Training on quantum detection, single-photon imaging, SiPMs, SPADs

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Book of Abstracts

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Silicon Photomultipliers and Applications (1st Module) / 0

Basics: avalanching theory, SPAD fundamentals, analog vs. digital SiPMs, readout architectures

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Advanced manufacturing technologies for modern image sensors have advanced to the point where uncooled single-photon image can be considered a consumer product. Single-photon imaging brings its own challenges, and has developed a number of niche applications, but the nature of building detectors at these extreme performance levels means performance developments that can filter down through more mainstream sensor technologies and applications.

This lecture has two segments: the first is devoted to avalanche theory, SPAD fundamentals, and silicon photomultipliers (SiPMs), both analog and digital; the second is focusing on timing estimation and processing in multi-channel digital SiPMs, including a discussion of the expected and measured statistical behavior of the device and its application in many fields of science and medical imaging.

Brief biography of the speaker:

Edoardo Charbon (SM'10) received the Diploma from ETH Zurich in 1988, the M.S. degree from UCSD in 1991, and the Ph.D. degree from UC-Berkeley in 1995, all in Electrical Engineering and EECS. In 2000, he joined Canesta Inc. as its Chief Architect, leading the development of wireless 3-D CMOS image sensors. Canesta was sold to Microsoft in 2010. Since November 2002, he has been a member of the Faculty of EPFL in Lausanne, Switzerland, working in the field of CMOS sensors, biophotonics, and ultra low-power wireless embedded systems. In Fall 2008 he has joined the Faculty of TU Delft, as full professor in VLSI design, succeeding Patrick Dewilde. His current research includes medical and space based image sensing, single-photon technology, and picosecond electronics.

Silicon Photomultipliers and Applications (1st Module) / 1

Timing evaluation and processing, multi-channel digital SiPMs: a statistical approach, system issues, testing and metrology, other applications

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Single-Photon Technology in Medicine (2nd Module) / **2**

Single-photon technology for HEP

Corresponding Author: york.haemisch@philips.com

The lecture will introduce the concept of disruptive technologies using the example of the Digital Photon Counter (DPC, dSiPM) developed at Philips since 2004. The major characteristics of disruptive technologies will be worked out and examples given. As the development of the technology at Philips was triggered by its potential application in medical imaging, in particular in Positron-Emission-Tomography (PET), the benefits of using DPC in PET will be explained.
The concepts of analog and digital SiPM will be compared and the advantages of the early digitization concept will be highlighted in particular in view of industrial applications. One of the most important prerequisites for this is scalability, so special focus and attention will be given to this aspect by introducing the Philips digital systems concept. The question of how to bring such a technology to market and how to define the product will also be discussed. First application examples will be shown and a brief outlook on future developments will be provided.

Brief biography of the speaker:

York Haemisch received the Diploma from Technical University of Dresden in 1989, the Ph.D. in solid state physics from University of Wuerzburg in 1994, and the M.Sc. Eng degree from University of Pennsylvania in 2002. In 1993, he joined GE Medical Systems as Product Specialist in PET-Systems. In 1997, he joined ADAC Laboratories as Product Manager PET Global. In 2001, he joined Philips Healthcare US as its Chief Scientific Officer PET. From 2006 to 2010 he worked in Bioscan Inc. as its VP Pre-clinical Imaging Technologies. Since 2010, as Senior Director of Philips Corporate Technologies, he is working in the field of Digital Photon Counting. Throughout his work, he has introduced the first Philips PET-CT, the first time-of-flight (TOF) PET/CT, the first pre-clinical sub-mm PET/CT and Digital Photon Counting technology.

Single-Photon Technology in Medicine (2nd Module) / **3**

The transition form HEP to Medical Imaging

Corresponding Author: york.haemisch@philips.com

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SiPM Materials and Modelling (3rd Module) / 4

New materials and fabrication for APDs, SPADs and SiPMs

The "new materials"that will be discussed in this lecture are depositions of pure boron and pure gallium, given the names PureB, PureGa and PureGaB. It may seem out of place to speak of boron as a novice in silicon technology since it has always been, and still is, the most commonly used p-dopant. Nevertheless, it is now recognized that boron, deposited by chemical-vapor deposition (CVD) in its pure form, exhibits both electrical and processing properties that make it a useful and unique supplement to the long list of materials already playing a role in silicon device integration. In particular, extremely shallow junctions for p+n diodes can be fabricated with PureB as the anode. To underline the unique behaviour of these junctions the lecture begins with an introduction to the device physics of truly ultrashallow junctions followed by the basics of the junction formation process.
At the moment, the most prominent application is for PureB Si photodiodes that are sensitive right up to the front-entrance window that can be made with PureB down to 2 nanometers thin. Therefore these photodiodes are particularly interesting for the detection of very low-penetration-depth radiation such as DUV/VUV/EUV light and charged particles such as low-energy electrons. Their performance has been shown to surpass that of other existing technologies on points such as internal/external quantum efficiency, dark current, degradation of responsivity. At the same time they readily lend themselves to detector integration schemes that allow low parasitic resistance and capacitance as well as the on-chip combination with other electronic elements. Focus will be placed on the special requirements for integration as SPADs.
Similarly outstanding results have been achieved with a pure-gallium deposition capped with a PureB deposition (PureGaB), also when applied to Ge devices. Infrared Ge-on-Si photodiodes with photon-counting capabilities at room temperature have been demonstrated in this PureGaB technology. All in all, the PureB/PureGaB diodes perform better than other ultrashallow junction technologies. The reasons for this will be highlighted while we walk through the applications to detectors/imagers that now span the whole electromagnetic spectrum going from terahertz –IR –visual –DUV/VUV/EUV –X-rays through to electron detectors.

Brief biography of the speaker:

Lis K. Nanver has a masters degree from the University of Aarhus, Denmark, and PhD degrees from ENST, Paris, France, and Delft University of Technology, The Netherlands. She has throughout her carrier been involved in many different aspects of research on silicon device integration and now heads a research group on this subject at TU Delft, where she is a professor. Her main research interests are new devices and integration processes, mainly for RF, microwave, or smart sensor applications. She has pioneered several new ultrashallow diode technologies using techniques such as epitaxy by chemical-vapor or metal-induced solid-phase deposition and excimer laser processing. She also developed a substrate transfer technology for true two-sided contacting of devices that has been instrumental in the development of new RF/microwave adaptive circuit concepts. In the last few years the research on new pure-dopant CVD processes for creating extremely shallow diodes has resulted in several leading-edge applications such as high-linearity silicon-on-glass varactor diodes, Si photodiode detectors for low penetration-depth beams and low-leakage Ge-on-Si photodiodes. For the Si detector work her group has received the 2010 IEDM Roger Haken Award.

SiPM Materials and Modelling (3rd Module) / 5

Modeling of SPADs and SiPMs

Single Photon Avalanche Diodes (SPADs) and Silicon PhotoMultipliers (SiPMs) have since long ceased to be a scientific curiosity and have become a valuable tool for many applications both in research and industrial fields. Such a transition, on one hand, has been favored by the remarkable improvement in SPADs and SiPMs performance obtained in the last years; on the other hand, the widespread use of these devices in many cutting edge applications push the research community for a continuous improvement in their performance and complexity.
A detector development based on a "trial and error"approach is in most cases ineffective and impractical both because of the remarkable time and costs needed for each iteration of the fabrication process and because of the difficulties in identifying the suitable modifications to the device structure. Actually, an effective detector's development requires a detailed understanding of the physical phenomena that regulate its behavior and the availability of physical models that allows the device designer to evaluate the effect of the main parameters (doping and electric field profiles, defects type and distribution, etc.) on detector performance.
In this lecture we will discuss the physical modeling of SPADs and SiPMs as a whole. In fact, although the latters are significant different from the formers in terms of applications, architectures and sometimes even in terms of the corresponding electronics circuits, the core of the detectors is the same and therefore a unified treatment is possible. In this optics we will present the main figures of merit common to both the detectors (Breakdown Voltage, Photon Detection Efficiency, Dark Count Rate, Afterpulsing Probability, Optical CrossTalk and Timing Jitter) and for each of them we will analyze the physical phenomena that influence its behavior. Then we will discuss the modeling of such phenomena highlighting both relevant parameters and possible limitations.

Brief biography of the speaker:

Angelo Gulinatti was born in Codogno, Italy, in 1977. He 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.
Since 2008 he is Assistant Professor at Politecnico di Milano where he carries out his research activity in the development and modeling of silicon Single Photon Avalanche Diodes (SPAD). In particular he contributed to the development of several generations of large 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.

SiPM Architecture and time-processing (4th Module) / 6

Time-to-digital converters

Time-to-digital converters (TDC) are devices which allow, with a certain precision, to digitally represent the time occurred. Their usage spawn over a large number of applications where a precise

time time stamp is required. Due to technological progresses, reconfigurable hardware devices (such as FPGAs) have become an attractive platform for implementing low cost and high performances TDCs.
This module presents the design and the implementation of a TDC on FPGA. More in details, the module will cover the basics of TDCs and of hardware design, with particular emphasis on design for re-configurable devices, their hardware description language and the tools used for programming them.

Brief biography of the speaker:

Dr. Francesco Regazzoni is a postdoctoral researcher at the Technical University of Delft (Delft, The Netherlands). After receiving his Master of Science degree from Politecnico di Milano (Italy), he completed his PhD degree at the ALaRI Institute of University of Lugano (Lugano, Switzerland), where he is still actively involved. He has been assistant researcher at the Crypto Group of the Université Catholique de Louvain (Louvain-la-Neuve, Belgium) and visiting researcher at several institutions, including NEC Labs America (Princeton, NJ, USA), Ruhr University of Bochum (Bochum, Germany), and EPFL (Lausanne, Switzerland). His research interests are mainly focused on embedded systems security, covering in particular side channel attacks, cryptographic hardware, and electronic design automation for security.

SiPM Architecture and time-processing (4th Module) / 7

CMOS SiPM design and signal compression

This lecture reviews several design solutions adopted in both analog and digital SiPMs to improve their characteristics, with particular focus on timing and spatial resolution.
A brief overview of SiPM technology developed at Fondazione Bruno Kessler (FBK) is given. The problem of optimum timing pickoff is analyzed and the solutions adopted at FBK are described. The main limitations to optimum timing resolution are addressed, indicating the directions of future SiPM design improvements. Position encoding approach, which was proposed to reduce the complexity of high-spatial resolution detector modules for preclinical PET systems, is also reviewed.
The architecture of a CMOS digital SiPM developed inside the EU project SPADnet is then presented. In this design, signal compression is used to reduce the complexity and area occupation of focal plane processing electronics. Each pixel, composed by 720 SPADs, provides the total counts and timestamp of detected gamma events. SiPM total counts, used to discriminate gamma event detection, are sampled at up to 100MS/s by an adder tree overlaid on top of the pixel array. Experimental results validating the approach are presented and critically discussed.

Brief biography of the speaker:

Lucio Pancheri received the Laurea degree in Materials Engineering from the University of Trento, Italy, in 2002, and the Ph.D. in Information and Communication Technologies from the same university in 2006. From 2006 to 2012 he has been a research scientist at Fondazione Bruno Kessler (FBK), Trento, Italy, where he has been involved in the development of optical and radiation sensors in CMOS technology for advanced imaging and biomedical applications. From May 2012 he is a researcher at the University of Trento. In the last years, his research activity has been mainly focused on the development of CMOS Single Photon Avalanche Diodes and readout circuits for time-resolved light detection and of electro-optical demodulating detectors for ToF 3D image sensors.

SiPM Simulation and Design Lab (Training Session) / 8

SiPM Simulation and Design Lab (Training Session)

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Silicon photomultipliers (SiPMs) are an alternative to photomultiplier tubes because of their robustness to magnetic fields, compactness, and low bias voltage. To take advantage of the merits of SiPMs, the deep understandings of SiPM characteristics are required. In this workshop, we will model and simulate the SiPM using Cadence spectre simulator to investigate the SiPM characteristics as well as building the schematic, drawing layout and verifying the design in Cadence design environment. We will also simulate the SiPM behavior assuming that a gamma photon hits a crystal scintillator and produce various number of photons to be detected by small cells in the SiPM.

TDC Design and Test Lab (Training Session) / 9

TDC Design and Test Lab (Training Session)

The previous module will be completed by an hands-on laboratory session in which the students will design a small TDC and implement it on the provided FPGA platform. The Xilinx design environment will be utilized for this task, and the resulting configuration file will be tested on an FPGA board.