Silicon Photomultiplier with High Photon Detection Efficiency

Fei Sun, Ning Duan, and Patrick Lo

***Abstract*—A new structure of silicon photomultiplier (SiPM) is presented. In this structure, a lateral bulk-Si quenching resistor was introduced to replace poly-Si resistor. Thus, the fill factor of SiPM can be greatly improved. Furthermore, the active region and contact region are separated from each other in the new design, which will help to achieve devices with high quantum efficiency. The expected improvements have been confirmed by numerical simulation. Quite noticeable increase of quantum efficiency, especially at ultra-violet wavelengths, has been observed. The quantum efficiency at 300nm wavelength increases from 20% to 86%. Therefore, SiPM devices with very high photon detection efficiency will be very likely to be achieved.**

***Index Terms*—Silicon photomultiplier, photon detection efficiency, quantum efficiency**

I. Introduction

Silicon photomultipliers (*SiPMs*) have been developed during recent years as a possible alternative to PMTs [1][2]. Nowadays the performances of *SiPMs* in single photon detection are fast approaching those of conventional *PMTs*. In addition, *SiPMs* have a lot of advantages over *PMTs*, such as compactness, low bias voltage operation, magnetic field insensitivity and fast timing response [3]. The *SiPMs* can also take advantage of the highly developed Si process technologies and the modern fabrication facilities for batch-processing in semiconductor industry, which guarantees the robustness and low fabrication costs of the devices. Thanks to these excellent properties, *SiPMs* have found widespread applications in high-energy physics, fluorescence and luminescence decay measurements, single-molecule detection, laser ranging, nuclear medical imaging like Positron Emission Tomography (PET), radiation detection for homeland security systems, and so on [4]. The detection of photons in visible and ultraviolet regions is of special interest in recent years.

An *SiPM* is formed by large numbers of identical cells, connected to each other in parallel. Each cell is built up by one avalanche photodiode (APD) and one serial resistor. The APDs are working in Geiger-mode, because its operating voltage is normally 10%-20% higher than the breakdown voltage, in order to achieve high detection sensitivity. In this working condition, a resistor in series with the APD will be quite necessary to control the current and the corresponding power consumption of the diode. Furthermore, the resistor can also be used to quench the fired diode. For example, when the diode is fired by a single photon, obvious current increase will be observed, which results in the bias increase on the resistor. Accordingly, the voltage that applied on the diode itself will be lowered down below the breakdown voltage. The avalanche process is consequently turned off until the diode is fired again by another photon. By parallel connection of large numbers of cells, the intensity of the incident light can be measured according to the analogue sum of the currents from each cell. The photon detection efficiency (PDE) of a *SiPM* is given by the product of three parameters: the quantum efficiency (QE), the avalanche triggering probability, and the fill factor (FF).

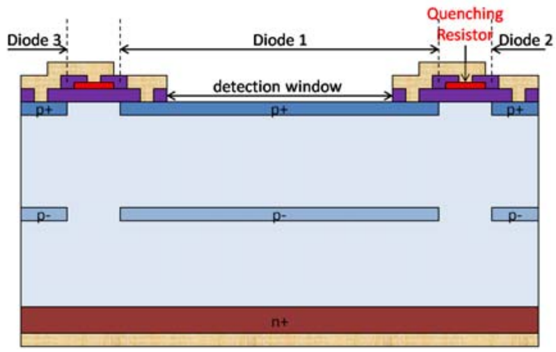

Fig. 1. Cross-sectional view of a conventional SiPM cell based on SACM structure.

Fig. 1 shows one example of the cross-sectional view of one cell schematically. As can be seen, only part of the device surface is adopted to collect incident photons. The areas outside the detection windows are assigned to accommodate the metal wires, integrated resistors and so on. Therefore, photons launched in these “dead regions” are quite unlikely to be detected. The area ratio between the detection window and the surface of the whole device is defined as Fill Factor (FF). Undoubtedly, photon detection efficiency of the device will increase with the fill factor.

Furthermore, p+ regions serve as active region of the *SiPM* cells in Fig. 1. This region is expected to be highly doped in order to maintain the uniformity of electric field and achieve perfect ohmic contact between metal and Si, both of which are quite critical for *SiPM* devices. However, the detection window overlaps this highly doped region. As a result, the photo-generated electrons are very likely to get recombined in this region, which will accordingly reduce the quantum efficiency (QE) of the device, especially for light with short wavelength.

In this paper, a new *SiPM* structure is proposed where increased fill factor and quantum efficiency can be achieved.

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Thus, high PDE will be expected in the device.

II. Quenching Ring SiPM

A. Working Principle

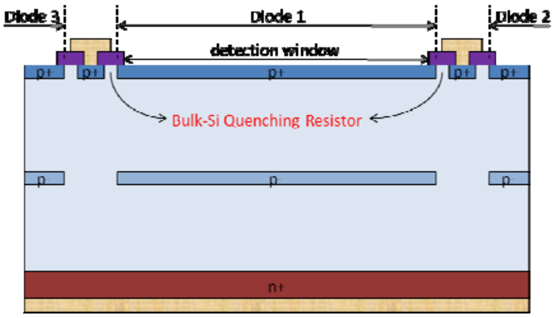


Fig. 2. Cross-sectional view of a QR-SiPM cell based on SACM structure.

The cross-section of our proposed *SiPM* structure is shown schematically in Fig. 2. It should be mentioned that the separate absorption, charge, and multiplication (SACM) structure shown in Fig. 2 is for ease of comparison with Fig. 1. Our proposed *SiPM* structure is not limited to this configuration. Many other device configurations, such as reach-through structure, can also be adopted to realize the proposed idea.

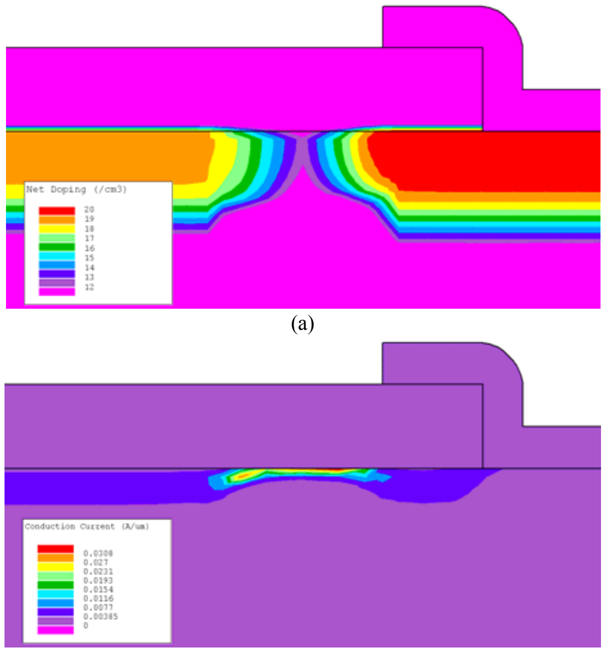
As can be seen in Fig. 2, no poly-Si resistors needed in this new structure. Instead, another highly doped region is introduced between two adjacent cells, serving as contact region to achieve ohmic contact between metal and Si. This contact region has the same doping type with the active region. Thus, when voltage applied, current will flow laterally through the high-resistance gap between these two highly doped regions as if it is flowing through a resistor. In this way, the gap serves as a lateral bulk-Si resistor in series with the diode, just like the poly-Si resistor in the conventional device shown in Fig. 1. This quenching resistor surrounds the active region along its periphery and becomes ring-like in real device. Thus, we name this new *SiPM* device as “Quenching Ring *SiPM*”, or *QR-SiPM* for short.

As shown in Fig. 2, because the lateral bulk-Si quenching resistor is connected to the active region and the contact region inherently, no metal wire is needed to realize the connection between diode and resistor. Thus, the metal wires are completely absent from the active region and almost all the active area can be used for light detection. Besides, sufficiently high resistance can still be achieved even when the gap is quite small, thanks to the high resistivity of intrinsic Si. Thus, in spite of the introduction of an extra highly doped contact region in our proposed structure, the dead regions between adjacent cells can still remain as narrow as, or even narrower than, the necessary cell separation width in conventional *SiPM* arrays. Therefore the fill factor will be obviously increased.

Furthermore, as previously mentioned, the p+ region in conventional *SiPM* shown in Fig. 2 serves not only as active region to maintain the uniformity of electric field, but also as contact region to achieve good ohmic contact between metal and Si. Therefore the p+ region needs to be very highly doped to simultaneously satisfy these two requirements. In our proposed structure (Fig. 2), however, the contact region and the active region can be optimally designed and defined separately. For example, only very thin and moderately doped p+ region will be sufficient for the active region to maintain the electric field uniformity. Thus, the quantum efficiency of the device at short wavelength will be obviously improved.

B. Simulation and Analysis

Numerical simulations were performed to verify the functionality of the proposed *SiPM* structure. Commercially available TCAD-based software was used to simulate the fabrication processes and the device characteristics. SACM structure was used to build the *SiPMs* under simulation. For simplicity, the layouts of the devices have a circular symmetry, and therefore, cylindrical coordinate system was used for the simulation. For comparison, the performances of one conventional *SiPM* and one *QR-SiPM* with comparable dimensions were investigated. The charge layers (p- region) were defined by implantation of 1.0x1012/cm2 Boron into the epitaxial Si layer under 10eV, followed by rapid thermal annealing (RTA) at 1050°C for 5s. The active and contact region (p+) in conventional *SiPM* was defined by implantation of 4.0x1015/cm2 Boron into the epitaxial Si layer under 10eV, also followed by RTA at 1050°C for 5s. The same doping and annealing processes applied to the definition of the contact region in *QR-SiPM*. However, varied doping dosage for the active region in *QR-SiPM* was adopted for comparison.



(b)

Fig. 3. Simulation results of a QR-SiPM with a 1e14/cm2 doping dosage in active region: (a) doping profile of active region and contact region; (b) current density through the quenching ring resistor

Fig. 3(a) shows the doping profiles of active region and contact region in a *QR-SiPM* structure, in which the doping dosage of the active region was set to be 1x1014/cm2. When certain reverse bias applied to the device, current will flow through the gap between active region and contact region, which serves as the quenching resistor. The simulated current density distribution shown in Fig. 3(b) has confirmed this prediction. Furthermore, we also evaluated the electric field distribution in the device by means of simulation. In spite of the obviously low doping dosage of active region compared with that of contact region, very uniform electric field distribution can still been achieved in both absorption region and multiplication region.

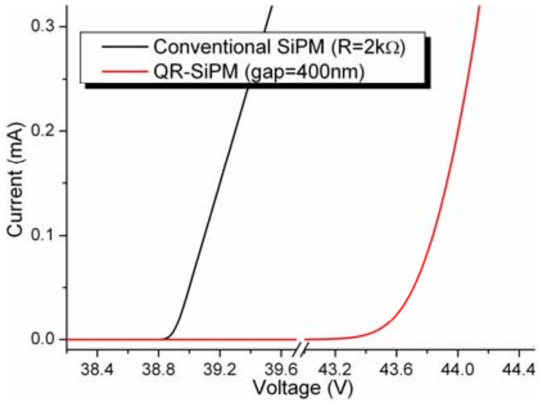


Fig. 4. I-V curves of SiPM devices under simulation

The simulated I-V curve of the above-mentioned QR-SiPM, in comparison with that of a conventional SiPM, is shown in Fig. 4. As can be seen, the breakdown voltage of QR-SiPM is a few voltages higher than the conventional device. And besides, the quenching-ring resistor does not have a constant resistance. Its value changes with the voltage applied. This is because not all the current flows through the quenching resistor (the gap between contact region and active region). A small portion of current might flow directly from cathode (n+ substrate) to anode (p+ contact region) without passing through the multiplication region, charge layer, absorption region, active region and the gap. The current distribution within the device changes with the voltage applied. Therefore, non-linear I-V curve was observed.

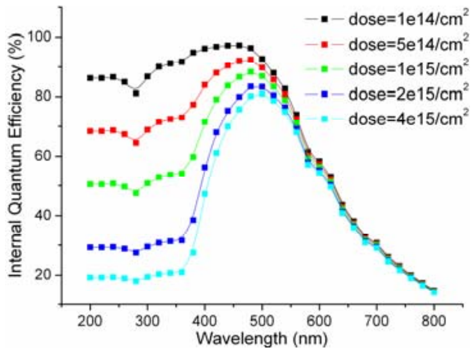


Fig. 5. Internal quantum efficiency of QR-SiPMs with different dosages applied to define the active p+ region

The internal quantum efficiency of *SiPM* can also be investigated by simulation. The devices were illuminated by a collimated light beam with a certain wavelength and a power density of $1mW/cm^2$. The incident light was vertically launched to the device surface. The dimension of the beam was set to be the same to the detection window. The internal quantum efficiency of a series of *QR-SiPMs*, the doping dosage of which are different from each other, was calculated and depicted as a function of wavelength in Fig. 5. As can be clearly seen, the quantum efficiency of the device increases noticeably with the decrease of doping dosage of the active region, especially when it's operated at ultra-violet wavelengths. At 300nm wavelength, for example, the quantum efficiency increases from 20% to 86%. This result is in accordance with our expectation, which confirms the correlation between doping concentration and carrier recombination. The quantum efficiency decreases at longer wavelengths (longer than 500nm), as shown in Fig. 5. This decrease should be mainly attributed to the incomplete absorption of incident light within the epitaxial layer.

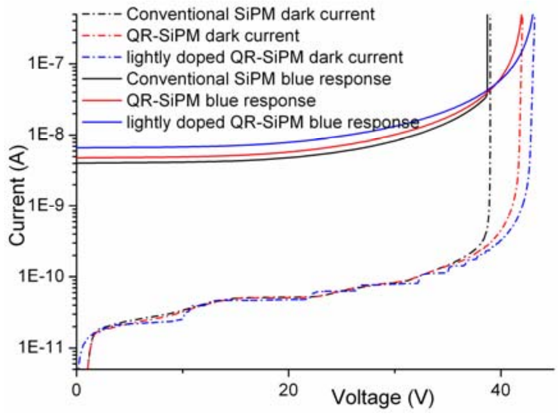


Fig. 6. Blue light responses of SiPM devices under simulation

I-V curves of the considered *SiPM* devices under illumination can also be calculated. Their responses under blue light (wavelength: 440nm; power density: 1mW/cm2) are shown in Fig. 6, together with the corresponding dark current curves of the *SiPMs*. As can be seen, the dark current of *QR-SiPM* is almost the same to that of the conventional device. However, obviously larger response to blue light was observed in *QR-SiPM*. Detailed analysis shows that the ratio between the responses in *QR-SiPM* and conventional *SiPM* is almost identical to the ratio between the areas of detection windows in these two devices, which further confirmed the close connection between detection sensitivity and fill factor of the device. Furthermore, the blue light responses of two *QR-SiPMs* with different doping profiles are also compared in Fig. 6. The blue curve corresponds to much lower doping dosage (1x1014/cm2) in active region than the red curve (4x1015/cm2). As can be seen, obviously higher response can be observed, which is in accordance with the increase of quantum efficiency shown in Fig. 5.

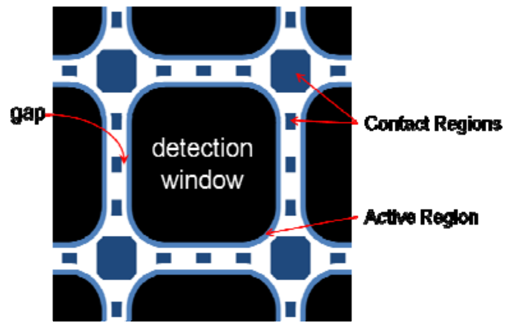


Fig. 7. QR-SiPM cell with discontinuous contact regions

In Fig. 4, the I-V curve slope of the *QR-SiPM* after breakdown is roughly identical to that of the conventional *SiPM* with a 2000Ω serial resistor. In real application of *SiPM* devices, however, quenching resistors with higher resistances, in the order of 105Ω, are expected. This high resistance can also be achieved in *QR-SiPM* by increase of the gap between the contact region and the active region, or by adoption of discontinuous quenching rings, as shown in Fig. 7.

III. Conclusion

A novel design of SiPM device with high photon detection efficiency has been disclosed. In the new structure, the quenching resistor of the device can be achieved within the Si bulk, and is connected with the diode inherently. Thus no metal wire connection is needed in the active region, and high fill factor can be achieved. Furthermore, because of the separation of the active region and the anode contact region, the concentration of dopants in the active region can be lowered down, which results in greatly improved quantum efficiency at short wavelength, especially for blue and ultraviolet light. The performance of the new *SiPM* has been confirmed by numerical simulation. Compared with SiPMs with conventional configurations, the new structure has the advantages of higher detection efficiency, more flexible device design and simpler fabrication processes.

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