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Recent developments in silicon photomultipliers

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Abstract

A novel type of avalanche photodetector with Geiger mode operation, known as a Silicon PhotoMultiplier (SiPM) provides an interesting advance in photodetection and is already an alternative to traditional PMTs in many applications. The state of the art of the SiPMs—their main properties and problems—are discussed.

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1. Introduction

Development of photodetectors for the detection of low-intensity photon flux is one of the critical issues for experimental physics, medical tomography and many other areas. In most of these applications as a photodetector standard PhotoMultiplier Tubes (PMTs) are used. However, PMTs have two main problems: they are very sensitive to the magnetic fields and command a high price due to the complicated production process. The search for an alternative detector started a long time ago. A promising candidate for the replacement of PMTs was the Avalanche PhotoDiode (APD). Although it has an internal gain it was not capable of detecting single photons. At the beginning of this millennium a new detector concept was developed, a silicon photodetector operated in limited Geiger mode, capable of detecting single photons like a PMT and was therefore given the name Silicon PhotoMultiplier (SiPM). For the past few years mainly Russian groups pursued the development of the new type of APD [1–3], but today the interest for these devices is increasing and they are being developed on many places around the world. Recently, a new concept was introduced: A Back Illuminated Drift SiPM (BID SiPM) where an APD is combined with a drift diode to form a building block for photodetector arrays [4–6]. These devices are to be produces in Max-Planck-Institute Semiconductor Laboratory [7].

2. The silicon photomultiplier concept

A SiPM is an array of small APDs (cells) combined to form a macroscopic unit (typically 500 to 4000 cells per mm^2). Each cell operates in limited Geiger mode. A small polysilicon resistor, which connects the cell to a conductive grid, limits the current through the junction and quenches the avalanche once the cell capacitance has been discharged. Single cells produce a standard signal when any of them is brought to breakdown. In the SiPM the independently operating APD cells are all connected to a common readout line. Therefore, the output signal is the superposition of the standardized signals from all fired cells. In the case of the BID SiPM concept radiation enters from the back of a fully depleted wafer and the photoelectrons are focused (drifted) onto a small "point-like" avalanche region located on the front side.

3. SiPM properties

A SiPM provides an intrinsic *gain* for single photoelectrons at the level of $\sim 10^6$. The amplitude of a single cell is

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proportional to the capacitance of the cell times the overvoltage (the difference between the operation voltage and the breakdown voltage).[1] In case of not too intense light flashes, the number of fired cells is in first order proportional to the number of photons thus compensating for the missing dynamic range of a single Geiger mode APD. For large light flashes saturation effects set in. In reality, the process is more complex because of the recovery time of the cells and the influence of dark current. The main domain of operation for SiPMs is for light levels with a photoelectron flux $\ll 1$ photoelectron/cell/recovery time. These devices have an excellent photon counting capability (see Fig. 1) which comes as a consequence of good cell to cell gain uniformity, negligible contribution of electronic noise and a very low excess noise factor of single cells.

Unfortunately, the breakdown can be triggered not only by an incoming photon but also by any generation of free carriers. The latter produces *dark counts* at a rate from 100 kHz to several MHz per mm^2 at 25 °C and with a threshold at half of the one photon amplitude. Thermally generated free carriers can be reduced by cooling. There is a factor 2 reduction of the dark counts every 8–10 °C. Another possibility is to operate at lower bias resulting in a smaller electric field and thereby lower Geiger efficiency. Field-assisted generation (tunneling) can only be reduced by using a smaller electric field. The dark counts can also be reduced in the SiPM production process by minimizing the number of generation-recombination centers, the impurities and crystal defects. The BID SiPM is expected to have an increased dark rate due to the bigger active volume. In order to keep dark rate lower one has to maintain good technology. Further reduction can be achieved by making the devices thinner.

In many applications the fact that in an avalanche breakdown there are in average three photons emitted per 10^5 carriers with a photon energy higher than 1.14 eV [8–10] may be considered a disadvantage. When these photons travel to a neighboring cell they can trigger a breakdown there. This gives rise to *optical crosstalk* which violates the pixel independence and leads to a non-Poissonian behavior of the distribution of the number of fired pixels. It acts like shower fluctuations in an APD. It is a stochastic process and introduces an excess noise factor like in a normal APD or a PMT. The crosstalk can be reduced in a dedicated design with implementation of grooves between the cells, which act as an optical insulation. Since the concept of BID SiPM is based on point-like high-field regions the cross talk effect should be reduced. However, a final evaluation can be performed only after the first prototype production.

The *timing* properties of SiPMs, even for single photoelectrons, are excellent (a FWHM of 123 ps has been measured for a single cell [11]) mainly because the avalanche breakdown process is fast and the signal amplitude is large. Fluctuations in the avalanche process are mainly due to a lateral spreading (~10 ps) by diffusion and by the photons emitted in the avalanche [8]. Operation at high overvoltage (high gain) may slightly improve the time resolution. For the BID SiPMs drifting of photoelectrons increases the time jitter. Reduction of the pixel size improves time jitter but increases the cross talk.

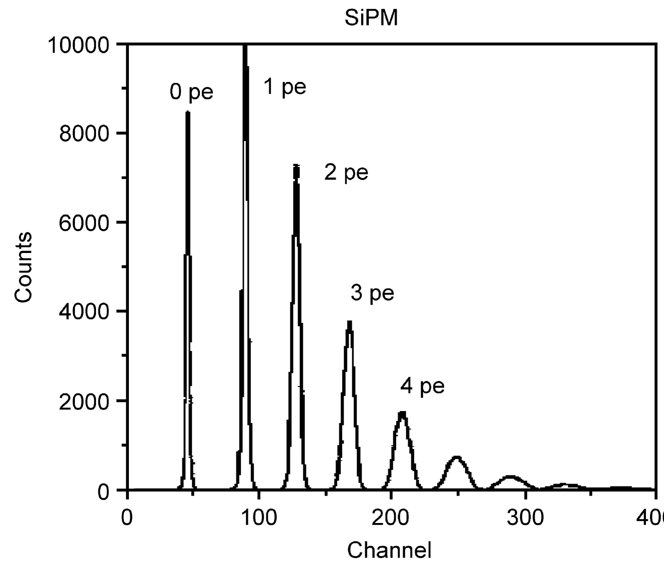

Fig. 1. Pulse height spectrum of light pulses with very low intensity recorded with a SiPM. Taken from Buzhan et al. [11].

The *photon detection efficiency* (PDE) of SiPMs is to the first order the product of the quantum efficiency of the active area (QE), a geometric factor (ratio of active to total area), the probability to initiate an avalanche breakdown (Geiger efficiency) and the fraction of active cells, i.e. those cells which are not quenched or are still recovering from a previous breakdown. QE is maximal 80–90% depending on the wavelength. It peaks in a relative narrow range of wavelengths because the sensitive layer of silicon is very thin. Devices with n-silicon on a p-substrate are more sensitive for green and red light and less for blue light because only the photons with longer wavelengths penetrate deep enough into the silicon (see Fig. 2). Additionally, electrons have a higher Geiger efficiency compared to holes. The geometric factor, which is limited by the dead area around each cell, depends on the construction and ranges typically between 20% and 70% of the total area. This is the parameter that can be optimized for specific application. Typical values of the PDE of recent SiPMs [13] are comparable to the QE of conventional bialkali photomultipliers. The main advantage of the BID SiPM concept is its expected PDE. The geometrical fill factor of 100% as well as a non-structured radiation entrance window, that allows deposition of different antireflective coatings [6,14,15], make this device unique and superior compared to SiPMs. A PDE as high as 85% at 400 nm can be expected for these devices [6].

[1]It should be noted that two photoelectrons detected by single cell are producing same output signal as a single one.Therefore, one cannot distinguish if one or more photoelectrons have been detected by a cell.

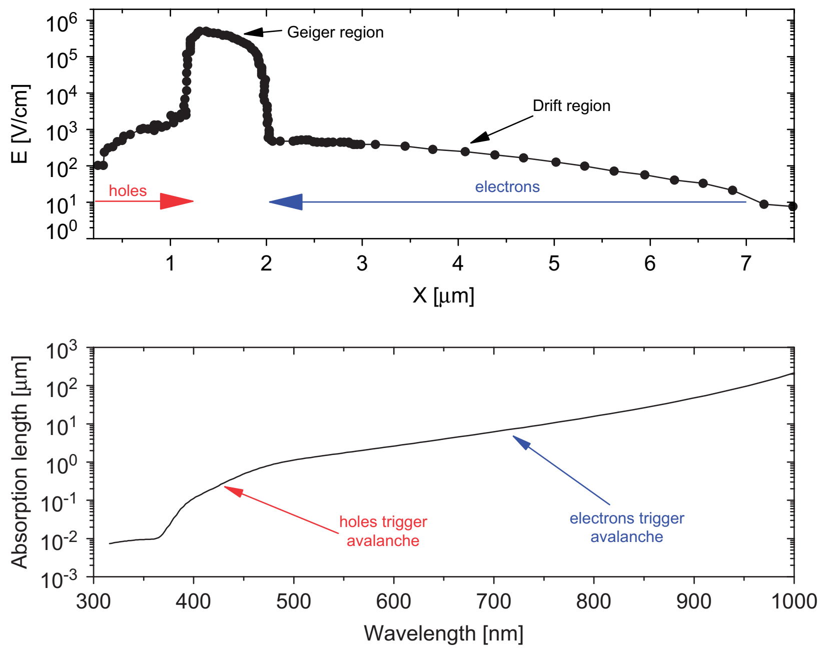

Fig. 2. Influence of difference in behavior of electrons and holes on the PDE. Top: electric field distribution in epitaxial layer (after Buzhan et al. [12]). Bottom: light absorption in silicon.

4. Conclusions

SiPMs are already now an alternative to PMTs. They are the better choice for the detection of light with very low intensity when there is a magnetic field and when space and power consumption are limited. Most of the devices are still small ($1\times 1\,\mathrm{mm}^2 \ldots 5\times 5\,\mathrm{mm}^2$) but areas of $10\times 10\,\mathrm{mm}^2$ are planned in the near future. The development started some 10 years ago but there is still a wide room for improvements. Many parameters can be adjusted to optimize the devices and to tailor them for special needs. However, one has to take into account that there are many cross-correlations which make it impossible to built a perfect device. Compromises are necessary and the device has to be optimized for its specific application. For example trenches reduce crosstalk, which allows the overvoltage increase improving the PDE and UV response but they still reduce the fill factor. For the use in PET, a high dark rate is uncritical, as one is interested in signals that exceed the one photoelectron level by a large margin while the integration window is only a few tens of nanoseconds for fast scintillators. For application in high-energy astrophysics, like MAGIC [16], devices with high PDE will increase the effective sensitivity of the experiment and therefore lower the observational threshold. Therefore the BID SiPM would be a better choice in this case.

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