Large Format Single-Photon and Multi-Photon Imaging

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***Abstract*—Large format detectors are traditionally used in several medical imaging domains, such as X-rays. Recently, new solid-state detectors have appeared in medical imaging domains, such as positron emission tomography, single-photon emission computed tomography, used in large tiles of semiconductor chips. In this paper, we explore these emerging sensor tiles in terms of their impact in time-of-flight embodiments of these imaging modalities.**

Keywords—Positron emission tomography, single-photon avalanche diode, SPAD, silicon photomultiplier.

I. Introduction

The range of applications for which large format single- and multi-photon image sensors are used today is quite large, from single-photon emission computed tomography (SPECT), positron emission tomography (PET), wide-field fluorescence lifetime imaging microscopy (FLIM), fluorescence correlation spectroscopy (FCS), time-resolved Raman spectroscopy, and time-of-flight cameras [1],[2].

The sensors of choice have been photomultiplier tubes (PMTs) and micro-channel plates (MCPs), until recently; however, the emergence of silicon photomultipliers (SiPMs), has created a paradigm shift in the fields of high energy physics and medical imaging, for which the above applications are leading embodiments. SiPMs [3] are arrays of Geiger-mode avalanche photodiodes (G-APDs), also known as single-photon avalanche diodes (SPADs) [4], whose avalanche currents or voltages are combined together to detect single or multiple photons over a large area, enabling photon counting at high speed with high timing resolution. Recently, multi-channel digital SiPMs (MD-SiPMs) have appeared, where photon showers generated during scintillation are collectively detected and individually processed in real time in order to evaluate important properties related to the timing of physical phenomena.

II. The MD-SiPM

MD-SiPMs can also be read out in terms of the individual SPADs making up the sensor, so as to build images without mechanical scanning, both for 2D and 3D sensing. These sensors require a much higher level of integration and higher pixel-level intelligence [2]. This paper outlines the most recent developments in the field of single- and multi-photon cameras based on SPADs and the current trends to maximize fill factor, minimize crosstalk, and achieve high readout data rates. The core technologies discussed in the paper include optical and electrical micro-lenses, backside-illuminated SPADs, and 3D integration.

III. Discussion

The latest tradeoffs between macro- and micro-optical systems we be discussed for super-resolution microscopy and time-of-flight vision for which we used 1/8 megapixel formats [5]. Architectural issues in readout speed, gating techniques, and massively parallel processing will also be looked at as key technologies to reconstruct time-resolved FLIM/FCS images and programmable event-driven pixel systems.

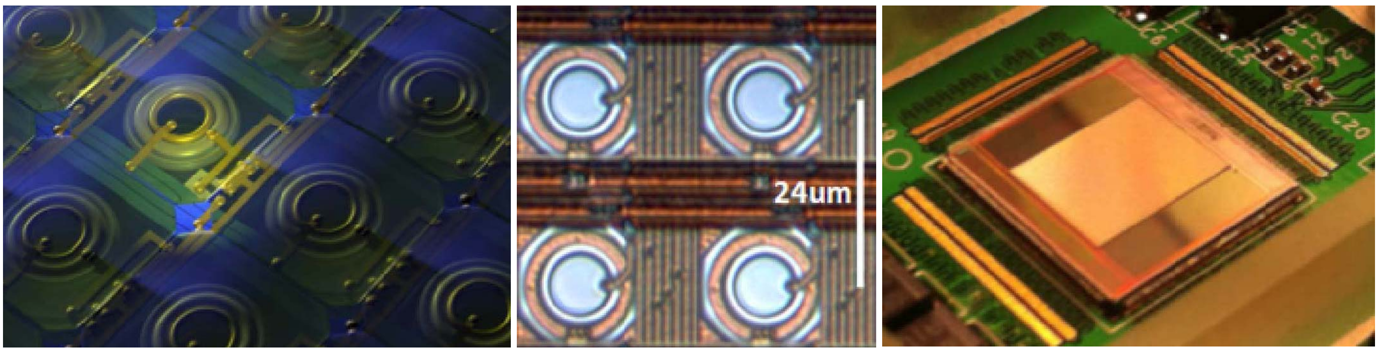

Fig. 1. Artist's rendering of an array of SPADs with optical micro-lenses as light concentrators (left); pixel detail of a high-density large format single-photon imaging sensor fabricated in 0.35µm CMOS technology (center); micro-optical sensor module (right).

We will present characterizations of the described devices placing them in a novel perspective for applications especially emphasizing the importance of photon detection efficiency (PDE) and dark count uniformity, temperature stability, radiation hardness, and fabrication yield. In this context, future trends are discussed with special attention to mass-production of next generation sensors and the emerging fields of application in consumer electronics, and quantum communications.

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