SPAD Arrays and Digital SiPMs for All-Digital Imaging

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Direct single- and multi-photon detection may be achieved by way of photomultiplier tubes (PMTs). Known since the 1930s, PMTs are versatile, non-solid-state devices that, until recently, have been the detector of choice in many applications requiring photon counting. In 2003 photomultiplication was reproduced in standard IC technologies, with the integration of single-photon avalanche diodes (SPADs) in a conventional high voltage CMOS process [1]. This breakthrough has paved the way to scalable photon counting image sensors for use in a number of all-digital imaging modalities, wherever photon time stamping is needed. Examples include, for instance, time-of-flight 3D cameras, LIDARs, (time-of-flight) positron emission tomography (TOF-PET), single-photon emission computed tomography (SPECT), and near-infrared optical tomography (NIROT) [2].

Recently, large format SPAD image sensors have emerged, featuring photon counting *in pixel* and deep-subnanosecond gating over a large array with high timing uniformity. These sensors are revolutionizing fluorescence lifetime imaging microscopy (FLIM), Förster resonance energy transfer (FRET), super-resolution microscopy, and other biomedical diagnostics techniques [3],[4],[5],[6],[7],[8]. The sensors have many embodiments, whereas in some the pixels are small, made of a single SPAD [7],[8], while in others the pixels are large, made of a large number of SPADs. The latter are generally known as silicon photomultipliers (SiPMs) or multi-pixel photon counters (MPPCs) [9],[10]. Several architectures exist for SiPMs: in analog SiPMs, for instance, SPAD anodes (or cathodes) are connected together through a quenching resistance, so as to sum all avalanche currents in order to achieve an overall current proportional to the number of detected photons [9]. In digital SiPMs the SPAD's digital outputs are combined through a logic gate [10].

Multi-channel digital SiPMs [11] and other high granularity SiPMs [12] represent a fusion of SPAD image sensors and SiPMs, thanks to the increased number of pixels, whereas each pixel retains the properties of SiPMs, while enabling one to compute a very large number of timestamps in multi-photon showers. This is especially useful whenever detailed statistics of complex photonic events are required, such as in the case of scintillation, at the core of PET image reconstruction [13],[14]. Photon statistics provided by SPAD image sensors and SiPMs can enhance the resolution of a medical image both in 2D and 3D, thanks to the increased accuracy of the reconstruction, which in turn is directly related to the timing accuracy of the photonic event.

In this talk, we focus on recent developments in SPAD image sensors and SiPMs, including the increase of fill factor, reduction of crosstalk, and the management of high data rates originated in the sensors. We will introduce the concept of all-digital imaging based on photon quanta detection that is enabled by SPAD image sensors and SiPMs. The tremendous amount of data generated by these sensors will be handled by processors operating *in situ* thanks to 3D integration, where SPADs and processors will be on separate chips [15],[16]. We will also discuss enabling technologies such as optical and electrical photon concentration, silicon-on-insulator SPADs, and backside-illumination.

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