Single-Photon Avalanche Diodes: devices and advanced applications

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Photon counting is the technique of choice for attaining ultimate detection sensitivity in measurements of very faint optical signals at very fast (picosecond) time scale. Photon counting and timing was introduced and developed with PMTs, but widespread advanced applications are enabled by means of microelectronic detectors, namely the Single-Photon Avalanche Diodes (SPADs). SPADs exploit avalanche multiplication in a p-n junction for producing a standard current pulse with macroscopic size and fast rise-time that marks the photon arrival time with high (few ps) precision. Nowadays, silicon SPADs (both single point and arrays) and InGaAs/InP SPADs are well assessed and are commercially available, while new solutions are under development for even better performance with reduced costs and size.

We present our recent results about Silicon SPADs developed in standard CMOS technology and custom InGaAs/InP SPADs for the near-infrared (NIR) wavelength range.

CMOS SPAD imagers based on smart pixels (including counting and timing circuitry, able to count photons and to measure their arrival time) are the basis for single-photon counting and timing cameras, at very high frame rate (100 kfps), low noise (dark count rate < 100 cps/pixel with 30 µm active area diameter), and high detection efficiency (> 50%) [1]. We employed such cameras (with up to 64x32 pixels) [2],[3] in a wide range of applications, in chemistry, biology, medicine, material science, and physics, including Forster Resonance Energy Transfer (FRET), Fluorescence Lifetime Imaging Microscopy (FLIM), Fluorescence Correlation Spectroscopy (FCS), and 3D acquisitions (LIDAR). Recently, we have developed an advanced fast-gated silicon SPAD, with very fast (~ 200 ps) rising edge, in order to greatly widen dynamic range and speed-up acquisition time in time-resolved measurements, such as diffuse optical spectroscopy for brain imaging.

For extended NIR sensitivity, we have designed and developed InGaAs/InP SPADs for up to 1.7 µm. The 25 µm active-area diameter detector shows very low dark count rate (< 10 kcps at 225 K), 30% photon detection efficiency at 1550 nm, low afterpulsing, and a timing response with less than 90 ps jitter [4]. We employed our InGaAs/InP SPADs in many different applications, like eye-safe ranging (LIDAR), time-resolved spectroscopy, single-photon source characterization, fluorescence decay analysis, ghost imaging.

References

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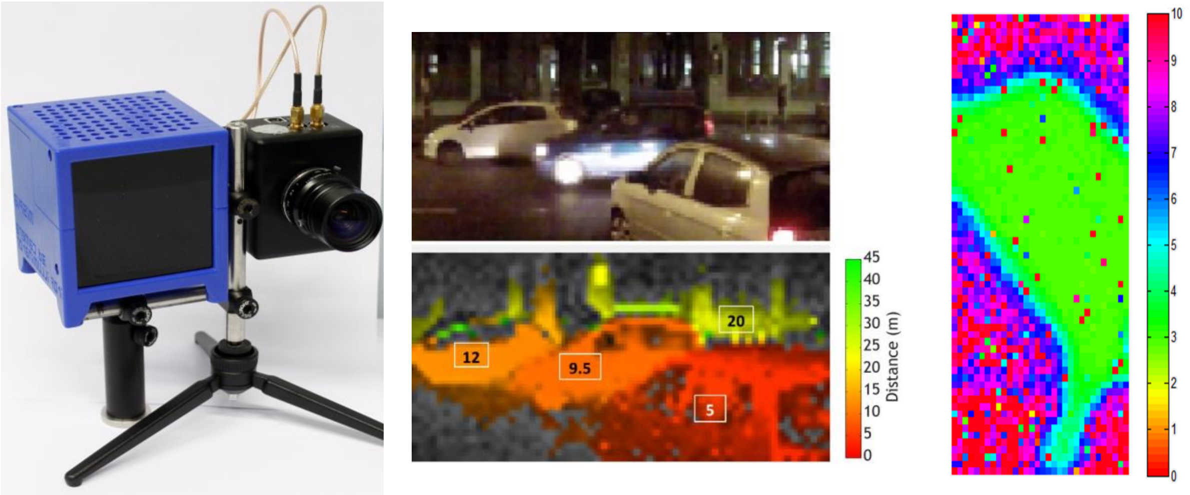

Figure 1: Left: Picture of a 64x32 SPAD camera with optics and laser illumination system. Center: Frames from a 3D movie at 100 fps acquired by the 64x32 SPAD camera: one car (in red at 5 m) is entering into a lane where another car (in orange at 9.5 m) is moving fast and a third car (in yellow-orange at 12 m) is parking. Right: Fluorescence lifetime of a transfected cell as measured by the 64x32 SPAD camera.

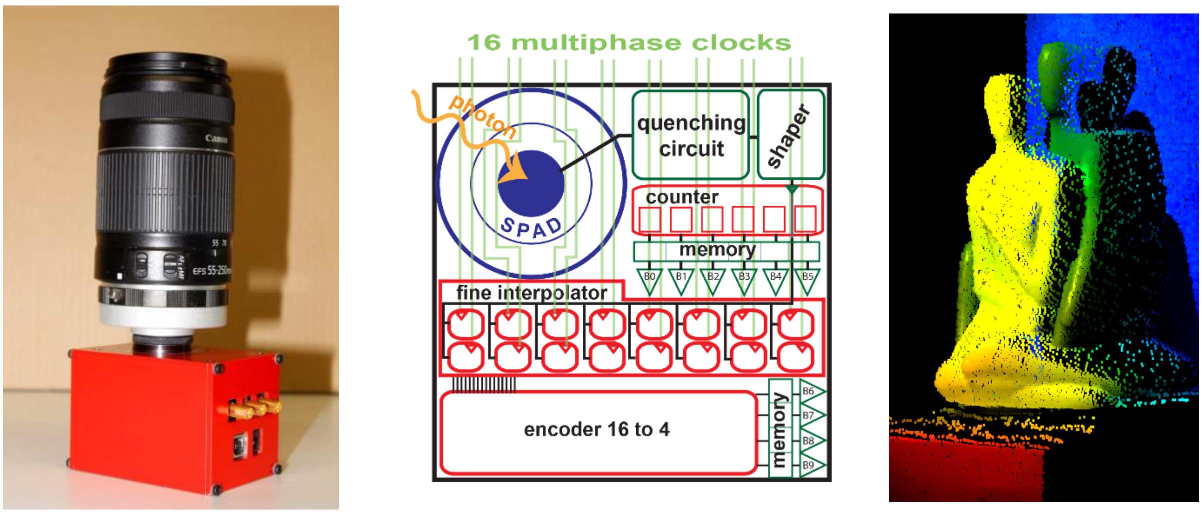

Figure 2: Left: Picture of the 32x32 SPAD camera with integrated Time-to-Digital Converters (TDCs). Center: Smart pixel of a 32x32 SPAD array in which a SPAD detector is coupled to a 10 bit TDC for measuring the time-of-flight of single photons. Right: 3D map of a 20 x 10 x 10 cm^3 statue acquired by the 32x32 SPAD camera.

Figure 3: Left: Picture of a single photon counter based on InGaAs/InP SPAD. Right: Depth profile scan at λ = 1550 nm of a life-sized mannequin at a range of 325 m using a per-pixel acquisition time of 5 ms.