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A very brief review of recent SiPM developments

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This paper gives an update of recent SiPM developments from the perspective of applications in high-energy astrophysics and high-energy physics applications. Technological advances that have been made over the last 5 years are discussed and examplified by presenting some performance parameters of three recent SiPMs from Hamamatsu, FBK, and SensL.

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1. Introduction

The detection of photons plays a crucial role in high-energy physics, astroparticle physics, medical imaging, and many other fields. Some of the most important requirements for photon detectors in these fields are very similar. Three of which are blue sensitivity, single photon detection capabilities, and fast timing down to sub-nanosecond time resolution. The significant overlap in requirements motivates an interdisciplinary interest in the development of new photon detectors, which would improve the performance of existing applications and make new applications possible.

One photon-detector type that has caught the attention of the community in recent years is the silicon photomultiplier (SiPM). Other names often found are MPPC, G-APD, or solid state photomultiplier. The concept of the SiPM was conceived in the late 1980s with major contributions from V. Golovin, and Z. Sadygov. SiPM prototypes from these pioneering groups became available to several other groups in the early 2000s, which was a crucial step in order to demonstrate the potential of the SiPM in several key applications. For a detailed review of the history of semiconductor photon detectors, in particular that of the SiPM, see [1].

Even though the performance of available SiPMs was limited at the time, those studies made a very compelling case for the SiPM. Key advantages of the SiPM are mechanical and electrical ruggedness, insensitivity to magnetic fields and accidental exposure to bright light when biased, operation voltages below 100 V, small volume and mass, low levels of intrinsic radioactivity, and mass fabrication while maintaining uniform device characteristics. These are major benefits compared to the classical photomultiplier, which is the workhorse for light detection in the aforementioned fields for the better part of the last one hundred years.

After the scientific and commercial potential of the SiPM had been demonstrated the user community rapidly grew and several companies started significant R&D efforts towards a commercial product. Ten years later, the SiPM has indeed matured and available devices satisfy the requirements for an increasing number of applications. Several producers of SiPMs exists of which some are AdvanSiD/FBK, Excelitas, Hamamatsu, Ketek, and SensL.

In this paper we briefly summarize the recent advancements in SiPM technology. This undertaking can merely be a snapshot of the present situation and will be out of date very soon, due to the rapid pace of ongoing developments. This review also does not attempt to give a complete overview of available SiPMs. Instead we describe the latest major developments on the example of a few devices. Section 2 is a brief summary of how SiPMs work and includes an overview of existing device geometries. The snapshot of recent device characteristics is presented in Section 3 and a discussion of future prospectives is given in Section 4.

2. The SiPM Concept

The basic building block of an SiPM is an avalanche photodiode (APD) that operates in Geiger mode. These cells are sometimes referred to as single photon avalanche diodes (SPADs). The advantage of the Geiger mode is that a large, easy detectable current pulse is produced after the conversion of a photon into an electron-hole pair and the initiation of a self-sustaining avalanche. The breakdown is either quenched with a resistor that limits the current (passive quenching) or by briefly lowering the bias voltage below the breakdown voltage (active quenching).

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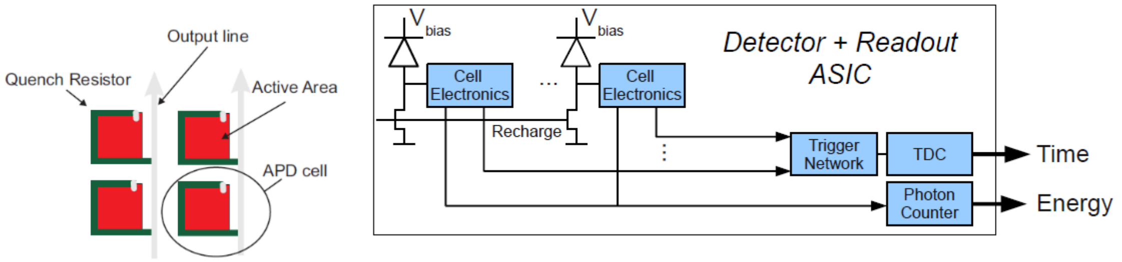

Figure 1: On the left is shown a sketch of four cells of a conventional SiPM. All cells are connected to one common output. The right sketch shows the schematics of two cells of a digital SiPM.

A major drawback of the SPAD is the inability to determine from the output signal how many photons have bin converted in the cell. This fundamental problem is avoided in the SiPM because the sensor area is divided into a large number of small, passively quenched, and independently operating SPADs. Furthermore, all SPAD cells are connected in parallel as is illustrated in the left sketch of Figure 1. The output of the SiPM thus corresponds directly to the number of fired cells and the number of detected photons as long as there is only a small probability of having more than one photon per cell.

A variant of the just described SiPM, also dubbed the conventional SiPM, is the digital SiPM (dSiPM), which is shown on the right side of Figure 1. The dSiPM has first emerged seven years ago [2]. Instead of connecting each cell to a resistor, each cell of a dSiPM is connected to integrated electronics that actively quenches a breakdown and produces a binary signal. The digital signal is then transferred to an on-chip counter and time-to-digital converter (TDC). Compared to a conventional SiPM the dSiPM offers better timing performance, faster cell recovery, and reduced dark rate after disabling noisy cells.

Dynamic range Irrespective of the type of SiPM, the response of an SiPM is linear as long as the average rate of detected photons per cell is much less then the inverse of the cell's recovery time. See [3] for an investigation of the detection of steady light levels with SiPMs. In case of the detection of light flashes, the response can be calculated analytically as

$$N_{\text{fired}} = N_{\text{cells}} \left[1 - e^{-\frac{N_{\text{phe}}}{N_{\text{cells}}}} \right] \tag{2.1}$$

Where N_{cells} is the number of cells of the SiPM and N_{phe} is the number of photoelectrons produced by photons of the external light flash and optical crosstalk photons[4]. In case the light flash lasts longer than a few ten nanoseconds, additionally fired cells due to afterpulses and delayed optical crosstalk photons need to be accounted for as well. It is also assumed that the device is uniformly illuminated. The equation, furthermore, neglects dynamic processes within the SiPM, which result in a deviation from the above relationship for very intense light flashes [5]. What comes clear from the equation, however, is that applications that demand a very high dynamic range, *e.g.* calorimetry require SiPMs with very high cell densities. To satisfies these needs SiPMs with cell sizes of less than 10 μm are now available from Hamamatsu, FBK, NDL, and Zecotek.

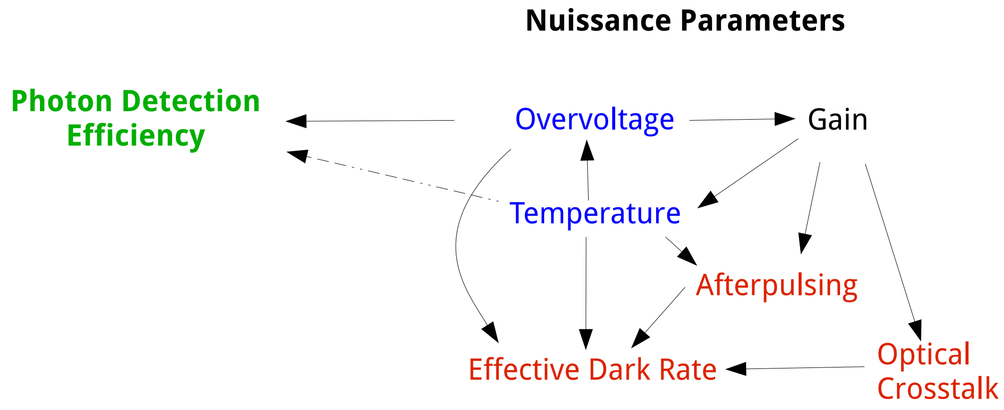

Figure 2: A block diagram of the interdependence of SiPM parameters. A user has control over bias voltage and temperature.

SiPM sizes Sizes of SiPMs have increased over the years and three different sizes have emerged as quasi standards: $1 \times 1\,\text{mm}^2$, $3 \times 3\,\text{mm}^2$, and $6 \times 6\,\text{mm}^2$. Unfortunately, devices from different vendors are not plug-in replaceable not only because of slightly different chip sizes but also because of vendor specific packaging. Even though there are different approaches to packaging, every major SiPM producer offers a package now that allows to form arbitrarily large arrays of SiPMs with minimal dead space between SiPMs.

3. Progress on SiPM Performance

The performance of the SiPM in an application depends on a number of parameters like spectral response, optical crosstalk, dark count rate, temperature dependence, etc. The importance of each of these parameters depends of course on the specific application. How the most important parameters are interconnected shows Figure 2. The user controls the bias voltage and ambient temperature. Once those two have been decided all other parameters are fixed. Only the manufacturer can independently change some of the parameters and strives towards making a device in which the impact of *nuisance* parameters is minimal. In the following we give a progress report on the outcome of these efforts.

Photon detection efficiency The main performance parameter of a photon detector is the photon detection efficiency (PDE). The PDE is influenced by several parameters. Following the path of a photon and subsequently the generated photoelectron, the first PDE affecting parameter is the geometrical efficiency of the SiPM. This is where some of the most remarkable improvements have been made over the past years. Early devices had geometrical efficiencies of about 20%. In latest devices the geometrical efficiency is more than 80%. Figure 3 shows pictures of a 2004 SiPM and a recent SiPM, which impressively demonstrates the improvements. Dead space at the edges of SiPMs and due to the packaging has also been minimized and sensors can now be closely packed with minimal dead space in between them (see Figure 4).

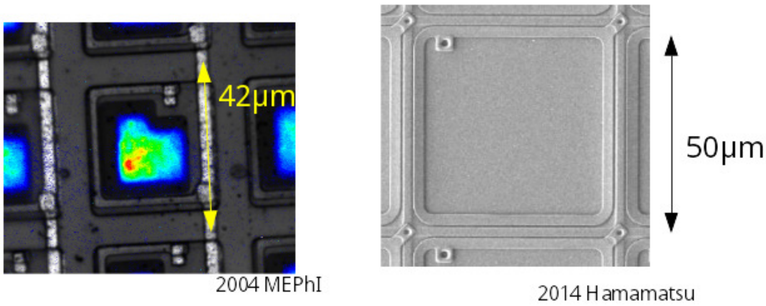

Figure 3: Microscope pictures of the cells of an early SiPM from MEPhI from 2004 on the left (picture from C. Merck) and on the right a recent device from Hamamatsu (picture from Hamamatsu). The comparison shows the improvements in increasing the geometrical efficiency.

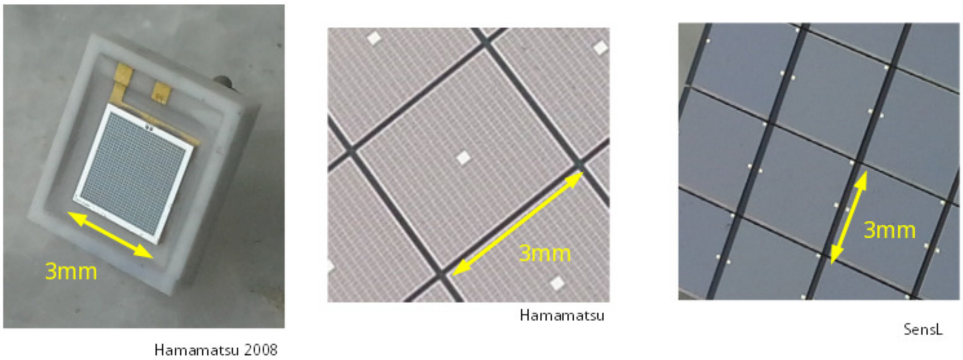

Figure 4: Evolution of SiPM geometries. The left SiPM is an early device from Hamamatsu from 2008. The guard ring around the borders of the chip and the ceramic packaging introduces significant dead space. The other two recent devices from Hamamatsu and SensL have only a narrow guard ring and, furthermore, use through silicon via technology that eliminates bond wires and allows a close packing of the chips.

The introduction of transparent metal-film resistors helped to further enhance the geometrical efficiency even though only in the red/IR. Transparent resistors allow the fabrication of SiPMs with much smaller cell sizes while maintaining a high PDE.

The next steps in the detection of a photon are its absorption, generation of an electron-hole pair, and the drift of the electron or hole into the high-field region. The combined effect of these steps results in the effective quantum efficiency[1] (QE). The effective QE for blue/UV photons is mostly determined by their short absorption length of one hundred nanometers and less. Enhancing the blue/UV sensitivity is thus achieved by increasing the transmission through the protective coating of the SiPM and by thinning the first implant. These are both major technological challenges, which could at least in part be mastered in the past years. One example is the application of a silicon resin instead of an epoxy to coat devices, which has helped to greatly enhance the PDE below 400 nm. But overall the UV sensitivity (<400 nm) of SiPMs remains a challenge and is not on par with what can be achieved with photomultiplier tubes.

[1]Note that the original definition of the quantum efficiency only describes the probability that a charge carrier is generated upon absorption of a photon.

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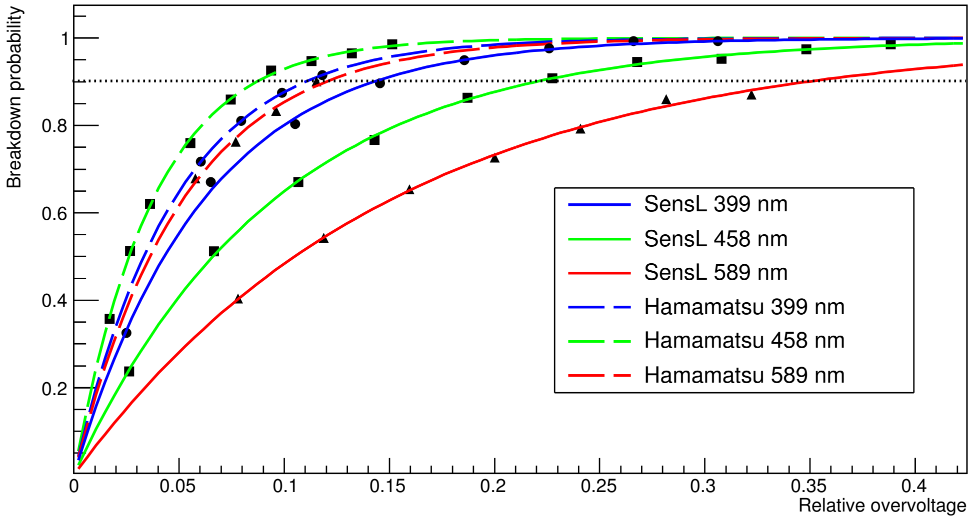

Figure 5: Breakdown probability as a function of relative overvoltage for a Hamamatsu device (S13083-050CS(X)) and a SensL device (ArrayES-30035-16P-TSV-E32), which had been illuminated with photons of different wavelengths. The horizontal dashed line indicates a breakdown probability of 90%, which the Hamamatsu sensor achieves at a relative overvoltage of about 10% for all tested wavelengths. The SensL device shows a wavelength dependent breakdown probability that reaches 90% for red light at an overvoltage of 35%.

The sensitivity in the red, on the other hand, is determined by the thickness of the depleted regions due to the rapidly increasing absorption length with increasing wavelength. The combination of both results in a gradual decrease in sensitivity towards larger wavelengths.

Both devices use a p-on-n structure. Inverting the structure to n-on-p would shift the peak response towards the red as the breakdown probability (see below) for red photons is then determined by electrons drifting into the avalanche region instead of holes.

The last step in the photon-detection process is the initiation of the avalanche breakdown. This statistical process is quantified by the breakdown probability, which depends mostly on the strength of the electric field, the width of the avalanche region, and where the electron-hole pair is created. Ionization coefficients for electrons in silicon are typically 10 to 100 times higher than for holes. Electrons drifting through the avalanche region have, therefore, a much higher probability to generate a breakdown than a hole. Only for very high electric fields the breakdown probability reaches 100% for both electrons and holes.

The difference between an electron and hole dominated breakdown is shown in Figure 5 on the example of a SensL (ArrayES-30035-16P-TSV-E32) and a Hamamatsu device (S13083-050CS(X)). Because both devices use a p-on-n structure, electrons that are generated by blue/UV photons close to the surface, drift into the avalanche region. In both devices the breakdown is, therefore, electron dominated for 399 nm photons and a 90% breakdown probability is achieved at about 10 % overvoltage.

For longer wavelengths the response of the two devices is different because Hamamatsu uses a structure in which the avalanche region is buried deeper in the device than in the SensL device.

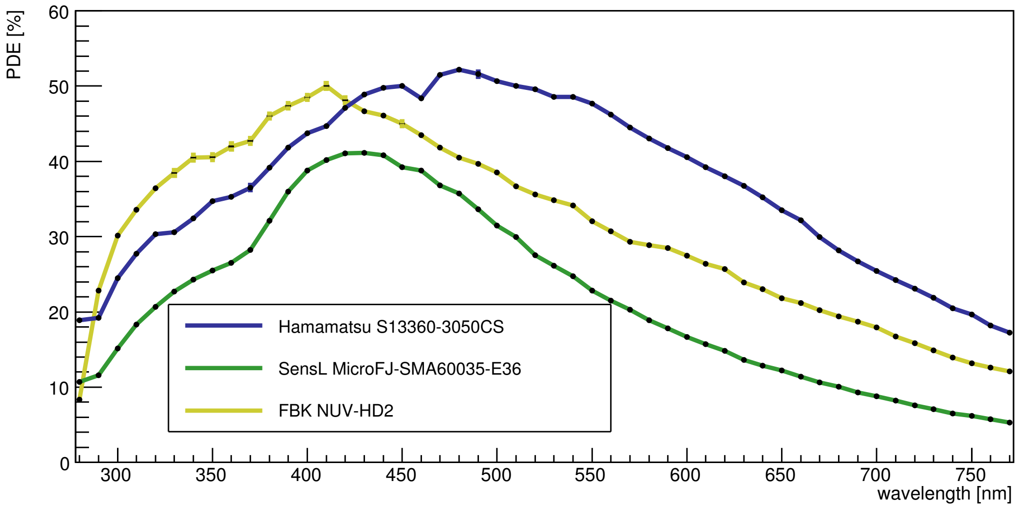

Figure 6: Photon detection efficiency of three different SiPMs biased to yield a breakdown probability of >90% below 600 nm. The devices are from FBK: NUV-HD (cell size 25 μm), SensL: J-series preproduction (cell size 40 μm), and Hamamatsu: LCT5 device (cell size 50 μm). The curves were obtained by illuminating the biased SiPMs with a steady monochromatic light source and recording the currents of the SiPMs and a calibrated photodiode as a function of wavelength. The relative response curves had then been scaled to match the absolute PDE at 399 nm, 453 nm, 499 nm, and 589 nm measured with the procedure outlined in [6].

Breakdowns initiated by longer wavelengths are, therefore, still electron dominated in the Hamamatsu device, whereas in the SensL device the photons get absorbed below the avalanche structure and the breakdown is initiated by a hole. Because it is the hole that starts the breakdown a higher overvoltage of up to 30% is required to reach 90% breakdown probability

What is remarkable is that recent devices can operate at breakdown probabilities of more than 90%. This is a clear improvement to earlier devices where too small quenching resistors, too high dark rates, too high afterpulsing, and too high optical crosstalk prevented one from doing so.

Figure 6 shows the PDE as a function of wavelength for three devices from FBK, Hamamatsu, and SensL, biased at 33.5 V, 56.7 V, and 29.5 V respectively, which corresponds to relative overvoltages above breakdown of 0.26, 0.10, and 0.20, respectively. In all three cases does the chosen bias voltage yield a breakdown probability of 90% or more up to a wavelength of 600 nm. The device from FBK achieves a peak efficiency of about 50% even though the device has the smallest cells of all three devices.

Optical crosstalk Optical crosstalk, probably the biggest nuisance of SiPMs in most applications, is due to IR photons that are emitted with a rate of one photon for every 10^4 electron-hole pairs generated in a breakdown [7, 8, 9]. These photons propagate into neighboring cells and can cause the breakdown of a new cell that is either delayed or quasi simultaneous with the first breakdown depending on whether the photon is absorbed in the non-depleted volume or in the depleted volume.

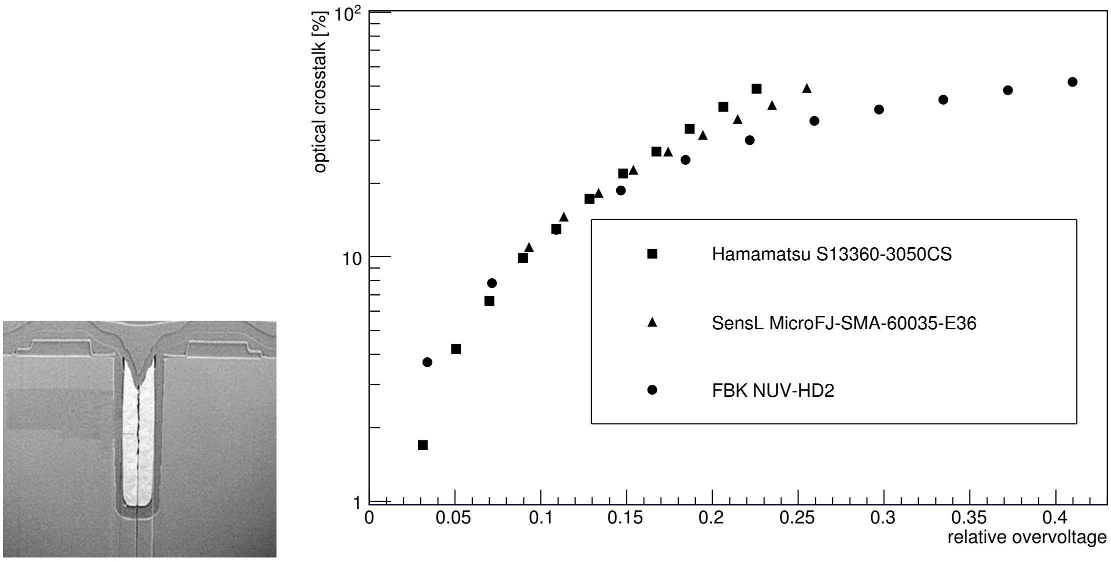

Figure 7: Left panel: An electron microscope picture of a filled trench to suppress optical crosstalk. (Courtesy of Hamamatsu) Right Panel: Optical crosstalk as a function of relative overvoltage at 25 °C for the same three devices shown in Figure 6.

Both types of optical crosstalk could be greatly reduced in the past few years by etching trenches in between cells to prevent photons from reaching a neighboring cell. The left side of Figure 7 shows a cross section through a filled trench of a Hamamatsu device. Indirect optical crosstalk is further suppressed by a potential barrier that is implemented in between the non-depleted bulk and the depleted epitaxial layer, which also helps to prevent thermal generated charge carriers to diffuse from the bulk into the active volume of the device.

Latest SiPMs can achieve optical crosstalk values of about 10% at a breakdown probability of 90%, which is still more than one would like in self-triggering applications but is a major improvement when compared to only a few years ago. Figure 7 shows the optical crosstalk performance for a latest FBK, Hamamatsu, and SensL device.

Effective Dark Rate The dark count rate of SiPMs constitutes from several sources: thermal generated, tunneling assisted, indirect optical crosstalk and afterpulsing. Due to several improvements in the fabrication of SiPMs and changes in device structures, dark rates of less than 100 kHz per square millimeter sensor area at room temperature are typical for recent devices. Figure 8 shows the dark rate performance for a latest FBK, Hamamatsu, and SensL device at room temperature. Early devices typically showed dark rates of 1 MHz per square millimeter sensor area

Temperature dependencies The reason for temperature dependencies observed in SiPMs is due to a shift of breakdown voltage with temperature. An increase in temperature causes more non-ionizing scattering processes to take place while a breakdown develops. The result is a decrease in breakdown probability, *i.e.* the breakdown voltage increases. As a rule of thumb the breakdown voltage increases with temperature by about 0.1% per °C.

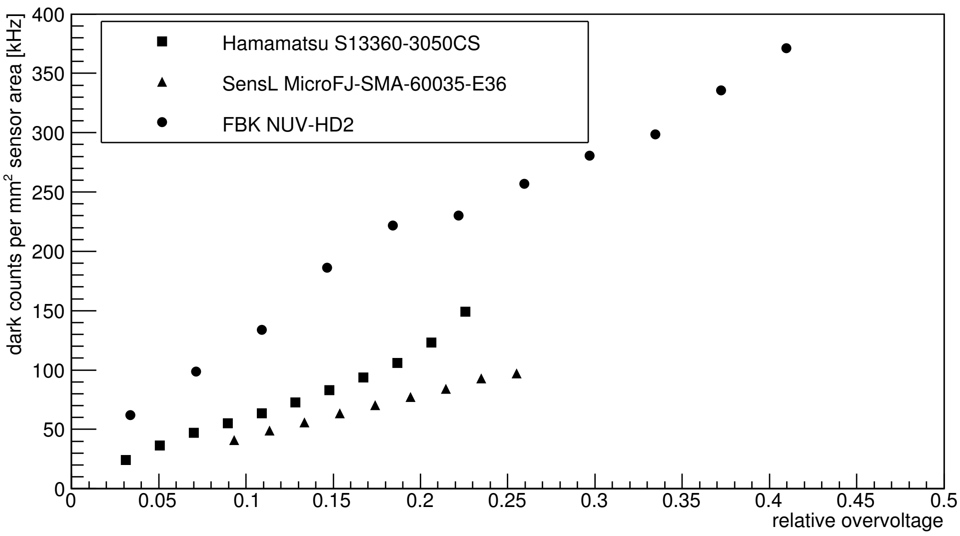

Figure 8: Effective dark count rate as function of relative overvoltage for the same three devices as in Figure 6.

The most important parameters affected by temperature are gain, PDE, and dark rate. Gain G increases direct proportional with overvoltage and, therefore, becomes less dependent on temperature T the higher the relative overvoltage is: $\Delta G/G = 0.1\%/^{\circ}\mathrm{C} \times 1/V_{\mathrm{rel\ over}} \times \Delta T$, where $V_{\mathrm{rel\ over}}$ is the relative overvoltage.

Early devices operated at a $V_{\mathrm{rel\ over}}$ of a few percent, which resulted in a few percent change in gain and PDE per °C. A fair number of new devices operate at $V_{\mathrm{rel\ over}} = 10\%$ or 20%, which reduces the gain dependence on temperatures to 0.5%-1.0% per °C.

Temperature dependencies of the PDE are even lower because the breakdown probability is above 90% for the same high overvoltages, *i.e.* the PDE is saturating and even less dependent on temperature than gain. In that regard SiPMs perform on par with classical bialkali photomultiplier tubes for which typical temperature dependencies of the photocathode are 0.1% to 0.2% per °C [10].

4. Discussion of future developments

Silicon photomultipliers have grown mature devices. Only a few years ago optical crosstalk, afterpulsing, and high dark rates had been major nuisances that are acceptable now. Peak photon detection efficiencies have improved from 20% to more than 50% and furthermore shifted towards the blue/UV. Combined with the added benefits of being electrically and mechanically robust the SiPM is now the device of choice for many applications. Costs of SiPMs are still a major concern despite a major drop over the past years. The classical photomultiplier, therefore, remains an attractive photon detector in applications where large areas need to be covered with photon detectors.

The SiPM will improve further and the question arises what will those improvements be and in which direction does the SiPM develop? The discussion can be split into improving device performance, *e.g.* better PDE and improving device integration, *i.e.* the direction of the dSiPM.

Device performance The peak photon detection efficiency of SiPMs is now above 50% and it is not unlikely that SiPMs will soon reach peak PDEs of 70%, *i.e.* approaching the theoretically maximum possible. The spectral response has shifted from the green into the blue but is not quite on par with the blue and near UV sensitivity of photomultipliers, which is wanted when it comes to the detection of scintillation light or Cherenkov light. Shifting the response of SiPMs further into the UV requires shallower entrance windows, anti-reflective coatings, and thinner first implants, which are difficult to control and adversely affects dark count rates.

One way around these limitations of the conventional SiPM is to change from silicon to compound semiconductors with engineered bandgaps. These devices are not called *Silicon* photomultipliers anymore but *solid-state* photomultipliers. Changing the bandgap allows to design devices with custom spectral response. Unfortunately, only a handful of companies is presently pursuing this path, which is not surprising given that silicon is far better understood and many silicon processing foundries exist. But solid-state photomultipliers do exist in prototypes, *e.g.* in silicon carbide [11].

Device integration The integration of readout electronics into SiPMs is an attractive path to pursue. With the dSiPM the first step towards an integrated SiPM approach has been accomplished. The next steps will likely involve technologies that allow to stack and interconnect chips. With that approach improved timing will become possible while consuming less power in the front end.

Acknowledgement

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