Improved APD Design Enables More Efficient Single Photon Counting Detectors

25 years ago few of us would have predicted the importance of single photon counting in the 21st century. Today scientists and engineers routinely rely on the technique when detection of extremely weak light signals is required and traditional detectors are unable to distinguish between signal and noise, and the areas of application are constantly increasing. Let us briefly consider the signal strengths to be detected in such cases before looking at the technology needed to do so. The number of photons per second corresponding to a particular optical power level can be expressed as

$$N(\lambda) = 5.03 \times 10^{15} \times \lambda \times P$$

where P is the optical power in Watts and λ the wavelength in nm. So, for example, we see that 1 fW at 405 nm corresponds to roughly 2,000 photons/second, whereas a count rate of 100 photons/second at 670 nm corresponds to a power level of merely 30 aW (Fig. 1).

Photon counting techniques are to be found in various areas of industry, research, and communication technology, with specific applications including astronomical LIDAR, fluorescence microscopy in many different forms, industrial particle sizing techniques, drug discovery, DNA analysis, and, more recently, quantum cryptography. While the specific requirements of these applications may differ considerably and a detailed analysis is beyond the scope of this article, they all have one thing in common; the need for a highly efficient, low noise single photon detector. Several technologies suitable for photon counting are outlined below.

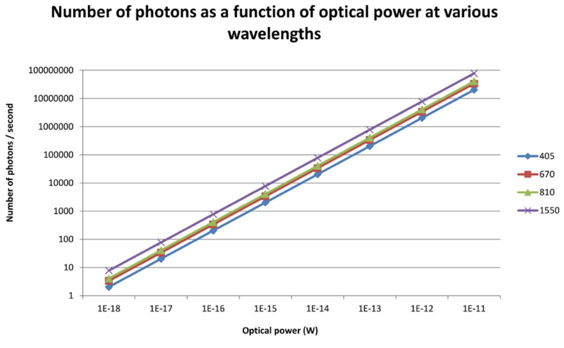

Figure 1: Wavelength-dependent correlation between power and number of incident photons

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Photomultipliers

The traditional photomultiplier (PMT) is a special form of vacuum tube which converts an incoming photon into an electrical signal which is internally amplified by a so-called electron multiplier. The photon strikes the photocathode material, generating an electron which is then focused into the electron multiplier, consisting of a series of secondary electrodes known as dynodes, each of which emits additional electrons upon absorption of incoming electrons, thus creating an avalanche effect through the device. The dynodes are maintained at a certain electrical potential, which increases from dynode to dynode in order to accelerate the electrons through the photomultiplier to the anode, where they are absorbed, this generating an output signal in the form of an electrical pulse. This requires a high voltage of typically 1-3 kV to be applied to the PMT. The PMT may be used in Geiger mode to detect single photons, however the very high internal current generated requires the device to be electrically reset following each photon event, leading to a dead time during which no further photon can be observed. While various cathode materials with differing spectral characteristics may be used depending on the wavelength range to be detected, traditional vacuum photomultipliers generally exhibit the best sensitivity in the shorter wavelength blue and UV ranges. PMTs generally feature relatively large active areas (several mm in diameter), but often have high dark noise levels and are prone to afterpulsing, an effect whereby a spurious output pulse is emitted although no photon has been detected.

Solid State Photomultipliers

More recently, CMOS-based multipixel Geiger mode silicon APDs, often referred to as silicon photomultipliers, have also been developed. This technology appears promising with advantages such as relatively low production cost thanks to conventional CMOS techniques, low operating voltage, compact construction with a large overall active area and good timing resolution. To date, however, dark noise, which is orders of magnitude higher than in conventional Geiger mode SPADs, and the low quantum efficiency at longer wavelengths mean that these devices remain significantly inferior to single element SPADs for most single photon counting applications.

Single Photon Avalanche Diode – SPAD

Avalanche photodiodes (APD) are highly sensitive photodiodes with very fast response times. Unlike normal PIN diodes, the APD uses internal gain to create an avalanche of electron-hole pairs by impact ionization. Prerequisite to this is a sufficiently high bias voltage to widen the absorption region of the APD to allow sufficient electron/hole ionization to occur. When operated below the breakdown voltage, the avalanche will soon extinguish itself due to friction losses within the semiconductor. Specially constructed APDs may also be used in Geiger mode, where the bias voltage is set above the APD's breakdown voltage, enabling the avalanche to be maintained and an internal gain of up to 108 to be achieved. Such APDs are commonly referred to as single photon avalanche diodes (SPAD).

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Geiger mode operation at such high gain inevitable leads to very high current levels within the SPAD, which must be kept under control using an appropriate quenching circuit in order to prevent damage to the device. In its simplest form, the quenching circuit may be based on a current limiting resistor placed in series with the APD, which will quench the avalanche if the resistor value is sufficiently large. However, such circuits typically have a long recovery time which limits the effective maximum count rate[1]. For this reason, most commercially available SPAD modules feature active quenching circuitry which detects the onset of the avalanche and then drops the APD bias to below Vbr within a few nanoseconds. The result is a relatively short dead time, typically around 50ns, after which the bias voltage is returned to the previous level, enabling the next photon event to be registered. In this way, maximum count rates of 10 MHz and upwards can be easily achieved. The best SPAD modules currently available exhibit dark count rates of <10, thus corresponding to a dynamic range in excess of 106. Commercially available SPAD modules combine a thermoelectrically cooled Geiger mode APD with an optimized active quenching circuit in a compact form factor to allow the user to achieve optimum performance from the SPAD.

Detection Efficiency: The Key to Performance

Several figures of merit may be used when comparing the suitability of detectors for photon counting. Dark noise, afterpulsing probability and dead time are all important, but for most applications the detection efficiency is paramount. For this reason SPADs are often considered preferable to PMTs because of their very high quantum efficiency (QE) across a broad spectral range from around 300 nm into the NIR. Typically, the sensitivity of a photon counting module will be given as quantum efficiency, the ratio of generated electrons to absorbed photons expressed as a percentage value. Manufacturers of certain devices prefer to specify a responsivity (in Amperes/Watt), which is related to the QE by

$$QE = (Ro \times 1240) / \lambda \times 100\%$$

where Ro is the responsivity in A/W and λ the wavelength in nm. When comparing devices with similar noise performance and afterpulsing probability, the detector with the highest QE will be generally be best suited for photon counting. It should be noted that the QE is an expression of the efficiency of the APD only, whereas in a complete SPAD module other factors such as electronics can also influence the overall performance slightly. For this reason, data sheets for SPAD modules often state a photon detection efficiency (P_d) or probability, which is the percentage probability of an incident photon generating an electrical pulse at the module output.

When designing a SPAD, it is important to keep in mind that both detection efficiency and dark count rate depend on the bias voltage applied to the APD. As discussed above, the APD is operated in Geiger mode above the breakdown voltage (Vop > Vbr), where the difference between V_{op} and V_{br} is known as the overvoltage, which can be tweaked to optimize a particular parameter as illustrated by Table 1. However, such optimization can only succeed if the underlying APD design is of a sufficiently high quality, which requires an APD structure designed for maximum quantum efficiency while keeping the semiconductor's K factor[2] (the ratio of hole to electron ionization properties) at a minimum to reduce noise. LASER COMPONENTS Detector Group's VLoK (Very Low K) APD was designed specifically for photon counting and enables SPAD modules with previously unattained performance such as dark count rates of < 10 c/s with detection efficiencies > 80% at 670 nm.

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Operating Voltage [V_{op}]	Over voltage [$V_{br-}V_{op}$]	P_d @ 405 nm [%]	P_d @ 670 nm [%]	P_d @ 810 nm [%]	Dark count rate [c/s]	Afterpulsing [%]	Dead time [ns]
346.3	2.0	30	55	32	15.4	0.04	61
348.4	4.1	36	69	43	31.4	0.11	55
350.6	6.3	40	79	51	57.4	0.24	51
352.3	8.0	43	85	55	91.4	0.42	50
355.0	10.7	45	90	60	138.2	0.89	49

Table 1: Variation of detection efficiency and dark count rate with operating voltage for a VLoK APD (LASER COMPONENTS).

While SPADs have traditionally been the device of choice for photon counting in the red and near-IR ranges, PMTs have dominated the blue to UV region of the spectrum due to their superior QE at shorter wavelengths. However, recent SPAD developments mean that today's SPADs can be used effectively from the UV to the near IR. A good example is the COUNT^{blue} series from LASER COMPONENTS, introduced in early 2011, and based on a UV-enhanced version of the VLoK APD (Fig. 2), which shows a typical detection efficiency of 55% at 405 nm and 70% at 532 nm. Further advantages of SPAD modules include straightforward operation with a low voltage DC supply (typically +5 or +12 V) as well as optional fiber connectors which can be optimized for specific wavelength ranges upon request.

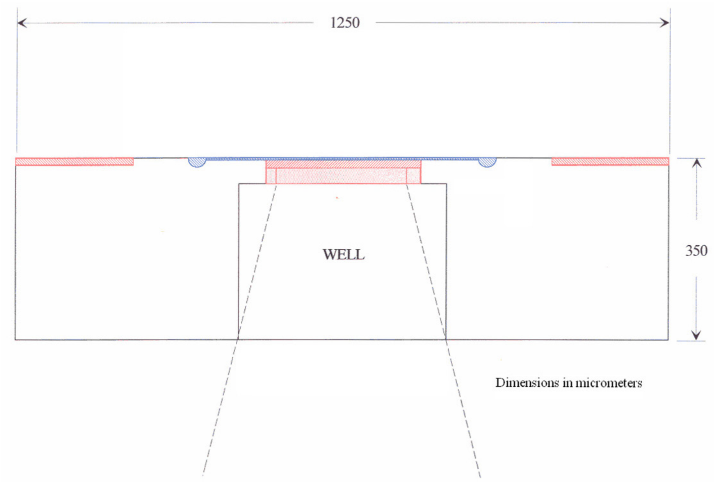

Figure 2: Schematic drawing of VLoK photon counting APD (LASER COMPONENTS Group)

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Although the majority of SPAD development effort to date has been focused on silicon-based devices, increasing interest in single photon counting at longer wavelengths has also resulted in the emergence of Geiger mode InGaAs APDs. These can be operated at detection efficiencies of up to 20% or more, albeit with significantly higher dark count rates than their silicon counterparts. Their development has been primarily driven by advances in quantum cryptography techniques, where transmission of data over long ranges via optical fibers is necessary; here the high efficiency of silicon detectors is cancelled out by high fiber transmission losses at shorter wavelengths, whereas the superior fiber transmission at 1550 nm more than compensates for the lower QE of the InGaAs detector.

With application areas continuing to grow rapidly, ongoing developments in detector technology from the UV into the IR ensure that the future of single photon counting remains bright indeed.

Figure 3: Example of SPAD modules: LASER COMPONENTS' COUNT® series of photon counters, red and blue-enhanced version, depicted in their fiber coupled configuration

References

[1] Stipcevic M., Skenderovic H., Gracin D., Characterization of a novel avalanche photodiode for single photon detection in VIS-NIR range, Optics Express 18(2010)17448-17459

[2] Webb, P.P. et al, Properties of Avalanche Photodiodes, RCA Review. Vol. 35, pp. 234-278. June 1974

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