64 | LASER+PHOTONICS 2014 | SENSORS & METROLOGY


Example of a SPAD module: Laser Components Count series of photon counting systems, red and blue enhanced versions with fiber coupling

# Single-photon avalanche diodes

**MORE EFFICIENT SINGLE-PHOTON DETECTORS. 25 years ago, no-one could have imagined the importance of single-photon detection in the 21st Century. Today, this technology is a reliable tool for both scientists and engineers for the detection of extremely weak light signals.**

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Single-photon detectors are used for applications where traditional detectors can no longer discern the difference between signal and noise. Prominent application examples here are quantum cryptography, spectroscopy, LIDAR, DNA analysis, particle measurements, fluorescence microscopy or detection of single molecules. The order of magnitude of the signal intensities involved in this regime make the term ›single-photon detection‹ self-explanatory. The number of photons per second that correspond to a particular optical power is given by the following formula:

$$N(\lambda) = 5.03\times10^{15}\cdot\lambda\cdot P$$

where $P$ is the optical power in watts and $\lambda$ is the wavelength in nanometers. Accordingly, 1 fW of optical power at a wavelength of 405 nm corresponds to around 2000 photons per second (**Figure 1**).

Although the application areas mentioned above differ greatly, the common aspect to all is the demand for a high-efficiency single-photon detector with minimum background noise. Various detector technologies well suited to this purpose are discussed in the following.

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## The photomultiplier

The photomultiplier tube (PMT) is a variant of the vacuum tube. The PMT makes use of the photoelectric effect and subsequent amplification in a secondary electron amplifier section to turn a single incident photon into an electrical signal. The (electron) amplification process is equivalent to an avalanche effect, the result being a measureable electrical pulse at the anode of the electron amplifier. However, for this process to succeed, PMTs require the use of very high voltages (1 to 3 kV). A schematic of a PMT is shown in **Figure 2**.

For the detection of single photons, a PMT can be operated in the so-called Geiger mode. The restriction here is that the very high transient currents that follow each photon event must first again return to zero (the so-called ›dead time‹) before the detector is ready to detect the next photon.

Assorted cathode materials with varying spectral properties are employed depending on the spectral window of interest. While these materials were originally most sensitive in the UV and blue regions of the spectrum, PMTs today have a greatly improved IR performance. PMTs also usually exhibit a relatively large detection area (up to 75 mm diameter), although these must then also be cooled in order to reduce dark noise to an absolute minimum. PMTs are very sensitive to external magnetic fields and are also inclined to exhibit so-called ›afterpulsing‹ – an effect in-

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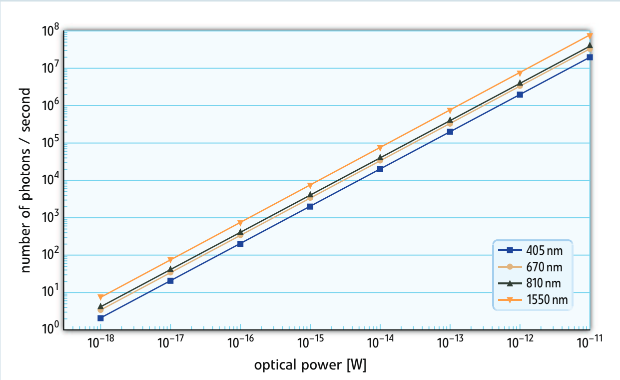


**1 Wavelength-dependent correlation between optical power and the number of incident photons**

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gion, rather than being amplified in an electron amplifier section of a conventional PMT. The principal advantage of this approach is the almost non-existence of afterpulsing effects, with additional plus factors being the large active area (on the mm scale) and the good time resolution. The down side is the awkward handling requirements for these systems (over 8000 V at the photocathode), the limited spectral range and the need for low-noise electronics downstream of the detector itself in order to ensure low dark count rates.

duced by the outgoing electrical pulse that does not correspond to the incoming (optical) signal.

## APD array

Photodiodes also make use of the photoelectric effect for the generation of electron-hole pairs and thus lead to the corresponding photocurrent. Recently, ›multipixel- avalanche photodiodes‹ have been developed, based on CMOS technology and also utilizing the Geiger mode for operation. Also known as ›silicon photomultipliers‹, these detectors are noted for their compact form factor, low cost, low voltage requirements and large active area together with good time resolution. However, still today there are unsolved issues for these arrays, for example, the dark count rate lies several orders of magnitude higher than for conventional Geiger-mode single-photon avalanche diodes. They also exhibit lower quantum efficiency at longer wavelengths.

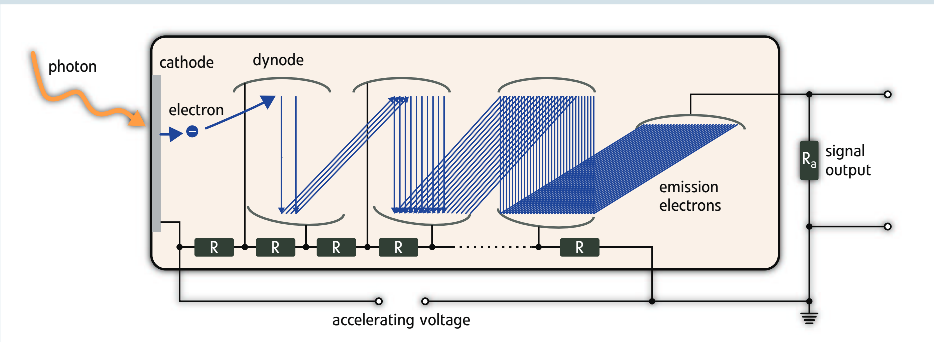
## PMT-APD hybrid

More recently, the field has seen the introduction of PMT-APD hybrid systems – a photon is incident on a photocathode material and frees an electron that then migrates through an APD re-

## Single-photon avalanche diodes

Contrary to conventional pin-photodiodes, avalanche photodiodes make use of an avalanche breakdown to provide amplification (and thus high sensitivity) internally. A requisite for this process is a high reverse bias, extending the absorption region in the APD and thus enabling sufficient electron-hole pair production via impact ionization. These secondary electrons are drawn through the transit region by the high voltage, causing further impact ionizations (multiplication) and thus yielding the desired avalanche effect (**Figure 3**). Conventional APDs are operated below the breakdown voltage, but if the reverse bias voltage is too low, (frictional/collisional) losses in the semiconductor material cause the avalanche effect to be too strongly damped. APDs can also be operated above their breakdown voltage (Geiger mode) and are then specially designed to promote the avalanche effect. With an internal amplification of up to $10^8$ these devices are capable of detecting single photon events – hence the term single-photon avalanche diodes (SPADs).

This mode of operation does however lead to high currents within the SPAD, and these must be properly controlled if the device is not to remain conducting or should not become damaged. In the simplest case this is achieved through the use of a series resistor (passive quenching) – the voltage drop across the resistor is responsible for the SPAD returning to its blocking state,




**2 Schematic illustration of a photomultiplier tube (PMT)**

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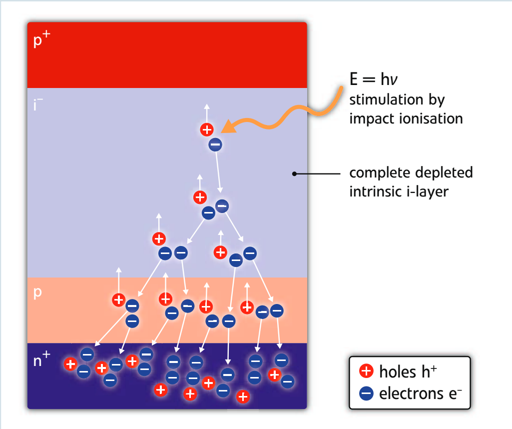


**3 Function principle of an avalanche photodiode (APD): An incident photon generates an electron-hole pair. The electron is accelerated toward the multiplication zone and generates further electron-hole pairs (avalanche).**

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but this does lead to very high dead-times and thus limited detection rates [1]. Most commercially available SPAD modules thus use electronics that are designed to sink the reverse bias (active quenching) as soon as the breakdown current has been detected. Achievable dead-times are in the order of 50 ns and count rates of up to 10 MHz or more can be realized.

In addition, modern SPADs are equipped with thermo-electric cooling, thus leading to extremely low dark count rates of around 10 c/s. **Figure 4** illustrates the block diagram for a fiber-coupled Count module from Laser Components.

## Detection efficiency is key to success

When comparing detector types, the relevant performance characteristics include the dark count rate, the probability for afterpulsing and the dead-time. However, the single most important parameter across the largest number of application areas is the detection efficiency. The significantly higher quantum efficiency (QE) for SPADs from 400 nm right across into the IR is one of the main reasons why SPADs are often chosen over PMTs. The QE is defined as the ratio of generated (primary) electrons per absorbed photon, and is thus ≤1. The QE can also be given as a percentage, and in relation to the spectral sensitivity of the detector is represented by:

$$QE=(R_0 \cdot 1240)/\lambda \cdot 100\%$$

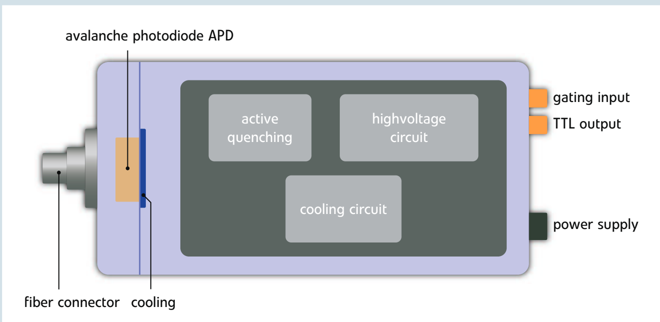
where $R_0$ is the spectral sensitivity in A/W and $\lambda$ is the wavelength in nm. The QE is a measure for the overall efficiency of the APD structure itself, while the efficiency of the entire module is also affected by that of the driver electronics. For this reason the data sheets for SPAD modules usually specify the photon detection efficiency (Pd) – that is, the probability that an incident photon results in an electrical pulse at the output of the module.

When designing a SPAD, it is important to understand that both the detection efficiency and the dark count rate are dependent on the bias voltage applied to the APD. As previously mentioned, the APD is operated in Geiger mode, so above the breakdown voltage ($V_{op}>V_{br}$). The difference between $V_{op}$ and $V_{br}$ is called overvoltage, and is chosen so as to optimize particular parameters such as the detection efficiency. An optimization is, however, only possible when the APD at the heart of each module is of sufficient quality. This in turn demands an APD structure that has been designed for maximum QE, but that at the same time also exhibits a minimum *K* factor [2] so that the dark noise remains as low as possible (the K factor compares the ionization properties of the holes to that of the electrons).

Laser Components Detector Group's ›VLoK‹-APD (very low *K*) has been especially engineered for this purpose and features previously unattained dark count rates below 10 c/s, while simultaneously exhibiting a detection efficiency of over 80 percent at 670 nm.

While SPADs have traditionally been the device of choice for applications in the red and NIR wavelength ranges, PMTs are still preferred for applications in the blue and UV because of their higher QE. That said, more recent developments for SPAD technology show that this differentiation is becoming increasingly unjustified. A good example here is the ›Count blue‹ series from Laser Components, utilizing a VLok-APD version that has improved UV response. The Count blue has a typical detection efficiency of 55 percent at 405 nm and 70 percent at 532 nm. Today, there are SPAD versions that have been optimized for the NIR range as well, for example the ›Count NIR‹, developed for applications in quantum optics and quantum information. This module exhibits an exceptionally high detection efficiency of typically 60 percent at 810 nm (**Figure 5**).

Further advantages of the SPAD modules include the simple interface, a requirement for low voltages (typically 5 or 12 V DC), and the wavelength-optimized fiber coupling options.




**4 Block diagram of a Count module from Laser Components**

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5 The SPAD modules Count NIR and Count Q

## Further into the NIR

Although most of the developments for SPAD technology have been in silicon, there is increasing demand for single-photon detectors with sensitivity in the IR. InGaAs-APDs are better suited for wavelengths longer than 1000 nm, for which the detection efficiency can be as high as 20 percent. As the principal application for these devices is in the field of quantum cryptography (at 1550 nm), the relatively low detection efficiency can be compensated by an almost lossless photon transport in optical fibers. Nonetheless, it must be noted that the dark count rates and the probability of afterpulsing for this type of APD is significantly higher than for Si-APDs.

The new ›Count Q‹ module (**Figure 5**) was specially developed for this type of application. Highlights of the device are the selectable QE (up to 20 percent, including correction for dark rate counts and afterpulsing) and the variable dead-time – both of which can thus be adjusted for a specific application by the customer.

## Summary

Given the increasing number of applications involving single photon generation right across the optical spectrum from the UV and into the IR, there is matching growth in the performance demands on the corresponding single-photon detectors. To help cater to these demands, it will become increasingly necessary to combine the cost-effective advantages of CMOS technology in the development of efficient and low-noise SPADs. ■

### Literature

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) pp. 17448-17459

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

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