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Simulations of the breakdown characteristics of n-on-p backside-illumination Silicon Photomultipliers by TCAD

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ABSTRACT

This paper investigates, using Synopsys Sentaurus TCAD simulation, the dependence of the breakdown voltage of n-on-p backside-illumination Silicon Photomultipliers (BSI-SiPM) on the implantation dose, the implantation energy and the screening SiO_2 thickness for implantation in p-enrichment region. The simulation results indicate that the breakdown voltage decreases linearly with the implantation dose and a high implantation energy can minimize the impact of the screening SiO_2 thickness on the breakdown voltage. Additionally, some key process parameters implemented in coming fabrication have been obtained.

Introduction

Silicon Photomultipliers (SiPM) are matrices of pixels operated in Geiger-mode above the breakdown voltage, which is considered a promising alternative to traditional photomultiplier tubes in Cherenkov telescopes, high energy physics and 3D imaging [1,2], due to its outstanding characteristics, such as good single-photon resolution, immunity to magnetic fields, and compactness [3]. However, since the poly-silicon quenching resistor and Al electrodes between pixels decrease the fill factor, the photon detection efficiency of SiPM is not high, which seriously limits its scope of application. To overcome the drawback and broaden its application, backside-illumination technology has been proposed to be applied in SiPM [4], i.e. BSI-SiPM, which have almost 100% fill factor and are sensitivity to both short and long wavelength.

Some issues have been investigated as part of developing fabrication processes for backside illuminated image sensors. The first issues are the backside thinning of the wafer, the hybridization and the packaging, which have been studied by MIT [4]. Another issue is premature edge breakdown. Fortunately, this can be avoided by utilizing junction termination techniques. The third issue is the breakdown voltage of BSI-SiPM, which must comply with following requirement:

$$V_{FD} < V_{BD-enrichment} < V_{BD-edge} \tag{1}$$

where V_{BD}-*enrichment* is the breakdown voltage in the p-enrichment region, V_{BD}-*edge* is the premature edge breakdown voltage, the V_{FD} is the fully depleted voltage of the BSI-SiPM. However, the dependent of breakdown voltage on the implantation dose was discussed, regardless of energy and oxide thickness for implantation in p-enrichment region [5]. Therefore, in order to obtain a proper V_{BD}-*enrichment* between them in BSI-SiPM design, this paper investigates the effects of three of them on V_{BD}-*enrichment*, obtaining some optimized process parameter implemented in coming fabrication.

Simulation and results

The simulation of the device structure was performed using Synopsys Sentaurus TCAD simulation with a two-dimensional model. As depicted in Fig. 1a, the material is a p-type epitaxial Si wafer with a resistivity of 150 Ω cm and a thickness of 15 μm. The pixels surrounded by two n^+-guard rings and one p-stop with both a 9 μm width and a 9 μm spacing between them. The device is fabricated by selective-region dopants. The width of the p-enrichment area is 28 μm. The n^+-doped region extends laterally beyond it by 2 μm. The n^+-guard rings prevent premature edge breakdown at the periphery of the device. In addition, a boron-doped p-spray was used to prevent from the inversion case caused by oxide charge. Under the designed structure, V_{FD} is 14.6 V and the simulated edge breakdown voltage is up to 140 V. The electric field is shown in Fig. 1b. It can be noted that the electric field in p-enrichment is much larger than it in the perimeter, which indicates

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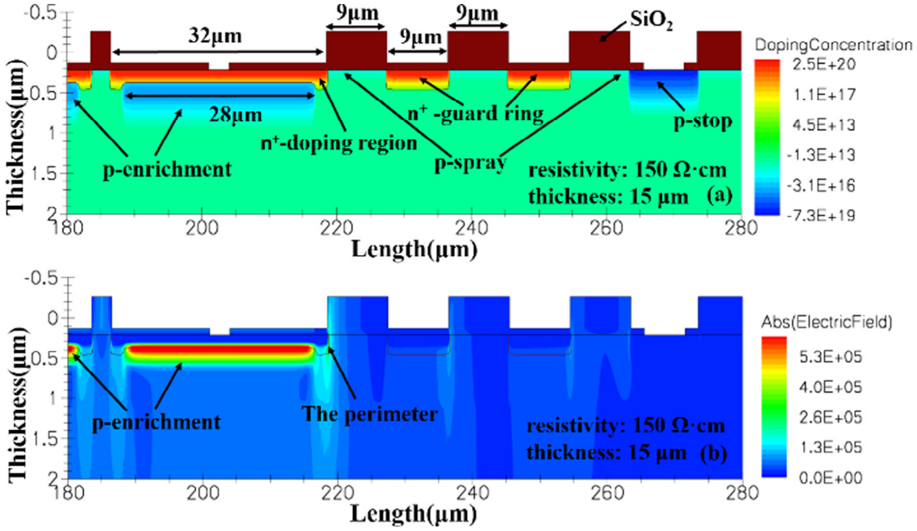

Fig. 1. Schematic view at the periphery of the BSI-SiPM detector simulated in this work (a). The electric field distribution at the periphery of the simulated structure at breakdown voltage (b).

the avalanche happens in p-enrichment and the device can operate well at breakdown voltage.

The implantation dose effect

Fig. 2 displays V_{BD}-*enrichment* as a function of p-enrichment BF_2 ion implantation doses. It is found that the higher the implantation dose is, the lower the breakdown voltage is. The breakdown voltage increases from 35 V to 98 V as the implantation dose decreases from 4.7×10^{12} cm^{-2} to 4.3×10^{12} cm^{-2}.

The remaining SiO_2 thickness effect

As shown in Fig. 1b, a layer of SiO_2 is thermally grown as a protecting layer to shield the device from the harsh ambient environment and is then etched to 800 Å used as a masking oxide for p-enrichment implantation. However, in the actual etching process, a maximum value of 100 Å deviation is reasonable for the remaining thickness of the SiO_2. Thus, the oxide thicknesses of 700 Å and 900 Å are also investigated. As shown in Fig. 3, it illustrates that V_{BD}-*enrichment* changes greatly with the deviation of the oxide thickness and further shows it decreases linearly with the p-enrichment implantation dose. The maximum deviation value is approximately 20 V. Since a uniform breakdown voltage is desirable, such a change of the breakdown voltage should be avoided. Fortunately, improving the implantation energy can achieve this goal as described in the following based on the simulation results.

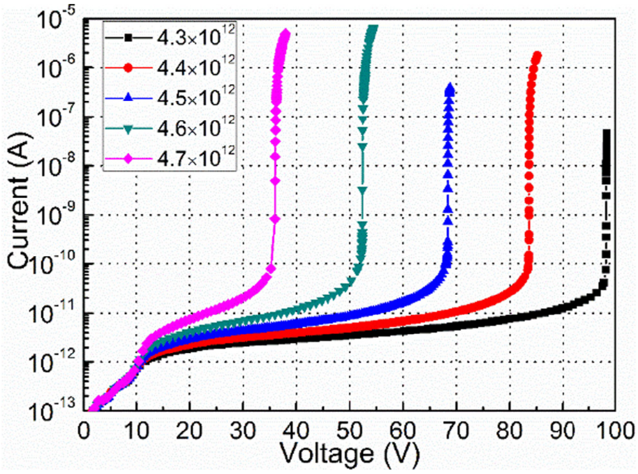

Fig. 2. The I-V characteristics of the simulated structure with different implantation doses of the p-enrichment at an energy of 110 keV and an oxide thickness of 800 Å with a tilt angle of 7 degree.

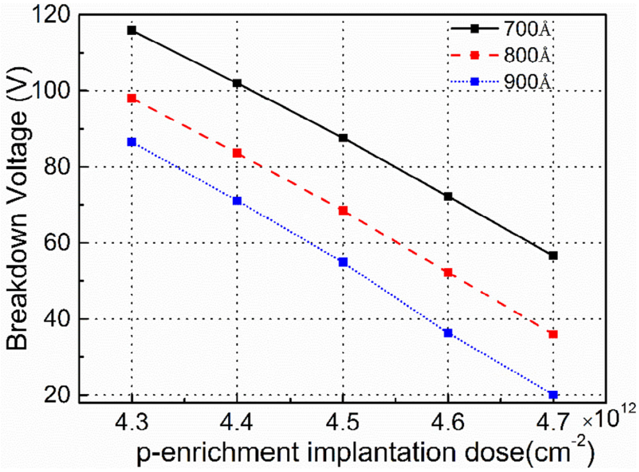

Fig. 3. The breakdown voltage as a function of the simulated implantation doses of p-enrichment and the different oxide thickness at an energy of 110 keV.

The implantation energy effect

We enlarge the implantation energy from 110 keV to 210 keV and 310 keV. Similar simulations to the previous are carried out. Obviously, as illustrated in Fig. 4, the improvement of the implantation energy reduces effectively the impact of oxide thickness on breakdown voltage. Different implantation energies have its range of proper implantation does for V_{BD}-*enrichment*.

Conclusion

Some estimated process parameters for V_{BD}-*enrichment* have been obtained, by simulating the effect of the implantation dose, the implantation energy and the oxide thickness on the breakdown voltage. To minimize the influence of the oxide thickness on breakdown voltage and get a more stable breakdown voltage and better device reproducibility, a high implantation energy would be adopted. In addition, to validate the simulation results with experimental data, different implantation doses and high implantation energies have been submitted for fabrication at the Novel Device Laboratory (NDL).

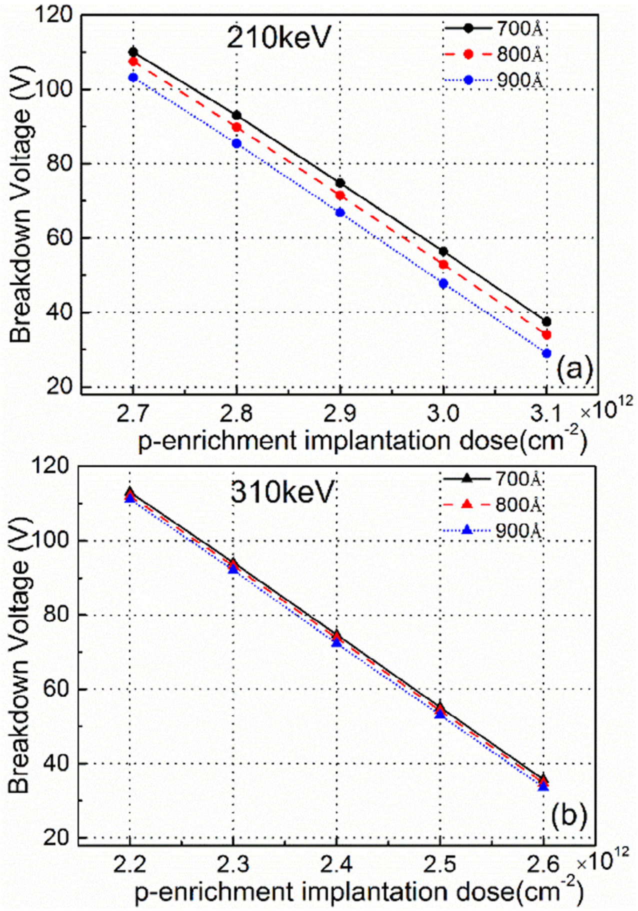

Fig. 4. The breakdown voltage as a function of the implantation doses of p-enrichment and the different oxide thickness with the implantation energy of 210 keV (a) and 310 keV (b).

Acknowledgements

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