Simulation and investigation of SiPM’s leakage currents at low voltages

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Abstract. Technology Computer-Aided Design (TCAD) allows us to use computers in order to develop semiconductor processing technologies and devices and optimize them. Within a framework of a study of silicon photomultipliers (SiPM) a simulation of these devices has been made. The simulation was performed for the irradiated SiPMs and current-voltage characteristics were obtained for the modeled devices. Investigation of current-voltage curve below breakdown with regard to the simulated structure was performed. Obtained curves are presented.

1. Introduction
SiPMs are semiconductor single photon sensitive devices with a high gain making them very promising photodetectors [1]. They can replace conventional vacuum tube photomultipliers (PMTs) in many areas due to following reasons. SiPMs are insensitive to magnetic fields, their bias voltage is much lower and they are very compact. SiPM represents an array of connected in parallel identical single pixels, each of which is a p-n junction with its own a serial resistor. Each pixel operates in Geiger mode which means the bias voltage is higher than the breakdown voltage [2].

Promising application areas of science for SiPMs are a high-energy physics, nuclear medicine and astroparticle physics. However, SiPMs face the problem of a radiation tolerance which limits their use in some of these areas. SiPM radiation hardness investigation started few years ago, for example in [3, 4, 5]. However, in such works no attempt was made to separate a bulk and surface damage. Recently, the investigation of the pure surface radiation damage has been started. Firstly, it has been done for the Hamamatsu MPCCs [6] and then for the SiPMs produced by KETEK GmbH [7]. Though the detailed analysis were done in these works, the simulation has not been performed.

Semiconductor manufactures have a strict time and cost budgets to develop a technology and produce devices. Simulations before producing of any devices lead to a reduction of a final cost of products and time consumption for their fabrication. Synopsys TCAD (Technology Computer-Aided Design) software [8] provides a number of powerful tools for the simulation of the semiconductor devices with an environment to analyze the simulation results. In this work, Synopsys TCAD was used to perform a simple design of SiPM and study a current-voltage characteristic behavior.

2. Simulation model
The SiPM model is presented in figure 1. Implemented structure is 20 µm long (marked as L in the figure) and has a 5.5 µm depth. The structure has a following layers: dielectric layer, which is
represented as a silicon dioxide (0.5 µm depth), boron highly doped p⁺ entrance window (0.45 µm depth), phosphorous n-type layer (2.5 µm depth) performed as a retrograde profile and phosphorous n⁺ highly doped substrate (from 3 to 5 µm depth). Also, bias and ground contacts for the device simulation have been added. The bias contact extends beyond p⁺-layer on silicon dioxide for 7 µm.

In order to reduce a simulation time this small model has been used. For the current-voltage characteristic investigation a high-quality spatial grid is needed on Si-SiO₂ interface and on p-n-junction region. A minimum grid step in a depth direction is 1 nm. This is caused by a thin inversion or accumulation layer (up to 10 nm) appearing at the Si-SiO₂ interface. The grid step limit in a lateral direction is 10 nm due to the p⁺-n junction region.

In work [9] the same model was used for the simulations of radiation damage of SiPMs. A procedure of the simulations and physical sense is fully described in this work. However, in this work the currents were not scaled for the whole SiPM device. One of the faced problems was a different slope of the simulated current-voltage characteristic and the measured one at the low biasing voltages. In this work the model for 200Gy dose were used with the following parameters: interface charge equal to \(-8.3 \cdot 10^{11}\) C and surface recombination parameter \(S_0 = 8.0\) cm/s.

3. Results
It has been assumed, that the current may rise faster or slower in consequence of the different propagation of a depleted region inside of the high doped p⁺-type region. In case of the higher propagation much more charge carriers from this region contribute to the current. Depleted region depths \(W_p\) and \(W_n\), for the p-type and n-type region, respectively, depend on a concentration according to equations (1):

\[
W_p = \left( \frac{2 \varepsilon \varepsilon_0 \Delta \phi}{q N_A^2 \left( \frac{1}{N_A} + \frac{1}{N_D} \right)} \right)^{1/2} \quad W_n = \left( \frac{2 \varepsilon \varepsilon_0 \Delta \phi}{q N_D^2 \left( \frac{1}{N_A} + \frac{1}{N_D} \right)} \right)^{1/2}
\]

where \(\varepsilon_0\) – vacuum permittivity, \(\varepsilon\) – relative permittivity of silicon, \(\Delta \phi\) – contact potential difference, \(q\) – elementary charge, \(N_A\) and \(N_D\) – acceptor and donor concentration, respectively.

Thus, if we change the concentration of the acceptors in p⁺-type region, this will affects on a current-voltage characteristics. For the simulations of p⁺-type region in a vertical dimension Gaussian profile with a peak at the surface were used. Lateral profiles of this region was specified with an error function distribution. In table 1 Parameters of the profiles are shown. The implemented structures with these concentration profiles and their initial depleted region at 0 V bias voltage are shown in figure 2. One can see the less propagation of the depleted region into p⁺-type region in case of higher concentration (basic structure used in [9]) in it.
Figure 2. Structure and initial depleted region with a) higher acceptor concentration on the p-n-junction and b) lower acceptor concentration on the p-n-junction.

Table 1. The p’-layer profile parameters.

| Parameter                        | Value  |
|----------------------------------|--------|
| Peak concentration, cm\(^{-3}\)  | 1·10\(^{19}\) |
| Junction concentration, cm\(^{-3}\) | 1·10\(^{15}\) |
| Junction depth, µm                | 0,5    |
| Basic error function factor       | 0,6    |
| Modified error function factor    | 0,66   |

The simulations of the structures with both type of concentration profiles have been performed. In figure 3 the current-voltage characteristics for the basic structure and for the structure with modified concentration are shown. It is clearly seen, for the modified structure with the lower p’-concentration on low bias voltages the current is rising faster and it gives an additive to the dark current on a “plato”.

Figure 3. Comparison of the currents for structures with different lateral profile concentration (solid lines are guide to the eyes).
4. Conclusion
In this work the adjustment of the current-voltage characteristic by changing concentration of p-type active window of silicon photomultiplier using Synopsys TCAD was presented. Using this method it is possible to tune the I-V curve of SiPM at the low voltages and obtain better convergence with a real devices.

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