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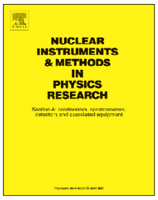

A novel Silicon Photomultiplier with bulk integrated quench resistors: utilization in optical detection and tracking applications for particle physics

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ABSTRACT

Silicon Photomultipliers (SiPMs) are a promising candidate for replacing conventional photomultiplier tubes (PMTs) in many applications, thanks to ongoing developments and advances in their technology. Conventional SiPMs are generally an array of avalanche photo diodes, operated in Geiger mode and read out in parallel, thus leading to the necessity of a high ohmic quenching resistor. This resistor enables passive quenching and is usually located on top of the array, limiting the fill factor of the device. In this paper, a novel detector concept with a bulk integrated quenching resistor will be recapped. In addition, due to other advantages of this novel detector design, a new concept, in which these devices will be utilized as tracking detectors for particle physics applications will be introduced, as well as first simulation studies and experimental measurements of this new approach.

1. Introduction

In recent years, SiPMs have gotten increased attention as possible alternatives for PMTs in a multitude of applications [1–3]. However, a drawback of conventional SiPMs is their limited fill factor, in many cases caused by the need for a high ohmic polysilicon quench resistor and its metal lines on the surface of the devices, which in turn limits the maximum photon detection efficiency. At the Semiconductor Laboratory of the Max-Planck Society (HLL) a novel detector concept was developed, integrating the quench resistor directly into the silicon bulk of the device resulting in a free entrance window. The feasibility of the concept was already confirmed by simulations and extensive studies of first prototype productions [4–7].

Recently, SiPMs were also considered as an attractive alternative for tracking applications in vertex detectors. The requirements for a fast response, simple design and high fill factor can all be met by SiPMs. In addition, the increased trigger probability for an avalanche by minimum ionizing particles (MIPs) allows device operations at lower overbias voltages, resulting in decreased noise. The concept can be evolved further towards an imaging photodetector. A new design for an application of these SiPM devices as vertex detectors with active quenching mechanism developed by HLL and DESY as well as first simulation results will be presented. Also, first measurements of the electron detection efficiency as a function of the applied overbias voltage will be shown.

2. The SiMPl (silicon multipixel light) concept

The following section will explain the basic working principle of the SiMPl detector. In order to circumvent the drawbacks arising from the high ohmic polysilicon quench resistor and its metal lines, the SiMPl detector concept incorporates the quenching resistor into the detector bulk itself.

A schematic cross section of two neighboring SiMPl cells is illustrated in Fig. 1. An unstructured n-type implant on the backside and p^+-type implant on the topside make up the basis of the detector. The high field area is formed in between the topside and the additional structured so-called deep n implant underneath the topside implant by applying a voltage difference between top and backside. Due to this potential difference, two separate areas will be formed in the detector bulk underneath the high field area. First, the gap region between two pixels will be a depleted bulk

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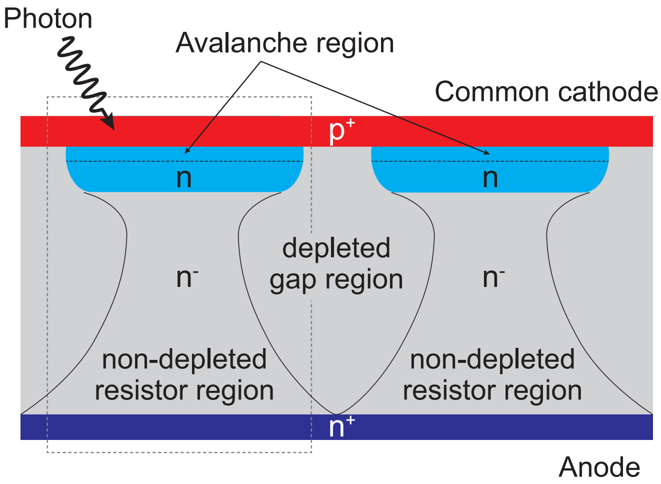

Fig. 1. Schematic cross section of two neighboring SiMPl pixels.

area, insulating the pixels from each other. Second, the area right beneath the high field region will remain non-depleted and now acts as the vertical, bulk integrated quenching resistor for the pixel above and is laterally defined by the gap region. The top and backside implant, representing the cathode and anode of this device, are common for all pixels and not structured, hence eliminating the need for additional contacts and metal lines within the matrix. A global cathode contact can be placed at the edge of the array and later connected to a readout amplifier.

As mentioned above, the main advantage lies in the omission of the polysilicon and the respective metal contacting lines on top of the active area of the sensor, thus increasing the maximum potential photon detection efficiency (PDE) and leading to a more cost-effective and simplified production process. Furthermore, this leads to a topologically flat topside surface, which in turn makes entrance window engineering by means of anti-reflective coatings much easier as well as the coupling to dedicated readout electronics via vertical interconnection. The deep n implant will moreover act as an inherent diffusion barrier against minorities from the bulk, thus decreasing the impact of optical cross talk.

3. Prototype characterizations and future improvements

The first prototype batches of SiMPl devices have shown improved characteristics compared to conventional SiPMs. More detailed characterization studies for optical detection devices can be found in Refs. [4–7]. Measurements of the optical cross talk have shown small levels within devices without optical trenches. These ranged from 15% to 30% at an overbias voltage of $V_{OB} = 2$ V with a fill factor ranging from $\approx 70\%$ to 85%. A peak PDE of $\approx 35\%$ at a wavelength of 405 nm can be found for $V_{OB} = 4$ V and a fill factor of 81%.

Currently the next iteration of optical SiMPl devices is being produced at the HLL. These structures will include a more improved process sequence which will decrease the overall dark count rate. In addition, a specifically engineered entrance window for visible light was manufactured, which will increase the maximum possible PDE even further. With the improved entrance window, a peak transmission percentage of more than 90% can be expected. Combining this with a Geiger efficiency of roughly 80% at $V_{OB} \approx 5$ V can result in peak PDE values of $\approx 65\%$. Future iterations of new prototypes will feature more improvements i.e. optical trenches to further decrease the impact of optical cross talk.

4. Tracking application

4.1. General idea and concept

In the following section, the novel approach of utilizing SiMPl devices as tracking detectors for particle physics will be elaborated.

SiPMs can accomplish many of the performance requirements for particle trackers such as a fast response, high signal gain and active area, insensitivity to magnetic fields, low material budget and high resolution. An extremely fast response time in the sub-nanosecond range for SiPMs can be expected to due the fast nature of the avalanche process. The requirements for a high gain are satisfied by the Geiger regime operation and a high resolution is already demonstrated by many commercially available SiPMs with pixel sizes in the range of 25 µm. Therefore the implementation of SiMPl into a particle tracking system promises feasible results.

To this end, a hybrid tracking detector prototype was design in collaboration with the DESY (Hamburg) and a schematic cross section of Digital SiMPl (DSiMPl) is shown in Fig. 2. In order to use DSiMPl for particle tracking, a single pixel readout is required, hence a structuring of the p^+-topside implant was performed while the backside is still common for the whole array. This concept now makes use of the advantage of a topologically flat surface to enable an easy coupling to readout electronics, which will be connected to the SiMPl device at first by means of bump bonding [8] on the structured topside. The cell size and therefore the fill factor is then only limited by the bump size. For this prototype a pixel size of 50 µm was chosen and the gap sizes vary with a minimum gap of 7 µm. One of the major advantages of applying SiPMs for the detection of MIPs is the resulting inherently high trigger efficiency (as explained in Section 4.2), which in turn allows device operation at a lower overbias voltage, thus decreasing the impact of i.e. dark counts and optical cross talk. However, operation at smaller overbias voltages requires a temperature stabilized bias circuitry, as even small temperature fluctuations can then cause a shift in the breakdown behavior of the device. By introducing an active quenching mechanism through the readout electronics, the requirements for the bulk resistor become less demanding in this approach. Hence, the device can be designed as thin as possible to assure a very low-mass detector. The first prototypes will feature a sensor thickness of 14 µm.

In addition to providing an active quenching mechanism for the every individual pixel within the array, the readout electronics will also have fast timing for matching the tracking requirements, hence a trigger and quenching time in the sub-nanosecond range as well as a pixel recovery of less than 20 ns can be expected. More details on the electronics component of the detector concept can be found in [9].

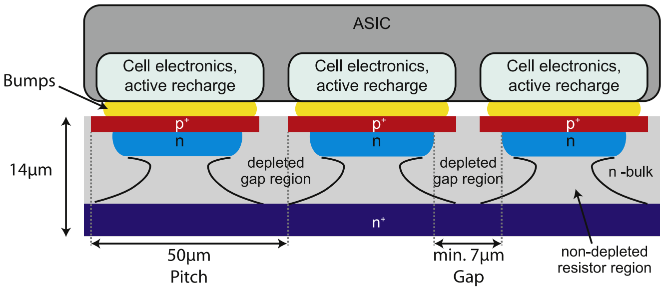

Fig. 2. Schematic cross section of the DSiMPl concept. The SiMPl detector device will be flip-chipped to readout electronics with single cell readout and active quenching capabilities.

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