

Large Format Single-Photon Image Sensors in CMOS Technology

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Large format single-photon image sensors may be used in a number of applications, where single-photon sensitivity, along with high timing resolution and parallelism, are required. Examples include 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].

Until recently, the sensors of choice in most of these applications have been photomultiplier tubes (PMTs) and micro-channel plates (MCPs), but the emergence of solid-state replacements, such as silicon photomultipliers (SiPMs), has created a true revolution in many fields of imaging science and engineering. 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.

SPAD arrays can also be individually addressed and read out, so as to build images without mechanical scanning. 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 SPAD based cameras and the current trends to address some of the outstanding issues, such as low fill factor, crosstalk, and high readout data rates. The core technologies discussed in the paper include optical and electrical micro-lenses, backside-illuminated SPAD arrays and 3D integration, and functionality sharing.

We discuss the latest results in high concentration factor polymer lenses and the tradeoffs between macro- and micro-optical systems in these sensors. The design and use of large format SPAD image sensors is also discussed with up to 1/8 megapixel formats [5], whereas readout speed, gating techniques, and massively parallel processing are key to reconstruct time-resolved FLIM/FCS images at programmable, possibly event-driven frame rates with better than 200ps timing resolution. Finally, we present novel applications exploiting the quantum nature of photons for a number of applications in physics and telecommunications.

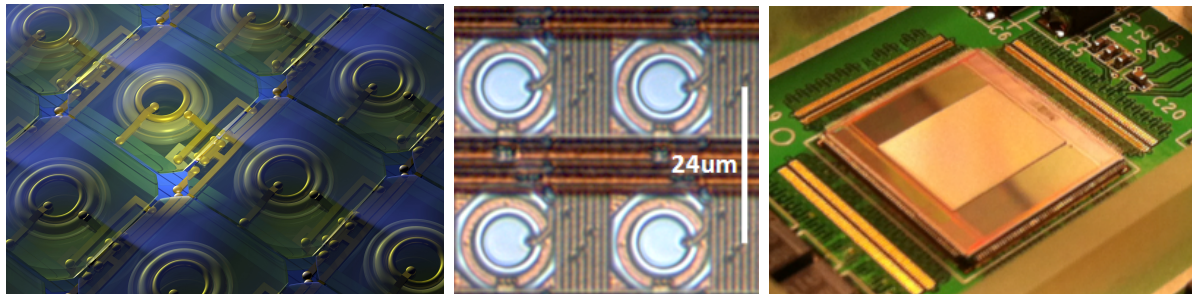


Fig. 1. Artist's rendering of an array of SPADs with optical micro-lenses as light concentrators (left); pixel detail of a high-density large format single-photon imaging sensor fabricated in 0.35μm CMOS technology (center); micro-optical sensor module (right).

In this paper, the results of the characterization of the described devices are placed in perspective vis-à-vis the applications envisioned for these sensors, 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, quantum communications, and data security.

References

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