Spectral sensitivity characteristics simulation for silicon p-i-n photodiode

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Abstract. In this paper the simulation results of the spectral sensitivity characteristics of silicon p-i-n-photodiodes are presented. The analysis of the characteristics of the semiconductor material (the doping level, lifetime, surface recombination velocity), the construction and operation modes on the characteristics of photosensitive structures in order to optimize them was carried out.

1. Introduction
In equipment types which use the yielding the radiation detector, in most cases, defines the basic parameters of optical systems. Modern development of optical receivers is characterized by the further parameters improvement and radiation characteristics detectors: sensitivity, speed, the spectral sensitivity range, reliability and etc. [1]

Silicon photodiodes have a long life usage, mechanical strength and compact size. P-I-N photodiodes have high bandwidth at low bias voltage, which makes them ideal detectors for use in high speed photometry of optical communication lines [2].

At the same time, the effective multilayer photodetector structures creation requires consideration of factors that affect the photosignal formation. Simultaneous optical radiation absorption consideration, the transfer of photogenerated charge carriers and their recombination, including recombination at the layer boundaries and surface requires computer simulation that allows a detailed analysis of the structure design influence and electrical characteristics of individual regions with the lowest material cost.

2. Results and discussion
In order to optimize physical and topological structure of multilayer silicon structures simulation program for spectral characteristics was developed. Simulating photosensitivity silicon of photosensitive structures was performed by solving the basic system of equations: Poisson equation, the continuity and the electrons and holes transfer [3-6]. The simulation program was developed using the language Borland Delphi 7. The program allows recreating the simulated layers structure,
specifying the layers quantity, the material, the conductivity type, doping level and the each layer thickness.

For determination of the spectral dependence of the photosensitivity it was given the spectral range and in every area of monochromatic spectral range the photocurrent was determined. Moreover, in order to analyze the physical processes occurring in the structure, and then optimize the design of the structure separately the photocurrents generated separately p- and n- regions and the space charge region were determined. As a result, the spectral sensitivity distribution of the units in A/W was achieved. As an initial structure for simulation it was adopted the structure shown in figure 1.

Figure 1. The initial silicon p-i-n-structure chosen for simulation

Figure 2 shows an example of calculated p-i-n-structure spectral characteristics.

Figure 2. Estimated multilayer p-i-n structure spectral characteristics

The program also allows to estimate the lifetime impact, recombination rate, thickness and doping level in various areas, consider the effect of changing the doping level without changing the lifetime and mobility. It may seem strange, but the total spectral sensitivity is not too dependent on the doping level of the lightly doped n-region (if not to take into account the change in mobility and lifetime) (fig. 3). Although the space charge region varies considerably.
Figure 3. Effect of the doping level of the lightly doped n-region on the spectral sensitivity characteristics (top) and contribute to the spectral sensitivity characteristics of the space charge region (bottom) ($N_d = 10^{12}\text{--}10^{17}\text{cm}^{-3}$).

At the same time, an increase in the p-region doping level does not lead to a significant change in the photosensitivity spectral characteristics, but there is a slight increase in sensitivity of the long waves part. This is due to the fact that the space charge region is expanded slightly by increasing the contact potential difference, which leads to an increase in the contribution of the space charge region. The n-region contribution is slightly reduced due to a decrease in the area where photons are absorbed, by expanding the space charge region (SCR). The top p-layer contribution in the spectral response curve is not changed (taking into account reducing the lifetime and the electron mobility with increasing doping level the p-region contribution should be decreased).

To check the results reliability which was obtained by the developed simulation program, additional calculations were carried out in a specialized software ISE TCAD. This software package gives opportunity fully enough to reproduce all the process steps of creating the final structure and analyze the device operation in electrical mode. One advantage of TCAD is the possibility to create two-dimensional structures, which currently in the developed program is not implemented. Also considers only the generation-recombination processes directly within the active structure and allows to save time required to adjust processes.

As the initial structure has been selected the structure shown in figure 1 with the thermal oxide (thickness - 100 nm). Figure 4 shows the calculated spectral characteristics obtained in the developed program and in TCAD program for maximum concentration in a low doped p-layer $10^{16}\text{cm}^{-3}$. The
results were normalized by the final structure area. There is good results correlation. Spectral peak at 0.5 microns wavelength is due to maximum transparency caused oxide (thickness- 100 nm).

![Figure 4](image)

**Figure 4.** p-i-n structure spectral characteristics

To improve the structure sensitivity in the short-wavelength spectrum region it is necessary to reduce the concentration in the low doped p-region to approach the SCR surface. Another way to increase the SCR width in the subsurface region is to create a mesh structure in which the high doped p-region alternating with the original substrate parts. Figure 5 shows the spectral characteristics of the mesh structure with a 5 micron pitch between p-type regions and used for comparison the structure (impurity concentration in the p-region - $10^{16}$ cm$^{-3}$). It is important that even with a sufficiently small distance between the p-type region it is possible to achieve a significant sensitivity increase in the blue and green spectrum regions.

![Figure 5](image)

**Figure 5.** The spectral characteristics of the standard structure and structure with mesh p-region

For the initial substrate parameters the voltage of full depletion $U_{dep}$ is about 80 V, which allows the p-i-n-diode using in mode when the applied voltage is 1.5 - 2 times higher than the $U_{dep}$. The maximum operating voltage will be determined by photodiode breakdown characteristics. This mode makes it possible not only to increase the overall output level, but also to raise the response.

### 3. Conclusions

It was carried out the various factors influence: the electrons and holes lifetime and mobility, surface recombination velocity on the spectral sensitivity characteristics of p-i-n-structures. In order to optimize the photodetector structure parameters it was calculated the parameters when changing the top layer depth of p-doping levels and changing doping areas of the structure. To expand the spectral
sensitivity characteristics of silicon photodetector structures toward shorter wavelengths it is required the maximum achieving space charge region to the surface. At the same time, action is required to ensure the improvement of the surface properties to reduce the surface recombination velocity and the simultaneous use of anti-reflection coatings.

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