Design and Simulation of Silicon Photo-Multiplier

R.A. Shukla[1,2], V. G. Achanta[1], S. R. Dugad[1], S. P. Duttagupta[2], S. K. Gupta[1], S. S. Prabhu[1]
[1]Tata Institute of Fundamental Research,
Mumbai, India
E-mail: raghunandan@tifr.res.in
[2]Indian Institute of Technology Bombay,
Mumbai, India

Abstract— **Silicon Photo-Multiplier (SiPM) is a state of the art photo-detector, capable of detecting extremely low light flux as low as single photon with high gain (~ 10^5) and high resolution. The SiPM consists of a large array of Avalanche Photo Diodes (APDs), connected to a common grid through individual series resistors and biased in 'Geiger' mode. Due to various advantages of SiPM such as high quantum efficiency, smaller footprint and smaller size it has been sought after as replacement for conventional Photo Multiplier Tubes. Thus, SiPM is being widely used in many high energy experiments such as CMS experiment at CERN. We have proposed indigenous design for the SiPM, designed and optimized through extensive TCAD simulations. The APD structure was optimized at the wavelength around 490 nm making it suitable for various high energy experiments like GRAPES-3 in India. Various characteristics of the device were studied such as I-V and C-V characteristics, spectral response of the device and transient response. Implanted guard rings were designed resulting in significantly reduced electric field near edges (~ 40000 V/cm) compared to its value of 4x10^5 V/cm at the main junction. This has ensured lower leakage currents and no edge breakdown of the device. Fabrication process for the proposed device was designed with local foundry parameters enabling more realistic design.**

Keywords—Silicon Photo-Multiplier, photo-detector, impact ionization, scintillator

I. INTRODUCTION

Silicon Photo-Multiplier (SiPM) is a sensitive photo-device capable of detecting very low light flux. SiPM provides very high gain (~ 10^5), high quantum efficiency, high resolution and many more advantages compared to conventionally used vacuum tube Photo Multiplier Tubes (PMTs). In view of many advantages coupled with its solid state design and small footprint (typically 3mm x 3mm), the SiPM has become viable replacement for PMTs. SiPM is being used in many high energy physics experiments such as CMS experiment at CERN [1] as well as medical diagnostics instruments such as PET camera [2,3,4] across the world. We have carried out extensive simulation studies to design an optimized SiPM structure suitable for high energy experiments such as GRAPES-3 experiment at Ooty, India [5].

Silicon Photo-Multiplier is essentially a 2-D array of large number of Avalanche Photo-Diodes, all connected to a common rail in parallel [6]. Fig. 1 shows the schematic representation of the SiPM. These APDs are biased above their breakdown voltage (in the Geiger mode) to produce very high gain. The individual APD acts as a digital device producing a fixed charge when triggered by an incident photon. Due to Geiger mode biasing, an APD can only indicate presence or absence of a photon(s) but addition of all the APD signals provide an analog output indicating number of triggered pixels. Under low light condition where number of incident photons are less than total number of pixels on the device, probability of two photons entering single pixel becomes negligible and SiPM behaves linearly.

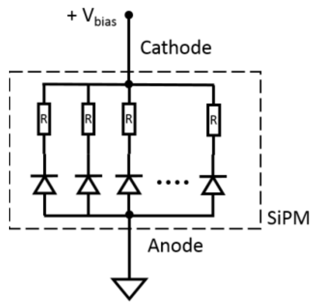

Fig. 1. Schematic Representation of Silicon Photo-Multiplier (SiPM).

A. Mechanism of avalanche breakdown

Since evolution of impact ionization theory [7], the phenomenon of avalanche breakdown has been studied extensively and applied to many modern day devices. When a photon incidents on to a reverse biased diode, if the energy of the incident photon(s) is greater than the band-gap of the semiconductor, it produces an electron-hole pair. Due to high reverse bias, high electric field is established across the junction of the device and due to presence of such high electric field generated carriers are swept across the junction. These carriers travel at high drift velocity to cause ionization in which new electron-hole pairs are generated takes place. This phenomenon multiplies if the applied electric field is high enough and avalanche breakdown takes place. Typically electric fields of the order of 10^5 V/cm are required to create an avalanche breakdown [7].

B. Design and Simulation of SiPM (APD)

Since APD is the basic element of a SiPM, extensive simulation studies were carried out to optimize APD design. Fabrication process was also optimized according to local foundry facilities. In most of the high energy physics experiments SiPM is used as a photo-readout element coupled to scintillators via wavelength shifting (WLS) fibers [1].

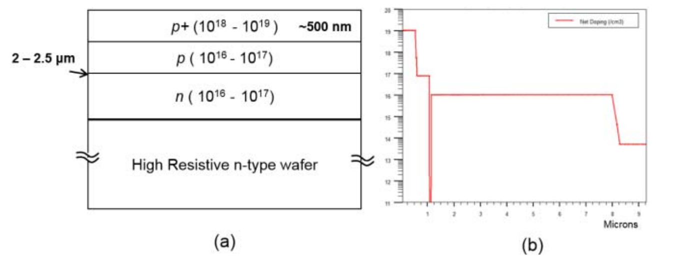

Fig. 2. (a) Simualted structure and (b) corrosponding doping profile, at device level simulations.

The emission from these WLS fiber is around 490 nm wavelength and therefore the APD structure was optimized for this wavelength range. TCAD tool was used to simulate the behavior of the device structure under various conditions. Simulations were carried out in two phases, first an ideal device structure was simulated and effect of various design parameters were studied on device characteristics. Electrical characteristics such as IV and CV were simulated and studied. Second phase of the simulation included design of the structure using virtual process package of the Silvaco TCAD tool. This allowed us to incorporate various imperfections introduced in the device structure due to fabrication process and its limitations. Typical process parameters such as ion implanter energy, dose availability, ramp time of the furnaces were incorporated in the process simulations. This made our design more realistic and adaptable for fabrication. Details of various simulations and their results have been discussed in consecutive sections.

II. SIMULATIONS

Extensive simulations have been performed to understand the APD design and optimize the response of the APD. Silvaco TCAD framework has been used to carry out various simulations. Two types of simulations were performed, a) device level and b) process level. Device level simulations are performed without considering non-ideal doping profiles and other imperfections in the device arising from fabrication process. Device structure is assumed to be ideal with step function doping profiles. This kind of simulations help quickly understand device behavior without going into depths of actual

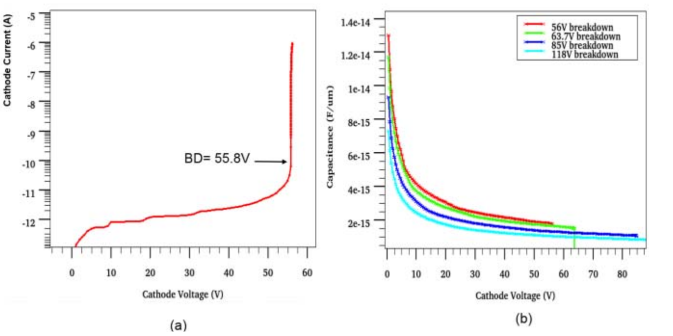

Fig. 3. (a) Simulated I-V characteristics and (b) Simulated C-V of the ideal structure. C-V characteristics from structures with different breakdown voltages have been overlaid.

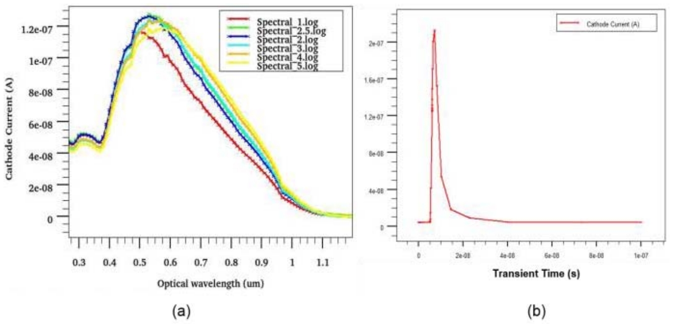

Fig. 4. (a) Response of the device to incident light of different wavelengths. Simulated response for devices with different junction depths are overlaid. (b) Transient response of the device to pulsed light. The response time of the device is ~ 100 ps.

fabrication details. With some of the literature survey and initial studies a basic multilayer structure was designed with comparatively deep junction. The depth of the junction directly affects the spectral response of the device as expected due to absorption characteristics of silicon.

A. Device simulation

Simulated device structure has been shown in Fig. 2 (a) with its corresponding doping profile in Fig. 2 (b). The surface was highly doped for good conductivity and passivation. The metallurgical junction was about 2 µm deep. While designing the device structure typical foundry process limitations were considered. Fig. 3 (a) shows one of the simulated I-V characteristics. At breakdown reverse current increases rapidly due to impact ionization. Fig. 3(b) shows overlay of C-V characteristics for structures with different breakdown voltages. The capacitance of the APD was observed to increase at lower breakdown voltage due to narrower depletion region.

As described earlier, the structure was optimized for response around visible wavelength of ~ 490nm. Fig. 4 shows the spectral response of the device. Spectral response at different junction depths has been overlaid in Fig 4 (a). The spectral response obtained with junction depth 2 um was observed to be optimum and hence the APD structure's junction depth was fixed at this value. The response of the device to the pulsed light was also studied with the help of transient simulations. Fig. 4 (b) shows the plot of device current as a function of time. The transient simulation was carried out at the breakdown voltage of the device. The response time of the device was observed to be about 100 ps, which is one of the major advantage of the SiPM. After establishing various device characteristics, process level simulations were carried out with proposed layer structure.

B. Process simulations:

Once the device characteristics were well understood and device structure was optimized, process simulations (virtual fab) was used to simulate various fabrication processes to obtain desirable structure. Implanted guard rings [8] were also designed to suppress the edge breakdown effect. A medium energy ion implanter (~ 10 – 150 keV) was considered for simulations. Implantations were carried out through thin oxide layer to avoid channeling. For all implantation steps, monte-carlo engine was

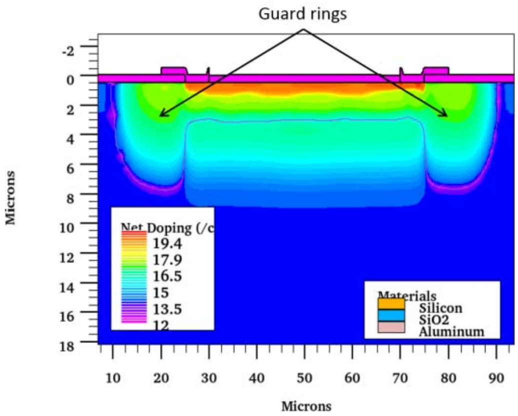

Fig. 5. Screenshot of the process simulated structure with net doping contour.

used for better accuracy. The device was built bottom up with different implantation layers and subsequent diffusion cycles.

1) Guard Rings

When the implantation is carried out with mask window dopants tend to segregate near edges. This segregation (higher concentration) of dopants reduce the width of the depletion region near edges, effectively reducing the breakdown voltage at that point [8]. Therefore when high reverse bias is applied, junction near the edges breakdown much earlier compared to major junction region; rendering the device useless. Guard rings were included in the design to avoid edge breakdown arising from the pile up of dopants near junction edges. Guard rings are essentially low doping regions which provide electrical as well as optical isolation between adjacent pixels and increases breakdown voltage of the region near edges to value higher than actual junction breakdown.

2) Process steps

A moderate resistivity substrate was chosen as a starting point. High resistivity wafer was avoided due to back side contact requirement. The whole process flow was based upon 7 lithography steps. At every implantation step a thin screen oxide

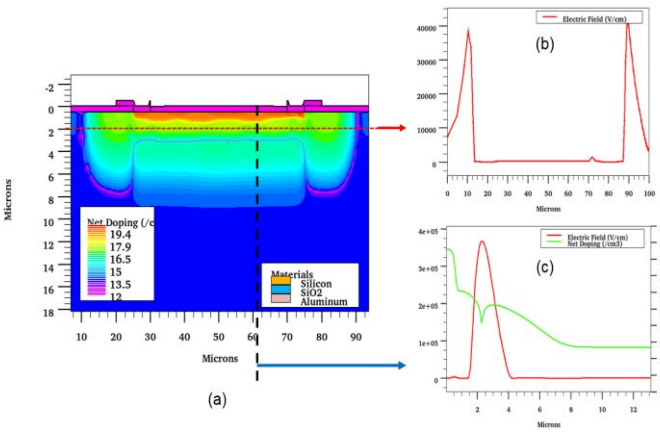

Fig. 6. (a) Net doping contour of the simulated structure. (b) Sectional views of electric field profile along horizontal direction. Reduction of the electric field near the edges can be seens as the effect of guard rings. (c) Sectional view of electric field as well as net doping along the depth of the device.

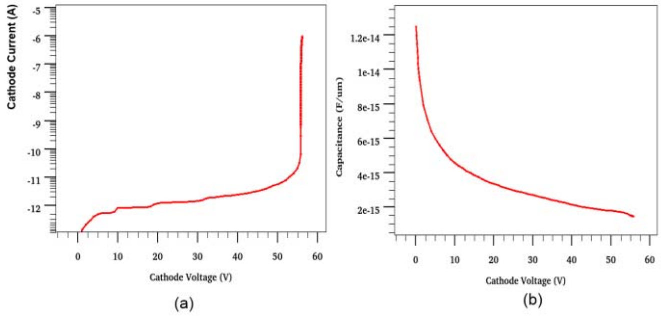

Fig. 7. (a) I-V characteristics of process simulated structure, (b) C-V characteristics of process simulated structure.

was used. First boron was implanted at 100 keV to form guard rings followed by implantation of phosphorus for n-tub. The structure was allowed to anneal at 1100 °C. Next, structure was implanted with boron to form p-n junction followed by annealing. Lastly low energy, high dose implants were carried out at top entrance window (boron, p+) and back side contact (phosphorus, n+). A short implantation cycle was designed for these implants to avoid diffusion. Pictorial representation of the structure with doping contour is shown in Fig. 5.

3) Characteristics

The shape and magnitude of the electric field is very important parameter which decides the breakdown probability of the APD structure. Typically electric fields of the order of $2x10^5$ V/cm is required to trigger the breakdown. Thus, study of the E-Field becomes vital. Fig. 6 (c) shows the E-field at the breakdown voltage across the junction along with the doping profile of the device. Generated electric field is about $4x10^5$ V/cm, sufficient for impact ionization. At the same time, as discussed earlier, the electric field near the edges was reduced with guard rings. This can be seen in Fig 6 (b). The electric field near the edges is significantly lower compared to electric field observed across the main junction. Various characterization studies as described earlier in case of ideal device simulation, were performed on final process simulated structure. These included I-V and C-V measurements, spectral response measurements and transient response measurements. Fig 7 (a) shows the I-V and Fig 7 (b) shows the C-V characteristics of simulated device. I-V characteristic indicate the breakdown

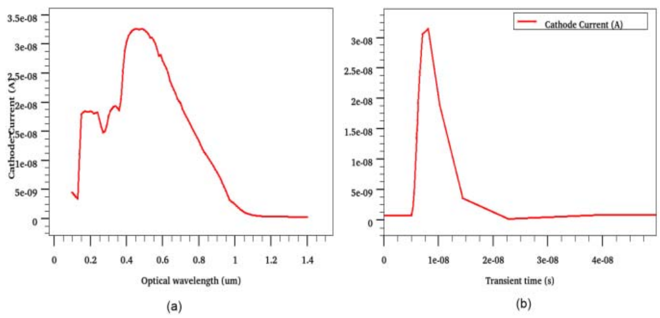

Fig. 8. (a) Spectral response of the process simulated device. (b) Transient resposnce of the device to input of short light pulse.

voltage of ~ 56 V. Fig. 8 (a) shows the spectral response of the device without any anti reflection coating. It can be seen that the response peaks around 490 nm as per the design requirement. An anti-reflection coating designed with thin layer of silicon nitride was further added to enhance the response. Fig 8 (b) shows the transient response of the device simulated at its breakdown voltage. Response time of ~ 100 ps was observed for short light pulse.

III. Discussion and Conclusion

SiPM has become most sought after photo-readout element in various high energy physics experiments as well as medical diagnostic instruments. Various superior features such as high gain, high quantum efficiency, smaller size and lower operating voltage has made this device suitable replacement for conventionally used PMTs.

Extensive TCAD simulations were carried out for the proposed indigenous design for the SiPM. The APD structure was optimized at the wavelength around 490 nm making it suitable for various high energy experiments like GRAPES-3. Various characteristics of the device were studied such as I-V and C-V characteristics, spectral response of the device and transient response. The junction depth was optimized to ~2 µm for better sensitivity near interested wavelength region. Implanted guard rings were designed and implemented through process simulations. The electric field was observed to be significantly reduced near edges (~ 40000 V/cm) compared to its value of 4×10^5 V/cm at the main junction. This has ensured lower leakage currents and no edge breakdown of the device. The guard ring structure also provided electrical and optical isolation of the nearby pixels. Fabrication process for the proposed device was designed with local foundry parameters enabling more realistic design.

Acknoledgment

We thank all members of the GRAPES-3 collaboration for their interaction.

References

[1] J. Freeman, "Silicon photomultipliers for the CMS hadron calorimeter", Nucl. Instrum. Methods Phys. Res., Sect. A 617, 393 (2010).

[2] S. I. Kwon, J. S. Lee, H. S. Yoon, M. Ito, G. B. Ko, J. Y. Choi, S.-H. Lee, I. Chan Song, J. M. Jeong, D. S. Lee, and S. J. Hong, "Development of Small-Animal PET Prototype Using Silicon Photomultiplier (SiPM): Initial Results of Phantom and Animal Imaging Studies", J. Nucl. Med. 52, 572 (2011).

[3] S. J. Hong, H. G. Kang, G. B. Ko, I. C. Song, J.-T. Rhee, and J. S. Lee, "SiPM-PET with a short optical fiber bundle for simultaneous PET-MR imaging", Phys. Med. Biol. 57, 3869 (2012).

[4] P. Buzhan, B. Dolgoshein, L. Filatov, A. Ilyin, V. Kantzerov, V. Kaplin, A. Karakash, F. Kayumov, S. Klemin, E. Popova, and S. Smirnov, Nucl. Instrum. Methods Phys. Res., Sect. A 504, 48 (2003).

[5] S. Gupta, Y. Aikawa, N. Gopalakrishnan, Y. Hayashi et.al, "GRAPES-3—A high-density air shower array for studies on the structure in the cosmic-ray energy spectrum near the knee", Nucl. Instrum. Methods Phys. Res., Sect. A 540, 311 (2005).

[6] R. A. Shukla, S. R. Dugad, C. S. Garde, A. V. Gopal, S. K. Gupta, and S. S. Prabhu, "A micron resolution optical scanner for characterization of silicon detectors", Review of Scientific Instruments 85, 023301 (2014); doi: 10.1063/1.4863880.

[7] R. J. McIntyre, "A New Look at Impact Ionization—Part I: A Theory of Gain, Noise, Breakdown Probability, and Frequency Response", IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 46, NO. 8, AUGUST 1999.

[8] Woo-Suk Sul, Jung-Hun Oh, Chae-Hun Lee, Gyu-Seong Cho, Wan-Gyu Lee, Sam-Dong Kim, and Jin-Koo Rhee, "Guard-Ring Structures for Silicon Photomultipliers", IEEE ELECTRON DEVICE LETTERS, VOL. 31, NO. 1, JANUARY 2010.