International Image Sensor Society

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

2018 1st International SPAD Sensor Workshop (ISSW)

February 26th – 28th, 2018
Les Diablerets, Switzerland

Sponsors

The International SPAD Sensor Workshop focuses on the study, modeling, design, fabrication and characterization of SPAD sensors. The workshop welcomes all researchers, practitioners and educators interested in SPADs, SPAD imagers, and associated applications, not only in imaging but also in other fields.
The first edition of the workshop will gather experts in all areas of SPADs and SPAD related applications in the Swiss Alps, where over 20 invited speakers will animate three days of study, information dissemination and debates. Genuine alpine activities will complete the event, everything in a spectacular setting.
The workshop is supported by the International Image Sensor Society (IISS).

Steering Committee

Sara Pellegrini, ST Microelectronics, United Kingdom

Robert K Henderson, Edinburgh University, United Kingdom

David Stoppa, AMS, Switzerland

Alberto Tosi, Politecnico di Milano, Italy

Edoardo Charbon, EPFL AQUA, Switzerland

Claudio Bruschini, EPFL AQUA, Switzerland

Local Organization

ISSW 2018 is organized by the Advanced Quantum Architecture Laboratory (AQUA) of the École Polytechnique Fédérale de Lausanne (EPFL).
The AQUA laboratory is based in Neuchâtel Switzerland. Its research mission is to model and develop hardware/software systems based on quantum devices. Particular emphasis is on high-speed 2D/3D optical sensing, embedded and reconfigurable processing architectures, single photon avalanche devices (SPAD) and design optimization techniques. Website: http://aqua.epfl.ch/

Venue

Les Diablerets is a village and ski resort located in the municipality of Ormont-Dessus in the canton of Vaud, Switzerland. The village lies at an altitude of 1,160 metres on the north side of the massif of the Diablerets in the Swiss Alps. It can be accessed by train or by road from Aigle.
Les Diablerets, is an important centre for adventure sports. Even in summer, the Glacier 3000 ski region in the heart of the Vaud Alps offers skiing and glacier enjoyment.
The workshop will take place at Eurotel Victoria, Chemin du Vernex 3, 1865 Les Diablerets.

Program — Monday, February 26th — DEVICES

Time	Event
12:00 – 13:00	**Registration**
13:00 – 13:30	**Welcome Speech** Edoardo Charbon, *EPFL*
13:30 – 14:15	**NIR SPADs and Fast-gating Circuits** Alberto Tosi, *Politecnico di Milano*
14:15 – 15:00	**Industrialised SPADs in Deep-submicron CMOS Technology** Sara Pellegrini, *ST Microelectronics*
15:00 – 15:45	**Industrialized NIR SPAD Technology in 180nm** Amos Fenigstein, *TowerJazz*
15:45 – 16:15	**Coffee break**
16:15 – 17:00	**NUV-HD and NIR-HD SiPMs and Applications** Alberto Gola, *Fondazione Bruno Kessler*
17:00 – 17:45	**SiPM and SPAD Arrays for Next Generation LiDAR** Carl Jackson, *SensL*
17:45 – 18:30	**Geiger-mode LiDAR with InP-based SPADs: From Airborne Platforms to Driverless Cars** Mark Itzler, *Argo AI*
18:30 – 20:00	**Welcome apero and dinner**

Program — Tuesday, February 27th — ARCHITECTURES

Time	Event	
08:00 – 08:45	**SPADs for FLIM** Robert Henderson, *University of Edinburgh*	
08:45 – 09:30	**From SPADs to Quantum Computing** Edoardo Charbon, *EPFL*	
09:30 – 10:15	**Multizone, Multiobject D-TOF System in 55nm** Robert Kappel, *ams AG*	
10:00 – 10:30	**Coffee break**	
10:30 – 11:15	**The Latest on SPAD Imaging in Japan** **- Event Detection and Quick Readout Schemes -** Kunihiro Asada, *University of Tokyo*	
11:15 – 12:00	**Optical Solutions for Light Intensity Enhancement in Large-Pixel Size SPAD Sensors** Ken Wu, *VisEra Technologies Company*	
12:00 – 13:30	**Lunch**	
13:30 – 14:15	**Angle Sensitive SPADs** Alyosha Molnar, *Cornell University*	
14:15 – 15:00	**A SPAD-based, Direct Time of Flight, 64 Zone, 15fps, Parallel Ranging Device Based on 40nm CMOS SPAD Technology** Bruce Rae and Pascal Mellot, *ST Microelectronics*	
15:00 – 15:45	**SPAD Based Streak Cameras** Wilfried Uhring, *University of Strasbourg*	
15:45 – 16:15	**Coffee break**	
16:15 – 17:00	**Space Secure Communications using Single Photons** Paolo Villoresi, *University of Padova*	
17:00 – 17:45	**BCD SPAD Imager with Reconfigurable Macropixels for Photon Counting, Timing and Coincidence Detection** Federica Villa, *Politecnico di Milano*	
18:00 – 20:00	**Night walk** (upon registration)	**Curling** (upon registration)
20:00	**Fondue - Chalet des Sources**	

Program — Wednesday, February 28th — APPLICATIONS

Time	Event
08:45 – 09:30	**Computational Single-photon Imaging** Gordon Wetzstein, *Stanford University*
09:30 – 10:15	**Imaging at the Speed of Light** Daniele Faccio, *University of Glasgow*
10:00 – 10:30	**Coffee break**
10:30 – 11:15	**SPAD Arrays: from Single-Molecule Detection to Wide-Field Phasor Fluorescence Lifetime Imaging** Xavier Michalet, *UCLA*
11:15 – 12:00	**LIDARs for Automotive and Industrial Applications** Lucio Carrara, *Fastree3D*
12:00 – 12:45	**Time-Domain Near Infrared Spectroscopy** Davide Contini, *Politecnico di Milano*
12:45 – 13:30	**Imaging with Entangled Photons** Matteo Perenzoni, *Fondazione Bruno Kessler*
12:00 – 13:30	**Sandwich lunch** (overlaps with previous presentations)
14:15 – 16:15	**Sledging** (upon registration)

DEVICES

NIR SPADs and Fast-gating Circuits

Alberto Tosi

Politecnico di Milano – Dipartimento di Elettronica, Informazione e Bioingegneria

InGaAs/InP Single-Photon Avalanche Diodes (SPADs) are the best choice for practical and reliable systems with high detection performance in the near-infrared wavelength range (1 µm - 1.7 µm). Recently, we developed planar InGaAs/InP SPADs with good performance in terms of photon detection efficiency (> 30%), dark-count rate (few kcps) and timing jitter (< 70 ps). The main limitation to the count rate is still afterpulsing, which can be limited by reducing the avalanche charge with short gates (few hundreds of ps). To this aim, we developed two fast-gating circuits for InGaAs/InP SPADs. The first one is a sinusoidal gating system based on the SPAD-dummy approach, with programmable gate frequency from 900 to 1400 MHz for synchronization with any external laser systems. When the system is running at 1.3 GHz, we achieved very low afterpulsing (~ 1.5%), high count rate (650 Mcount/s), high photon detection efficiency (> 30 % at 1550 nm), low dark count rate ($2.2 \cdot 10^{-5}$ per gate) and low timing jitter (< 70 ps FWHM). The second approach is based on a SiGe integrated circuit (ASIC) for sub-nanosecond gating with < 300 ps rising/falling edges and low (< 20 ps) time jitter. Such ASIC enables the development of high-performance compact modules and arrays.

Industrialised SPADs in Deep-submicron CMOS Technology

Sara Pellegrini

ST Microelectronics

We present STMicroelectronics' first fully industrialised SPAD device in advanced 40 nm technology. The advantages of integrating such a devices within an intrinsically digital technology are presented. STM succeed in integrating dedicated microlens on top of SPADs pushing overall pixel fill factor to in excess of 70%. Thanks to junction engineering, a low DCR median of 50cps at room temperature and a high PDP of 5% at 840nm is reported, while maintaining a VBD of only 15V. This enables a fully integrated chip with on chip high voltage generation and significant digital processing to be realised for use in small area Time-of-Flight products suitable for mobile application. STM's 40nm technology is automotive grade, making it suitable for a wider range of application beyond consumers.
By taking advantage of the small digital node, a larger amount of logic can be integrated inside the pixel, which is ready to be ported to a 3D stacked technology, where the logic can implemented in a fully digital dedicated layer, giving freedom to have a fully dedicated technology for the top tier SPAD.

Industrialized NIR SPAD Technology in 180nm

Amos Fenigstein[1], Tomer Leitner[1], Alex Katz[2], Avi Shoham[2], Yael Nemirovsky[2]

1. *TowerJazz, Migdal Haemek, Israel*
2. *Technion, Israel Institute of Technology, Haifa, Israel*

Though SPADs, and Silicon SPADs in particular, have been around for many years, exciting device engineers' imagination, they were rarely seen in commercial applications. However, in recent years SPADs are getting a lot of attention in the fast growing applications and markets of Time of Flight (ToF) and 3D imaging. Applications vary from gaming and gesture control to automotive, where many LiDAR systems use SPAD as their sensor. The combination of sensitivity down to very few photons with excellent time resolution makes the SPAD a superior solution for such applications. The ToF applications use near Infrared (NIR) wavelength so as not to annoy viewers' eye. Therefore, SPADs should be designed to operate well in the NIR. Due to the NIR's absorption deep in the Si, the SPAD's need to be "deep SPAD", sometimes called "bulk isolated" SPADs. This makes it harder to build fast quenching circuits which need access to both the SPAD's cathode and anode. Tower developed two kinds of SPADs: one is a "shallow" SPAD with access to both anode and cathode, and a deep SPAD with enhanced NIR sensitivity. Both the SPADs are embedded into a well-established 0.18µm CIS technology platform. This enables having all the required analog and digital circuitry on the same chip, and in addition, a fully optimized CIS pinned photo diode pixel. Both kinds of SPADs will be described along with their performance parameters. For the "two sided" SPAD a specific novel application will be presented. For the deep SPAD we will present the optimization steps (electrical and optical) and the enabling process modifications, including very high resistance resistors for compact quenching circuit and elevated large micro-lenses for optimized optics. This, of course, in addition to the SPAD diode optimization. Possible novel in-pixel circuitry will be discussed and Roadmap for further development activities.

NUV-HD and NIR-HD SiPMs and Applications

Alberto Gola

Fondazione Bruno Kessler (FBK), Center for Materials and Microsystems, Trento, Italy

Different SiPM technologies have been developed at FBK (Trento, Italy) for different applications. Near Ultraviolet, High Density (NUV-HD) SiPM technology, based on a p-on-n junction, features peak photon detection efficiency (PDE) of 65% at 410 nm, Dark Count Rate (DCR) in the order of 50 kHz/mm2, correlated noise of 10% at 55% PDE. Sensitivity remains high down to 320 nm, with a PDE of 48% (in package). Single Photon Timing Resolution (SPTR) is below 30 ps FWHM, when measured on single SPAD with covered edges, and 75 ps FWHM for SiPMs with active areas of 1x1 mm2. NUV-HD SiPMs provide state-of-the art 85 ps FWHM coincidence resolving time (CRT) in PET applications, when used to readout the light of a Ca co-doped LYSO crystal. The low-electric-field variant of the NUV-HD technology (NUV-HD-LF) was optimized to operate at cryogenic temperatures and features a DCR of a few mHz/mm2 at 77 K. At this temperature, few-photon counting capability was demonstrated using a 24 cm2 SiPM array coupled to a single analog readout channel: the measured S/N was 13.8 on the single photon peak. Ongoing optimizations include the development of devices with extended deep-UV sensitivity: preliminary results show a PDE of 20 % at 178 nm. Focusing on the improvement of sensitivity at longer wavelengths, FBK has recently developed a NIR-HD SiPM technology, using an n-on-p junction and a thicker epitaxial layer. Thanks to the tuning of the electric field for better charge collection, recent results show a PDE of 20% at 850 nm and 13.5% at 900 nm with 25 µm cell pitch at 10 V excess bias.

SiPM and SPAD Arrays for Next Generation LiDAR

Carl Jackson

SensL

Long distance LiDAR systems require high sensitivity to detect the weak return laser echos from low reflective objects. Silicon photomultipliers (SiPM) enable single-photon sensitivity thanks to the Geiger mode operation which provides high timing accuracy and high internal gain that overcomes the amplification noise limitation of external amplifiers for typical linear photodiodes (PIN and ADP). The next generation LiDAR systems must satisfy the industry requirement for staring LiDAR receivers. To preserve the long distance performance, a high pixelization of compact SiPM receivers is required. Alternatively, SPAD arrays provide single-photon sensitivity together with a high pixelization, fast readout and low noise. SensL will present solutions for high sensitivity and low noise SiPM and SPAD array based LiDAR receivers for a large variety of applications such as outdoors high rate automotive LiDAR systems.

Geiger-mode LiDAR with InP-based SPADs: From Airborne Platforms to Driverless Cars

Mark Itzler

Argo AI

The operation of avalanche photodiodes in Geiger mode provides single-photon detection with excellent timing accuracy on a scalable semiconductor device platform. For detection in the shortwave infrared (SWIR) region of the optical spectrum, single-photon avalanche diodes (SPADs) based on the InGaAs/InP materials system and designed to operate in Geiger mode have begun to mature over the past decade. Discrete SWIR SPAD detectors have enabled significant advances in quantum communications in optical fiber, and arrays of these detectors have been central to the development of single-photon imaging in the SWIR band. In particular, the use of InP-based arrays of Geiger-mode detectors for light detection and ranging (LiDAR) from airborne platforms enables the high-rate collection of 3D point cloud imagery from extremely long (>10 km) stand-off distances and has resulted in order-of-magnitude increases in performance metrics such as area coverage rate and 3D image resolution. More recently, we have applied Geiger-mode technology to shorter range LiDAR systems designed for automotive applications. The combination of two factors—single-photon sensitivity and the greater eye-safety of lasers at wavelengths beyond 1400 nm—provides disruptive automotive LiDAR performance that will be essential to future autonomous vehicle navigation.

ARCHITECTURES

SPADs for FLIM

Robert K. Henderson

University of Edinburgh

This talk will compare three recent SPAD imagers aiming to provide competitive performance levels with other scientific imagers such as EMCCD or sCMOS sensors. The three cases are (1) a 256x256, 100 kfps, 61% fill-factor 16 µm pitch binary image sensor (2) a 320x240 20kfps microlensed 50% effective fill-factor, 8 µm pixel pitch analogue photon counting imager (3) a 128x128, 45% fill-factor, 500fps digital photon counting imager. Imaging examples will demonstrate that the fast frame, noiseless frame summation and picosecond time resolution extend the capabilities of existing sensors enabling particle tracking, fluorescence lifetime imaging and superresolution localization imaging. New frame boundary-free image processing approaches such the smart aggregation technique and motion distortion correction become possible with the oversampled read-noiseless data from these cameras. Despite around 4x less sensitivity to an EMCCD camera we are able to obtain a modest improvement in dSTORM localisation precision, indicating the promise of the technology. Scanning time-resolved microscopy approaches will then be presented employing complex SPAD pixels with time to digital converters. The 32x32 pixel MegaFrame sensor has been embedded in a multi-beam two-photon microscope allowing few frame per second FRET/FLIM z-sectioning of live cells. Finally, a new 1024x8 histogramming line sensor is being applied to scanning in-vivo FLIM delivering video rate lifetime images over multicore optical fibre in a lung endoscopy system. The new sensor can deliver spectrally resolved FLIM as well as time-resolved Raman data using a histogram time zooming feature.

From SPADs to Quantum Computing

Edoardo Charbon

EPFL

CMOS SPADs have appeared in 2003 and soon have risen to the status of image sensors with the creation of deep-submicron SPAD technology. The format of these image sensors has expanded from 8x4 pixels of our first LIDAR in 2004 to 512x512 pixels of recent time-resolved cameras, and the applications have literally exploded in the last three years, with the introduction of proximity sensing and portable telemeters. The current promise is that SPAD based sensors will be in every smartphone by 2018 and in every car by 2022. But SPAD technology was born for scientific applications and in scientific applications it will continue to innovate. For instance, super-resolution microscopy has already benefitted from SPAD imagers and this trend is expected to continue well in the next decade. In addition, other time-resolved techniques, such as time-of-flight PET, NIROT, FLIM, FRET, useful in many biomedical imaging modalities, will become more and more accurate and less and less expensive thanks to the scalability of CMOS technologies. With the introduction of SPADs in 3D CMOS IC technologies in 2014, SPAD based imagers will be more compact, while at the same time more advanced techniques and functionalities will be available. Very recently, SPADs have been proposed as an interface to quantum processors, due to their sensitivity and the capability of operating normally at cryogenic temperatures. The talk will conclude with a technical and economic perspective on SPADs and SPAD imagers, and a vision for SPADs and other cryo-CMOS circuits in quantum computing.

Multizone, Multiobject D-TOF System in 55nm

Robert Kappel

ams AG

Direct Time-of-Flight (D-TOF) becomes more and more important for many functions in smartphones, such as proximity detection, auto focus assist, gesture or presence detection as this technology enables compact devices with low power consumption.
This presentation will show the system architecture of the ams D-TOF technology for mobile devices and provides insights into the most important blocks, such as VCSEL driver, SPAD with quencher, the dual-input TDC and histogram memory.
The module is based on TSMC 55nmHV technology and contains sensor, processor and laser driver on a monolithic die, as well as a multi-mesa VCSEL within the module. A custom developed Single-Photon-Avalanche-Diode and the corresponding sensor array enable multi-zone and multi-object detection using histogram based data collection. The availability of the raw histogram data allows multi-object detection and makes the system insensitive to crosstalk and smudge on the sensor. Distance resolution in the mm-range is achieved by using a free running ring oscillator based Time-to-Digital converter with digital calibration. On the emitter side, the on-chip VCSEL driver pulses a multi-emitter VCSEL with high optical peak power and sub-ns pulse width which results in an improved SNR and allows distinction of multiple objects at close distance to each other within the observed scene. The complete system is class 1 eye safe.
The system detects a white card (90%) at a distance up to 3m under incident office light conditions. Measurement results showing distance accuracy, immunity to smudge, operation under sunlight and multi-object test cases, such as accurately detecting an object behind glass will be presented.

The Latest on SPAD Imaging in Japan
- Event Detection and Quick Readout Schemes -

Kunihiro Asada and Xiao Yang

VLSI Design and Education Center, University of Tokyo

Though the SPAD is a high sensitive photon detector, an array of SPAD as an imager is not always advantageous in terms of S/N ratio compared with linear CMOS imagers, since both the SPAD and linear imagers are suffering from the same thermal noises. SPAD imagers can mainly show their advantageous feature for capturing high speed events in photon detection at low photon densities, making use of the high regenerative
non-linear gain feature. In this presentation we will show design of 2-D SPAD imagers with quick readout circuits, which can selectively read out pixels activated by incident photons. It is designed using a row parallel architecture, so as to be especially suited for detecting photon events intermittent in time and local in space. A statistical thermal noise filtering mechanism is also included in the hardware to eliminate unnecessary readout of pixels activated by the thermal noise. We implemented the SPAD imagers using a standard CMOS of 0.18 µm technology. Some experimental results will be also reported for demonstrating the SPAD characteristics based on the standard CMOS technology and performance of the row parallel SPAD architectures.

Optical Solutions for Light Intensity Enhancement in Large-Pixel Size SPAD Sensors

Sheng-Chuan Cheng, Chin-Han Lin, Kuo-Feng Lin, Ken Wu, JC Hsieh.

VisEra Technologies Company, No12, Dusing Rd.1, Hsinchu Science Park, Taiwan (30078)

Near-infrared (NIR) imaging application of time-of-light (TOF) is more and more popular. Single-photon avalanche diodes (SPAD) have been utilized in a variety of applications that acquire time-of-flight system information in addition to light intensity. However, complex electronics layout limited Photodioed area and then cause bad NIR collection efficienence. To solve this problem, we proposed a optical solution (Planar lens with binary level) to concentrate incoming light in our previous study. The finite-difference time-domain method is used to simulate the optimization of the new structural development, particularly the focus length to photodiodes, lens height, and refractive index of the lens. The effects of focus height, lens height, and refractive index of lens are subsequently described. We also demonstrated an efficient optical design and related process to enhance NIR collection efficiency in large pixel size SPAD sensor successfully. Base on previous experience, we continued to improve the NIR collection efficiency by Planar lens structure. According to the newest optical simulation results, Planar lens with multi-level can improve NIR collection efficiency obviously that is better than previous Planar lens with binary level. The physical structure and process will be also introduced in this paper.

Spherical micro lenses is a popular solution for CMOS image sensor because of its excellent capability to concentrate incoming light on the photodiode. In the past time, our traditional material and process only can reach 3μm micro lens height under 10μm pixel size. It can't meet the requirement for common SPAD's structure definitely. To solve this problem, we developed a new solution to meet 10μm micro lens height under 20μm pixel size. According to testing result, the NIR collection efficiency can be increase 60% when compare to without micro lens.

Angle Sensitive SPADs

Alyosha Molnar

Cornell University

This talk brings together two different modalities of light sensing: the fine time resolution and high sensitivity provided by the Geiger-mode behavior of SPADs, and the angular resolution provided by pixel-scale diffractive structures placed immediately above each light sensor. When implemented in a standard semiconductor manufacturing process, these two functions (Single-photon detection and angle sensing) rely on different fabrication steps, with SPAD function implemented in the FEOL semiconductor structures, and angle sensitivity relying on engineering the BEOL interconnect and dielectric layers. Interestingly, these two techniques also take advantage of the two different behaviors of photons: SPAD function depends upon the particle-like behavior of light, while incident angle is computed from photons' wave-behavior, based on spatial gradients in the incoming photons' phase.

This talk will first review techniques for making pixels (or small collections of pixels) usefully angle sensitive, as well as some of the variants on angle sensitive pixels, and some of the ways they can be used. How to best combine these structures with standard SPAD structures will be discussed, and an example array of angle-sensitive SPADs will be presented. Ways in which the two types of information gathered by an angle-sensitive SPAD can be meaningfully combined will also be discussed. Several example applications of such multi-modal sensors will be discussed, including lens-less, filter-less FLIM, and "depth-field imaging", where time-of-flight and light-filed techniques are combined. Finally, potential future applications will be discussed, as well as implications for optimal co-design of angle-sensitive SPADs, both at the sensor level, and in conjunction with associated electronics.

A SPAD-based, Direct Time of Flight, 64 Zone, 15fps, Parallel Ranging Device Based on 40nm CMOS SPAD Technology

Bruce Rae and Pascal Mellot

ST Microelectronics

We present a SPAD-based, direct time of flight, multi-zone parallel ranging device based on STMicroelectronics 40nm CMOS SPAD technology. Capable of streaming up to 64 zones at 15fps, this all-in-one device includes on-chip VCSEL driver (coupled to in-module VCSEL), multi-target detection with parallel 8x8 ambient and signal map generation. Taking advantage of the 40nm advanced digital node, 16 parallel full histogram read-out channels have been implemented, each capable of capturing multiple targets within the "zone" field of view. Featuring an on-board 32bit 250MHz MCU with custom hardware acceleration features, the device is capable of extensive HQ processing with multiple target and statistics reporting. A reconfigurable SPAD array has been implemented offering flexibility in zone size, location and binning. With a maximum ranging distance of 5 metres and millimetre range accuracy, this device is suitable for a wide range of applications.

SPAD Based Streak Cameras

Wilfried Uhring

University of Strasbourg

During the measurement of a fast event with a high speed camera, the instantaneous pixel rate can be as large as a few Giga pixel/s to several Tera pixel/S or even some Peta pixel/s depending of the camera's technology. This huge data rate is mandatory for the record of a unique phenomenon that can't be repeated and thus the measurement has to be operated in the single shot mode.
In the field of high speed imaging, the streak imaging is a specific image acquisition paradigm that offers the best temporal resolution. Contrary to the frame imaging where a full image is taken with two dimensions in both the x and y axis at a given sampling rate, the so called streak imaging consists in acquiring the scene to be observed through a single line only on the x axis. At the cost of the loose of a spatial dimension, for a given and constant overall pixel rate, the temporal resolution can be enhanced by a factor equivalent to the number of row. Indeed, the history of high speed imaging shows that streak imagers offers a temporal resolution about 100 to 1000 times better than frame imager and that whatever the used technology, such as the opto-mechanic, the vacuum tube or the solid state devices.
The time resolved or time gated photon counting is an image acquisition paradigm that imply that the phenomenon can be repeated as only a poor information is fetched each time the recurrent phenomenon is measured. In this case the required sample rate is drastically reduced and the streak imaging paradigm seems less useful. Nevertheless, the streak imaging approach releases the space constraints inherent to the matrix architecture of the frame sensor, and the sensor can be enhanced with both more performing electronics and smart operation. For instance, a histogram construction embedded processing makes it possible to radically reduce the amount of data while achieving the fastest photon counting inside the sensor.

Space Secure Communications using Single Photons

Paolo Villoresi

University of Padova

The paradigm shift that Quantum Communications represent vs. classical counterpart allows envisaging the global application of Quantum Information protocols as the cryptographic key distribution as well as of the use of the qubits as a probe for fundamental tests of Quantum Mechanics and Gravity on a scale beyond terrestrial limits. Single photons are the natural carrier of the degrees of freedom needed to encode the qubits, as they may travel with very little decoherence and be detected efficiently. We shall report on the extension of tests on basic principles of Quantum Mechanics using Quantum Communications to an orbiting terminal in Space using different encoding in single photons. Indeed, it was possible to demonstrate the Quantum Communications with Low-Earth-Orbit satellites using polarization degree of freedom to encode the qubits. Temporal modes were used to demonstrate the quantum interference along a Space channel will be also described. The recent results on the extension to Space of the Gedankenexperiment proposed by John Wheeler on the wave- particle duality, then about the very nature of the quantum entities, will be described.

BCD SPAD Imager with Reconfigurable Macropixels for Photon Counting, Timing and Coincidence Detection

F. Villa, D. Portaluppi, E. Conca, F. Zappa

Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria

Array of Single Photon Avalanche Diodes (SPADs) are gaining increasing interest both in the scientific research and in industry automation and automotive assistance systems. Single-photon sensitivity, precise timing information, high fill-factor, enhanced efficiency in the near infra-red and background light robustness are the main requirements for most of these applications. We designed and fabricated a single-photon sensitive imager based on SPADs in a 0.16 µm Bipolar CMOS DMOS (BCD) technology with 16×16 reconfigurable macropixels. The innovative pixel architecture includes 4 separate detectors with independent active time-gating and quenching circuit, a shared Time-to-Digital Converter (TDC) with 75 ps resolution, 4 independent photon counters, and multiple operation modes. SPADs have a square shape (32 µm ×32 µm) with rounded corners and 100 µm pitch, resulting in 9.6% fill-factor. The TDC is constituted by a **7**-bit coarse counter and two 5-bit fine interpolators, namely the global START interpolator and the in-pixel STOP one. Interpolators are made of fast latches, which sample the status of multiphase-clocks generated by a global Delay Locked Loop (DLL) at the rising edge of the input event; then, a thermometric-to-binary decoder generates the 5-bit interpolation result. Multiple events can be converted and stored during each frame of acquisition and an arbitration logic preserves spatial information among the 4 SPADs connected to the shared TDC, by storing the result in the memory cell associated with the triggering SPAD. Light intensity and photon arrival time can be measured simultaneously for capturing 2D and 3D images of the scene in a single shot (frame) or only counting can be enabled to reduce power consumption and increase achievable frame-rate when timing information is not needed. Photon-coincidence on multiple detectors is exploited to reduce the effect of high background levels, e.g. in LIDAR applications with strong ambient light.

The achieved detection performance is among the best reported in the literature: PDE of 60 % at 500 nm wavelength and still 12 % at 800 nm; low dark count rate of < 0.2 cps/µm^2 (counts per second per unit area); afterpulsing probability lower than 1 % with 50 ns dead-time; temporal response with 30 ps full-width at half maximum and less than 50 ps diffusion tail time constant. According to a preliminary characterization the TDC single shot precision is 115 ps FWHM.

APPLICATIONS

Computational Single-photon Imaging

Gordon Wetzstein

Stanford University

Time-of-flight imaging and LIDAR systems enable 3D scene acquisition at long range using active illumination. This is useful for autonomous driving, robotic vision, human-computer interaction and many other applications. The technological requirements on these imaging systems are extreme: individual photon events need to be recorded and time-stamped at a picosecond timescale, which is facilitated by emerging single-photon detectors. In this talk, we discuss a new class of computational cameras based on single-photon detectors. These enable efficient ways for non-line-of-sight imaging (i.e., looking around corners) and efficient depth sensing as well as other unprecedented imaging modalities.

Imaging at the Speed of Light

Daniele Faccio

University of Glasgow

I will talk about some of the exciting research that is taking place in the field of ultrafast imaging and imaging with single photon counting cameras. Single photon sensitivity and short acquisition times enable the direct observation of a light pulse propagating in air and we will discuss some results in which we use the timing information to measured light propagation.

We will also discuss applications to the tracking of objects hidden from view. Our approach is essentially based on non-line-of-sight laser ranging that relies on the ability to send light around an obstacle using a scattering floor and to then detect the return signal from a hidden object with only a few seconds of acquisition time. We can track a moving object located up to a few metres away from the camera with centimetre precision.

We will discuss recent progress in this field, including the long-distance detection and machine learning applied to the identification of hidden people.

Finally, we will discuss applications of time-resolved single photon counting to imaging through diffusive media.

SPAD Arrays: from Single-Molecule Detection to Wide-Field Phasor Fluorescence Lifetime Imaging

X. Michalet[1], A. Ingargiola[1], M. Segal[1], S. Weiss[1], A. Gulinatti[2], I. Rech[2], M. Ghioni[2], S. Burri[3], A. Ulku[3], C. Bruschini[3], E. Charbon[3]

1. *Department of Chemistry & Biochemistry, UCLA*
2. *Dipartimento di Elettronica, Informazione e Bioingeneria, Politecnico di Milano*
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The advent of the Slik™ single-photon avalanche diode in the early 90's has made single-molecule spectroscopy, and specifically, single-molecule FRET, a practical reality. Similarly, custom-technology SPAD arrays developed since the mid 2000's, have opened up the way to high-throughput single-molecule detection, bringing us one step closer to mainstream applications of these techniques, as well as offering exciting new basic research opportunities. Meanwhile, CMOS SPAD arrays are closing the gap in terms of sensitivity, while pushing ahead in terms of size (number of pixels) and embedded functionalities. These "imagers" are much more than fancy cameras, and offer exciting new prospects for biomedical imaging, in particular for fluorescence lifetime imaging, with applications in *in vivo* molecular imaging, fluorescence tomography and image-guided surgery. In both cases, the ability to preprocess raw data in FPGA before transferring it to the user appears almost as an important as the raw detection capabilities of these devices, and raises interesting challenges on how to let the user harness this potential.

LIDARs for Automotive and Industrial Applications

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Flash LIDAR technology is anticipated as a prime enabler of advanced driving assistance and autonomous navigation in automotive and machine vision applications.

While SPAD-based sensors are known to provide the flexibility and reliability required by such applications, their integration in full-fledged camera systems is a complex and multidisciplinary task, which demands balancing multiple conflicting requirements.

This talk will explore the fundamental challenges related to designing flash LIDAR systems based on SPADs for automotive and machine vision applications. Key challenges, such as the resilience against ambient light, optical interference, and the reliability of measurements, will be introduced, and important implementation trade-offs will be shown in the context of cutting-edge system architectures.

Time-Domain Near Infrared Spectroscopy

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Diffuse optics studies biological tissues by means of photons. Applications range from neuroscience to the food quality assessment. Time-Domain Near Infrared Spectroscopy (TD-NIRS) is one of the technique used to measure optical properties of a turbid medium like biological tissues. From a physical point of view, time domain measurements are the most straightforward and informative in the framework of diffuse optics. Unfortunately, its limit in terms of robustness, cost and complexity prevented its diffusion and applications outside research laboratories. In the last decade, TD-NIRS is undergoing fascinating technology advancements, permitting to overcome its limitations. With respect to other optical techniques, TD-NIRS systems guarantee higher information content, sensitivity, penetration in the tissue and insensibility to motion artifact. In order to maximize their performances, 4 conditions are needed, being nowadays the main technological challenges: i) dense distribution of miniaturized pulsed sources to maximize the injected power; ii) dense distribution of miniaturized probe-hosted TD detectors to maximize the harvesting of diffused light (SPAD, array of SPADs, SiPM) ; iii) fast time-gating capability to implement the gated acquisition technique, thus achieving the largest dynamic range of acquisition (gated SPADs); iv) high throughput compact electronics for photon timing. In the future with the achievement of these 4 conditions, TD-NIRS could potentially reach a penetration depth of 6 cm in human tissues, with the possibility to non-invasively probe organs, as for example the lung or the heart, which are today unreachable with the standard optical techniques.

Imaging with Entangled Photons

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Spatially entangled photons behave as a single quantum object characterized by its de Broglie wavelength. This quantum object offers super-resolution capabilities as compared to imaging with a classical light. In both cases, the Rayleigh resolution limit is set at a half of the wavelength, but in the case of N entangled photons, the effective wavelength is reduced by a factor of N. In order to benefit from such super-resolution capabilities, a dedicated detector is needed, capable of implementing high-order cross-correlations of arrival time coincidence events between N detector pixels. Coincidences for pixel pairs, triads, tetrads etc. must be measured within a time bin. Such functionality renders the detector architecture to be drastically different from existing state-of-the-art time-resolved single-photon detectors, e.g. large SPAD arrays for time resolved measurements implemented in CMOS. One can easily spot that such detector system would rapidly reach any feasible limits of the data transmission rates and data storage capabilities to handle all possible multi-pixel combinations if specific measures were not taken in the design. Here we report on SuperEllen sensor developed within the project SUPERTWIN for super-resolution imaging applications with correlated photons. It is implemented in 150 nm CMOS technology and consists of 32x32 pixels with sub 200 ps timing capability and a high fill factor of 20 %. We will present first measurements with this sensor showing the potential of the technology for quantum optics imaging. We show results obtained with entangled photon pairs and by recording 4-th order correlation images with thermal light.

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