring" WO 2019/020472 A1, 31 January 2019

Alexander Zimmer received M.E. degree in nanotechnology from the University of Applied Sciences Zwickau.
Since 2015, he joined the "Opto- Process Development Team" at X-FAB in Erfurt, Germany. There he leads as a "Staff Engineer" for optical sensors the development project for APD and SPAD. This includes also design, simulation and process development activities. He is (Co-) author of 4 patents in the field of APD/SPAD and optical sensors.

Daniel Gäbler is a "Member of Technical Staff" within the "Opto- Process Development Team" at X-FAB and is based in Erfurt. He is working on the simulation, design and implementation of optical elements and sensors for integrating optical functionalities into foundry CMOS processes for more than 15 years. Daniel holds a diploma degree in Electrical Engineering from the Technical University in Ilmenau, Germany. He is author of 29 patents in the field of optical devices and X-FAB application expert for Sensors, Ambient Light and Proximity Sensing.

Ge on Si SPADs for LIDAR and Quantum Technology Applications

Douglas J. Paul[1], Jaroslaw Kirdoda[1], Lourdes Ferre Llin[1], Derek C.S. Dumas[1], Muhammad M. Mirza[1], Ross W. Millar[1], Kateryna Kuzmenko[2], Peter Vines[2], Fiona Thorburn[2], Zoë M. Greener[2], Abderrahim Halimi[2], Robert J. Collins[2], Aurora Maccarone[2], Aongus McCarthy[2] and Gerald S. Buller[2]

1. University of Glasgow, James Watt School of Engineering, Rankine Building, Oakfield Avenue, Glasgow, G12 8LT, U.K.
2. Institute of Photonics and Quantum Sciences, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, U.K.

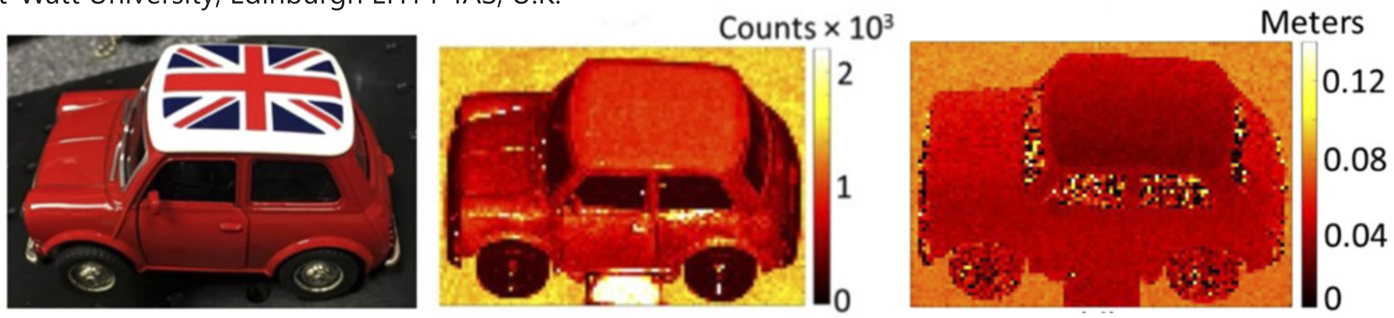

Fig. 1 Left: a 95 x 45 x 60 mm toy car used for LiDAR at l = 1450 nm at a 0.4 m stand-off distance. Centre: intensity profile and right: time-of-flight depth image using a Ge-on-Si SPAD detector [2].

For many mass market applications, CMOS single-photon avalanche diode (SPAD) detectors provide high performance but are limited to operate below wavelengths (l) ~ 1 µm. There are many applications requiring single-photon detectors at longer l including fibre-based quantum communications. Light detection and ranging (LiDAR) also has significant advantages for l>1.4 µm as solar blindness decreases and eye safe laser power increases resulting in higher signal-to-noise.

We demonstrate SPADs using Ge absorbers-on-Si avalanche regions to expand the single-photon operating wavelength using silicon substrates to l ≥ 1310 nm. At 1310 nm single-photon detection efficiencies (SPDE) up to 38% for 100 µm diameter devices are demonstrated at 125 K [1]. By reducing the diameter to 26 µm, the dark count rates (DCR) under identical conditions decreases by a factor of 54 demonstrating 36.8 kcps with 25% SPDE at 5.5% excess bias. These devices demonstrate a best jitter of 134 ± 10 ps and best noise equivalent power (NEP) of 7.7 x 10–17 W Hz– 1/2. Similar to previous CMOS based SPADs the Ge-on-Si SPADs demonstrate lower afterpulsing than InGaAs/InP SPADs when operated under identical conditions which is important for high repetitionrate applications including GHz rate quantum key distribution and LiDAR sampling rates.

We also present a first demonstration of LiDAR at l = 1450 nm over a 0.4 m stand-off distance in a laboratory with 912 pW laser power and a 104 kHz laser repetition rate using Ge-on-Si SPADs (Fig. 1). A single 100 µm Ge-on-Si SPAD was raster scanned to build up the image with a 23 mm aperture lens using a monostatic configuration [2]. Extrapolating with the LiDAR equation, it was estimated that 1 km rangefinding could be achieved with < 2 mW of laser power for 10 ms acquisition times [2].

[1] P. Vines et al. "High performance planar Ge-on-Si single-photon avalanche detectors" Nature Comms. 10, 1086 (2016).
[2] K. Kuzmenko et al., "3D LIDAR imaging using Ge-on-Si single-photon avalanche diode detectors" Optics Exp. 28, 1330 (2020).

Douglas J. Paul has a MA degree in Physics and Theoretical Physics and a PhD from the Cavendish Laboratory, University of Cambridge. He was Director of the James Watt Nanofabrication Centre in the University of Glasgow and since 2015 he has held an EPSRC Quantum Technology Established Research Fellowship and a Dstl Visiting Fellowship. His research group is working on quantum technology with chip scale (cold) atom systems,
MEMS gravimeters, Ge on Si single photon avalanche detectors, range-finding / lidar and single electron devices. He is a member of the UK Quantum Technology Hub in Sensors and Metrology / Timing, QuantiC (the UK Quantum Technology Hub for Quantum Enhanced Imaging) and the UK Quantum Technology Hub for Quantum Communications. In 2014 he was awarded the Institute of Physics President's Medal for his work translating advanced technology into products.

3D-Stacked SPAD in 40/45nm BSI Technology

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1. ams AG, Tobelbader Strasse 30, 8141 Premstaetten, Austria
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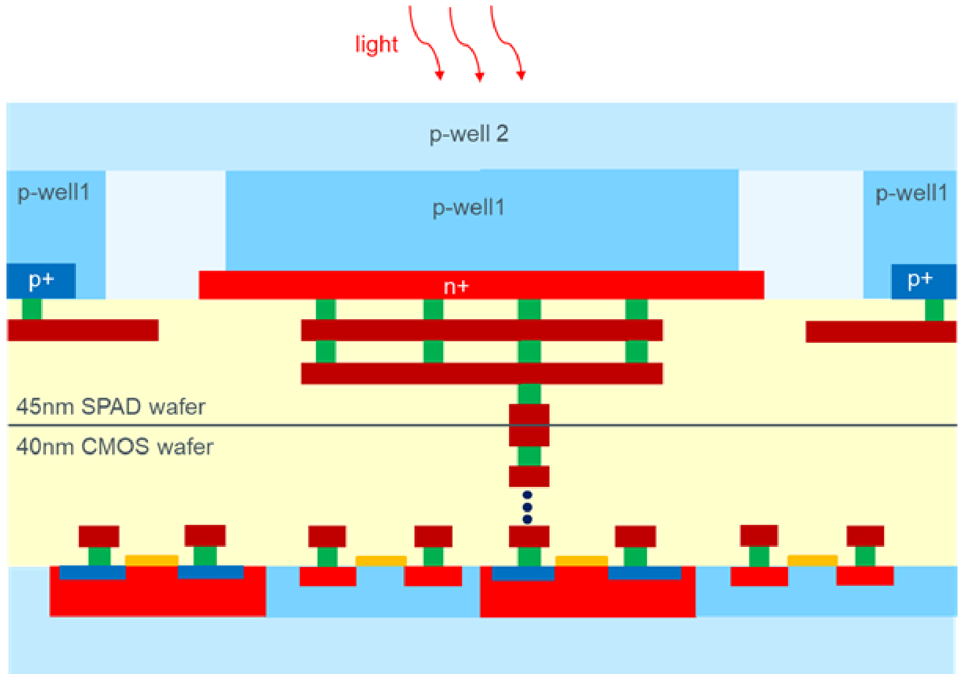

Fig. 1: Cross-section through 3D stacked BSI SPAD.

We present a Single Photon Avalanche Diode (SPAD) fabricated in a 3D stacked backside illumination (BSI) technology. The wafer stack consists of a 45nm wafer customized for SPAD performance and a 40nm CMOS wafer. 3D stacking allows the customization of the SPAD process without restrictions imposed by the CMOS process. Furthermore, the achievable fill factor (FF) is increased since quenching and signal processing is placed underneath the SPAD.

The octagonal SPAD structure is formed by an n+ in p-well diode with an enhancement layer and a virtual guard ring.

Several SPAD layouts with a pitch of ~12.5um, but differing by the fill factor in the range of 25% to 57% are compared with respect to key performance parameters like breakdown voltage(VBD), dark count rate (DCR), photon detection efficiency (PDE), timing jitter, cross-talk and after pulsing probability. The parameters most impacted by the fill factor are PDE and cross talk.

The best performing SPAD with a breakdown voltage of 17V achieves a DCR of 15cps and a PDE of 4.8% at 940nm when operated with an excess bias of 2.0V. The full width half maximum (FWHM) of the timing jitter is 140ps. This is an excellent performance for time of flight applications with infrared illumination.

Georg Roehrer received the M.Sc. degree from the Technical University of Graz, Austria in 1999. He joined ams AG in 2000 and has made significant contributions in the field of, bipolar transistors, Hall effect sensors, high voltage devices and SPADs. He is the author of over 30 patents in these fields.

BSI SPAD arrays based on wafer bond technology

Werner Brockherde, Jennifer Ruskowski

Fraunhofer Institute for Microelectronic Circuits and Systems, Duisburg, Germany

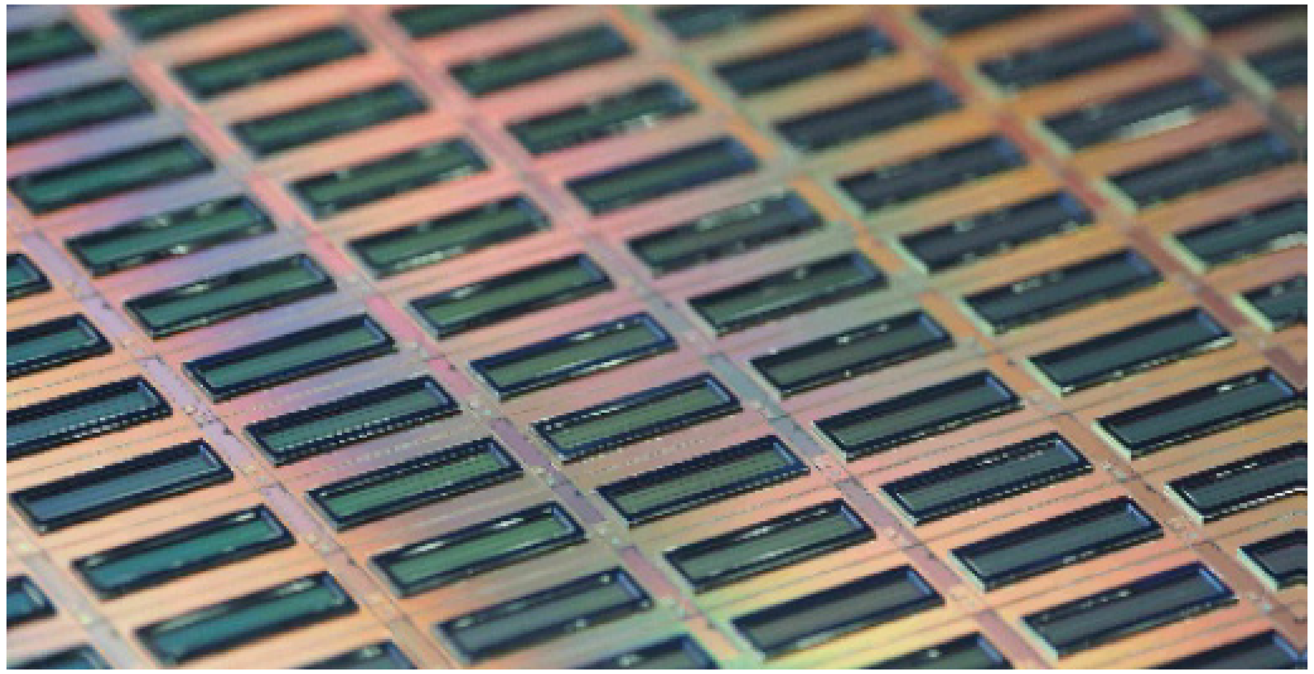

Fig. 1: CMOS Wafer with SPAD array bonded in chip-to-wafer process technologie

LiDAR sensors will become mandatory in autonomous vehicles of level 3+. Thus, the availability of low-cost LiDAR solutions is essential. Solid-state LiDAR will need highly sensitive detector arrays with excellent time resolution. CMOS integrated SPAD arrays are the most promising candidates.

A major drawback of SPAD based sensor arrays is the large pixel size mainly caused by complex pixel electronics which also reduces the fill factor. To overcome this weakness the stacking of SPAD array and ROIC wafer has been proposed earlier. Both, chip-to wafer and wafer-to-wafer technologies have been shown so far. In this presentation we demonstrate a novel 3D wafer stacking process with 200mm wafers. The BSI process features direct wafer bonding, backside thinning and in-pixel fine-pitch electrical connection with new TSμV (through silicon micro vias). First BSI SPAD detectors have been fabricated and successfully tested.

[1] Ruskowski, J.; Drewes, J.H.; Brockherde,W.: 64x48 pixel backside illuminated SPAD detector array for LiDAR applications. SPIE Photonics West 2020, SPIE Opto, San Francisco, Calif., USA

Werner Brockherde graduated in Electrical Engineering at the University of Dortmund, Germany, in 1982. In 1985 he joined the Fraunhofer Institute of Microelectronic Circuits and Systems, Duisburg, Germany, where he is actually heading the department for Optical Sensor Systems. His research interests include CMOS image sensor device technology and design techniques as well as optical sensor applications.

W. Brockherde authored or coauthored >120 scientific publications and holds >25 patents.

Planar microlenses for SPAD sensors

L. Dilhan[1,2], J. Vaillant[2], A. Ostrovsky[1], L. Masarotto[2], C. Pichard[2], R. Paquet[2], N. Moussy[2]
1. STMicroelectronics, 850 rue Jean Monnet, F-38920 Crolles, France
2. Univ. Grenoble Alpes, CEA, LETI, F38000 Grenoble, France

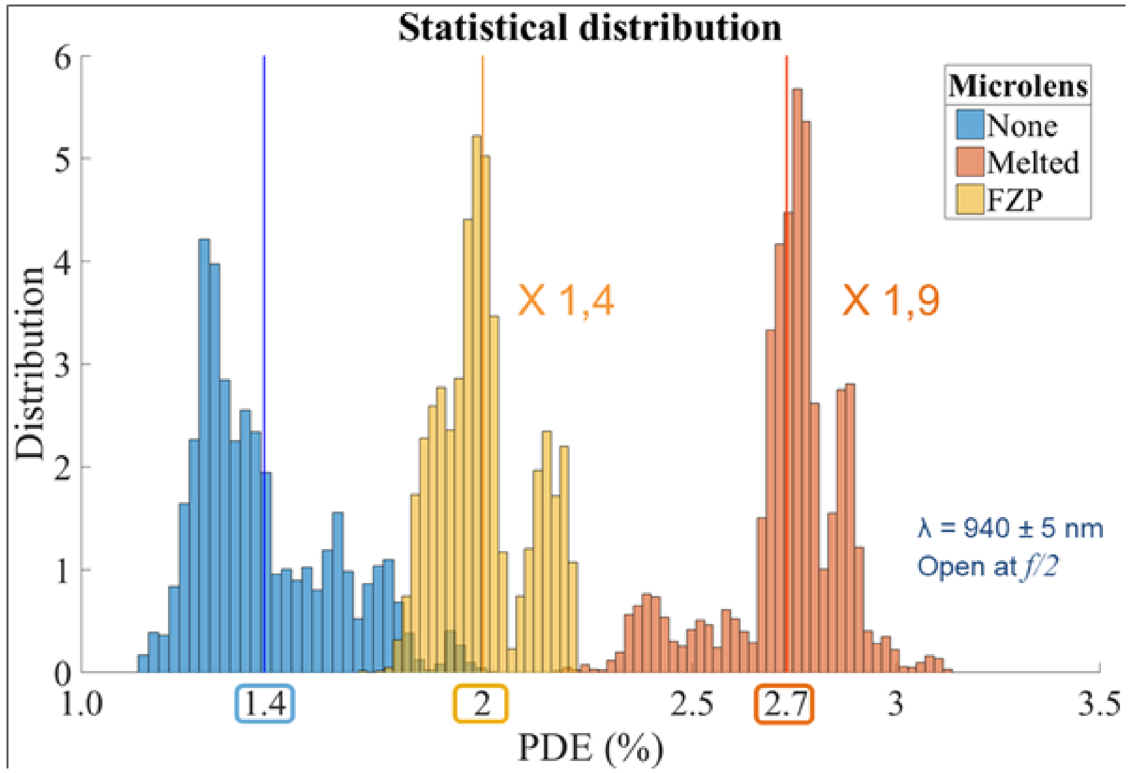

Fig. 1 Distribution of SPAD sensitivity at 940 nm with Melted, Fresnel Zone Plate and without microlenses.

We present planar microlenses designed to improve the sensitivity of SPAD pixels in near infrared. The conception of diffractive microlenses (Fresnel Zone Plate) and metasurface microlens (nanopillar structures) is based on rigorous optical simulations taking into account the SPAD layout and the CMOS technology [1].

The current melted microlens solution and designed diffractive microlens were implemented on STMicroelectronics 40nm CMOS testchips (32 x 32 SPAD array) [2], and average gains of 1.9 and 1.4 in sensitivity respectively were measured, compared to a SPAD without microlens.

[1] J. Vaillant et al, SPAD array sensitivity improvement by diffractive microlens, International Image Sensor Workshop (IISW), P28 (2019).
[2] S. Pellegrini et al, Industrialised SPAD in 40 Nm Technology, 2017, IEEE International Electron Devices Meeting (IEDM), pp. 16.5.1- 16.5.4 (2017).

NORBERT MOUSSY received the Ph.D. degree in superconductivity effects and very low temperature instrumentation in Grenoble. Since 2001, he has been working with CEA-LETI on process integration of innovative imager structures and materials, such as backside illumination technology and InGaAs integration in silicon processes. Since 2013, he has been in charge of the development of single photon avalanche diode for time of flight imaging and 3-D-stacking integration on advanced integrated circuit.

3D Integrated Front side Illuminated Photon-to-Digital Converters: Status and Applications

Jean-François Pratte, Simon Carrier, Keven Deslandes, Valérie Gauthier, Pascal Gendron, Michel Labrecque-Dias, Philippe Martel-Dion, Frédéric Nolet, Caroline Paulin, Samuel Parent, Tommy Rossignol, Nicolas Roy, Gabriel St-Hilaire, Artur Turala, Frédéric Vachon, Nicolas Viscogliosi, Réjean Fontaine, Serge A. Charlebois

Université de Sherbrooke, Interdisciplinary Institute for Technological Innovation

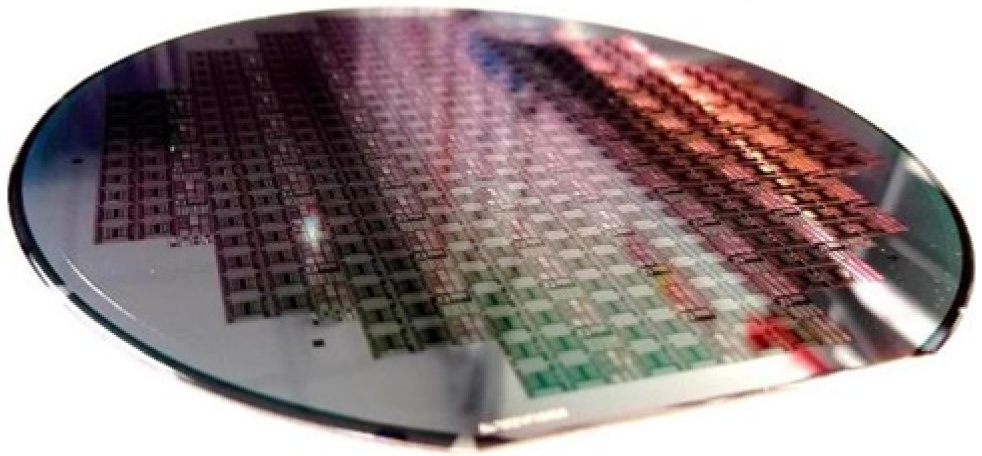

Fig. 1 Front side illumination SPAD array wafer implemented by Sherbrooke at Teledyne-DALSA. Various test structures are embedded for process optimization. Second optimization of the SPAD process delivered devices in March 2020. (Testing is pending due to Covid-19 situation.)

3D Photon-to-Digital Converter (3D-PDC, a.k.a. 3D digital SiPM) is composed of an array of single photon avalanche diodes (SPAD) integrated vertically in 3D with its microelectronic readout circuit, enabling direct photons-to-bit conversion and embedded digital signal processing. Because the 3D-PDC is developed for particle physics and medical imaging, such as positron emission tomography, its spectral sensitivity is optimized from VUV up to ~550 nm. Some experiments in these fields also require the highest single photon timing resolution possible, with a general effort from the community to achieve sub 10 ps FWHM. This motivates the R&D of a front side illuminated SPAD array. The team at Université de Sherbrooke (Québec, Canada) is working on every step of the design, fabrication and the implementation of the 3D-PDC. SPAD array and 3D bonding processes are developed on Teledyne-DALSA (Bromont, Canada) 6" CCD fabrication line, while CMOS (TSMC 180 nm and TSMC 65 nm) readout circuit are custom-designed to the various experiments' requirements. This talk will present an overview of the 3D-PDC development at Sherbrooke and the experiments motivating this research.

Jean-Francois Pratte received his M.A. Sc. in electrical engineering at Université de Sherbrooke, Sherbrooke, Canada in 2002. He then held a position as a research engineer at the Instrumentation Division of the Brookhaven National Laboratory (BNL, U.S. DOE) and obtained in parallel his Ph.D. in 2008 for the realization of the RatCAP (Rat Conscious Animal PET scanner). He was a key designer in the implementation of the first dual modality PET and magnetic resonance imaging scanner. While at BNL, he has coauthored 3 patents—all transferred to the industry, one paper in Nature Methods and contributed to the startup of a company.

In 2009, he joined the Electrical and Computer Engineering Department at Université de Sherbrooke where he currently holds a professor position. His research interests target microsystem design and integration of Photon-to-Digital Converters, where an array of single photon avalanche diodes is integrated vertically in 3D with a pixelated CMOS readout circuit. His current research areas are: radiation instrumentation for neutrino physics (double beta decay neutrinoless—member of the nEXO collaboration), dark matter search and medical imaging (positron emission tomography) as well as quantum key distribution receivers and time-to-digital converters. He was awarded the prestigious 2018 Radiation Instrumentation Early Career Award of the IEEE Nuclear and Plasma Science Society "For Spearheading the Development of per Pixel Picosecond Timing with Single Photon Avalanche Diodes Three-Dimensionally Integrated to Custom Readout Circuits".

Combining linear and SPAD-mode diode operation in pixel for wide dynamic range CMOS optical sensing

Hyunkyu Ouh[1], Boyu Shen[1], and Matthew L. Johnston[1]
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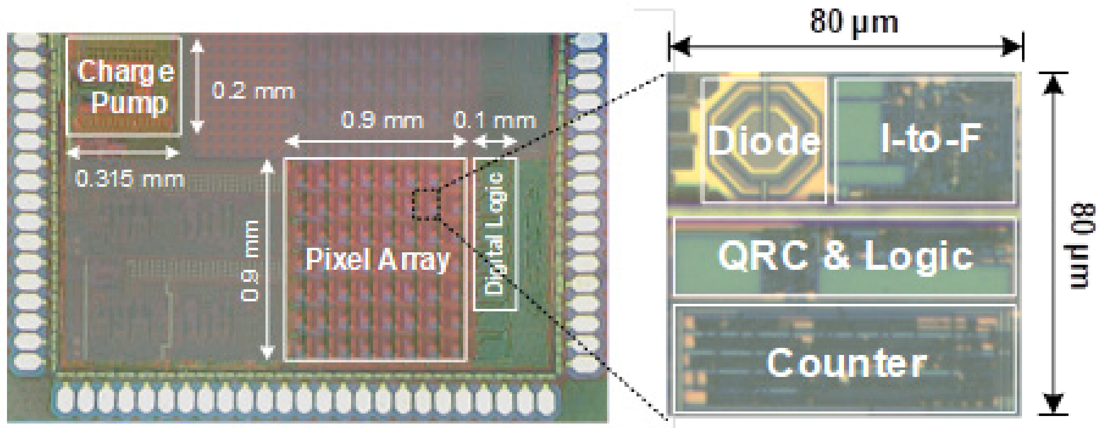
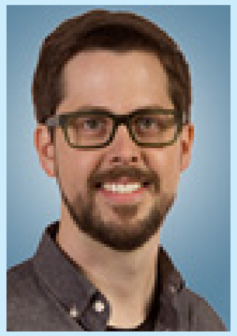


Fig. 1 Geiger-mode and linear mode operation are combined in-pixel for a wide-DR CMOS optical sensor.

We present an overview of our recent work developing hybrid pixel architectures for achieving wide optical dynamic range by combining the Geiger-mode and linear mode of operation in a single, digital-output pixel. The approach demonstrates high linearity and SNR over a broad optical illumination range. An in-pixel pulse-based readout architecture supports the dual-mode operation of a single CMOS-integrated; a current-to-frequency converter measures continuous photocurrent, and a QRC processes SPAD output pulses; pulses are accumulated using in-pixel digital counter for fully independent pixel operation and readout. An 8 × 8 array prototype IC was fabricated in a general purpose 180-nm CMOS process and demonstrates 129-dB DR while maintaining linear photoresponse and operating with a dual-mode frame rate of 20 Hz [1, 2]. We also describe our work developing integrated charge pump architectures for dual-mode (HV/LV) photodiode biasing, including high-voltage generation in a general purpose, low-voltage CMOS process [1, 3].

[1] H. Ouh et al., "Combined in-pixel linear and single-photon avalanche diode operation with integrated biasing for wide-dynamic-range optical sensing," IEEE JSSC, vol. 55, no. 2, pp. 392-403, 2020.
[2] H. Ouh and M.L. Johnston, "Dual-mode, in-pixel linear and single-photon avalanche diode readout for low-light dynamic range extension in photodetector arrays," IEEE CICC 2018.
[3] B. Shen et al., "Fully-integrated charge pump design optimization for above-breakdown biasing of single-photon avalanche diodes in 0.13 µm CMOS," IEEE TCAS-I, vol. 66, no. 3, pp. 1258-1269, 2019.



Matthew L. Johnston received the B.S. degree in electrical engineering from the California Institute of Technology, Pasadena, CA, USA, in 2005, and the M.S. and Ph.D. degrees in electrical engineering from Columbia University, New York, NY, USA, in 2006 and 2012, respectively. He was Co-Founder and the Manager of research with Helixis, a Caltech-based spinout developing instrumentation for real-time DNA amplification, from 2007 until its acquisition by Illumina in 2010. From 2012 to 2013, he was a Post-Doctoral Scholar with the Bioelectronic Systems Laboratory, Columbia University. He is currently an Assistant Professor with the School of Electrical Engineering and Computer Science at Oregon State University. His research is focused on the integration of sensors and transducers with active CMOS substrates, lab-on-CMOS platforms, bio-energy harvesting, and low-power distributed sensing applications.

Dr. Johnston is currently an Associate Editor of the IEEE Transactions on Biomedical Circuits and Systems and the IEEE Open Journal of Circuits and Systems, and he serves on the Biomedical and Life Science Circuits and Systems Technical Committee and the Analog Signal Processing Technical Committee for the IEEE Circuits and Systems Society.

Day 2 - Abstract Presentations

ToF Image Sensor Systems using SPADs and Photodiodes

Simon Kennedy[1], Daniel Morrison[1], Dennis Delic[2], Mehmet Yuce[1], and Jean-Michel Redoute[1,3]
1. Monash University
2. Australian Defence Science Technology
3. University of Liège

Fig. 1: VisionSens SPAD and Photodiode camera system developed by Monash University

Modern semi-autonomous vehicles currently utilise LIDAR, radar, ultrasound, video and stereo cameras to enable the simultaneous capture of depth, intensity and motion data. The VisionSens image sensor, developed by Monash University, utilises the concurrent operation of independent SPAD and Photodiode sensor arrays, allowing all of these data types to be captured simultaneously from a single sensor.

VisionSens sensor technology enables the image sensor to leverage the advantages of the different technologies to produce a more capable imager, with the potential to replace each independent sensor system with a single unified vision system.

Simon Kennedy received a BE(Hons) in electrical and electronics engineering and BSc in physics from The University of Melbourne, Australia in 2011. In 2012, he started working with Grey Innovation, Melbourne, Australia and was involved in the design of biomedical electronic devices. In February 2014 he joined the BICS Laboratory at Monash University, Clayton, Australia where completed his Ph.D. degree in 2018. His Ph.D thesis was entitled "Fully-Integrated 3D Image Sensor Systems using SPADs and Photodiodes". He is currently an image sensor hardware engineer at Blackmagic Design in Melbourne, Australia

THE UNIVERSITY of EDINBURGH ISSW2020 Day 2 - 9th June

A 1.1 mega-pixels vertical avalanche photodiode (VAPD) CMOS image sensor for a long range time-of-flight (TOF) system

Y. Hirose, S. Koyama, T. Okino, M. Ishii, S. Kasuga, A. Inoue, M. Tamaru, H. Koshida, T. Kabe, S. Saito, S. Yamada, Y. Sugiura, K. Nakanishi, N. Torasawa, T. Shirono, Y. Nose, T. Kunikyo, M. Takemoto, M. Usuda, Y. Sakata, Y. Yuasa, M. Mori, M. Sawada, A. Odagawa, T. Tanaka
Panasonic Corporation

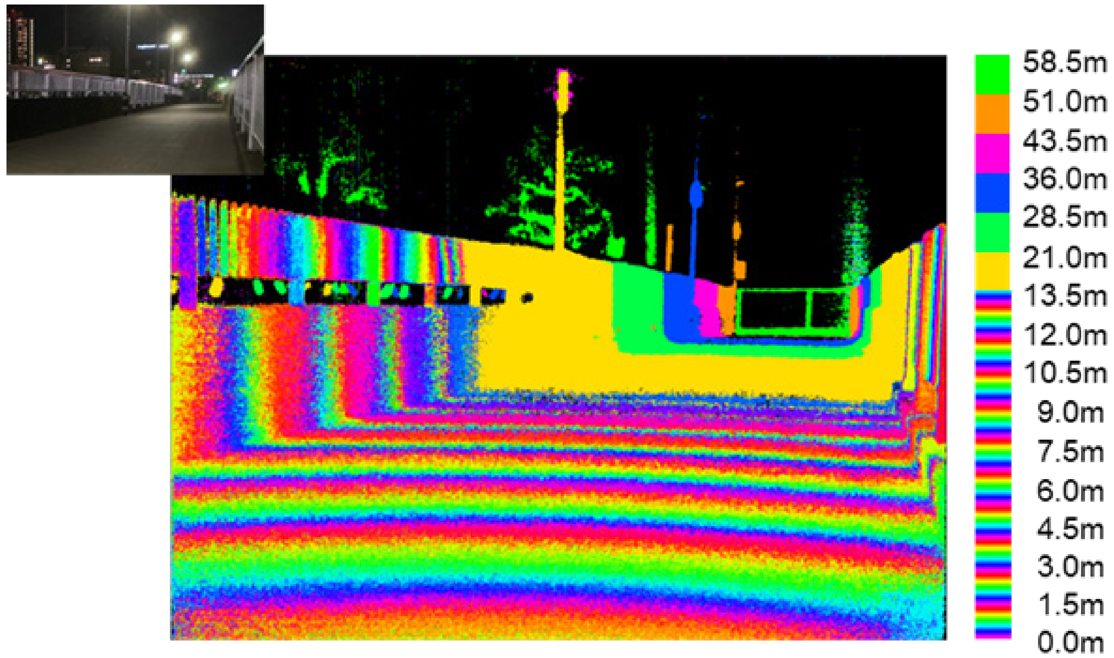


Fig. 1 A Geiger-mode DITOF mixed image with configurable depth resolution from 10 cm (near range) to 7.5m (far range). The top-left is a 2D image of the same scene.

We present an SPAD-based 1M pixels CIS capable of ranging with a direct/indirect-TOF (DITOF) mixed mode [1]. In a pixel avalanche photodiode, carriers flow vertically, named VAPD, with after-pulse-free capacitive self-quenching of the Geiger-mode [2]. Thus, VAPD enables one to use a standard 4T pixel circuit of a CIS with a conventional frame readout scheme. An in-pixel charge accumulator and charge packet spatula (slicer) give rise to a precise photon counting function [1].

For TOF range imaging, sub-range synthesis (SRS) method is employed. A full range extendable up to 250 m is divided into 15 sub-ranges with variable sizes; far ranges with large size, e.g. 7.5 m, and near ranges with small size, e.g. 1.5 m. In addition, for near range measurement, indirect TOF with a resolution of 10 cm is realized by phase differentiation of successive sub-ranges outputs. By synthesizing all the sub-range images, a long range 3D (DITOF) imaging with a speed of 30 fps compatible with 450fps 2D imaging is demonstrated.

[1] T. Okino, et al., ISSCC 2020 Tech. Digest. 5.2.;
[2] Y. Hirose et al., ISSCC 2020 Tech. Digest. 5.6.

Yutaka Hirose graduated from Princeton University with Ph. D., Electrical Eng., in 1996. He joined Texas Instruments Japan where he was engaged in developments of CCDs and DRAMs. Since 2001, he has been with Panasonic corporation where he has been engaged in development of CMOS image sensors (CISs) including vertical avalanche photodiode (VAPD) CISs and a time-of-flight (TOF) ranging system.

Single photon detector for space active debris removal and exploration

Alexandre Pollini[1], Christophe Pache[1], Fabien Droz[1], Jacques Haesler[1], Matteo Perenzoni[2]
1. Centre Suisse d'Electronique et de Microtechnique (CSEM)
2. Fondazione Bruno Kessler (FBK)

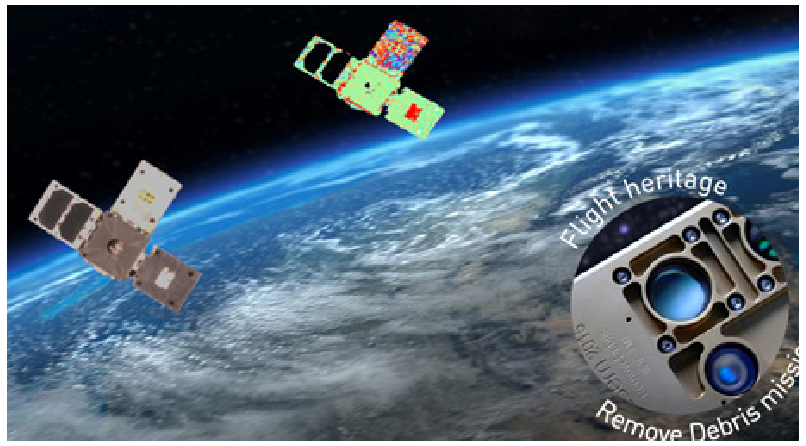


Fig. 1 Photomontage of pictures captured in-orbit by the color camera and the LiDAR of the vision-based navigation sensor during RemoveDebris mission

Space fearing nations agencies are defining future missions aiming at landing softly and precisely precious payloads on the surface of various celestial object such as: Mars, the Moon or asteroids. At the same time, new kind of missions in low Earth orbit necessities mastering fully automated rendezvous between spacecraft and not collaborative objects in any background light conditions. The most challenging one is Active Debris Removal (ADR).

Thousands of space junk parts, inactive bits of old spacecrafts or rockets orbiting Earth cause safety issues for active ones. The International Space Station (ISS) change often its altitude because of them. This problem will become even more sensitive with the extremely large satellites constellations currently launched or soon to be launched such as: Starlink aiming at placing in-orbit 10'000 satellites or Oneweb with more than 1000 satellites.

To allow 3D mapping in real-time of the surface of a celestial body in landing phase or the unequivocal characterization of a space junk, imaging LiDAR is the perfect sensor. While 10 years ago, Europe was focused on scanning systems, in the USA several groups were working on flash LiDAR. At that time, the European Space Agency (ESA) released a first "invitation to tender" aiming at working on the first European flash imaging LiDAR for space applications. This competition was won by CSEM and its partners as the Fondazione Bruno Kessler (FBK).

The talk is about development steps achieved at component and system levels. The most critical component of a flash imaging LiDAR is the TOF matrix detector, designed by FBK. The detector is the heart of the single photon LiDAR architecture. We are working on the third generation of LiDAR with the support of ESA. The knowledge accumulated allowed us to build a first LiDAR flight model that flown on the RemoveDebris mission. We will conclude the presentation with a few hints about the specifications of the latest generation detector currently under development based on the flight experience and outcomes of previous activities.

Alexandre Pollini is the LiDAR activity manager at the Swiss Center for Electronics and Micro-technics (CSEM). He is involved in every aspects of developing imaging LiDARs for clients such as the European Space Agency (ESA) from paper concepts to delivery of flying models.
Alexandre acted as CSEM's project manager for the RemoveDebris mission funded by the European Commission completed early 2019. RemoveDevris was a mission aiming at assessing technologies for debris capture and removal in real-conditions in Low-Earth Orbit (300 km). CSEM provided the Pro-to-Flight model of a Vision Based Navigation sensor made of a flash imaging LiDAR and a color camera. Both were tested successfully.
When not working, he loves spending time with 2 super-active kids. He oversees the football school of his village St-Blaise and is an active member of the Swiss Alpine Club and still enjoy skiing off-road like it was the first time.
He has a Master in Electrical Engineering from the Ecole Polytechnique de Lausanne and a Master in Business Administration from the Lausanne University.

THE UNIVERSITY of EDINBURGH ISSW2020 Day 2 - 9th June

4D solid state LIDAR – NEXT Generation NOW

Ünsal Kabuk

Nowadays, LiDAR is a very hot topic and exiting field to work in. 100+ companies in this field have various solutions showing their next generation of LiDAR sensors.

In this talk a detailed overview of the ibeoNext 4D solid-State LiDAR will be given.

Although there might be various definitions of solid-state lidar architectures, it will be shown why SPAD technology is a key enabler for automotive solid-state LiDAR.

Demo data and short videos of the ibeoNext will close the talk and fascilitates an experience of real use cases.

Ünsal Kabuk (male): joined ibeo at 2003 after receiving his diploma in high frequency electronics and communication engineering from the university of Wuppertal (UW) in 2002. At Ibeo he contributed to system studies, hardware development and experimentation in several electro-optic areas for next generation LIDAR systems. Currently he is leading the research and advance development group at ibeo with emphasize on solid state technologies, new products and applications.

Depth and Intensity LiDAR imaging with Pandion SPAD array

Salvatore Gnecchi[1], Carl Jackson[1]
1. ON Semiconductor – SensL Division, Cork, Ireland

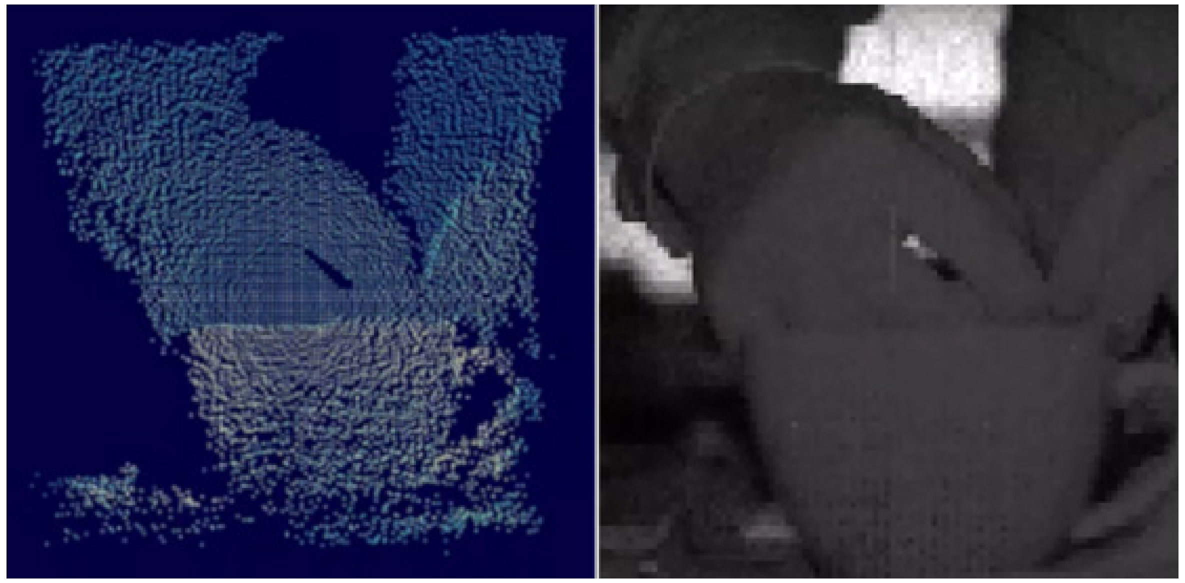


Fig. 1 Depth map (left) and intensity B\W picture simultaneously capture with Pandion SPAD array (portion of central 100 × 100 pixels)

Our paper and presentation will discuss the challenge faced in modern LiDAR systems of capturing depth and intensity information in a scene using direct Time of Flight (dToF) in a LiDAR system with a SPAD time of flight (ToF) imager.

We will demonstrate a system based on single photon avalanche diode (SPAD) arrays which provide high timing performance required for dToF [1] and simultaneously provide intensity information to directly image the scene. We will present results taken with an evaluation kit and a demonstration platform for Pandion, a first generation, 400 × 100 SPAD array based on ON Semiconductor's SPAD process [2].

We discuss the Pandion chip architecture, its modelled performance and the collected ranging data from the demonstration system in the optics of the development of the next generation SPAD array (future Pandion devices) for a variety of LiDAR applications.

[1] Niclass, C. L., Rochas, A., Besse, P. A., & Charbon, E. (2004). A CMOS single photon avalanche diode array for 3D imaging. Solid-State Circuits Conference, 2004. Digest of Technical Papers. ISSCC. 2004 IEEE International, 15(7), 120–517.
[2] Palubiak, D., Gnecchi, S., Jackson, C.(2019). Pandion : A 400 × 100 SPAD sensor for ToF LiDAR with 5 Hz median DCR and 11 ns mean. International Image Sensor Workshop, 40–43.

Salvatore Gnecchi has received the Laurea Magistrale in Physics at the Università degli Studi di Milano in 2012. He then joined the University of Edinburgh where he completed his PhD in high dynamic range digital SiPM in 2016. He joined SensL Technologies in October 2015 as LiDAR architect for SiPM and SPAD sensors. Since May 2018, he joined ON Semiconductor with the same role. His current works focus on SPAD and SiPM arrays for outdoors long range LiDAR for automotive and industrial.

256 x 16 SPAD Array and 16-Channel Ultrashort Pulsed Laser Driver for Automotive LiDAR

A. Srowig, F. Finkeldey, J. Stein-Cichoszewski, T. Rotter, S. Blumenthal, R. Krumm, R. Kühnhold
Elmos Semiconductor AG

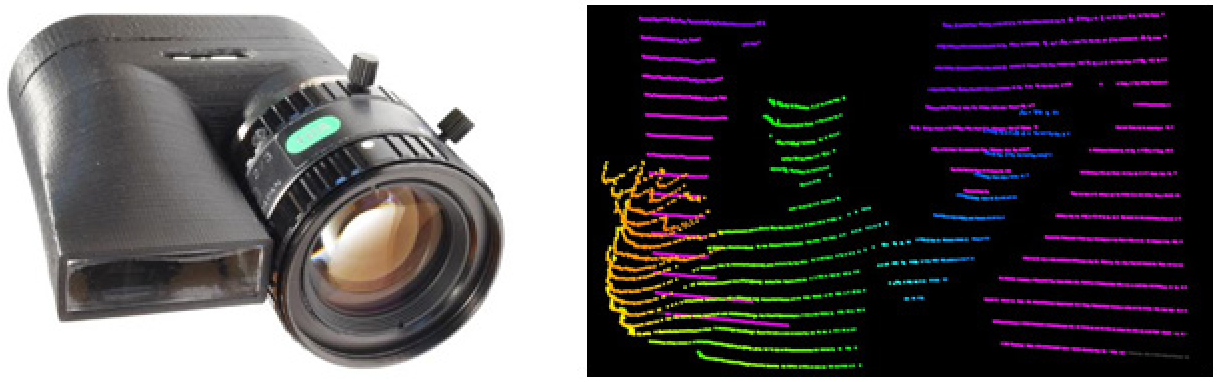


Fig.1 a) Solid-state LiDAR demonstrator b) Image data 3D representation

High performance, low cost solid-state LiDAR systems require novel system architectures regarding sensor and readout circuits in combination with tailored illumination solutions. This talk will focus on performance trade-offs, suitable transmitting and receiving units, efficient operating modes, and the integration in scalable systems.

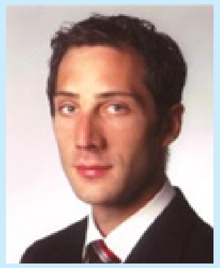
On the detector-side, we are presenting a Single-Photon Avalanche Diode (SPAD) array with 256 x 16 pixels, aimed at flash and line-scanning LiDAR-Systems. The design, developed in close cooperation between the Fraunhofer IMS and us, achieves a high fill-factor by using a rolling shutter readout and successfully addresses shortcomings of SPADs: low immunity to ambient light and first photon detection only.

For background light rejection each pixel uses four vertically arranged single SPADs generating events based on the detection of temporally correlated photons. The parameters of the coincidence circuit are adjusted in real time based on the ambient light conditions [1]. A TDC with a resolution of 312.5ps enables a depth resolution of 3mm using interpolation. Up to four events per laser pulse per pixel are stored to detect small or semi-transparent objects and to improve ranging capability.

We are also presenting a scalable multi-channel laser-driver generating short high intensity pulses for direct time-of-flight measurements. Using a die stacking approach to minimize parasitic inductance, peak currents of up to 50A are applied to the laser-diodes within a 1ns pulse. The multi-channel module uses a dedicated laser-diode for every line of pixels of the detector to match the spatial scanning nature of the rolling-shutter readout. We implemented evaluation-circuits for both subsystems in automotive qualified 350nm CMOS technology and designed a compact 905nm solid state LiDAR system for demonstration purposes.

Acknowledgements:
Parts of the research is funded by the Federal Ministry for Economic Affairs and Energy in the framework of the "IPCEI Microelectronics". Reference

[1] Beer, M., Schrey, O. M., Hosticka, B. J., & Kokozinski, R. (2017, June). Coincidence in SPAD-based time-of-flight sensors. In 2017 13th Conference on Ph. D. Research in Microelectronics and Electronics (PRIME) (pp. 381-384). IEEE.



Dr. André Srowig received his Diploma in physics in 2001 at the University of Heidelberg graduating on radiation-hard readout electronics for the Large Hadron Collider (LHC) at CERN Switzerland. During his dissertation at the Max-Planck-Institute for Nuclear Physics Heidelberg, he continued his specialization in CMOS design with the realization of multichannel low-noise sensor and readout electronics for cosmic dust. From 2008, he worked on definition and industrialization of structured photosensors and encoder ASICS in 180nm CMOS at Heidenhain GmbH. In 2015 he joined Elmos Semiconductor AG as a system development engineer and has been responsible for the design and analysis of different optical TOF measurement architectures. His latest achievement has been the invention, design, and realization of a novel CMOS based solid-state LiDAR demonstrator presented at CES 2020.

LIDAR using SPADs in the visible and short-wave infrared

Gerald S Buller[1], Aongus McCarthy[1], Rachael Tobin[1], Aurora Maccarone[1], Julián Tachella[1]; Yoann Altmann[1], Abderrahim Halimi[1], Stephen McLaughlin[1], Francesco Mattioli Della Rocca[2], Robert Henderson[2]

1. School of Engineering and Physical Sciences, Heriot-Watt University (United Kingdom)
2. University of Edinburgh (United Kingdom)

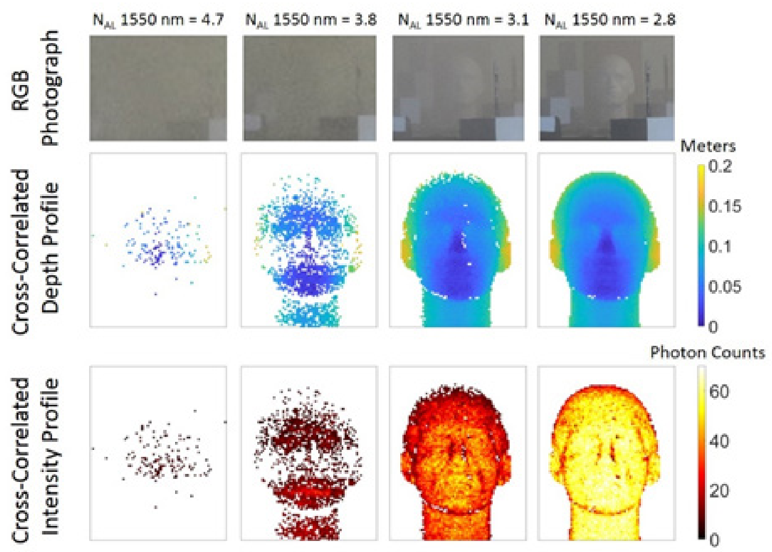


Fig. 1 Depth and intensity profiles of the polystyrene head target seen through fog, measured using a λ = 1550 nm single-photon transceiver. Figure illustrates measurements at different densities of fog, shown as varying numbers of attenuation lengths between transeiver and target, NAL. After ref [1].

LIDAR using SPADs offer long-distance depth profiling in the short-wave infrared. In addition, SPADs offer excellent sensitivity and surface-to-surface resolution permit good three-dimensional imaging performance through atmospheric obscurants [1].

We present some examples of imaging through atmospheric obscurants, and describe the development of these approaches towards real-time imaging of targets both in obscurants and in complex, multiple-surface scenes [2].

In the visible region, SPADs have been used to demonstrate depth profiling at up to 9 attenuation lengths between transceiver and target in single-detector scanning systems, and also shown good penetration in turbid underwater scenarios using CMOS SPAD detector arrays [3].

We will compare and contrast these approaches to underwater single-photon imaging.

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[2] J Tachella, Y Altmann, N Mellado, A McCarthy, R Tobin, GS Buller, J-Y Tourneret & S McLaughlin, "Real-time 3D reconstruction from single-photon lidar data using plug-and-play point cloud denoisers", Nature Communications. 10, 4984 (2019).
[3] A Maccarone, F Mattioli Della Rocca, A McCarthy, R Henderson, and GS Buller,"3D imaging of stationary and moving targets in turbid underwater environments using a single-photon detector array", Optics Express 27 (20), pp. 28437-28456 (2019).

Gerald Buller received the B.Sc.in Natural Philosophy from the University of Glasgow in 1986, and the Ph.D. in Physics from Heriot-Watt University in Edinburgh, UK in 1989, where he is currently a Professor of Physics. In 2002, he co-founded Helia Photonics Ltd., where he remains company Chairman. His research interests include aspects of single-photon detection, including short-wave infrared single-photon detectors, quantum communications and quantum enhanced imaging. In 2015, Professor Buller was awarded an EPSRC Established Career Fellowship in Quantum Technology. He is Principal Investigator of the collaborative "SPEXS" EPSRC Programme Grant. He is a Fellow of the Institute of Physics, a Fellow of the Optical Society of America and a Fellow of the Royal Society of Edinburgh.

InP-based SPADs for Automotive Lidar

Mark A. Itzler
Argo AI, 2555 US Route 130 S., Cranbury, NJ 08512 USA

Over the past decade, the benefits of single-photon sensitive Geiger-mode lidar have been established for high-altitude airborne applications, and this sensing technology is now poised for much broader deployment in 3D imaging systems for automotive platforms. A key innovation enabling these systems has been the development of shortwave infrared focal plane arrays based on InP/InGaAs single-photon avalanche diodes (SPADs) with single-photon sensitivity and sub-nanosecond timing accuracy.

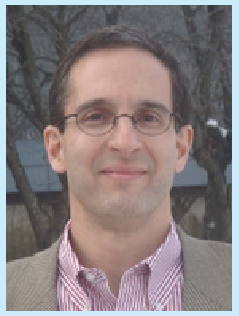
The unique combination of several factors—particularly single-photon sensitivity, the greater eye-safety of lasers at wavelengths beyond 1400 nm, and the use of arrayed semiconductor devices—provides a path toward realizing higher performance scalable lidar for automotive applications. However, deployment of InP-based SPAD technology for automotive lidar [1] involves operational challenges that are quite distinct from those encountered in deploying these sensors on airborne platforms [2]. As examples, device operation at substantially higher temperatures and reliability characteristics commensurate with automotive requirements are being addressed for the first time. Additionally, to meet the needs of these new platforms, we have significantly reduced pixel pitch relative to the pitch of InP/InGaAs SPAD arrays demonstrated previously [3].

In this talk, I will review work being done on the development of InP-based SPADs at Argo to support next generation automotive lidar deployment on autonomous vehicles, and I will compare recent results with those obtained from past SPAD development work [3] supporting Geiger-mode cameras for airborne applications.

[1] M. A. Itzler, M. Entwistle, S. Wilton, I. Kudryashov, J. Kotelnikov, X. Jiang, B. Piccione, M. Owens, S. Rangwala, "Geiger-Mode LiDAR: From Airborne Platforms To Driverless Cars", OSA Imaging and Applied Optics Congress 2017, Applied Industrial Optics, paper ATu3A-3 (Jun 2017).

[2] W. E. Clifton, B. Steele, G. Nelson, A. Truscott, M. Itzler, M. Entwistle, "Medium Altitude Airborne Geiger-mode Mapping Lidar System," Proceedings of the SPIE 9465, 946506 (May 2015).

[3] M. A. Itzler, M. Entwistle, U. Krishnamachari, M. Owens, X. Jiang, K. Slomkowski, S. Rangwala, "SWIR Geiger-mode APD detectors and cameras for 3D imaging," Proceedings of the SPIE 9114, 91140F (June 2014).



Mark Itzler is VP Lidar at Argo AI, where he provides technical leadership for the development of Argo's high-performance long-range lidar product for autonomous vehicles. Mark came to Argo in 2017 through its acquisition of Princeton Lightwave Inc. (PLI), where he was Chief Executive Officer and Chief Technical Officer. Prior to joining PLI in 2003, Mark was the CTO and VP Device Engineering of the Epitaxx Division of JDSU. He has a Ph.D. in Physics from the University of Pennsylvania and completed post-doctoral work at Harvard University. His technical focus has been semiconductor photodetector technology and its application to 3D lidar imaging, single-photon detection, and fiber optic communications. He is an IEEE Fellow and an SPIE Fellow.

Custom Focal Plane Arrays of SWIR SPADs

Erik K. Duerr[1]
1. Lincoln Laboratory, Massachusetts Institu¬¬te of Technology, 244 Wood St, Lexington, MA 02421

The NASA Psyche mission is set to explore an asteroid located between Mars and Jupiter with a launch date in 2022. On-board the Psyche spacecraft is experimental demonstrator technology that will allow scientists to explore the capabilities of optical communications – a program called Deep Space Optical Communication (DSOC) led by Jet Propulsion Laboratory.

DSOC seeks to improve communications performance by developing a space-based Flight Laser Transceiver (FLT) and a ground-based transceiver to enable photon-efficient communications with equipment in deep space. An integral part to this FLT system is a high-efficiency photon-counting camera (PCC) that is able to detect both the 1064nm uplink/beacon laser photons and 1550nm downlink laser photons with low background noise, and is capable of withstanding the rigors of space-travel.

The paper details the characterization of several asynchronous Geiger-Mode Avalanche Photodiode (GmAPD) arrays developed by MIT Lincoln Laboratory for use in the PCC- specifically evaluating the temperature dependence of background noise, photon detection efficiency at 1064nm and 1550nm wavelengths, pixel lifetime testing, and angle of acceptance measurements. The results of this characterization are used to determine the nominal conditions for the device to operate in while in flight to maintain an efficient link with the ground-based transceiver.

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Dr. Erik K. Duerr is an assistant leader in the Advanced Imager Technology Group. He is pursuing research in the design and characterization of novel infrared optoelectronic devices.
Dr. Duerr is leading the development of novel photodiodes, including single-photon-sensitive avalanche photodiodes as well as novel midwave infrared photodiodes. He has been involved in the development of infrared, Geiger-mode (single photon) avalanche photodiodes for almost two decades.
Dr. Duerr has authored or coauthored numerous papers and conference presentations in the field of infrared detector technology. He has chaired technical program subcommittees for the Conference on Lasers and Electro-optics and the IEEE Photonics Conference.
Dr. Duerr received a BS degree from the University of Virginia and SM and PhD degrees from MIT, all in electrical engineering. His graduate research concerned the development of sources and detectors for millimeter-wave and terahertz radiation.

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CMOS SPAD Sensors with Embedded Smartness

Ion Vornicu[1], Ricardo Carmona-Galán[1] and Ángel Rodríguez-Vázquez[1],
1. Instituto de Microelectrónica de Sevilla (IMSE-CNM), Universidad de Sevilla -CSIC, Avda .Americo Vespucio 28, Parque Científico y Tecnológico de la Cartuja 41092 – Sevilla, Spain

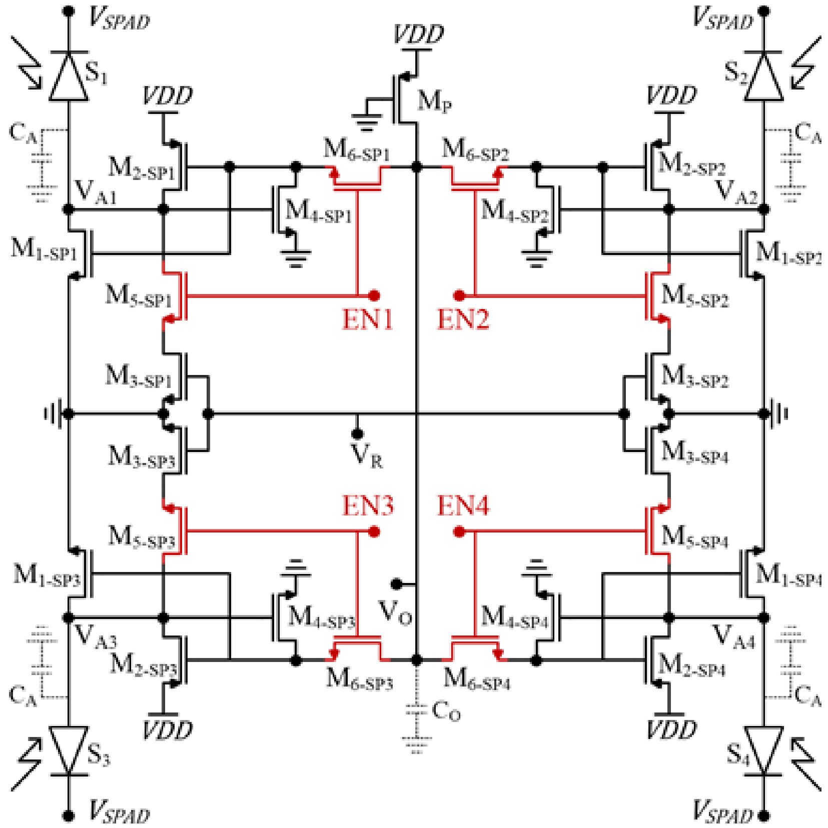

Fig. 1 Illustration of smartness at pixel-level. AQR and disable circuits are shared by SPAD clusters seeking for power-efficient waeveform and dead-time control with large fill factor. The concept (proved in CMOS 110nm technology) is scalable to larger number of SPADs.

Based on previous work on image and vision sensors [1] with integration photodiodes, we address the incorporation of intelligence at different hierarchical levels of SPAD sensor systems. Specifically:

- At pixel-level, to support the implementation of power-efficient AQR circuits for enhanced control of internal waveforms.
- At readout level, related to the design of power- and area-efficient TDCs [2] .
- At the camera system-level, to support the design of memory-efficient inter-frame histogram post-processors [3] .

The presentation also outlines architectural ideas for embedding vision analysis on SPAD sensor chips by merging concepts of Dynamic Vision Sensors and Feature-Based Vision Sensors that are adapted from non-SPAD based architectures.

[1] A. Rodríguez-Vázquez et al., "CMOS Vision Sensors: Embedding Computer Vision at Imaging Front-Ends". IEEE CIrcuits and Systems MagazIne, Vol. 2ndQuarter 2018, pp. 90-107, April 2018.
[2] I. Vornicu, R. Carmona-Galán and A. Rodríguez-Vázquez, "Arrayable Voltage-Controlled Ring-Oscillator for Direct Time-of-Flight Image Sensors". IEEE Trans. on Circuits and Systems-I, Vol. 64, No. 11, pp. 2821-2834, Nov. 2017.
[3] I. Vornicu, R. Carmona-Galán and A. Rodríguez-Vázquez, "Compact Real-Time Inter-Frame Histogram Builder for 15 Bits High-Speed ToF-Imagers based on Single-Photon Detection". IEEE Sensors Journal, Vol. 19, pp. 2181-2190, March 2019.

Ángel Rodríguez-Vázquez (IEEE Fellow, 1999) received the Ph.D. degree in Physics-Electronics (Universidad de Sevilla, 1982). After stays at the University of California-Berkeley and Texas A&M University, he became a Full Professor of Electronics at the University of Sevilla in 1995. In 2001, he was the main promotor of AnaFocus Ltd. and served it as CEO until June 2009, when the company reached maturity as a worldwide provider of smart CMOS imagers. The company was acquired by E2V in 2014 and is currently part of Teledyne Technologies. He also participated in the foundation of the Hungarian start-up AnaLogic Ltd. Starting in 2019 he is a part of the team of promotors on a new start-up: Photonvis. He has eleven patents filed; AnaFocus and Photonvis started based on patents co-authored by him on vision chip architectures and SPAD sensors, respectively.
His research embraces smart imagers, vision chips, and biomedical circuits, always with an emphasis on system integration. His publications have some 9,900 citations. He has an h-index of 49 and an i10-index of 193 (Google Scholar). He got the 2019 Mac Van

Modelling TDC Circuit Performance for SPAD Sensor Arrays

Daniel Van Blerkom
Forza Silicon (Ametek), 2947 Bradley St, Suite 130, Pasadena, CA, 91107, USA

The time-to-digital converter (TDC) is a critical circuit component in a SPAD Time-of-Flight (TOF) sensor, as it determines the time-resolving capability and throughput of the sensor. We report on Forza's recent experience with digital TDC circuits, specifically the challenges in designing large arrays of TDC channels. A common SPAD sensor architecture is to share multiple SPADs with a single TDC. This sharing is motivated by the high expense in circuit area and power for a TDC, as well as the sparsity of events from a single SPAD given its dead time and the statistics of photon arrival. In addition, to mitigate pile-up and increase the number of photons detected on each laser pulse, many scanning systems rely on combining and histogramming events from multiple-element SPAD detectors [1].

When many SPADs share a TDC, to avoid missing any SPAD events during the pulse return, the TDC should be able to produce a new result at every time step. It is also desirable to run the TDC as fast as possible, to improve the timing resolution [2]. However, this introduces a bottleneck at the interface from the TDC to the histogram memory. To keep the memory speed from limiting the TDC resolution, the interface can implement pipelining and rotate among multiple memory banks [3].

However, each additional memory bank increases the average power of the channel and the complexity of the multiplexing logic into the memories, which further complicates the timing closure. The peak current spikes also increase with additional memories, and these cause power supply and ground disturbances that can affect the timing of the TDC.

We investigate this trade-off in digital circuit complexity versus timing resolution in the ST Microelectronics 40nm SPAD process. We relate the TDC resolution to the area and power of the TDC and histogram circuit, and the effect of the power supply excursions on the timing jitter of the front end. Finally, we discuss design approaches to mitigate the effect of the power supply induced jitter.

[1] S. Patanwala, I. Gyongy, N. Dutton, B. Rae, R. Henderson, "A Reconfigurable 40 nm CMOS SPAD Array for LiDAR Receiver Validation," Int'l Image Sensor Workshop, 2019.
[2] T. Al abbas, N. Dutton, O. Almer, N. Finlayson, F. Mattioli Della Rocca and R. Henderson, "A CMOS SPAD Sensor with a Multi-Event Folded Flash Time-to-Digital Converter for Ultra-fast Optical Transient Capture", IEEE Sensors Journal, vol. 18, no. 8, pp. 3163-3173.
[3] C. Niclass, M. Soga, H. Matsubara, M. Ogawa and M. Kagami, "A 0.18- µm CMOS SoC for a 100-m-Range 10-Frame/s 200x96-Pixel Time-of-Flight Depth Sensor," IEEE Journal of Solid-State Circuits, vol. 49, no. 1, pp. 315-330, Jan. 2014.

Daniel Van Blerkom Co-founder and CTO of Forza Silicon, which in 2018 became a unit of Ametek, Inc. Prior to Forza Silicon, Daniel was with Photobit Corporation from 1998 to 2001. He holds 16 image sensor patents and was co-recipient of the 2007 Jack Raper Award for Outstanding Technology Directions Paper at ISSCC. He joined the Board of Directors of the International Image Sensor Society (IISS) in 2017. He holds a Ph.D. in Applied Physics from the University of California, San Diego.

Day 3 - Abstract Presentations

Data processing of SPAD sensors for high quality imaging

Chao Zhang[1], Shuang Li[1], Jieyang Jia[1], Zhijie Ma[1], Kai Zang[1]
1. Adaps Photonics Inc.

Single Photon Avalanche Diode Image Sensor (SPADIS) is gaining increasing interest in consumer electronics, advanced driver assistance systems (ADAS)andscientific research. With the capability to sense single-photon and to acquire complete profile of incident photon signal, SPADIS has demonstrated great potential to revolutionize the imaging world as it offers powerful direct time-of-flight (dToF) 3D imaging solution.

Compared to the pixels in traditional CMOS image sensors, in SPADIS each SPAD pixel generates serveral orders of magnitude more data, which creates challenges in subsequent data processing and system integration. Nevertheless, real-world 3D sensing applicationswould require new on-chip methods to process the enormous volumes of data from SPAD imaging, with the constraint of limited energy budget and pixel resolution. In most cases, this limits the actual pixel resolution. In this talk, we present a newly developed SPADIS with resolution of 80x60, featuring shared TDC and rolling shutter readout.

We also present a new algorithm to process this massive data from our new 80x60 SPADIS sensor. These new methods would improve the image resolution and quality both in timing and spatial dimensions.

[1] C. Zhang, S. Linder, I. Antolovic, J. M. Pavia, M. Wolf, E. Charbon, " A 30-frames/s, 252 x 144 SPAD Flash LiDAR With 1728 Dual-Clock 48.8-ps TDCs, and Pixel-Wise Integrated Histogramming", JSSC, 2018.

S. W. Hutchings, N. Johnston, I. Gyongy, T. A. Abbas, N. A. W. Dutton, M. Tyler, S. Chan, J. Leach, R.K. Henderson, " A Reconfigurable 3-D-Stacked SPAD Imager With In-Pixel Histogramming for Flash LIDAR or High-Speed Time-of-Flight Imaging", JSSC, 2019.

Chao Zhang received the M.S. degree from Jiangnan University, Wuxi, China, in 2011, and Ph.D. degree from Delft University of Technology, Delft, The Netherlands in 2019, with a focus on single photon imaging with single-photon avalanche diode (SPAD) sensors. From 2011 to 2012, he was a Digital Design Engineer with Nvidia. He is now working at Adaps photonics, China, on SPAD image sensor design.

Scalable, Multi-functional CMOS SPAD arrays for Scientific Imaging

L. Gasparini[1], M. Moreno Garcia[1,2], M. Zarghami[1], L. Parmesan[1], H. Xu[1,3], M. Unternährer[4], B. Bessire[4], A. Stefanov[4], M. Perenzoni[1]
1. Fondazione Bruno Kessler, Trento, Italy
2. now with Sony, Norway
3. now with Ams, Switzerland
4. University of Bern, Bern, Switzerland

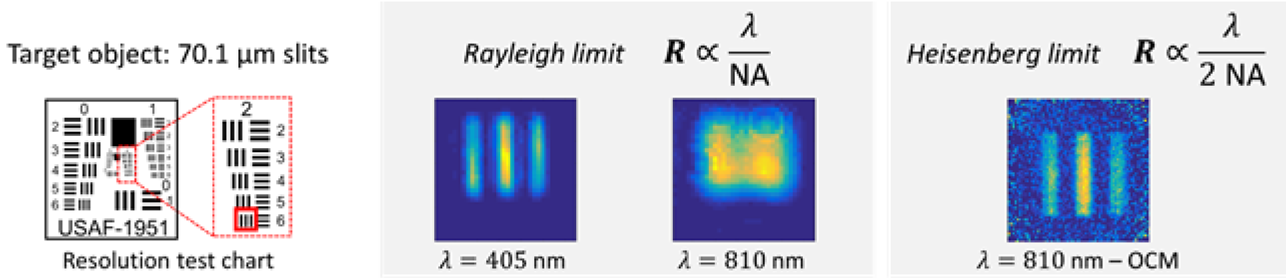

Fig.1 Super-resolution Quantum Imaging at the Heisenberg limit using the 32×32 SPAD imager [1].

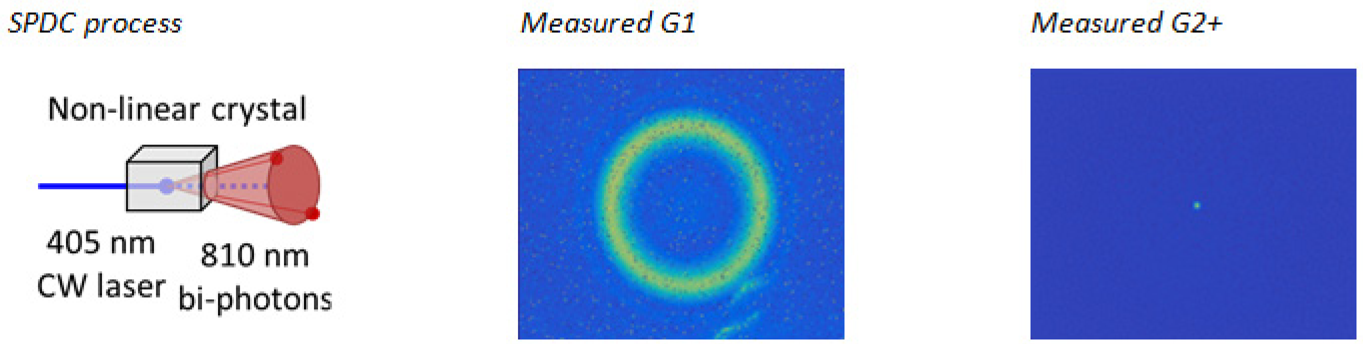

Fig. 2. Far-field acquisition of SPDC bi-photons using the 60k pixel SPAD imager. Photons of each pair reach the focal plane < 1 ps apart and in opposite position with respect to a common centroid.

The unique combination of imaging and timestamping capabilities at the level of single photons make CMOS SPAD arrays attractive for scientific applications like quantum imaging, biomedical imaging and high-energy physics. Nevertheless, the market is still dominated by EM-CCDs, intensified cameras and scanning systems based on vacuum or superconducting detectors. An effort is required to increase the overall efficiency of CMOS-SPAD and make them competitive in this market.
In 2018 we presented a 32×32 CMOS-SPAD array [2] with in-pixel 200-ps TDC in 150nm CMOS std technology. Efforts have been made to shrink the size of the pixel (~45 μm) while preserving a high fill-factor (~20%). On-chip readout features which are efficient in terms of area and power exploit the sparsity of data to achieve a high duty cycle. Fig. 1 shows the results of a quantum optics experiment showing the ability of entangled photons to overcome the limits of classical optics.

Here, we introduce for the first time a new 60kpixel CMOS-SPAD imager in a 110-nm CIS technology. Pixels support multiple working modes: fine or coarse timestamping, photon counting or fast bit-plane imaging. Such a flexible approach extends the use of the detector to a wide range of scientific applications and can thus attract the interest of a market of significant size. Fig.2 shows the output of a source of momentum entangled photon pairs at a high resolution.

[2] M. Unternährer et al., "Super-resolution quantum imaging at the Heisenberg limit," Optica, 2018
[3] L. Gasparini et al., "A 32× 32-pixel time-resolved single-photon image sensor with 44.64 μm pitch and 19.48% fill-factor with on-chip row/frame skipping features reaching 800kHz observation rate for quantum physics applications.", ISSCC, 2018

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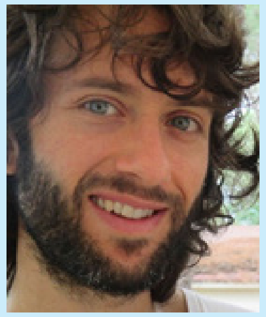

Leonardo Gasparini received the Ph.D. in Information and Communication Technologies in 2011, from the University of Trento, working with ultra-low-power camera systems. During his studies he had the opportunity to work as a visiting researcher at the University of California, Santa Cruz. Currently, he works as a researcher at Fondazione Bruno Kessler, where he is involved in the design of CMOS image sensors, mostly oriented towards single-photon image sensors applied to biomedicine, particle physics, quantum optics and LiDAR applications. In 2017, he has been a visiting researcher at the Institute of Applied Physics of the University of Bern, working on the detection of entangled photons for super-resolution imaging using CMOS-SPAD arrays.

Small and Smart Pixels

Edoardo Charbon
EPFL, Neuchâtel, Switzerland

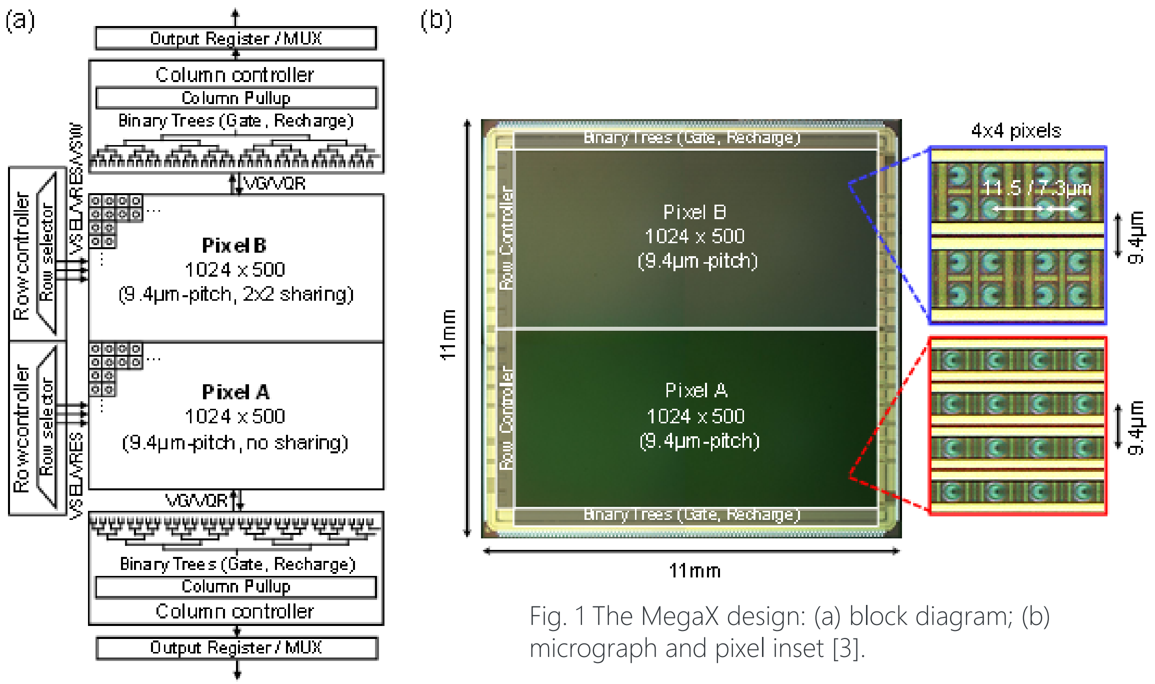

Fig. 1 The MegaX design: (a) block diagram; (b) micrograph and pixel inset [3].

Recent progress in large-format SPAD cameras has received great attention from communities interested in performing time-resolved imaging at high speed for scientific and consumer applications [1,2,3]. Three problems have emerged. In primis, the pitch of SPADs, which is still too large to enable multi-megapixel cameras. This issue has been addressed with SPADs that share diffusions and guard rings [4] and even more exotic structures, like the vertical APDs [5] and charge-focusing SPADs [6].

The second problem is power. Current megapixel SPAD architectures dissipate several hundred milliwatts, while further scaling up will certainly require rethinking pixels and readout architectures, often rediscovering some of the techniques CIS counterparts have used for decades. Given the high voltage required by SPADs and the dynamics involved in photon detection, this will prove a formidable challenge.

The third problem is data. Due to the way images are created, stored, and read out in SPAD chips, data management will be key to keep new emerging image sensors viable. We propose the concept of smart pixels and smart pixel clusters that will ensure flexibility and locally-oriented processing involving neural nets and machine learning. These kinds of architectures will require 3D integration and BSI/FSI SPAD arrays with integrated optics.

[1] N.A.W. Dutton, I. Gyongy, L. Parmesan, S. Gnecchi, N. Calder, B. Rae, , S. Pellegrini, L.A. Grant, R.K. Henderson, "A SPAD-Based QVGA Image Sensor for Single-Photon Counting and Quanta Imaging", IEEE Trans. Electron Devices, 63(1), 189-196, Jan. 2016. Doi: 10.1109/TED.2015.2464682.
[2] A.C. Ulku, C. Bruschini, I.M. Antolović, Y. Kuo, R. Ankri, S. Weiss, X. Michalet, E. Charbon, "A 512x512 SPAD Image Sensor With Integrated Gating for Widefield FLIM", IEEE JSTQE, 25(1), 6801212, Aug. 2018. Doi: 10.1109/JSTQE.2018.2867439.
[3] K. Morimoto, A. Ardelean, M.-L., Wu, A.C. Ulku, I.M. Antolovic, C. Bruschini, E. Charbon, "A megapixel time-gated SPAD image sensor for 2D and 3D imaging applications", Optica, 7(4), 346-354, Apr. 2020. Doi: 10.1364/OPTICA.386574.
[4] K. Morimoto and E. Charbon, "High fill-factor miniaturized SPAD arrays with guard-ring-sharing technique", Optics Express, 28(9), 13068-13080, Apr. 2020. Doi: 10.1364/OE.389216.

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[5] T. Okino, S. Yamada, Y. Sakata, S. Kasuga, M. Takemoto, Y. Nose, H. Koshida, M. Tamaru, Y. Sugiura, S. Saito, S. Koyama, M. Mori, Y. Hirose, M. Sawada, A. Odagawa, T. Tanaka, "1200×900 6µm 450fps Geiger-Mode Vertical Avalanche Photodiodes CMOS Image Sensor for a 250m Time-of-Flight Ranging System Using Direct-Indirect-Mixed Frame Synthesis with Configurable-Depth-Resolution Down to 10cm", IEEE ISSCC 2020. Doi: 10.1109/ISSCC19947.2020.9063045.
[6] K. Morimoto, "Charge-Focusing SPAD Image Sensors for Low Light Imaging Applications", ISSW 2020.

Edoardo Charbon (SM'00 F'17) received the Diploma from ETH Zurich, the M.S. from the University of California at San Diego, and the Ph.D. from the University of California at Berkeley in 1988, 1991, and 1995, respectively, all in electrical engineering and EECS. He has consulted with numerous organizations, including Bosch, X-Fab, Texas Instruments, Maxim, Sony, Agilent, and the Carlyle Group. He was with Cadence Design Systems from 1995 to 2000, where he was the Architect of the company's initiative on information hiding for intellectual property protection. In 2000, he joined Canesta Inc., as the Chief Architect, where he led the development of wireless 3-D CMOS image sensors. Since 2002 he has been a member of the faculty of EPFL, where is a full professor since 2015. From 2008 to 2016 he was with Delft University of Technology's as Chair of VLSI design. He has been the driving force behind the creation of deep-submicron CMOS SPAD technology, which is mass-produced since 2015.

His interests span from 3-D vision, LiDAR, FLIM, FCS, NIROT to super-resolution microscopy, time-resolved Raman spectroscopy, and cryo-CMOS circuits and systems for quantum computing. He has authored or co-authored over 350 papers and two books, and he holds 22 patents. Dr. Charbon is a distinguished visiting scholar of the W. M. Keck Institute for Space at Caltech, a fellow of the Kavli Institute of Nanoscience Delft, a distinguished lecturer of the IEEE Photonics Society, and a fellow of the IEEE.

High speed 2-photon fluorescence lifetime imaging of protein-protein interactions with a swept array microscope

Simon P. Poland[1], Maddy Carpenter[1], Kelly O'Toole[2], Melissa Méndez[1], Hanning Mai[3], Richard Walker[4], Andrea Serio[2], Robert K. Henderson[3] & Simon M. Ameer Beg[1]

1. School of Cancer and Pharmaceutical Sciences, Kings College London.
2. Francis Crick Institute, London.
3. Institute for Integrated Micro and Nano Systems, University of Edinburgh,
4. Photon Force Ltd., Edinburgh, UK

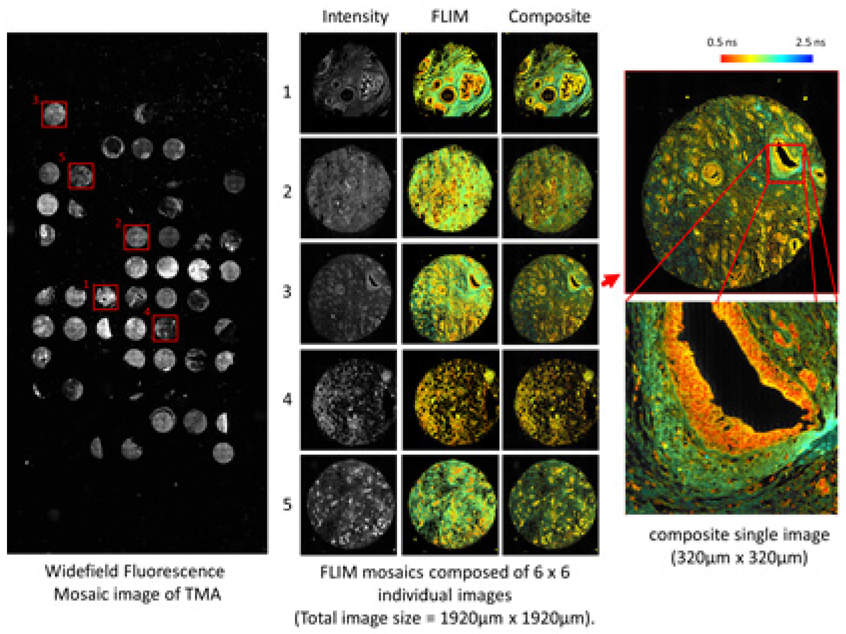

Fig. 1 High Content Fluorescence Lifetime Imaging of H&E stained Human Breast Cancer Tissue Microarray. [Right] Fluorescence Intensity overview from Widefield Microscope; [Middle] Selected Tissue Cores acquired with high speed confocal fluorescence lifetime Imaging of 6x6 image tiles of 1024x1024 pixels; [Right Top] Highlight single core image; [Bottom Right] Single fluorescence lifetime image tile acquired in 10s.

For high precision FLIM, time-correlated single photon counting (TCSPC) is unparalleled in its measurement accuracy particularly for multi-exponential decays. Until recently, high speed FLIM could only be performed using modulated or time-gated image intensifier systems as TCSPC was fundamentally limited with respect to photon counting rate in implementations of laser scanning microscopy. This has restricted its use in a number of time-critical applications including live cell imaging. We have previously demonstrated multifocal multiphoton fluorescence lifetime imaging microscopy (MM-FLIM) for applications utilizing TCSPC which increases the acquisition rate of high-resolution fluorescence lifetime imaging by a factor of 64 by parallelizing excitation and detection [1]. The system consists of a two dimensional array of ultrafast beams which are then optically conjugated with a Megaframe camera consisting of 32×32 individual 10-bit time-to-digital convertor (TDC) array with integrated single-photon avalanche diodes (SPADs), each of which operates in TCSPC mode and provides FLIM capability.

Here we report the development of a novel massively parallelised multifocal multiphoton FLIM laser scanning high speed microscope that we term SWept Array Microscopy (SWARM) with the ability to acquire ~250 million photon arrival events per second. This allows us to operate in full frame mode (32×32 beamlets) unlocking more potential from the Megaframe camera for FLIM imaging. Utilising a diffractive optical element to generate the beamlet array and an innovative scanning approach we have been able to simplify and reduce the optical footprint of the system. We demonstrate the applicability of the system to live cell imaging using the PercivalHR biosensor [2] in iPSC derived neuron cultures. We demonstrate for the first time that the ratiometric PercivalHR biosensor demonstrates fluorescence lifetime contrast which can be attributed to ADP and ATP bound fractions. We will demonstrate the ability of the new system to observe dynamic changes in fluorescence lifetime at sub-second acquisition times with minimal photo-toxicity compared to single beam scanning approaches.

[1] Poland, S.P., Krstajić, N., Monypenny, J., Coelho, S., Tyndall, D., Walker, R.J., Devauges, V., Richardson, J., Dutton, N., Barber, P.R., Li, D.D-U., Suhling, K., Ng, T., Henderson, R.K., Ameer-Beg, S.M., A High Speed Multifocal Multiphoton Fluorescence Lifetime Imaging Microscope For Live-cell FRET Imaging, Biomedical Optics Express, 6(2), pp. 277-296 (2015).
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[3] Tantama, M., Martínez-François, J., Mongeon, R., Yellen, G., Imaging energy status in live cells with a fluorescent biosensor of the intracellular ATP-to-ADP ratio. Nat Commun 4, 2550 (2013).

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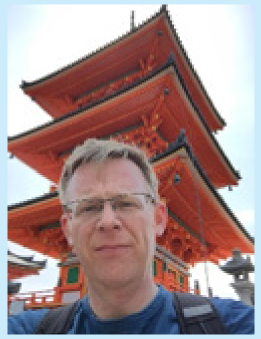

Simon M. Ameer-Beg: is a Professor within the Richard Dimbleby Laboratory of Cancer Research at King's College London (KCL). He studied Physics with Laser Physics at University of Essex before undertaking a PhD in ultrafast spectroscopy in industry with British Nuclear Fuels Ltd before moving into bioimaging and cancer research in 1998 at the Gray Cancer Institute. He has developed an interdisciplinary research portfolio principally in the field of time-resolved multiphoton fluorescence lifetime imaging (FLIM) for application to quantitative analysis of protein-protein interactions. Much of his research relates to high-content screening methodologies based on fluorescence anisotropy/lifetime for protein interaction perturbation using siRNA and biologics.

Image scanning microscopy with classical and quantum correlation contrasts

Ron Tenne[1], Gur Lubin[1], Uri Rossman[1], Ivan Michel Antolovic[2], Adrian Makowski[3], Aleksandra Sorda[3], Radek Lapkiewicz[3], Edoardo Charbon[2], Claudio Bruschini[2], Dan Oron[1]
1 - Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot, Israel
2 - School of Engineering, Ecole polytechnique fédérale de Lausanne (EPFL), Neuchâtel, Switzerland
3 - Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Progress in sensitive imagers, detecting single molecules, has fueled the super-resolution microscopy revolution in the early 2000's. The more recent development of photon-counting single-photon avalanche diode (SPAD) arrays with high temporal resolution opens exciting new avenues in super-resolved imaging. Quantum imaging is one such approach, relying on the timing of photon detections with nano-second precision. Traditionally, a lack of fast and sensitive detector arrays severely curbed their development.
In this talk I will present a novel method, quantum image scanning microscopy (Q-ISM)1, which uses photon correlations in the fluorescence of standard bio-markers and can achieve a lateral resolution up to x4 beyond the diffraction limit. A simple implementation of the method, requiring a minimal change to the standard confocal microscope, was achieved using a high-performance 23-pixel SPAD array2. Although the detection efficiency of such arrays, for red fluorescence, is somewhat smaller than that of individual custom SPADs, it is a highly cost-effective solution that can be scaled up to support widefield and multi-beam applications.
More recently, we harnessed the potential of classical, rather than quantum, correlations to produce similar improvements in resolution. Super-resolution optical fluctuation imaging (SOFI) was the first method to break the diffraction limit by taking advantage of the natural fluctuations in the fluorescence intensity of standard labels3. However, much of the extra information stored in these fast fluctuations is lost when using cameras with a minimal exposure time of more than a millisecond. As in the case of Q-ISM, we combine the correlation contrast together with a confocal microscopy technique, image scanning microscopy (ISM), to achieve a resolution improvement in all three dimensions. This combination allows a dramatic speed-up with respect to Q-ISM, requiring an exposure time of a few milliseconds per scan pixel4.

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3. Dertinger, T., Colyera, R., Iyer, G., Weiss, S. & Enderlein, J. Fast, background-free, 3D super-resolution optical fluctuation imaging (SOFI). Proc. Natl. Acad. Sci. U. S. A. 106, 22287–22292 (2009).
4. Sroda, A. et al. Super-resolution optical fluctuation image scanning microscopy (SOFISM). arXiv (2020). doi:10.1364/fio.2019.ftu6a.4

Ron Tenne
Following his undergraduate studies in the Tehchnion (Israel), Ron continued for a MSc and PhD in physics at Weizmann Institute (Israel) under the supervision of prof. Dan Oron where he is currently a postdoc. He is set to join the group of prof. Alfred Leitenstorfer at University of Konstanz (Germany) in a few months to work on ultrafast spectroscopy of nano-particles.
His research interests can be roughly divided to two parts. The first is developing microscopy techniques based on the extra information stored in the correlation of the photon stream. In addition, Ron studies such photon correlations in the emission of colloidal quantum dots to gain new spectroscopic insight. He received the Israel Dostrovsky award of excellence for his PhD thesis and recently the Minerva foundation fellowship for a his upcoming postdoc.

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Imaging oxygenation by near-infrared optical tomography based on SPAD image sensors

A. Kalyanov[1], J. Jiang[1], A. Di Costanzo Mata[1], S. Lindner[1,2], C. Zhang[2], E. Charbon[2], M. Wolf[1]
1. Biomedical Optics Research Laboratory (BORL), Dept. of Neonatology, University Hospital Zurich, University of Zurich, Switzerland
2. Advanced Quantum Architecture Laboratory, EPFL, 2002 Neuchâtel, Switzerland

Fig. 1: NIROT measuring a realistic phantom of a preterm head in an incubator.

Near-infrared optical tomography (NIROT) images tissue oxygen saturation inside the human body. Oxygenation is a parameter of tremendous importance in many clinical fields. State-of-the-art implementations of NIROT are based on up to 32 photomultiplier tubes (PMTs) as detectors that were already successfully tested in vivo e.g. for neonatal brain, achieving ~1cm spatial resolution. For clinical applications, a higher spatial resolution, in the order of mm, is desired. This requires increasing the number of detectors, which is difficult with current time resolved (TR) systems based on PMTs. These systems are already bulky and cannot be upscaled. Here, we solve this issue by replacing PMTs with Piccolo, a 32x32 array of single-photon avalanche diodes (SPADs), which also includes a bank of time-to-digital converters (TDCs), thus dramatically increasing resolution both in space and in time. This increased complexity also forced us to develop a new concept of NIROT. The aim of this paper is to introduce this new concept and to present the first laboratory and in vivo tests.

Piccolo with microlenses has a relatively high PDE of 10.0 % at 800nn and it is optimized for NIROT. It has 116ps time response and a fill factor of 28%. Since it is not possible to couple the sensor with 1024 optical fibers, which to transmit the light to the tissue, a novel concept has been developed to take advantage of Piccolo. Light from a super continuum laser (SuperK Extreme EXR-15, NKT, Danmark), where specific wavelengths are selected by an acoustooptical filter is guided through a fiber switch which currently serves 11 source positions. The laser output power is constantly monitored by a power meter (PM100USB, Thorlabs, USA) which is introduced into the optical path. The source fibers are embedded in a source ring to be placed in close proximity to the tissue. The light emerging from the tissue inside the ring (diameter of 25mm) is projected onto Piccolo by a lens.

We present the new generation TD multispectral NIROT based on Piccolo. The NIROT instrument was successfully tested in phantoms for localization and quantitative accuracy. The experiments show good agreement of acquired with simulated data. Moreover, results of a first in vivo experiment, a brain activation study in a healthy adult subject will be presented, which shows a typical activation pattern.

Martin Wolf is professor of Biomedical Optics at the University of Zurich. He received his diploma in Electrical Engineering and his Ph.D. in Biomedical Engineering from ETH Zurich. He worked as postdoctoral research associate at the University of Illinois at Urbana-Champaign. Prof. Wolf heads the Biomedical Optics Research Laboratory, which specializes in developing techniques to non-invasively measure and quantitatively image oxygenation and other biomarkers of brain, muscle, tumor and other tissues. His aim is to translate these techniques to clinical application for the benefit of adult patients and preterm infants. He has co-founded two startup companies.

Raman spectroscopy utilizing a time resolving CMOS SPAD line sensor with a pulsed laser excitation

Ilkka Nissinen[1], Jere Kekkonen[1], Tuomo Talala[1]
1. University of Oulu, Circuits and Systems Research Unit

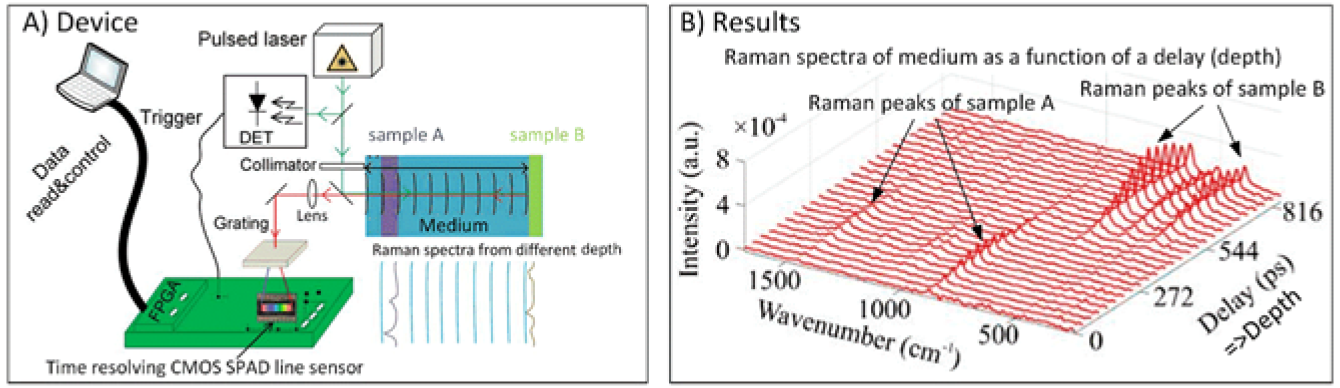

Fig. 1 A) A Raman spectrometer utilizing a time resolving SPAD line sensor and a pulsed laser, B) Raman spectra (and thus chemical compounds) of different samples inside medium can be detected and the depths of these samples can be derived by means of a time resolving SPAD sensor.

Raman spectroscopy is a powerful tool to be used in many applications where chemical compounds of samples have to be distinguished. The main challenge of Raman spectroscopy is a high fluorescence background of many samples, especially biological and mineral samples. Fortunately, the fluorescence photons can be partly rejected by using a pulsed laser ~100 ps and a time-gated detector [1,2].

As Raman scattering occurs only during the 100 ps laser pulse but fluorescence has a lifetime of nanosecond scale, time-gated detection during the laser pulse collects all Raman photons while rejecting the most of fluorescence photons. CMOS technologies have enabled to fabricate time resolving SPAD arrays for Raman spectroscopy and the complexity of a line sensor could have been decreased by integrating all the time resolving electronics and SPADs in the same die [3,4].

In CMOS technology, additional functionalities can also be integrated in the same die with a line sensor. This presentation shows how the time domain signal processing can be utilized in Raman spectroscopy. It can be practically used to measure Raman spectra of different samples inside a semitransparent medium as a function of depth when the time-of-flight of Raman scattered photons correponds to different depths or distances [4]. A short laser pulse and time-gating (constructed electrically or by post-processing TOF results) can effectively suppress background radiation and the fluorescences of medium or samples inside the medium. The quality of spectra can be further improved by means of a time domain compensation method [5].

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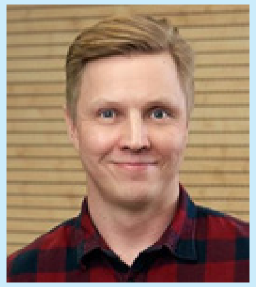

Ikka Nissinen received the M.Sc. (Eng.) and Dr. Tech. degrees in electrical engineering from the University of Oulu, Finland, in 2002 and 2011, respectively. Since 2018, he has been an Associate Professor of Analogue and Mixed-Signal Microelectronic Circuit Design with the Circuits and Systems Research Unit, University of Oulu. He is PI of two project funded by Academy of Finland, Single-photon detector array for simultaneous label-free Raman and fluorescence lifetime spectroscopy (2018-2021) and Development of a time resolving CMOS single photon avalanche diode (SPAD) sensor enabling a depth resolving Raman radar (9/2019-8/2023). His research interest includes the design of time interval measurement architecture for the integrated sensors of pulsed time-of-flight laser technologies.

Optical Wireless Communication with SPAD Receivers

Hiwa Mahmoudi[1], Michael Hofbauer[1], Bernhard Goll[1], Kerstin Schneider-Hornstein[1], Horst Zimmermann[1]
1. TU Wien, Institute of Electrodynamics, Microwave and Circuit Engineering

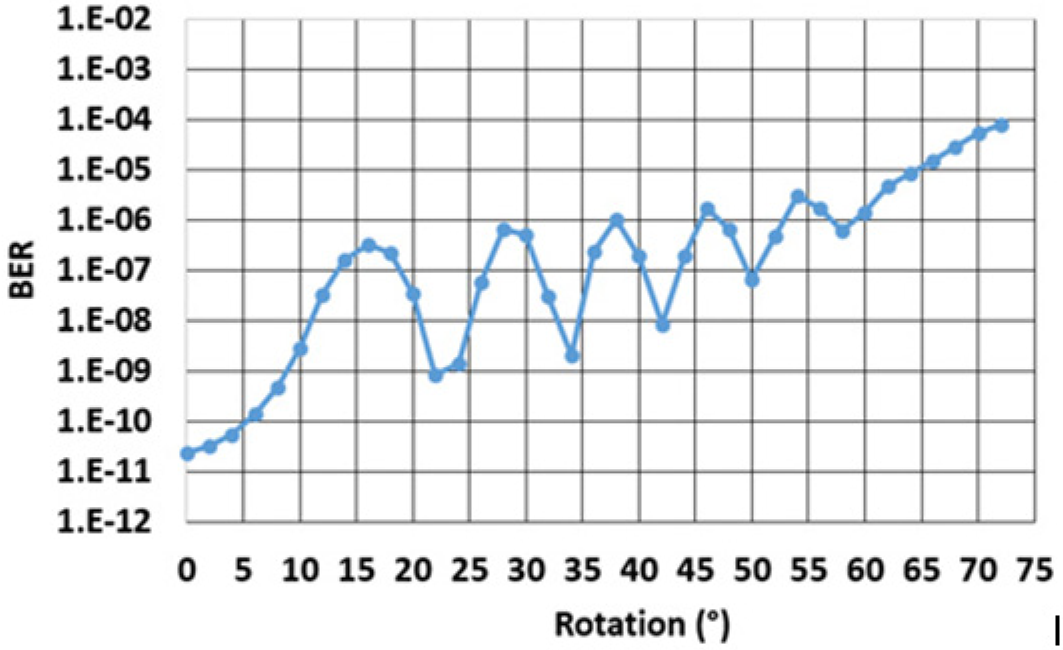

Fig. 1 BER of an APD receiver in dependence on light incidence angle.

Single-photon avalanche diode based receivers will be described. Their results in optical wireless communication (OWC) experiments will be shown. Furthermore, the influence of the incidence angle of the signal light on the BER will be investigated for SPAD receivers with the standard isolation and passivation stack on top of the photodiodes similar to the case of linear-mode APD receivers (Fig. 1) [1]. The importance of anti-reflection coating for the performance of SPAD receivers for OWC applications will be demonstrated.

[1] D. Milovancev, Tomislav Jukic, Bernhard Steindl, Paul Brandl, Horst Zimmermann, "Optical wireless communication using a fully integrated 400 µm diameter APD receiver", J. Eng., 2017, Vol. 2017, Iss. 8, pp. 506–511; doi: 10.1049/joe.2017.0247

Horst Zimmermann, received the Dr.-Ing. degree from the University Erlangen-Nürnberg working at the Fraunhofer Institute for Integrated Circuits (IIS-B), Erlangen, Germany in 1991. Then, Dr. Zimmermann was an Alexander-von-Humboldt Research-Fellow at Duke University, Durham, N.C., working on diffusion in Si, GaAs, and InP until 1992. In 1993, he joined the Chair for Semiconductor Electronics at Kiel University, Kiel, Germany, where he lectured optoelectronics and worked on optoelectronic integration. Since 2000 he is full professor for Electronic Circuit Engineering at Vienna University of Technology, Vienna, Austria. His main interests are in design and characterization of analog and nanometer CMOS circuits as well as optoelectronic integrated (Bi)CMOS circuits, in optical wireless communication, in single-photon detection and in electronic-photonic integration. Since a few years high-PDP SPADs, fast active quenchers and SPAD receivers have been investigated. He is author of two Springer books and coauthor of five more. In addition he is author and co-author of more than 550 publications. In 2002, he became Senior Member IEEE. He was primary guest editor of the Nov./Dec. 2014 issue of IEEE J. Selected Topics in Quantum Electronics on Optical Detectors: Technology and Applications.

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SPAD Arrays for Non-Line-of-Sight Imaging

Andreas Velten
University of Wisconsin - Madison

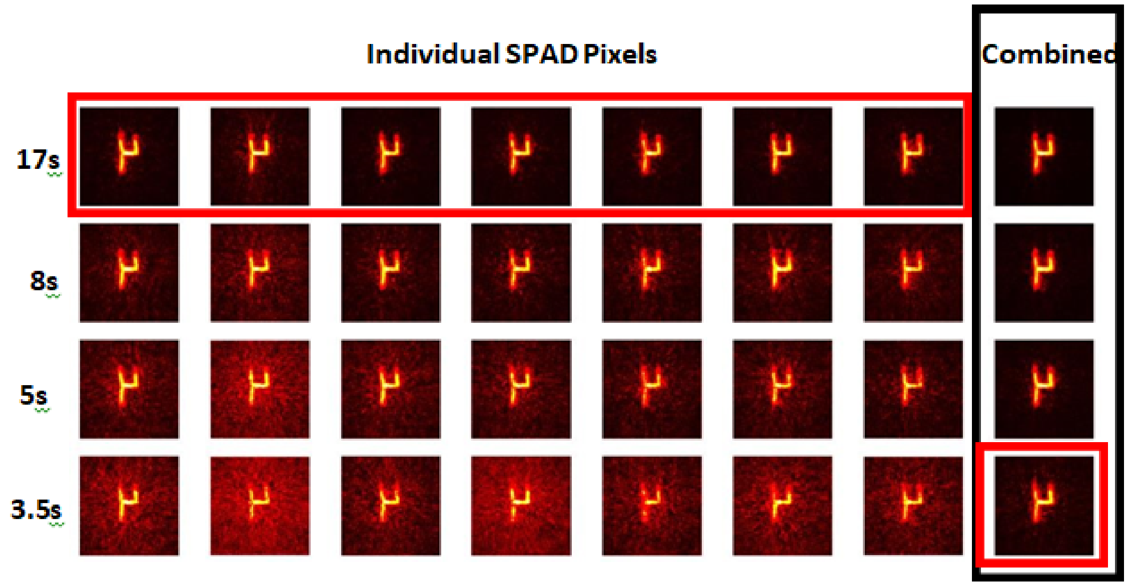

Figure 1: Images reconstructed by individual pixels of a 7 pixel SPAD array along with the reconstruction using a combination of all pixels.

Light transport in non-line-of-sight (NLOS) imaging problems can be described by wave propagation operators [1]–[4]. The reconstruction of NLOS imaginges in this framework amounts to the application of inverse wave propagation and diffraction operators such as the Rayleigh Sommerfeld Diffraction propagator or the approximate Fresnel Diffraction propagator. These operators are are well studied from line of sight imaging problems and fast computational implementations exist. In our most recent work, we develop a fast and memory-efficient diffraction-based reconstruction algorithm that processes data acquired in a scanning-free NLOS acquisition architecture [5]. This acquisition architecture uses a scanned laser with a stationary SPAD or SPAD array as opposed to the confocal single pixel scanning mode. This configuration enables the use of fast acquisition devices using as Single-Photon Avalanche Diode (SPAD) arrays, which allow NLOS signals to be captured independently in parallel. The result of combining multiple reconstruction from a small 7 pixel SPAD array are shown in Figure 1. I will discuss our capture and reconstruction strategy that allows us to both capture and reconstruct NLOS images of large scenes in seconds or less.

[1] X. Liu et al., "Non-line-of-sight imaging using phasor-field virtual wave optics," Nature, pp. 1–4, Aug. 2019, doi: 10.1038/s41586-019-1461-3.
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Andreas Velten is Assistant Professor at the Department of Biostatistics and Medical Informatics and the department of Electrical and Computer Engineering at the University of Wisconsin-Madison and directs the Computational Optics Group. He obtained his PhD in Physics at the University of New Mexico in Albuquerque and was a postdoctoral associate of the Camera Culture Group of Ramesh Raskar at the MIT Media Lab. He has won numerous awards for his research, such as inclusion in the MIT TR35 list of the world's top innovators under the age of 35. He has founded multiple companies and is co-Founder and Chief Technology officer of Onlume, a company that develops imaging solutions for medical procedures.

Participants

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Konstantinos Bantounos	PhD Researcher, the University of Edinburgh
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Lionel Graff	ST, CIS Foundry
Kevin Moore	ST
Bruce Rae	ST, Photonics Pixel Architect
Denis Rideau	ST
Alexandre Lopez	ST, Process Technology Development

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Shaohui An	Shanghai United Imaging Healthcare Co. Ltd
Andy Sun	CTO Luminwave
Risto Hyypiö	Principal R&D engineer
Renato Turchetta	Imasenic CEO
Biay-Cheng Hseih	R&D
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Michele Benetti	Senior Engineer
Sanjeeb Tripathy	Research Manager Sensor
Yusuke Matsumura	Specialist
Joris De Bondt	Sr. Image Sensor Architect
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Leonardo Gasparini	Researcher
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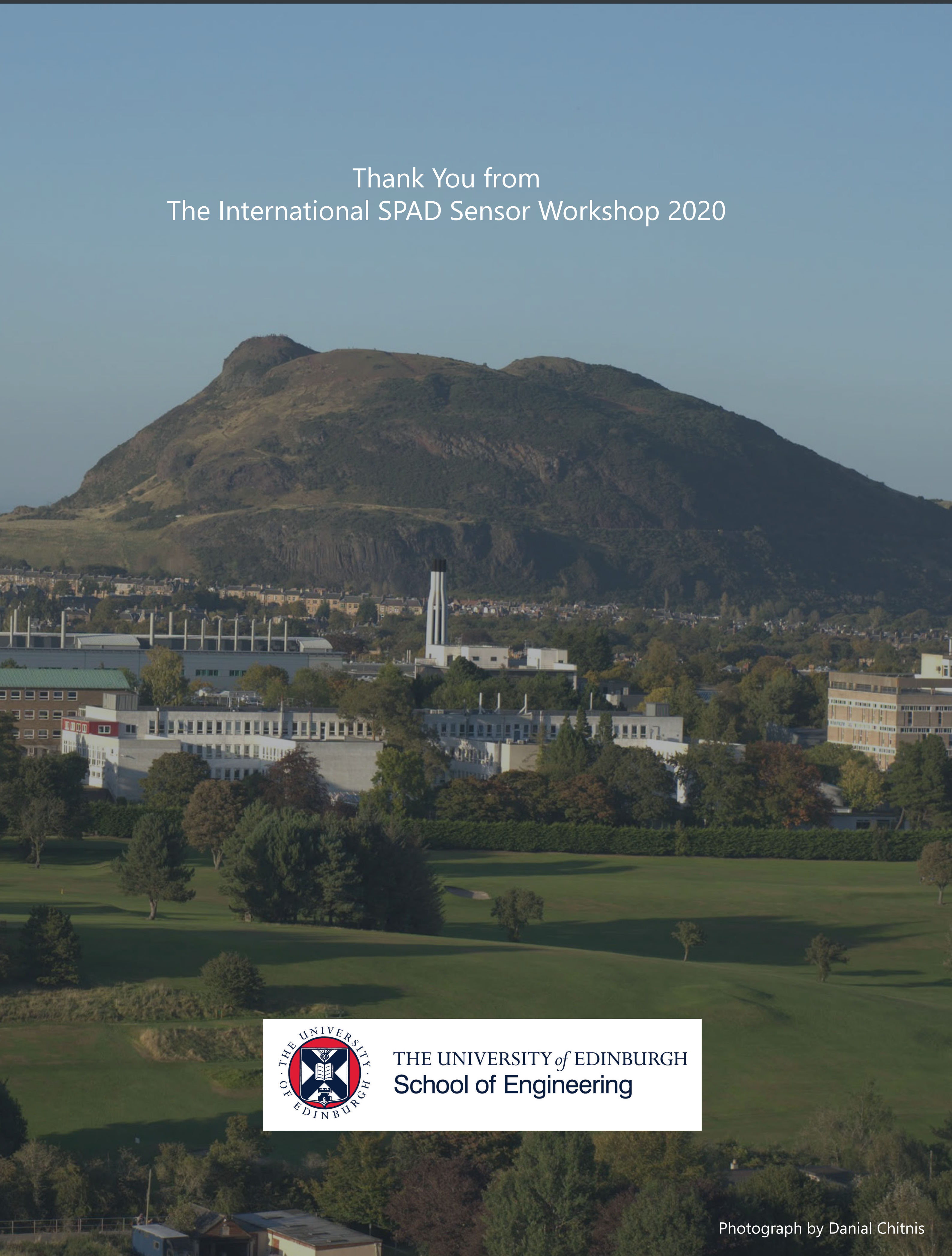

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