All-Digital Biomedical Imaging

Edoardo Charbon
TU Delft, Delft, Netherlands

***Abstract*— The appearance of miniaturized single-photon detectors has enabled massively parallel conversion of photons to digital signals that can be readily processed and/or transported with negligible losses. As a consequence, a new class of imaging sensors is emerging, known collectively as all-digital image sensors, for detection and processing of ultra-fast and complex photonic events, often present in biomedical imaging systems. All-digital image sensors are fast and robust, often enabling unprecedented accuracy in a number of biomedical imaging modalities. This paper describes several all-digital image sensors for all-digital biomedical imaging designed to efficiently process large data volumes, so as to minimize power dissipation, improve flexibility, and shorten overall time-to-market.**

I. All-Digital Image Sensors: the SPAD

The conversion of photons to digital signals can be achieved by way of single-photon detectors. Single- and multi-photon detection was first demonstrated in the 1930s, but it is only since 2003 that it can be achieved in standard CMOS technologies, with the integration of single-photon avalanche diodes (SPADs) in CMOS [1]. This breakthrough has paved the way to scalable all-digital image sensors for use in a number of biomedical imaging modalities, where photon counting and time stamping is needed. Examples include, for instance, (time-of-flight) positron emission tomography (TOF-PET), single-photon emission computed tomography (SPECT), and near-infrared optical tomography (NIROT) [2].

II. Large Format Sensors: SiPM Tiles

Recently, large format SPAD image sensors have emerged, featuring photon counting *in pixel* and accurate gating over a large array. 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].

Large format 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, the SPAD anodes (or cathodes) are summed in current through a quenching resistance, so as to achieve an overall current proportional to the number of detected photons [9]. In digital SiPMs the SPAD's digital outputs are ORed through a logic gate [10].

In the all-digital image sensor field, 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 single multi-photon bundles or 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.

III. All-Digital Biomedical Imaging

Recent developments in SPAD image sensors and SiPMs focus on maximizing fill factor, minimizing crosstalk, and achieving high readout data rates, the enabling technologies being optical and electrical photon concentration, backside-illumination, and 3D integration.

In an all-digital biomedical imaging paradigm, SPAD image sensors and SiPMs generate a tremendous amount of data that is usually handled by processors and/or field-programmable gate arrays (FPGAs), however, this implies chip-to-chip data rates of Gbps to Tbps. Thus, *in situ* processing is achieved by 3D integration, where SPAD image sensors/SiPMs and processors are on separate chips [15],[16].

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