Towards Large-Format SPAD Quantum Imaging

Edoardo Charbon

EPFL, 2002 Neuchâtel, Switzerland

Quantum imaging, or quantum-informed imaging, is broadly understood as a domain where quantum phenomena and optics combine to overcome fundamental limitations of classical imaging, such as diffraction and shot noise [1]. The idea to use quantum properties of light to enhance imaging emerged in the 1960s, when entangled- or single-photon generation and squeezed light became available. Squeezed light and single photons enable low-noise imaging and better spatial resolution, while entangled photons enable novel imaging paradigms, such as ghost imaging. Ghost imaging uses position-momentum entanglement between signal and idler photons to image an object in the signal channel by detecting photons and time-correlating them with photons imaged from the idler channel, which contains no object. This is useful, for instance, when the object must be illuminated at a wavelength where a large-format imager is not practical or when one wants to increase spatial resolution using the Boto effect. Entangled photons can also be used to perform imaging with undetected photons, where two coherently generated pairs of entangled photons, whose signals are overlapped through a beam splitter and interfere if their partners are indistinguishable. Any object placed in the idler channel undoes indistinguishability, thus allowing detection. Fig. 1 shows these configurations; besides photon entanglement and dedicated optics, single-photon detection granularity and time-resolved capability are needed, while large formats are still unexplored.

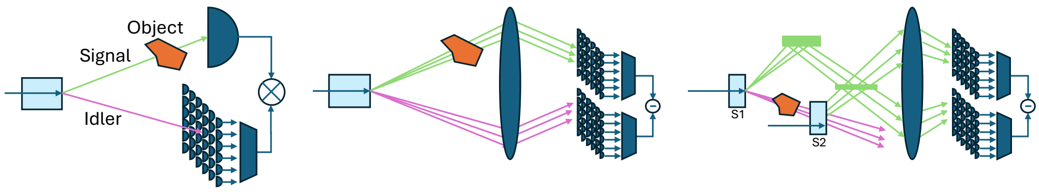

Fig. 1: *Quantum imaging configurations. Ghost imaging with entangled photons (left), sub-shot-noise imaging with twin beams (center), and imaging with undetected photons (right); fig. inspired by [1].*

In this paper, we advocate the use of large-format SPAD image sensors to achieve all these features both in InGaAs-InP and Si technologies with underlying CMOS control and data acquisition in a 3D-stacked configuration. CMOS enables (1) higher speed, (2) smaller pitch, and (3) embedded processing, including AI and ML engines to enable data interpretation and/or low data rates.

This idea has led to the creation of the first Mpixel SPAD camera, where time stamping was achieved through gating and externally computed in a field-programmable gate array (FPGA) [2]. A better solution is however to compute time stamps *in situ* and to handle them at high speed, while minimizing data communication off chip. A possible solution was proposed in 2011 by way of a 130-nm CMOS technology adapted to accommodate SPAD requirements [3]. In this case, a time-to-digital converter (TDC) was placed in every pixel. As a result, a small fill factor could be possible and micro-optics could only partially recover it. A preliminary solution to the fill-factor conundrum came from linear arrays of SPAD pixels, whose outputs were processed *in parallel* by an FPGA or an ASIC. An example of this solution is [4], where 43% fill factor was achieved.

Extending this approach to a 2D SPAD array is not trivial, as it requires real estate to place electronics, thus competing with pixel fill factor. A possible solution has been proposed in [5], where the SPAD pixels use a common bus that codes the originating pixel, along with the timestamp, generated by 1728 column-parallel TDCs. The time stamps are organized in histograms that are then sent off chip. Nonetheless, this approach requires a certain level of sharing –in this case, 21 pixels share a TDC, on average– and set some limits to the number of pixels. More recently, with the introduction of 3D-stacked SPAD imagers [6], advanced cameras were possible, which added more functionality on chip and the need of less sharing [7]; this has also led to larger image sensors [8].

Assuming that even larger formats are possible and that the highest achievable single-photon time resolution (SPTR) in a SPAD is 7.5 ps (FWHM) [9], the data traffic would grow exponentially, making it impossible to even store the data, let alone processing and interpreting the data. Solutions to this problem have been proposed clustering pixels [6,10] or creating partial histograms [5]. Nevertheless, most of the times the structure of the scene is known *a priori* and thus it is reasonable to program pre-defined configurations on the cluster [11] or to create an FPGA-like fabric underneath the pixel array [12]. Fig. 2 shows some of the sensors described above, along with the salient features.

In the paper, we describe these and emerging solutions, as well as new hybrid InGaAs-InP/Si sensors, that have been explored to achieve quantum imaging modalities described above using SPAD sensors in NIR, VIS, and NUV, all amenable to larger formats. A perspective will conclude the paper with a description of several quantum imaging applications based on these SPAD sensors.

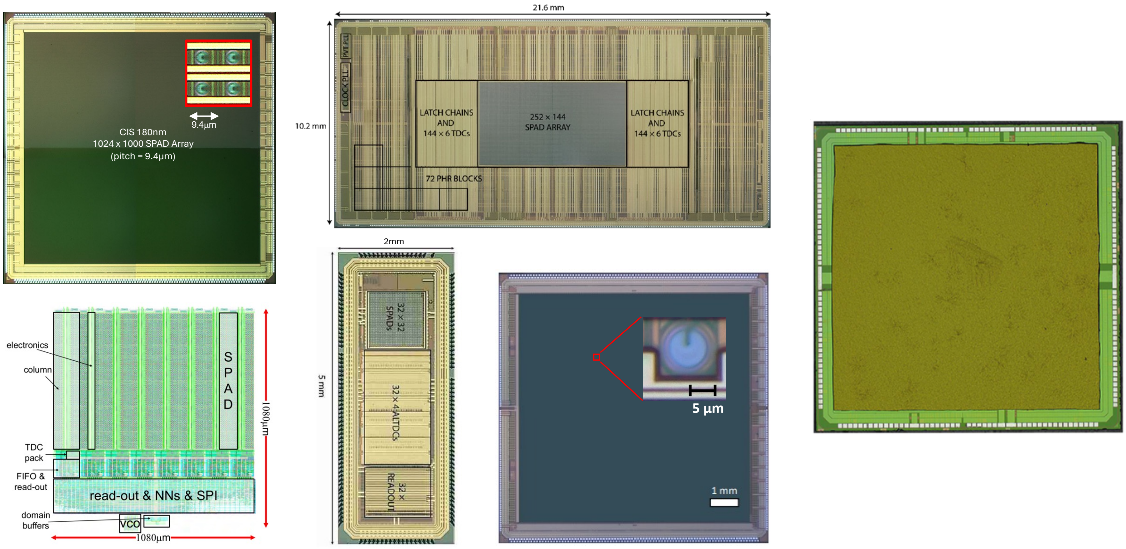

Fig. 2: *Large-format single-photon sensors (clockwise, from top left): MegaX [2], Ocelot [5], Phoenix [13], Mindhive [14], Piccolo [15], SwissSPAD3 [16].*

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