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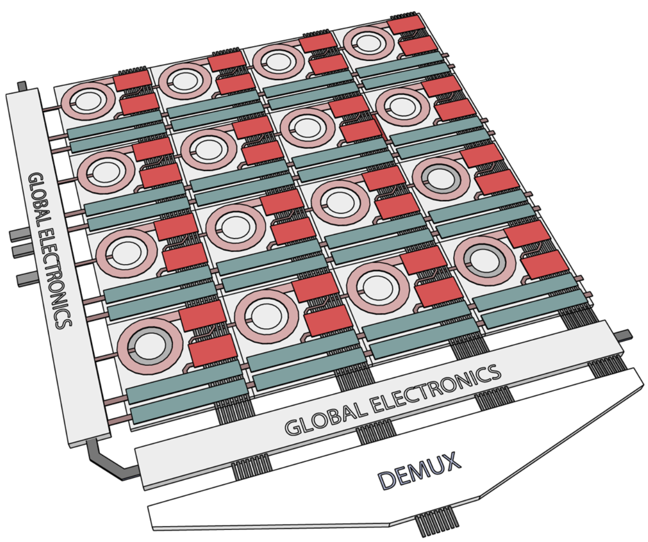

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Single-Photon Counting Detectors

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(Invited Paper)

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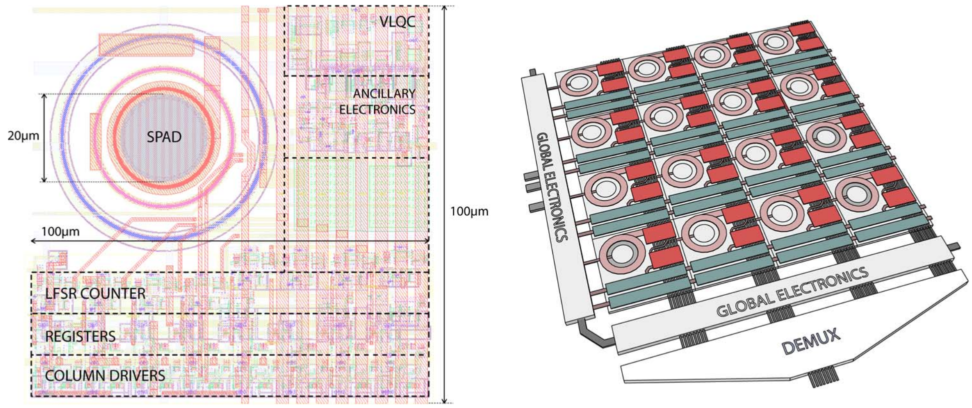
Abstract: Various new developments for array detectors based on Silicon Single-Photon Avalanche Diodes (SPADs) were reported. Improved Si-SPAD technologies brought higher detection efficiency in the red wavelength range. Higher performance was attained with InGaAs/InP SPADs by employing fast circuit techniques and by monolithic resistor-detector integration. New InGaAs(P)/InP SPAD array detectors provide remarkable performance in the near-infrared range (NIR). Photon detection at longer wavelengths (up to 3.5 μm) was pursued with antimonide SPADs and Superconducting Single-Photon Detectors (SSPD).

Index Terms: Photon counting, photon timing, array detector, avalanche diode.

Photon counting applications require high detector performance (high photon detection efficiency (PDE), low dark count rate (DCR), and small photon timing jitter), but they also require reliability, as well as ease of implementation, miniaturization, and integration in systems. This review will deal with detectors that satisfy such requirements and not with other remarkable cases that represent demonstrations of detection principles based on appealing physical effects. Many applications (e.g., analytical techniques in life sciences, 3-D imaging, or laser detection and ranging (LADAR), etc.) concern the visible spectral range (VIS); others of high interest (e.g., quantum key distribution (QKD) and eye-safe LADAR) concern the near-infrared range (NIR). The two ranges will be separately considered. A basic issue must be well focused: advanced analog detectors (back-illuminated charge-coupled devices (CCDs), etc.) have ultraweak dark current and measure very weak photon fluxes; therefore, when and why are photon-counting detectors advantageous? Essentially, it is when the measurement time is very short, e.g., with high frame-rate imaging, fluorescence correlation spectroscopy (FCS), fast optical pulses, etc. The reason is the electronic readout noise of analog detectors. At short measurement time, the readout noise is dominant over the dark-current noise and sets the sensitivity limit to analog detectors, whereas it simply does not exist in photon-counting detectors.

In the VIS Photomultiplier Tubes (PMTs), the classic photon counting detectors are progressively replaced by Silicon microelectronic detectors. A new micro-PMT technology has also been announced, with miniaturized multiplier structure built with microelectromechanical systems technology [1]. Microsystem integration prospects are open by new developments in Single-Photon Avalanche Diodes (SPADs), which are the digital detectors that work in Geiger avalanche mode above the breakdown level. Incidentally, SPAD devices are also the basic element of Silicon PhotoMultipliers (SiPMs), which are intended to replace PMTs as multiphoton pulse detectors. Silicon technology with submicron resolution makes possible SPAD array detectors that are suitable for 3-D imaging, i.e., with high number of pixels, adequate filling factor, and smart pixels with integrated electronics. Remarkable results have been obtained in 130-nm technology in



(a) (b)

Fig. 1. The 32 × 32 imaging array detector developed at SPADlab [8] in 350-nm HV-CMOS technology. (a) Smart pixel structure and (b) pictorial view of the 2-D array architecture.

collaboration by various groups [2]. A 32 × 32 pixel SPAD array with an in-pixel Time-to-Digital Converter (TDC) [3] was developed and experimented in 3-D imaging and Fluorescence Lifetime Imaging (FLIM) [4]. Extension to 160 × 128 pixels has been announced [5]. A tough basic issue must be faced: Inherent features of superscaled technologies conflict with detector performance. The thin junction depth limits the PDE, the high electric fields enhance the DCR, and afterpulsing effects are strong. Peak PDE 25% was attained at 500 nm wavelength, falling below 5% at 800 nm, with a DCR of hundreds of counts/s for a detector diameter of less than 10 μm. Specific modifications have also been devised within the standard 130-nm technology and experimented with significant results [6]. The trend to superscaled technologies to attain higher system integration is anyway hindered. For instance, working in 90-nm scaled technology, SPAD devices have been demonstrated but with remarkably lower performance [7].

An attractive alternative is given by high-voltage complementary metal–oxide semiconductor (CMOS) technologies (HV-CMOS) for automotive and industrial control electronics. Their scaling is less marked, but technological features for accommodating high-voltage devices are also favorable to SPAD junctions. In 350-nm HV-CMOS technology, SPADs with noteworthy performance have been obtained, and a 32 × 32 pixel SPAD array with smart pixels (see Fig. 1) has been demonstrated at our laboratory (SPADlab) [8]. Better than 35% peak PDE is attained at 450 nm wavelength, decreasing to 8% at 800 nm, with DCR in the range of kcounts/s for 20-μm diameter SPADs. In-pixel information storage capability (similar to a CCD) is given by an 8-bit counter. Noteworthy results have been obtained in challenging experiments [9]. Work is in progress on a 32 × 32 SPAD array for 3-D imaging with an in-pixel TDC [10].

Technologies with dedicated features can better exploit the SPAD detector performance, and arrays of SPADs can also be implemented with moderate scaling, although with significant limitations to the system integration. Linear 1 × 8 array and 2-D 6 × 8 arrays were developed at SPADlab in a custom 1-μm technology, with pixels of 50 μm diameter, > 50% peak PDE at 550 nm, reduced to 15% at 800 nm, and a DCR of few hundreds of counts/s [11]. Significant results were obtained in demanding applications, such as multispot FCS with single-molecule detection [12]. In-pixel circuitry was added with modifications to the custom technology [13], and further evolution is under way.

New developments in single detectors are mainly concerned with wide sensitive area and enhanced PDE in the red wavelength range (600 nm to 900 nm) of high interest for fluorescence-based techniques in biomedical applications. PDE $> 70\%$ at 670 nm with diameter > 100 μm was announced for a new commercial detector [14] but with technology unsuitable to integration and producing high-voltage devices with high power dissipation. To obtain red-enhanced PDE, low-voltage operation, and suitability to monolithic integration, a new SPADlab custom technology was developed [15]. A deeper depletion layer with a new profile of the electric field was devised and designed for optimal tradeoff between operating voltage, avalanche triggering probability, DCR, and timing jitter.

The PDE in the NIR is extremely low for classic PMTs and ~1% for PMTs with advanced photocathodes, which have high photon timing jitter and DCR. Photon counting was first extended to the NIR with Ge SPAD and consolidated with InGaAs/InP SPADs, which are now the workhorse for experiments. A thorough review of their state of the art is available [16]. Compound semiconductor devices have physics and technology that is inherently more complex than Silicon and do not benefit of such a huge research effort. They are strongly plagued by carrier generation centers and other point defects that affect the SPAD performance. Carrier trapping and delayed release in deep levels produce strong afterpulsing. In recent years, significant progress has been achieved in fabrication technology and device design, but important limitations remain, particularly concerning the capability of working in free-running mode or with very high counting rate in gated mode.

To circumvent these limitations at least in part, fast electronic circuit techniques have been exploited, and intriguing results have been reported with ultrafast detector gating in a self-differencing arrangement [17]. New devices, called Negative-Feedback Avalanche Diodes (NFADs), integrate a high-value thin film resistor in the chip to obtain passive quenching with very low parasitic capacitance and, thereby, fast operation with reduced avalanche charge and afterpulsing effect [18].

Very remarkable new developments of 2-D arrays of NIR-sensitive SPADs have been reported. With improved planar technology (contaminant reduction, uniform processing, etc.), monolithic focal plane arrays (FPA) with 32×32 SPADs of 34 μm diameter were developed. InGaAsP/InP structure was employed for operation at 1064 nm and InGaAs/InP for 1550 nm [19]. Results are particularly striking for the InGaAsP/InP array, with high uniformity, yield and reliability, and high performance level: PDE better than 40% and DCR $<$ 20 kcounts/s in operation at ~250 K. The array detector chip was hybridized to CMOS integrated circuitry that enables independent time-of-flight measurements for each pixel with subnanosecond jitter for LADAR applications with frame rates up to 200 kHz.

Pioneering work was carried out at the Lincoln Laboratory at the Massachusetts Institute of Technology for extending photon counting deeper into the NIR [20]. For 2-μm wavelength photons, devices of 30 μm diameter with InGaAsSb absorber layer were developed for operation at 77K. Arrays of 1000 pixels interfaced with a CMOS readout circuit were demonstrated in a 3-D imaging system with acceptable performance for applications. Further extension to 3.4-μm wavelength was pursued by developing devices with an InAsSb absorber. Correct SPAD operation of these devices was demonstrated, and detection of 3.4-μm photons was verified, but with very low PDE and very high DCR, which is not suitable for applications.

The extension of photon counting to longer wavelengths was also pursued with Superconducting Single-Photon Detectors (SSPDs) based on NbN nanowires. Novel device structures with strip width reduced to 55 nm and multiple nanowires in parallel were developed and experimented up to 3.5 μm wavelength with appreciable PDE and low DCR [21]. For operation at telecom wavelengths (1.3–1.55 μm), the SSPD technology is well established and provides single-photon detectors capable of free running operation with good PDE, low DCR, and timing jitter better than 100 ps, although there is a fairly high cost and moderate miniaturization and system integration. A new achievement aiming to improve the system integration has been reported, namely, a chip with four-channel SSPD integrated into an optical cavity structure [22].

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