Time-of-flight single-photon avalanche diode imagers

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Abstract The growing interest for very sensitive, single-chip, cost-effective imagers with single-photon sensitivity, ultra-precise time-tagging capability, and on-chip processing availability, is driving the development of Single-Photon Avalanche Diode (SPAD) arrays in microelectronic technologies. This paper presents SPAD imagers developed in CMOS and BCD processes, able to provide 2D (two spatial dimensions) images of the optical intensity through photon-counting, and 3D (two spatial dimensions, plus the photon arrival time) videos by means of photon-timing. The very high frame-rates (up to hundreds of kframe/s) and the picosecond resolution in measuring the photon arrival time enable many applications, e.g. automotive Time-of-Flight (TOF) 3D Light Detection and Ranging (LIDAR), Fluorescence Lifetime Imaging (FLIM), Diffusive Optical Tomography (DOT).

Keywords: Single Photon Avalanche Diode (SPAD), Time-of-Flight (TOF), imaging, Light Detection and Ranging (LIDAR).

1. CMOS and BCD SPADs

Single photon detectors and imagers are becoming the optical sensors of choice when very faint optical signals must be detected and precisely time-tagged. The slowly-varying (μs-time scale) intensity of signals can be measured by “photon counting” incoming single photons within well-defined integration time windows through digital counters, while ultrafast (ps-time scale) events can be acquired by photon-timing (also known as Time-Correlated Single-Photon Counting), e.g. through Time-to-Digital Converters (TDCs) able to measure the arrival time of single photons, in order to reconstruct a histogram of their time-distribution. Single-Photon Avalanche Diode (SPAD) detectors are the microelectronic-compatible solution, because they can be developed in standard microelectronic silicon foundries.

At first, CMOS SPADs traded-off detection performance for compatibility with transistors, to offer on-chip coexistence of both. Then, performance improved [1] and recently we pioneered novel SPAD designs [2] in a BCD (Bipolar-CMOS-MOS transistors on the same chip) technology, for increasing photodetection probability, reducing dark-counting rate and afterpulsing noise, and speeding up the sensing of the avalanche current ignition, thus minimizing timing jitter and afterpulsing.

In this paper, we report the performance of such SPADs: with 60% detection probability at 500 nm wavelength and still 12% at 800 nm (see Fig. 1); dark count rate lower than 0.2 cps/μm^2 (counts per second per unit area); 30 ps full-width at half-maximum timing jitter and < 50 ps diffusion tail time constant.

2. Time-of-Flight ranging

More and more automotive companies are developing Advanced Driver Assistance Systems (ADAS), aimed at avoiding/mitigating accidents and at improving the driving experience. For collision avoidance and adaptive cruise control, many systems employ radar-, lidar-, ultrasonic- or videocamera-based depth sensors for 3D mapping of vehicle surroundings.

Camera-based 3D vision systems can be grouped into two main categories, namely stereo-vision and time-of-flight (TOF) ones. The formers employ two cameras to provide high spatial resolution at low power consumption, but they are only suitable for high-contrast scenes and they require high computational efforts to solve the correspondence problem for matching the information from the two cameras. On the other hand, TOF vision systems make use of a single camera, synchronized with an active (laser diode or LED) light source, require less data processing, and achieve high frame-rates.

In principle, the “direct” time-of-flight (dTOF) is the most straightforward TOF technique, relying on the measurement of the round-trip flight time of a narrow (sub-nanosecond) light pulse, reflected back by the target [3]. The trade-off between maximum range and power consumption can be mitigated by employing very sensitive detectors, such as linear-mode Avalanche Photodiodes (APDs) or digital-mode SPADs operated in photon-timing [4]. However, many cameras that implement single-photon dTOF technique cannot be operated in full daylight conditions, since they can only measure the arrival time of the first photon in each frame, thus being easily saturated by ambient background light, due to photon pile-up.

The “indirect” time-of-flight (iTOF) approach computes distance information from the phase-delay between a continuous-wave or pulsed (tens or hundreds of ns) light excitation shone toward the target and its back-reflected light echo. This technique does not need precise arrival time estimation and it can be implemented either by means of linear-mode (e.g. CMOS or CCD) detectors, which provide an analog voltage proportional to the light intensity, or through SPADs in photon-counting mode [5] [6].

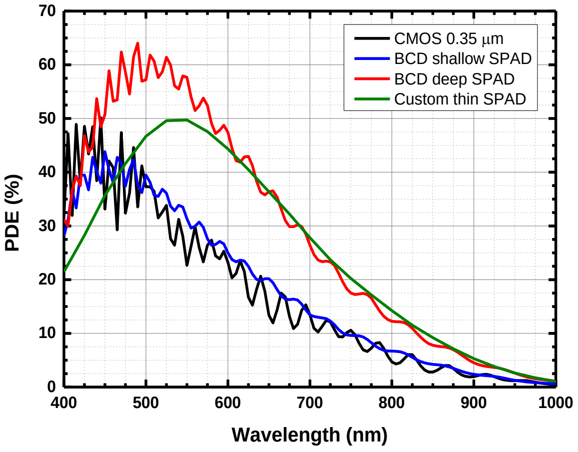

Fig. 1. Photon Detection Efficiency of silicon SPADs in different technologies.

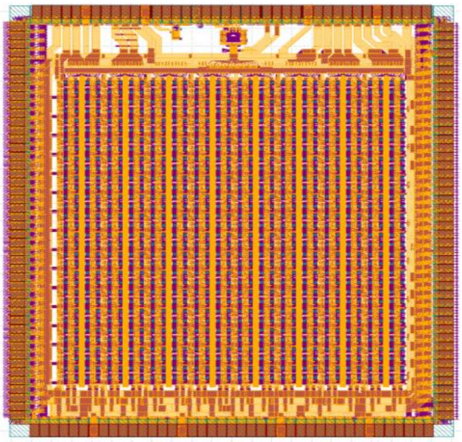

Fig. 2. Imager based on 1024 SPADs and 256 TDCs.

In short- and medium-range applications, the iTOF technique is usually preferable compared to dTOF, since it results in simpler, more compact, more cost-effective systems, requiring neither high-bandwidth electronics nor too short a laser pulse. However, more and more companies are looking for actual dTOF SPAD 3D imagers.

3. 3D TOF SPAD imagers

We conceived and designed different SPAD array chips for counting and timing single photons, for either free-running light signals or fast gated-mode acquisitions, targeting different application fields. We report on a photon-counting SPAD system for iToF 3D ranging, based on 64×32-pixels SPAD imager and an eye-safe active illuminator at 808 nm [5] and a photon-timing 32x32-pixels and 60x1-pixels SPAD imagers for dTOF 3D ranging. We validated both, indoor and outdoor, yielding to 110 dB dynamic-range and 100 fps 3D movies.

In order to cope with the ambient light and to share on-chip resources, SPAD ignitions can be processed at the pixel level in order to reject random events due to either SPAD noise or background illumination, while selecting those triggering due to the return light echoes. We report on the development of a SPAD imager (Fig. 2) based on an innovative macropixel architecture (Fig. 3), with four separate SPADs with independent active time-gating and quenching circuits, one shared TDC, four independent photon counters, and featuring multiple operation modes (e.g., for photon-coincidences) [7].

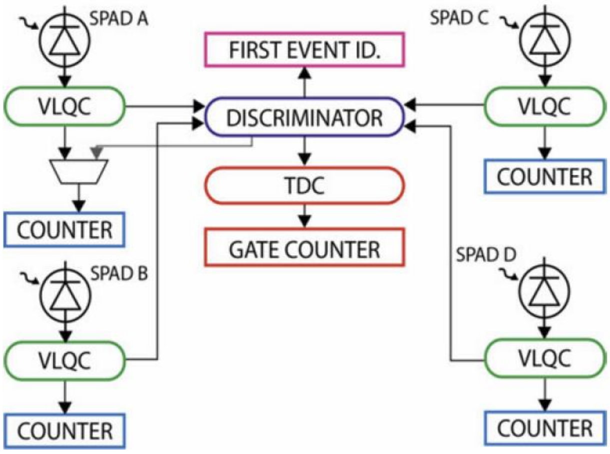

Fig. 3. Macropixel based on four SPADs with one shared TDC and individual counters for simultaneous photon-counting and timing with background light suppression.

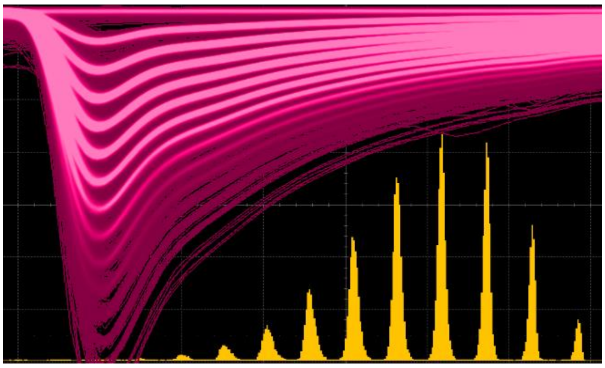

Fig. 4. Multiple-photon output pulses from a BCD SiPM and amplitude spectrum.

The TDC is made by a coarse counter and two fine interpolators, thus allowing 12-bit TOF resolution with a nominal 50 ps LSB and a 204.8 ns FSR and resulting in a precision of about 8 mm resolution over a 30 m range and with few cm precision. The FSR can be easily increased by means of deeper (more bits) counters. We integrated a similar TDC together with a novel BCD SiPM (Silicon Photomultiplier) with photon-number resolved capability, up to tens of photons per pulse (Fig. 4), for effective ambient light suppression.

4. InGaAs/InP SPADs for the NIR range

Finally, SPADs made in InGaAs/InP are the best choice for reliable systems with high detection performance in the near-infrared wavelength range (1 µm – 1.7 µm) [8]. We present our results with >30% photon detection efficiency, just few kcps dark-count rate, and better than 70 ps timing jitter at 1550 nn. We overcame the main limitation set by afterpulsing, through proper electronics. At first, a fast-gating circuit based on sinusoidal gating (at 900 – 1400 MHz) for extremely high (650 Mcount/s) count rate [9]. Then, a SiGe integrated circuit for sub-nanosecond gating with < 300 ps rising/falling edges and low (< 20 ps) time jitter.

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