WhitePaper

PHOTOMULTIPLIER TECHNOLOGIES IN RADIOMETRY

A Comparative Analysis of Vacuum PMT and SiPM

BERTHOLD

Introduction

Radiometric measurements have become indispensable tools across various industrial applications, serving critical roles as level, density, and concentration measurements. The fundamental setup of a radiometric measurement, comprising a gamma radiation source – typically Cs-137 or Co-60 – and a radiation detector, is shown in Figure 1. These components are normally mounted on opposite sides of a vessel or a pipe. The gamma count rate (usually provided as counts per second, cps) measured by the detector is directly proportional to the absorption of gamma radiation by the product inside the vessel – hence, the measured process value is dependent on the level of the product between source and detector as well as its density.
The detectors employed in radiometric measurements can differ widely in construction, physical properties, and performance capabilities. One prevailing measurement principle that is widely adopted in industry is the scintillation technology. This principle encapsulates a threefold process involving a scintillator, a photomultiplier, and processing electronics as primary components as shown in Figure 2.
The scintillator is responsible for converting incident gamma radiation into visible light flashes, while a photomultiplier is employed for detecting the light signals and transforming them into electrical signals. For the last step of the signal generation, processing electronics are used that facilitate further amplification and smoothing.
Within the area of industrial radiometric measurements, two photomultiplying techniques have taken center stage: vacuum photomultiplier tubes (vacuum PMT), representing the current industrial standard, and silicon photomultipliers (SiPM), which have been on the market for approximately two decades. This article aims to explain distinctions between these two techniques, shedding light on their respective advantages and applications.

Fig. 1 Typical setup for a radiometric level measurement.

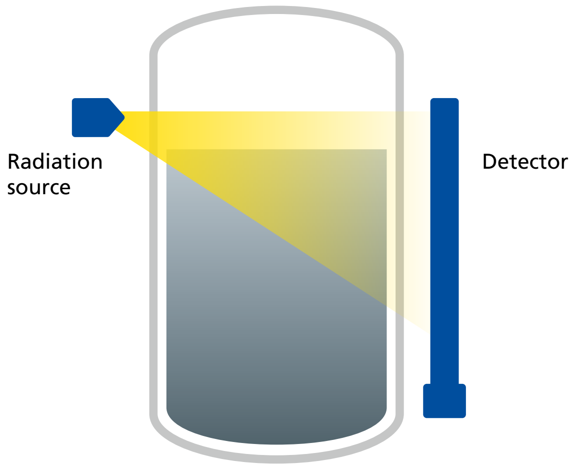
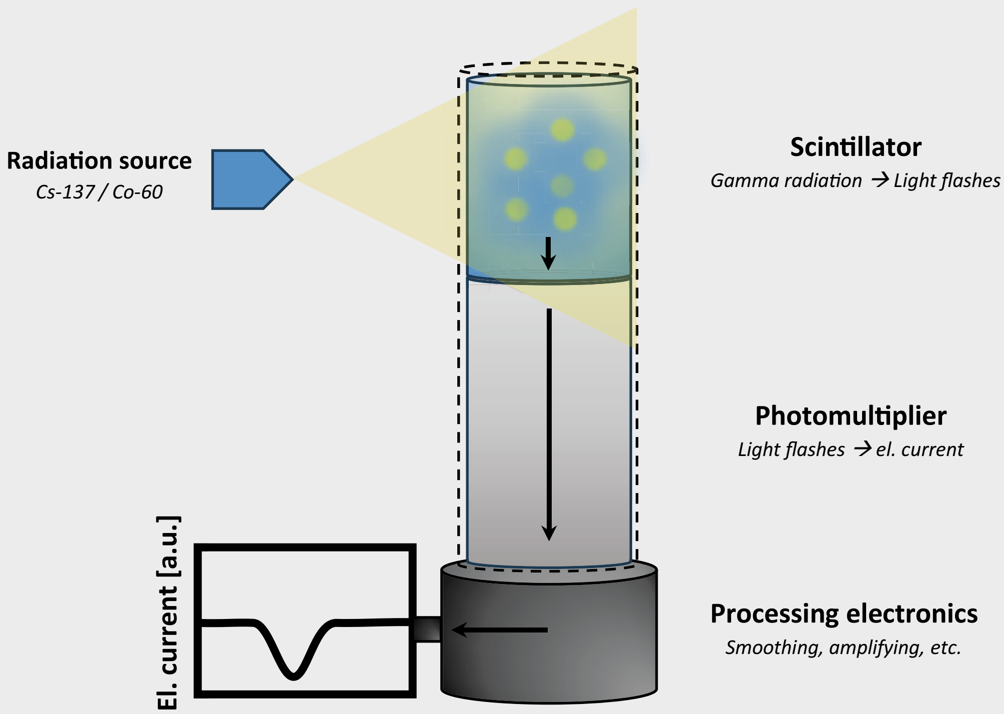


Fig. 2 Typical setup of a scintillation detector used for radiometry. The three main components



Vacuum-Photomultiplier Tubes (vacuum PMT)

A vacuum photomultiplier, the standard for industrial radiometric applications, is designed to amplify weak light signals through a cascade of electron multiplication within an evacuated glass tube. Its key components include the photocathode, focusing electrode, dynodes, and anode, each playing a vital role in the photomultiplier's function.

Photocathode

The process begins with the photocathode, a photosensitive material typically made of cesium-antimony or other similar compounds. When exposed to incident photons, the photocathode releases electrons through the photoelectric effect. These photoelectrons are the initial carriers of the incoming light signal.

Focusing Electrode

Following the release of photoelectrons, a focusing electrode strategically placed within the photomultiplier helps direct and concentrate these electrons towards the next component, the dynodes. This electrode ensures that the electrons maintain a controlled trajectory, enhancing the efficiency of the entire multiplication process.

Dynodes

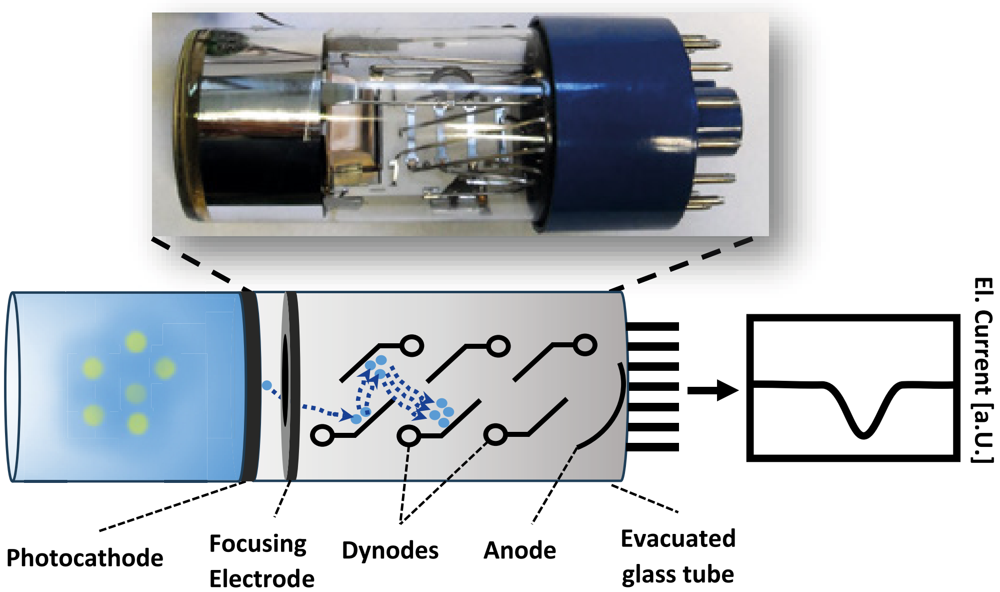
The dynodes are a series of metal electrodes arranged in a cascading fashion within the evacuated glass tube. Each dynode is biased at a slightly higher voltage than the previous one. As the photoelectrons approach the first dynode, they undergo a process of secondary electron emission, releasing additional electrons. These secondary electrons are then accelerated towards the next dynode, resulting in a continuous cascade of electron multiplication. The cascade effect occurs through a combination of electron multiplication mechanisms, such as secondary emission and electron impact ionization. This process ensures that the original signal is significantly amplified as it progresses through the dynode chain.

Anode

At the end of the dynode chain, the now-amplified electron signal reaches the anode. The anode is maintained at a high positive voltage relative to the dynodes, creating an electrostatic field that accelerates the electrons towards it. As the electrons strike the anode, they generate a measurable current, providing an output signal that is proportional to the intensity of the incoming light.

In summary, the vacuum photomultiplier efficiently converts weak light signals into measurable electrical currents, making it an indispensable tool for industrial radiometry and various other applications, including spectroscopy, medical imaging, or even detecting of particles in high energy physics (#1).

Figure 3 Top image: Real photograph of a vacuum photomultiplier tube (PMT). Bottom image: Schematic representation of a vPMT with all main components (Photocathode, focusing electrode, dynodes and anode inside a evacuated glass tube.



Silicon-Photomultiplier (SiPM)

The silicon photomultiplier (SiPM) is a cutting-edge device that revolutionizes light detection by employing an array of avalanche photodiodes (APDs) organized in microcells. This innovative design provides excellent photon sensitivity and single-photon resolution, making SiPMs valuable in various applications, from medical imaging to high-energy physics (#2).

Avalanche Photo Diode (APD)

The fundamental building block of a silicon photomultiplier is the avalanche photodiode. A schematic representation of such an APD is shown in Figure 3 on the left side. These diodes can undergo avalanche breakdown when exposed to incident photons, leading to the generation of a significant number of charge carriers. The APD is created through the process of diode doping, where the semiconductor materials are intentionally impregnated with certain dopants to alter their electrical properties. As a result of this doping, the APD establishes a robust electrical field within its structure. This field is crucial for the functioning of the device and is spatially differentiated into an absorption and an adjacent multiplication zone. When a photon strikes the APD, it is absorbed by the silicon material in the absorption zone. The energy from the absorbed photon triggers the initial charge carrier generation. The released photoelectrons undergo an avalanche multiplication process within the multiplication zone. Due to the high electric field across the diode, the charge carriers gain sufficient energy to ionize other atoms in the silicon lattice, leading to a cascade effect known as avalanche breakdown. This process results in the exponential amplification of charge carriers, creating a detectable signal.

To preserve the energy information, SiPMs consist of an array of microcells as shown in Figure 4, each containing an individual avalanche photodiode. These microcells are typically very small, often on the order of tens of micrometers, allowing for high-density packing of APDs on a single silicon substrate. The small size also minimizes the probability of simultaneous events on one microcell. To ensure the SiPM operates within a controlled range, a quenching resistor is employed. This resistor helps limit the duration of the avalanche breakdown, preventing excessive charge buildup and ensuring a rapid reset of the microcell for subsequent photon detections. The microcell arrangement enables the SiPM to achieve high photon detection efficiency and excellent temporal resolution. The individual signals from each microcell are read out and processed. The output is a digital signal proportional to the number of photons detected. The high density of microcells allows SiPMs to provide excellent spatial resolution and sensitivity, making them particularly useful in applications demanding precise detection of low-intensity light signals. The signals from all the microcells are summed, providing a collective output that corresponds to the total photon flux incident on the SiPM. This summation process allows SiPMs to operate over a wide dynamic range, accommodating both low and high-intensity light conditions.

Fig. 3 [Left side] Functional schematic of an APD including the absorption zone where charge carriers are generated by incident ionizing radiation and the multiplication zone responsible for the acceleration and multiplication of photoelectrons during the avalanche breakdown. [Right side] As the amplification factor is only defined by the applied bias voltage and the diode capacitance, every photon detection event generates the same pulse height.

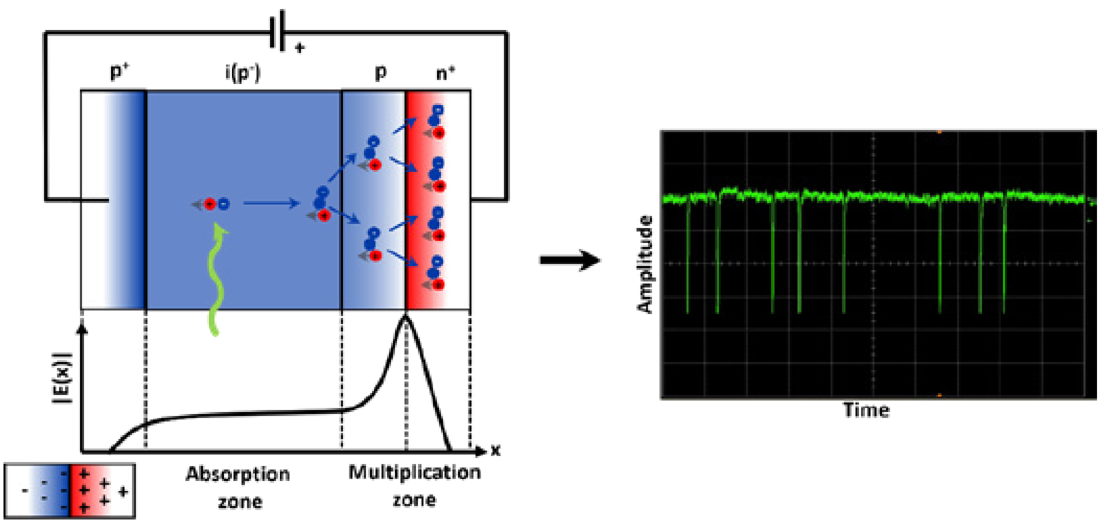
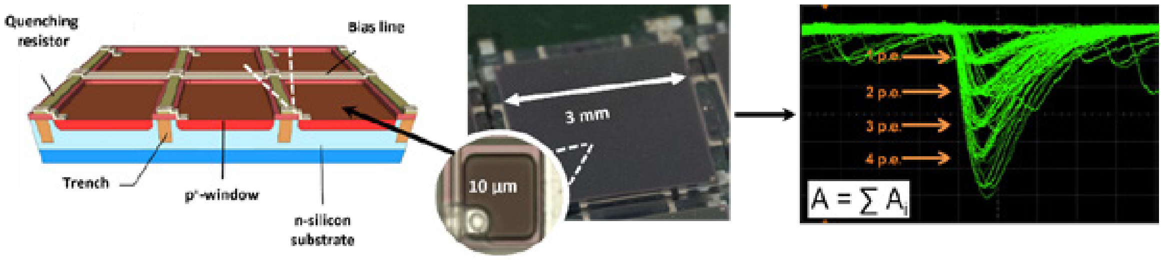


Fig. 4 [Left] Schematic representation of a SiPM as an array of APD microcells. The p+-doped windows are all connected to a joint n-silicon substrate and are separated by a trench connected to a quenching resistor each to prevent excessive charge buildup and ensuring a rapid reset. [Middle] SiPM-arrays normally consist of thousands of microcrells with a size of approx. 10 µm each. [Right] The signal of each microcell is read-out, and all signals can be summed up to preserve the information about the amount of incident photons interacting with the SiPM.



Differences between vacuum PMT and SiPM

Vacuum PMTs and SiPMs are distinct technologies rooted in the scintillation principle, where photon detection generates a measurable current. However, there are huge differences in terms of constructional integration, mechanical and electromagnetic robustness, power consumption and performance, just to name a few. An overview of the technological differences that are explained in this article is shown in Table 1. These differences, influenced by mechanical design and underlying physical principles, dictate suitability for specific applications.

Installation size

Vacuum-PMTs, housed in evacuated glass tubes, have for example larger installation sizes of approximately 2-5 cm in diameter and 5-20 cm in length, depending on the manufacturer. SiPMs, with dimensions in the range of millimeters, offer compactness for direct integration of multiple arrays on one circuit board, as shown in Figure 5.

Redundancy

SiPMs consist of an array of many individual independent photodiodes, shown in the magnification in Figure 5. This pixel-like structure provides a high degree of redundancy. If one of the photodiodes fails due to defects or overload, the other photodiodes in the matrix remain functional, providing increased reliability and robustness (#3). In contrast, the components of vacuum PMTs are built in as a single copy, which leads to an immediate failure of the measurement in case of defective components. Redundancy can only be achieved here by additional measuring instruments.

Mechanical robustness

Additionally, SiPMs and vacuum PMTs show differences in mechanical robustness due to their construction. While vacuum PMTs are also designed to withstand mechanical loads, the glass tube construction is

Tab. 1 Differences between vacuum PMTs and SiPMs briefly summarized. Detailed descriptions can be found in the following paragraph..

Photomultiplier	Vacuum PMT	SiPM
Installation size (length)	5 – 20 cm	0.5 – 1 mm
Redundancy	Multiple detectors	Built in
Mechanical robustness	Moderate	Good
Power consumption	Approx. 12 W	Approx. 30 mW
Electromagnetic robustness	Moderate	Good
Temperature dependency	Slightly dependent	Moderately dependent
Signal-to-noise ratio	Good	Good (low temp.) Moderate (high temp.)
Response time	Pico- to nanoseconds	Nano- to miliseconds
Quantum efficiency	30 – 35 %	30 – 50 %
Ageing	Several significant effects e.g. "yellowing"	No significant effects

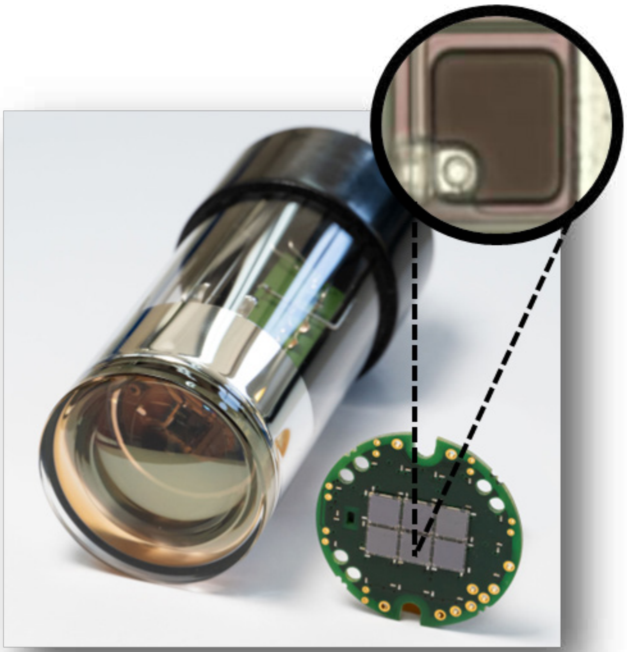


Fig. 5 Comparison of a vacuum PMT with a SiPM. A vacuum PMT has a length of approximately 5-20 cm, whereas SiPMs are typically about 1 mm in height. Additionally, in the magnification, a microcell is shown, which is the basic building block of a SiPM (size approximately 10 µm).

naturally more vulnerable than the compact design of SiPMs, which are suited for exceptionally harsh environments, e.g. when strong vibrations are present.

Power consumption

Also, the physical operating principle results in some profound differences between vacuum PMTs and SiPMs.The main difference in the operating principle between vacuum PMTs and SiPMs lies in the way in which the charge carriers are generated and accelerated. While electrons are knocked out of a material in a vacuum PMT and accelerated through a vacuum, the charge carriers in a SiPM, i.e. holes and electrons, do not leave the material. Because high energies are needed to accelerate electrons inside a vacuum, vacuum PMTs must be operated with high voltages between 500 to 2000 V, depending on the manufacturer. SiPMs on the other hand can already be operated at bias voltages between 25 to 80 V since the intrinsic electric field of the diodes favours the acceleration and multiplication of charge carriers (#4). The difference in operating voltage has a direct impact on the power consumption of the photomultipliers. While detectors featuring vacuum PMTs consume about 12 W in average, the power consumption of a SiPM-featured detector can be as low as 30 mW in average. Therefore, SiPM's can also be integrated in so-called "loop-powered" devices, which are only using the dataline (4 to 20 mA loop, APL, …) as a power supply.

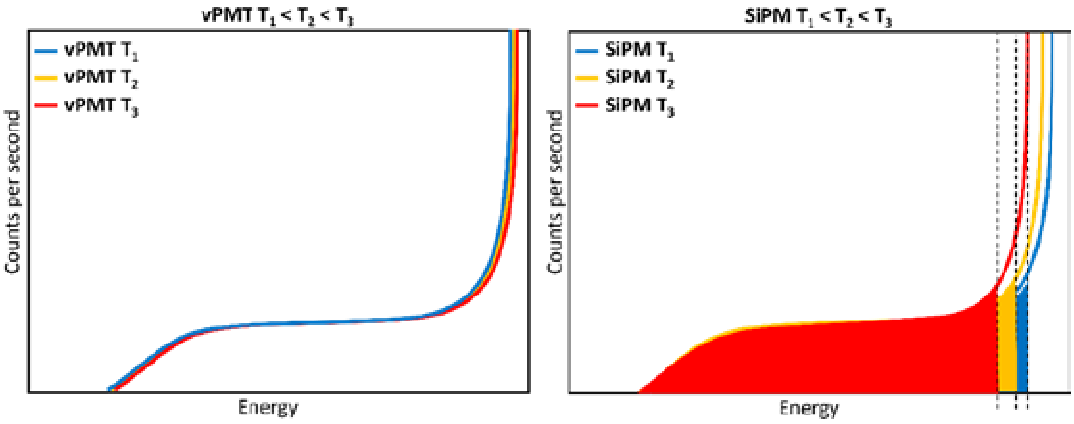
Electromagnetic robustness

A different picture emerges when looking at electromagnetic robustness. As the charge carriers in SiPMs are firmly bonded to the material, high energies are required to separate them out, whereas the charge carriers in vacuum PMTs are already separated from their material through pure operation. Strong electromagnetic fields can therefore strongly deflect the electrons in a vacuum PMT and influence the measurement, while the charge carriers of a SiPM remain unaffected by these external influences. Due to the differences mentioned so far, it would be easy to claim that SiPMs are superior to vacuum PMTs in all respects. However, vacuum PMTs also have advantages in terms of performance, which are of course also evaluated here.

Temperature-dependent performance

Especially regarding the performance over a wide temperature range, vacuum PMTs show extremely stable characteristics. This becomes clearer by looking differences in the count spectrums of a vacuum PMT over several temperatures, as shown schematically in Figure 6 (left) for three temperatures (T1 is the lowest, T3 the highest temperature). As the characteristics of a vacuum PMT do not change significantly, this technology is easy to handle over a wide range of temperatures. The temperature characteristics of a SiPM on the other hand, as shown schematically in Figure 6 (right), shows more dynamics. When temperatures rise, the spectrum together with the noise edge shifts, leading to a slightly decreased sensitivity of a SiPM in higher temperatures, as can be seen in the colored spectrum integral representing the number of counts that can be used for the measurement.The reason for these differences is based on the material-specific thermal activity and is therefore due to the construction of vacuum PMTs and SiPMs. Dark counts, meaning the detection of a signal without photon interaction, can occur in both technologies. However, within a vacuum PMT, the electrons that are thermally knocked out of the photocathode only appear as isolated events. Some studies have shown that the output voltage, pulse height and gain of vacuum PMT's can decrease with increasing temperature due to these dark counts. Yet, there are also vacuum PMT's that can have higher efficiency at higher temperatures (#5).

Figure 6 Schematic representation of count rate spectra for a vacuum PMT (left) and a SiPM (right) at different temperatures, where T1 (blue) represents the lowest, T2 (yellow) the intermediate, and T3 (red) the highest temperature. The illustration aims to convey that the spectrum of a vacuum PMT remains nearly unchanged across temperature variations, whereas the spectrum of a SiPM undergoes changes with increasing temperatures, resulting in a slight reduction in sensitivity.



A SiPM on the other hand consists of thousands of units, the microcells, which have a probability for dark counts. There are some studies that have shown that SiPM's have higher sensitivity and lower dark current rate at lower temperatures, while they show reduced efficiency, increased dark current rate, and higher electronic noise at higher temperatures (#6). It is conceivable that the construction and physics dictate this behavior of SiPMs in higher temperatures. However, this effect can be counteracted by a sophisticated temperature-voltage control for SiPMs.

Response time-based performance

SiPMs still have some advantages in performance, as they show significantly faster response times in the range of pico- to nanoseconds compared to vacuum PMTs that show response times of nano- to milliseconds (#7). It must be mentioned here that these response times are normally not reached with an overall measurement signal, as this is limited by the processing electronics. The SiPM-technology merely has a lot of buffers for fast evaluation electronics that may be used in the future.

Quantum efficiency-based performance

Another difference between vacuum PMTs and SiPMs relates to the quantum efficiency (QE), i.e. the probability that an incoming photon will trigger a signal. Depending on the manufacturer, the QE of SiPM's in the visible spectral range varies between 30 % and 50 %, but there are also SiPM's with a QE of over 50 % in certain spectral ranges. It must be mentioned here that the QE of SiPM's depends on various factors such as the wavelength of the incident light, the point accuracy of the detector structure as well as the specific manufacturing technology (#8). For vacuum PMT's, the QE is usually in the range of 30 % to 35 % in the visible spectral range, varying between different manufacturers. There are exceptions due to special vacuum PMT's with a QE of more than 40 %. (#9).

Ageing effects

The effect of aging on SiPM's is a current research topic and so far, not many measurable ageing effects have been demonstrated. Initial studies found that SiPM's can exhibit only slight aging phenomena over time, such as a small increase in dark current rate as well as a small decrease in gain (#10). But the reasons for this are largely unknown. In vacuum PMT's, unlike SiPM's, electrons are actively knocked out of the photocathode as well as the dynodes during operation with each detection, causing the cathode material to wear out over time, also known as "yellowing effect". This causes vacuum PMT's to lose photosensitivity over time and dark current to increase compared to the measuring current (#11). The ageing effects of a vacuum PMT however are well known and can be compensated for. The exact aging rate for both technologies is of course varying depending on the manufacturer and operating conditions.

Suitable applications for vacuum PMTs and SiPMs

In summary, both technologies have their advantages and disadvantages and the decision which one is the better depends on many factors like the process environment and the needs of the application itself.

Application of vacuum PMTs

The vacuum PMT technology plays a crucial role in various applications within the process industry, with vacuum PMTs being particularly prominent due to their unique characteristics. Moreover, vacuum PMTs have become the industry standard in many applications within the process industry such as the oil and gas or the petrochemical industry (Figure 7).
Their widespread adoption is a testament to their proven performance and reliability. The established reputation of vacuum PMTs has led to their integration into various analytical instruments and measurement systems used in industrial processes. One significant advantage of vacuum PMTs in the process industry is their remarkable resilience to temperature variations across a wide range. This immunity is particularly valuable in industrial settings where ambient temperatures can fluctuate significantly. The well-known technology associated with vacuum PMTs is another key factor contributing to their widespread use in the process industry. Over time, components of a vacuum PMT may degrade, affecting performance; however, the well-established nature of these devices allows for effective monitoring and correction of these effects. This reliability is essential in industrial applications where consistency and accuracy are paramount. In addition to their temperature resilience and industry-standard status, the construction of evacuated glass tubes used in vacuum PMTs becomes more and more robust. These tubes are designed to withstand most harsh environmental conditions, making them also suitable for deployment in many challenging industrial environments such as the mining industry (Figure 8). It is important to note that while vacuum PMTs exhibit exceptional qualities suitable for numerous applications within the process industry, they may not be universally applicable. The differences between vacuum PMTs and SiPMs underscore the importance of choosing the right detector for a given application. There are instances where the unique characteristics of SiPMs make them more suitable than vacuum PMTs.

Application of SiPMs

The SiPM technology has emerged as valuable component in the process industry, offering distinct advantages that makes it particularly well-suited for the most challenging environments and applications. SiPMs boast a solid and compact construction, providing increased mechanical robustness. This attribute makes them highly suitable for demanding environments, such as the fractioning industry, where equipment is subjected to strong vibrations (Figure 9). The durability of SiPMs allows them to withstand these physical stresses commonly encountered in this rugged industrial setting, ensuring reliable performance over extended periods.

They also exhibit enhanced electromagnetic robustness, rendering them suitable for applications in the presence of strong electromagnetic fields. This characteristic is particularly valuable in industries like steel manufacturing (Figure 10), where electromagnetic brakes (EMR) are employed during casting processes. SiPMs can operate seamlessly in such environments without being adversely affected and can therefore be employed perfectly to measure the level of fluid steel inside the mold.

Finally, SiPMs offer increased cost efficiency, primarily due to their lower energy consumption. This makes them well-suited for integration into „loop-powered" devices, which rely on power supplied via the dataline, such as the 4 to 20 mA loop or industrial ethernet/APL. The reduced energy requirements of SiPMs not only contribute to energy savings but also enable the implementation of cost-effective and simplified wiring solutions. This, in turn, leads to significant cost and time savings, making SiPMs an economically viable choice for a wide range of applications in the process industry.

Conclusion

In conclusion, vacuum PMTs find extensive application in the process industry due to their immunity to temperature fluctuations, well-known technology with effective ageing compensation, industry-standard status, and robust construction. These qualities make vacuum PMTs indispensable tools for precise measurements and reliable data acquisition in various industrial processes. The SiPM technology also has emerged as a valuable component that plays a crucial role in the process industry. It provides increased mechanical robustness for challenging environments like fracking, enhanced electromagnetic robustness for applications in the steel industry, and greater cost efficiency through reduced energy consumption and simplified wiring solutions. Both techniques have different advantages in their respective applications and therefore both complement each other perfectly in every process control portfolio, contributing together to improved performance, reliability, and economic viability in industrial processes.

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