Single-Photon Counting Detectors for the Visible Range Between 300 and 1,000 nm

Andreas Bülter

Abstract Single-photon counting in the visible spectral range has become a standard method for many applications today, ranging from fluorescence spectroscopy to single-molecule detection and quantum optics. One of the key components for every setup is single-photon sensitive detectors. Unfortunately a detector with "ultimate" features, i.e., high detection efficiency at a large wavelength range, high temporal resolution, and low dark counts, does not exist. For most of the applications, it is therefore necessary to choose a detector based on the most crucial parameters for the targeted application.

This chapter provides an overview about the typically used single-pixel detectors for photon counting in the visible range. It provides information about the key parameters such as detection efficiency, dark counts and timing resolution that principally allow to choose the best suited detector for a targeted application.

Keywords Hybrid-PMT · MCP · PMT · Single photon · SPAD

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1 General Introduction

Detectors are core components in every setup based on photon counting. For the spectral range between approx. 300 and 1,000 nm, there are essentially two detector classes available: detectors based on the external photoelectric effect such as photomultiplier tubes, microchannel plate photomultipliers, or hybrid photomultiplier tubes or detectors based on the internal photoelectric effect such as single-photon avalanche diodes. When comparing detectors in order to find the most suited model for the targeted application, there are five key parameters that must be considered:

1. Sensitivity – no detector covers the complete spectral range from 300 to 1,000 nm with a uniform sensitivity. It is therefore necessary to look at the sensitivity of each detector at the targeted detection wavelength (range). The sensitivity is usually expressed as a "quantum efficiency" or "detection efficiency," given in percent. This value essentially corresponds to the probability that a photon is converted into a measurable electrical pulse.
2. Dark counts – dark counts refer to output pulses generated "inside" the detector in the absence of light. Dark counts are emitted at random times and expressed in counts per second (cps). They add a baseline (or offset) to all photon counting measurements and cannot be avoided or removed. It is therefore advisable to choose a detector with a dark count rate much lower than the expected signal rate. Otherwise the effective usable signal count rate might be reduced due to a competition between dark counts and "real" photon counts.
3. Afterpulsing – afterpulsing refers to additional, artificial output signals that are not related to a photon detection event but correlated to a previous detection event. In time-resolved measurements, afterpulses are visible as additional signal peaks at a defined temporal spacing to the main signal. Afterpulses are

generated “inside” the detector and cannot be avoided or removed. Afterpulsing is usually expressed as a percentage that expresses the probability that one detected photon creates an afterpulsing event. In many applications afterpulsing is not a big problem as it can be treated (or ignored) in the data analysis or by using a suited optical setup (e.g., by using two detectors for a cross-correlation analysis). Nonetheless, an afterpulsing probability as low as possible is recommended to minimize the efforts necessary to correct for this effect.

4. Timing resolution – for time-resolved applications, the internal temporal resolution (the “jitter”) of the detector is a crucial parameter. The better the timing resolution, i.e., the lower the full width at half maximum (FHWM) of the detector response, the better the overall temporal resolution of the complete setup. Note that this is not the width of the electrical output pulses but the histogram of time differences between photon arrival and electrical output.
5. Size of the active area – this is a geometrical factor that needs to be considered when designing the optical setup. Detectors based on the external photoelectric effect usually have active areas of several mm, whereas detectors based on the internal photoelectric effect only have active areas in the range between 20 and 200 μm. In the latter case, the optical setup must be designed in way that allows to couple the collected light from the sample effectively on the small active area (e.g., by means of optical fibers or using a confocal setup)

In the following sections, the currently commercially available and typically used detector types for the visible range (photomultiplier tubes, microchannel plate photomultiplier tubes, hybrid photomultiplier tubes, and single-photon avalanche diodes) will be described and discussed with respect to these five key parameters. Other detectors which are also suited for photon counting in the visible range such as superconducting nanowires or transition edge sensors are covered in more detail in the next chapter as they are typically used for photon counting in the infrared.

2 Photomultiplier Tubes (PMTs)

2.1 General Description

Photomultiplier tubes (PMTs) are the most established detectors for single-photon counting. The first PMT was already demonstrated in the mid-1930s, after intensive studies of the photoelectric effect and secondary emission multipliers (dynodes) [1].

A PMT is basically a vacuum tube that includes three core components (see Fig. 1):

1. A photocathode in which photons are converted to electrons by the photoelectric effect and emitted into the vacuum. Depending on the material of the photocathode, PMTs can be effective for detection of light at varying wavelengths.

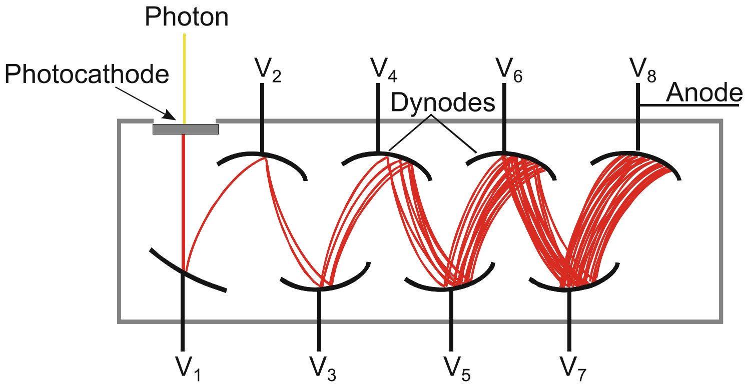

Fig. 1 Basic principle of a photomultiplier tube. Photons are converted to electrons by the photoelectric effect. The electrons are multiplied in a dynode chain and finally collected by an anode to provide an electrical output signal

The most common photocathodes for the visible spectral range are of bialkali, multialkali, GaAs, or GaAsP type.

2. A dynode stage where the electrons are multiplied by means of secondary electron emission. There are a variety of dynode types available, and each type exhibits different gain, time response, uniformity, and secondary electron collection efficiency depending on the structure and the number of stages. Briefly, once an electron is emitted from the photocathode, it is accelerated toward the first positively charged dynode. The electron collides with the dynode and releases further electrons, which are then accelerated toward the next dynode, where they collide and release even more electrons. Each successive dynode in the PMT is charged to a higher positive potential than the preceding one, which thus results in an amplification as the increasing number of electrons collide with later dynodes. The amplification of electrons is very effective and typically leads to multiplication factors in the range of 10^6–10^7.
3. An anode, which collects the multiplied secondary electrons emitted from the last dynode.

The dynode stages typically require operating voltages in the order of 1 kV. This, along with the necessary design of the multiple dynode stages, made PMTs rather large and bulky detectors in the past. In the recent years, however, PMTs have been successfully miniaturized and are now available as small compact units that even include the necessary high-voltage power supply [2, 3]).

Over a certain range of light intensity, PMTs are analog devices, i.e., they output a current, which is proportional to the light level on the photocathode. At high light intensity, the output pulses of individually amplified photoelectrons overlap and can no longer be detected as individual pulses. Due to the varying pulse amplitude and pulse width as well as the underlying Poisson statistics, it is very difficult to define an upper count rate limit where this happens. Only at very low light intensities the PMT

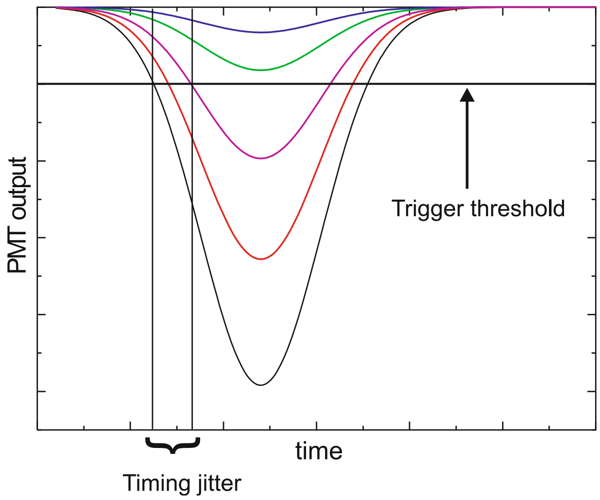

Fig. 2 PMT output pulses show fluctuating pulse amplitudes due to fluctuations in the amplification process of the dynodes. Combined with a simple level trigger threshold, this leads to a timing jitter in time-resolved measurements

outputs individual, well-separated pulses that can be amplified and further processed by photon counting electronics.

The output pulses of a PMT never show a constant amplitude due to fluctuations in the amplification process of the dynodes. These fluctuations will effectively lead to a timing jitter of the order of the pulse rise time in time-resolved measurements, unless the PMT is connected through a constant fraction discriminator to the photon counting electronics (see Fig. 2).

2.2 Detection Efficiency

The detection efficiency of a PMT is determined by the photocathode material (see Fig. 3). Bialkali types are sensitive in the range between approx. 230 and 700 nm. They are most efficient at wavelengths below 500 nm, where they can reach detection efficiencies up to 40 % ("ultra-bialkali"). PMTs based on multialkali photocathodes generally cover larger spectral ranges from approx. 230 to 920 nm but have a lower detection efficiency that reaches values around 15 % between 400 and 700 nm. PMTs based on GaAs and GaAsP photocathodes are sensitive in the spectral range between 300 and 890 nm. Compared to multialkali photocathodes, the GaAsP features a higher detection efficiency reaching up to 40 % at 600 nm.

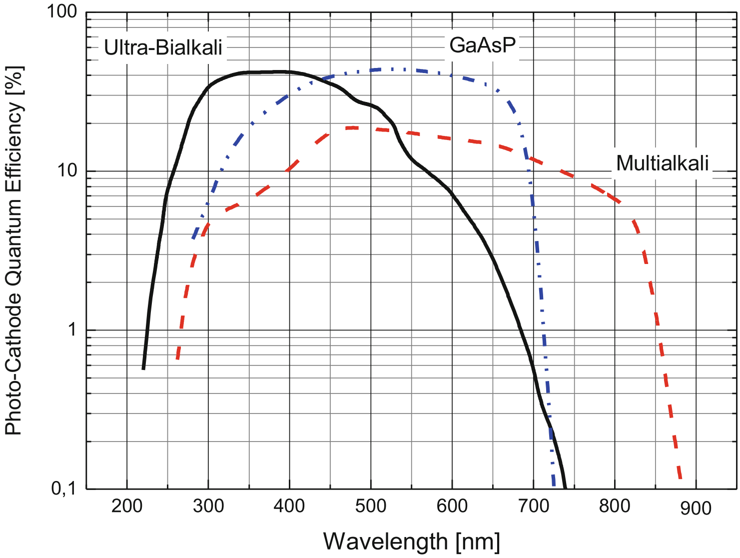

Fig. 3 The detection efficiency of a PMT is determined by the photocathode material. The plot shows typical examples for bialkali [3], multialkali [3], and GaAsP [2] photocathodes

2.3 *Dark Counts and Afterpulsing*

Dark counts or dark current of a PMT refers to a small amount of current flow even when operated in a completely dark state. The most prominent cause of dark current in a PMT is thermionic emission current from the photocathode or the dynodes [1]. The magnitude of this effect depends on the photocathode material as well as on the temperature. Bialkali photocathodes generally show a much lower thermionic emission than multialkali, GaAs, or GaAsP photocathodes and therefore have correspondingly low dark counts. Typical values are less than 50 cps for bialkali PMTs and can be as high as 10,000 cps for multialkali PMTs. The amount of thermionic emission can be strongly reduced by lowering the operation temperature, which is the reason why especially multialkali, GaAs, or GaAsP PMTs are usually operated in a Peltier-cooled housing. When cooled, the dark counts of these detectors reach values around 1,000 cps, which is small compared to typical count rates in photon counting setups of 10^5 cps.

Afterpulsing in PMTs is visible by additional peaks several nanoseconds after the main pulse (see Fig. 4). This afterpulsing signal is mainly caused by positive ions which are generated by the ionization of residual gases in the PMT [1]. These positive ions return to the photocathode and produce additional photoelectrons, resulting in afterpulsing. The influence of afterpulsing in PMTs can be strongly reduced by a constant, strong illumination (e.g., 48 h at 3×10^6 cps). This strong illumination essentially ionizes most of the residual gases that get trapped at the

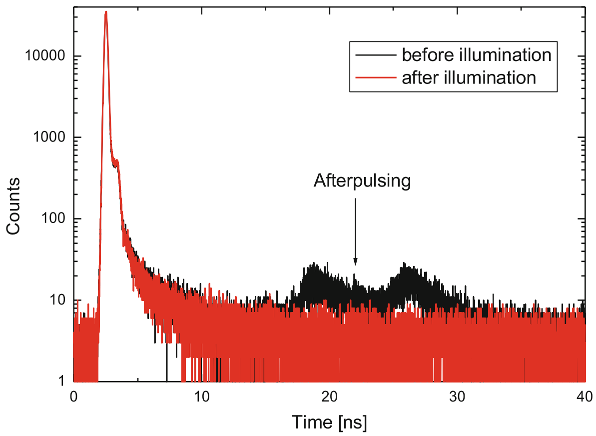

Fig. 4 Afterpulsing in PMTs is visible in the timing response profiles by additional peaks several nanoseconds after the main pulse. The influence of afterpulsing can be strongly reduced by a constant, intense illumination

photocathode. However, once the PMT is switched off, some gases diffuse back into the photomultiplier tube. As a consequence, afterpulsing can again be visible if a PMT has not been used for longer times.

A second common feature of the timing response profile of a PMT is an additional peak a few nanoseconds after the main peak with an amplitude around 2 orders of magnitude lower (see Fig. 4). This peak is caused by elastic scattering of the photoelectrons from the first dynode [1]. It is usually no problem in photon counting experiments due to its low amplitude and because it is independent from the detection wavelength and can therefore be treated in the data analysis procedure.

2.4 Timing Resolution

The timing resolution of a PMT in a photon counting setup is determined by the so-called transit time spread (TTS). The TTS is a measure of the different transit times of the photoelectrons on their way from the photocathode through the dynodes. The major source of the different transit times is the photocathode. As the photoelectrons are emitted at the photocathode at random locations, with random velocities, and in random directions, the time they need to reach the first dynode is slightly different for each photoelectron. This finally leads to different transit times for each photoelectron, which is measurable as the FWHM of the timing response. Modern, compact PMTs based on bialkali or multialkali photocathodes reach TTS values around 140 ps (FWHM) (see Fig. 4), whereas GaAsP PMTs usually have a higher TTS around 200–350 ps (FWHM) [2].

2.5 Geometrical Factors

The active area of a PMT is determined by the size of the photocathode. Typical values are between 5 and 8 mm in diameter. This large active area makes the PMT suitable for more or less all optical setups used in photon counting experiments. PMTs are typically used in setups where the light is collected from a larger volume, such as mm-sized cuvettes in fluorescence spectrometers or tissue surface in diffuse optical imaging (see Grosenick [4]). For similar reasons PMTs are also ideal detectors for confocal scanning microscopes in a non-descanned detection scheme. As the dark count rate is roughly proportional to the active area of the detector, it might be advisable especially for GaAs and GaAsP cathodes to check if PMTs with a smaller active area are available.

3 Microchannel Plate Photomultipliers Tubes (MCP-PMT or MCP)

3.1 General Description

Microchannel plate photomultiplier tubes (MCP) can be considered as a 2-dimensional array of devices that work at similar principles like the PMT [1]. An MCP is assembled from a large number of glass capillaries (channels) with an internal diameter between approx. 6 and 20 μm. The inner wall of these capillaries is coated with a photoemissive material and biased at each end, so that it acts as a continuous dynode. When a primary photoelectron impinges on the inner wall of a channel, secondary electrons are emitted, which again collide with the inner wall to release even more electrons, resulting an exponential multiplication of the electron flux (see Fig. 5). MCPs require rather high operating voltages on the order of 3 kV. Their gain is, however, lower than that of conventional PMTs. MCPs can easily be damaged by overload, which is why the

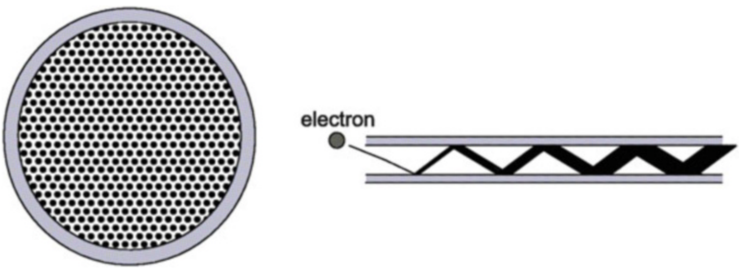

Fig. 5 Schematic structure of an MCP. An MCP is assembled from a large number of glass capillaries (channels), whose inner wall is coated with a photoemissive material and biased at each end, so that it acts as a continuous dynode. Photoelectron impinges on the inner wall of a channel lead to emission of secondary electrons, resulting an exponential multiplication of the electron flux

manufacturers usually suggest to limit the maximum count rate to less than 20,000 cps [5]. It is, however, still possible to use MCPs at higher count rates up to, e.g., 200,000 cps, but it is then recommend to illuminate the full active area of the detector and not to focus the light to a few channels only. Otherwise, since each channel needs a certain time (μs to ms) to be recharged, the count rate the device can deliver is limited by channel saturation.

A second problem is the limited lifetime when used at high count rate, due to degradation of the microchannels under the influence of the flux of electrons. Similar to PMTs, the output pulse of an MCP has fluctuating pulse heights and therefore needs to be connected through a constant fraction discriminator for time-resolved photon counting measurements.

3.2 Detection Efficiency

MCPs essentially use the same cathode material as PMTs, i.e., they are available based on standard bialkali, multialkali, GaAs, or GaAsP photocathodes (see Fig. 6). The different cathodes cover spectral ranges from approx. 160 to 910 nm with detection efficiencies reaching 15 % at 400 nm for bialkali and multialkali photocathodes, which is lower than for conventional PMTs. MCPs based on GaAsP photocathodes reach up 40 % efficiency around 500 nm [5, 6].

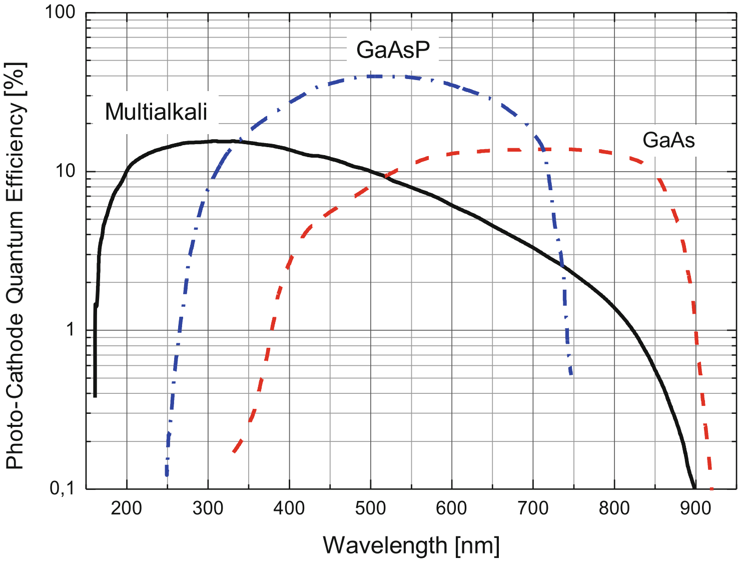

Fig. 6 The detection efficiency of an MCP is determined by the photocathode material. The plot shows typical examples for multialkali [4], GaAsP, and GaAs [5] photocathodes

3.3 Dark Counts and Afterpulsing

The dark counts of MCPs are similar to conventional PMTs. Typical values are less than 50 cps for bialkali MCPs and can be as high as 10,000 cps for multialkali or GaAsP MCPs. When cooled, the dark counts of these detectors usually reach values around 1,000 cps, which is, however, still low compared to typical count rates in photon counting setups of 10^5 cps. Afterpulsing is usually not observed in MCPs.

3.4 Timing Resolution

Due to the small diameter of the glass capillaries of only a few micrometers and the resulting low transit time spread, MCPs have a very good timing resolution that can reach values down to 25 ps (FWHM) for the bialkali or multialkali types and less than 150 ps (FWHM) for the GaAs and down to 60 ps (FWHM) for the GaAsP photocathodes. MCPs are therefore the detectors of choice for applications that require a very high temporal resolution.

3.5 Geometrical Factors

The active area of an MCP is determined by the size of the photocathode. Typical values are around 10 mm in diameter, which is even larger than conventional PMTs. This large active area makes the MCP therefore suitable for more or less all optical setups used in photon counting experiments. Their inherent problem with saturation and damage by overload is, however, limiting their usage. Consequently, MCPs are typically used in setups that allow the precise control of signal intensity, e.g., in fluorescence lifetime spectrometers. In scanning microscopy or other setups that have a strongly fluctuating signal rate, MCPs are usually not chosen.

4 Hybrid PMTs

4.1 General Description

A hybrid PMT is a photomultiplier tube that incorporates a silicon avalanche photodiode in an evacuated electron tube. When light strikes the photocathode, photoelectrons are emitted and then accelerated by a high-intensity electric field of a few kilovolts applied to the photocathode. The photoelectrons are then "bombarded" onto the silicon avalanche photodiode where they create electron-hole pairs according to the energy of the photoelectron (see Fig. 7). These carriers are then further amplified

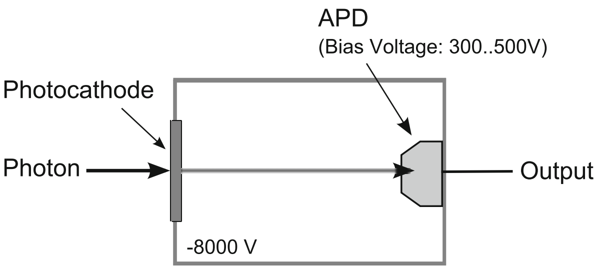

Fig. 7 Schematic of a hybrid PMT. When light hits the photocathode, photoelectrons are emitted and then "bombarded" onto the silicon avalanche photodiode (APD)

by the linear gain of the avalanche diode. The total gain of a hybrid PMT is on the order of 10^5 and thus lower than the gain of PMTs or MCPs but still large enough to be combined with suited preamplifiers for photon counting applications. Similar to PMTs, the output pulse of a hybrid PMT has fluctuating pulse heights and therefore needs to be connected through a constant fraction discriminator for time-resolved photon counting measurements.

Bare hybrid PMTs are not easy to handle as they require an operating voltage of 8 kV and an extremely good shielding and low-noise amplification to deal with the small amplitude of the single-photon pulses [7]. They also require a carefully designed integrated cooling system that controls the temperature of the APD to avoid fluctuations in the gain and dark counts. Nonetheless, complete detector modules based on the hybrid PMT are available today [8] that integrate the necessary high-voltage power supply, temperature stabilization, and preamplification.

4.2 Detection Efficiency

Hybrid PMTs essentially use the same cathode material as PMTs and are currently available based on bialkali, GaAs, or GaAsP photocathodes. The different cathodes cover spectral ranges from approx. 220 to 890 nm with detection efficiencies reaching up 30 % efficiency around 400 nm for the bialkali cathodes and even up to 40 % at 500 nm for the GaAsP cathodes [7, 8] (see Fig. 8).

4.3 Dark Counts and Afterpulsing

The dark counts of hybrid PMTs are similar to conventional PMTs. Typical values range from less than 100 cps for bialkali hybrid PMTs to approx. 1,000 cps for GaAs or GaAsP photocathodes.

One of the most striking features of the hybrid PMT is the virtual absence of afterpulsing. Afterpulsing in single-photon detectors is usually due to two reasons – either, as in PMTs, caused by ionization of residual gas molecules by the electrons traveling through the dynode system or, as in single-photon avalanche diodes,

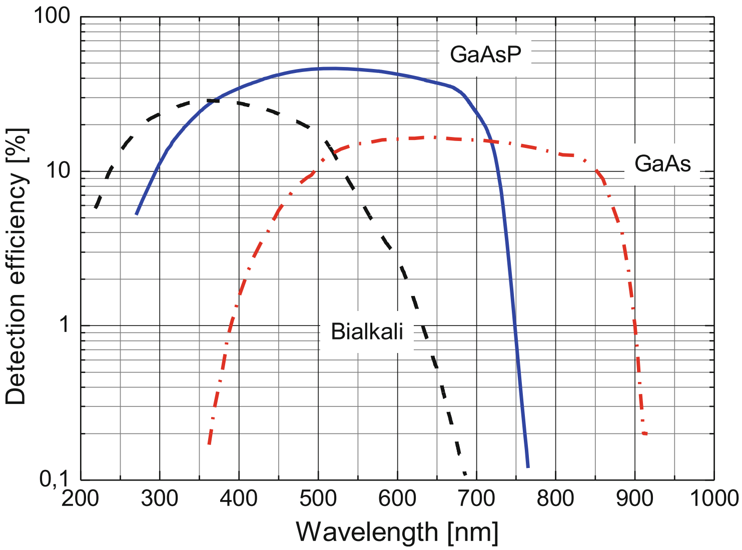

Fig. 8 The detection efficiency of a hybrid PMT is determined by the photocathode material. The plot shows typical examples for multialkali GaAs and GaAsP photocathodes [7, 8]

resulting from trapped carriers of the previous avalanche breakdown. Both causes have no influence in hybrid PMTs because only single electrons are traveling in the vacuum and because the APD works in linear mode, which causes no avalanche breakdown.

4.4 Timing Resolution

The high acceleration of the photoelectrons by the 8 kV acceleration voltage leads to a very low transit time spread. Hybrid PMTs therefore generally feature a very good timing resolution that can be as fast as 50 ps (FWHM) for the bialkali types and $<$120 ps (FWHM) or $<$160 ps (FWHM) for the GaAsP and GaAs photocathode types. Moreover, the timing response of a hybrid PMT is very clean, without significant tails, bumps, or secondary peaks.

4.5 Geometrical Factors

The active area of a hybrid PMT is determined by the size of the photocathode. Typical values are between 3 and 5 mm in diameter. This large active area makes the hybrid PMT suitable for more or less all optical setups used in photon counting experiments. Due to their fast timing response, the good detection efficiency and the absence of afterpulsing, hybrid PMTs are now becoming the “standard” detector for many photon counting experiments, ranging from classical spectroscopy on bulk material to imaging and correlation spectroscopy in microscopy applications [9].

5 Single-Photon Avalanche Diodes (SPAD)

5.1 General Description

In contrast to photomultiplier tubes, which are based on the external photoelectric effect, i.e., the generation of photoelectrons through a photocathode, avalanche photodiodes are based on the internal photoelectric effect, i.e., the generation of photoelectrons inside the device. An avalanche photodiode is a device formed by a junction between a semiconductor with an excess of holes (p-type) and a semiconductor with an excess of carriers (n-type). Diffusion at the junction leads to a region depleted of free carriers. When a voltage is applied so that the n-type semiconductor is at a higher potential than the p-type semiconductor, the junction is said to be reverse biased, creating an effective voltage gradient in the semiconductor. A drifting electron created, e.g., by the absorption of a single photon, is accelerated along the gradient and can gain enough kinetic energy to knock an electron out of its bound state on collision with an atom. This electron is then again accelerated in the electric field and can also create additional free electrons by collision with atoms, resulting finally in an avalanche of carriers. If the applied electric field across the device is sufficiently high, above the so-called breakdown voltage, single-photon-generated carriers can trigger a self-sustaining avalanche. When operated in this so-called “Geiger” mode, the device is called a single-photon avalanche diode (SPAD) [10].

The avalanche leads to a rise of the current to a macroscopic constant level within less than a nanosecond, which can then be easily detected by suited electronics. If the primary carrier is photogenerated, the leading edge of the avalanche pulse marks the arrival time of the detected photon with picosecond time jitter. The avalanche current will keep flowing as long as the applied voltage is kept above the breakdown voltage. In this stage absorption of additional photons will not lead to any change in the signal output, making the device useless. It is therefore necessary to stop the self-sustained avalanche and reset the detector to be able to detect the next photon. This process of resetting is called “quenching” of the avalanche.

The process of quenching involves detecting of the leading edge of the avalanche, then generating a closely time-correlated electrical pulse that reduces the bias voltage below the breakdown level and finally restoring the voltage to the operating level above the breakdown voltage. There are essentially three principle realizations of quenching circuits for SPADs: passive, active, and gated quenching. The latter is only used for SPADs that are sensitive in the infrared (see Buller and Collins [11]).

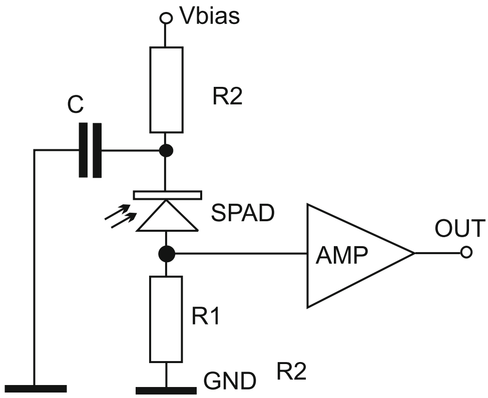

Fig. 9 In passive quenching, a high impedance resistor, connected in series to the SPAD, limits the current flow and effectively quenches the avalanche

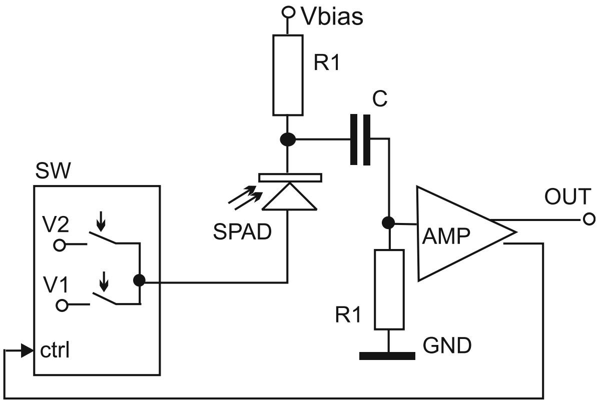

Fig. 10 In active quenching, the operation voltage is actively switched below the breakdown voltage, once the beginning of the avalanche has been detected by a dedicated sensing circuit. The operating voltage is then switched back above the breakdown voltage after a certain (dead) time

In passive quenching a high impedance resistor, connected in series to the SPAD, limits the current flow and effectively leads to the breakdown of the voltage at the diode and thus quenches the avalanche (see Fig. 9) [12]. An additional capacitor is usually included to generate a detectable output pulse. Passive quenching circuits have a slow recovery time (dead time) in the microsecond range in which no further photon detection events can be registered. This long dead time limits the maximum count rate to some hundred kHz. SPADs with passive quenching circuits are therefore usually not employed in current photon counting setups.

In active quenching, the operation voltage is actively switched below the breakdown voltage, once the beginning of the avalanche has been detected by a dedicated sensing circuit (see Fig. 10). This switching must happen within a few nanoseconds in order to avoid damage to the SPAD. The operation voltage is then kept below the breakdown voltage for a certain time in order to remove remaining carriers from the avalanche region. This process typically takes some tens of nanoseconds and corresponds to the dead time of the SPAD. SPADs with active quenching therefore permit photon detection rates up to several MHz and are thus commonly used in photon counting setups today.

SPADs for the visible range are based on silicon. There are two main types of Si-SPADs architecture available today: thick [13–15] and thin-junction devices [16, 17]. The main difference between these two designs is the thickness of the depletion region in which photon absorption takes place. Thick-junction SPADs usually feature a depletion region of a few tens of μm, whereas thin-junction SPADs only have a few μm thickness.

5.2 Detection Efficiency

SPADs based on silicon can generally be used in the spectral range between 400 and 1,100 nm. Their detection efficiency varies not only with detection wavelength but also depends on the type of SPAD. Thin-junction SPADs typically have a lower detection efficiency than thick-junction devices, simply because the depletion region (absorption region) is smaller. Their maximum efficiency typically reaches values around 50 % in the blue/green spectral range around 500 nm falling to approx. 5 % at 1,000 nm. Thick devices on the other hand often reach detection efficiencies of more than 70 % in the red spectral range around 700 nm falling to approx. 15 % at 1,000 nm (see Fig. 11).

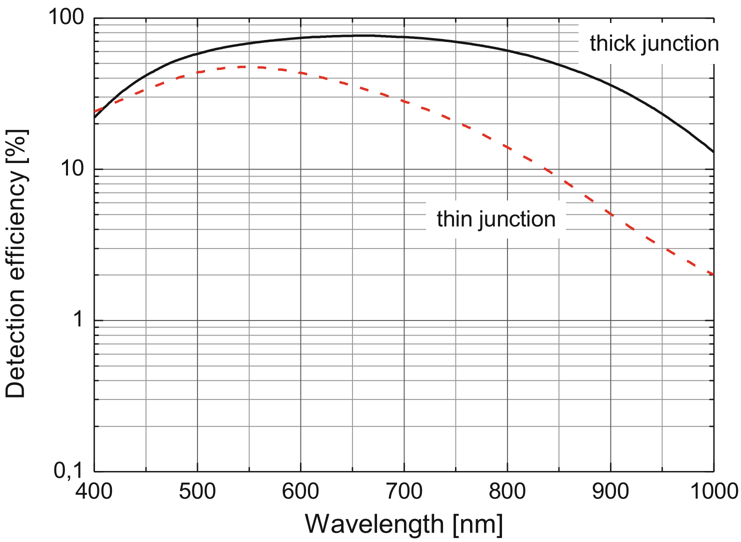

Fig. 11 Typical detection efficiency of a thick-junction SPAD [8] and a thin-junction SPAD [9]

5.3 Dark Counts and Afterpulsing

The dark count rate of an SPAD depends on the size of the active area as well as the chip temperature. Generally speaking, the dark count rate increases with size of the active area and decreases with the chip temperature. Typical values for a cooled device with 100 μm active area are <250 cps, whereas modules with 20 μm active area can reach <5 cps. Thick-junction cooled Si-SPADs usually have dark counts of <250 cps, but as the dark count rate strongly depends on the characteristics of the individual APD, it is also possible to get modules with <20 cps.

Afterpulsing is a common feature of SPADs, caused by impurities and crystal defects which act as "carrier traps." During each avalanche pulse, a few avalanche carriers can be trapped and are subsequently released after increasing the voltage again above the breakdown voltage. The released carriers can then re-trigger the avalanche, thereby generating correlated afterpulses [18]. The overall, measurable afterpulsing probability of a SPAD decreases exponentially after the quenching process. It can therefore be lowered by increasing the dead time of the SPAD, which, however, also reduces the maximum count rate of the device. Typical afterpulsing probabilities for commercially available (actively quenched) Si-SPADs are <1 % at dead times around 50–70 ns.

An often underestimated feature of SPADs is the so-called afterglow or breakdown flash [19]. This term describes the fact that Si-SPADs emit broadband light during the avalanche process. This light is emitted isotropically from the sensor and usually covers a spectral range between approx. 700 and 1,000 nm with varying intensities. Especially in coincidence correlation measurements using a Hanbury-Brown-Twiss (HBT) setup, the afterglow can lead to problems as the light emitted by one SPAD can be detected by the second SPAD. This results in a characteristic double-peak structure in the measurement result. Afterglow cannot be avoided. It is only possible to minimize the influence on the measurement data by, e.g., temporal delay and spectral or spatial filtering.

5.4 Timing Resolution

Thin-junction SPADs have been demonstrated to achieve timing resolutions down to 20 ps [20]. Mainstream commercial solutions feature timing resolutions down to 50 ps for wavelengths >500 nm. At lower detection wavelengths, the timing uncertainty increases and can reach values around 200–300 ps. This increase is caused by the SPAD structure – blue and UV light is not absorbed in the depletion region but near the silicon surface. The generated carriers therefore have to diffuse to the depletion region first to start the avalanche, which increases the timing jitter. The pulse shape of thin-junction SPADs is also very characteristic – it is a narrow peak with a small FHWM, followed by a long "diffusion tail" with much lower amplitude (see Fig. 12). The diffusion tail is due to carriers photogenerated in

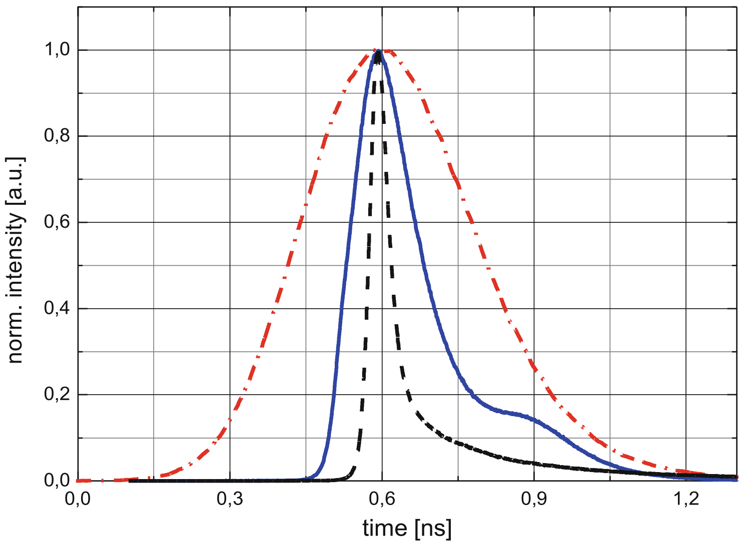

Fig. 12 Thin-junction SPADs have a wavelength-dependent timing response, which can be as fast as 50 ps for wavelengths >500 nm. Thick-junction SPADs do also show a dependence of the pulse profile from the detection wavelength, but the change is less pronounced. The plot shows the pulse profile of a thick-junction SPAD at 670 nm (*red*, *dash-dot*) and the response of thin-junction SPADs at 670 nm (*black*, *dotted*) and at 405 nm (*blue*, *solid*)

neutral regions near the depletion region that walk around by diffusion and eventually reach the edge of the depletion layer, where they are finally accelerated by the electric field. At 1/10th of the maximum, the FWHM of the tail can be as great as 20 times the value of the peak. The timing resolution of thin-junction SPADs is usually not dependent on the signal rate.

Thick-junction devices generally exhibit a timing resolution between 300 and 800 ps. The best timing resolution is obtained in the red spectral range above 600 nm and signal rates below 10^6 cps. At higher signal rates, the temporal response width of the thick-junction SPAD increases and can, in the worst case, reach twice the value at low signal rates. In early commercial products, this rate dependency has to some extent been due to the readout electronics and was reduced in more recent designs [14].

The wavelength-dependent timing resolution of SPADs, the so-called color shift, can be a problem in, e.g., fluorescence lifetime-based applications, where it is often necessary to use reconvolution techniques in the analysis to correct for the finite resolution of the measurement instrument [21]. This resolution includes the influence from the detector and consequently depends on the wavelength due to the color shift of the detector. It would therefore be necessary to characterize the so-called instrument response function (IRF) of a setup at the same wavelength as the fluorescence. This can be realized by, e.g., using samples with ultrafast fluorescence decays in the same spectral range as the analyzed sample instead of the typically employed scattering media recorded at the excitation wavelength.

5.5 Geometrical Factors

The active area of an SPAD is much smaller than that of a PMT. Commercial thick-junction SPADs usually have active areas in the order of 150 μm, whereas thin-junction SPADs currently have active areas between 20 and 100 μm. This small active area requires a suited optical setup that allows to focus the collected fluorescence on the active area. Over-illumination of the active area will lead to signal loss and, in case of thick-junction SPADs, also to a decrease of the overall detection efficiency and timing resolution. SPADs are therefore usually used along with confocal microscope setup or in all-fiber setups. For the same reason, they are not suited to be used in fluorescence spectrometers, where the light is collected from a large area.

Due to their high detection efficiency, SPADs are usually used in all single-molecule-based applications such as fluorescence correlation spectroscopy or coincidence correlation (see Dertinger and Rüttinger [22] and Grußmayer and Herten [23]).

6 Summary

There are essentially five different detector types available today for photon counting in the spectral range between approx. 300 and 1,000 nm. Unfortunately there is no detector with "ultimate" combination of features available, i.e., high

Table 1 Overview about typical key parameters of the discussed detector types

	Max. detection efficiency	Timing resolution (FWHM) (ps)	Active sensor area	Max. useful count rate	Dark counts/s
PMT (ultra-bialkali)	42 % @ 380 nm	<150	8 mm	10 MHz	<50
PMT (multialkali)	15 % @ 500 nm	<150	8 mm	10 MHz	<1,500
PMT (GaAsP)	40 % @ 600 nm	250–350	5 mm	10 MHz	< 400
Hybrid PMT (GaAsP)	46 % @ 500 nm	<120	3 mm	2 MHz	<700
Hybrid PMT (GaAs)	18 % @ 650 nm	<160	3 mm	1 MHz	< 1,000
Hybrid PMT (bialkali)	30 % @ 350 nm	<50	6 mm	1 MHz	< 100
MCP-PMT (bialkali)	20 % @ 450 nm	<25	11 mm	20 kHz	<50
MCP-PMT (multialkali)	20 % @ 450 nm	<25	11 mm	20 kHz	<500
MCP-PMT (GaAs)	15 % @ 700 nm	<150	11 mm	20 kHz	<3,000
Si-SPAD (thick junction)	75 % @ 670 nm	300–800	150 μm	1 MHz	<20 to <250
Si-SPAD (thin junction)	50 % @ 520 nm	<50–300	100 μm	10 MHz	<25 to <250

detection efficiency at a large wavelength range, large active area, high temporal resolution, and low dark counts and afterpulsing. It is therefore necessary to choose a detector based on the most crucial parameters for the targeted application. If the experiment is expected to yield very few photons, then the detection efficiency is the most important parameter. In case of time-resolved photon counting applications, the temporal resolution is of course one of the crucial parameters.

Table 1 briefly summarizes the typical main characteristics of the discussed detector types and can be used as a guide to select a suited detector. Note that the table only lists typical values.

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