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Analysis of the *p-i-n*-structures Electrophysical Characteristics Influence on the Spectral Characteristics Sensitivity

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

Keywords: Silicon *p-i-n*-photodiode characteristics simulation, Spectral sensitivity, Optimization design of photodetectors.

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1. INTRODUCTION

In the work of any equipment type that uses optical radiation the radiation detector, in most cases, defines the basic parameters of optical systems. Optical receiver modern development is characterized by the further parameters and characteristics improvement of radiation detectors: sensitivity, speed, the spectral sensitivity range, reliability and etc. [1].

Silicon photodiodes have a long life, mechanical strength and compact size. *p-i-n* photodiodes have high bandwidth transmission at low bias voltage, which makes them ideal for use in detectors of high photometric and optical communication lines. When connecting the silicon *p-i-n*-photodiodes to the high speed preamplifier their small total capacity provides high performance and low noise level. In industrial conditions, photodetectors are used most frequently in industrial automation, security systems, fiber-optic communication lines. Based on the *p-i-n*-structures micropixel avalanche photodiodes [2], charge coupled devices [3] position-sensitive detectors of nuclear radiation [4-9], temperature – magnetic field sensors [10, 11] and etc. are reduced.

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

2. EXPERIMENTAL PROCEDURES

p-i-n-photodiode structure is designed to avoid the p-n-type photodiode disadvantages. But all the basic registration principles are stored. Inputting intrinsic semiconductor layer between *p*- and *n*- impurity semiconductor layers can significantly increase the space charge region size.

In contrast to the same area the *i*-doped layers are made thin. All together this is done to the main part of the optical radiation is absorbed in the *i*-layer and reduces the charge transfer time from the *i*- zone doped regions is reduced.

As an initial structure for simulation it was adopted the structure shown in Fig. 1.

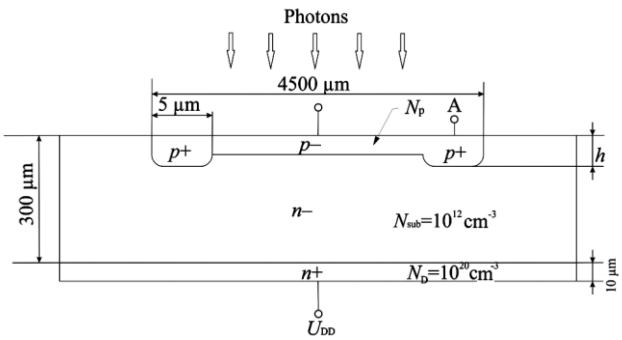

Fig. 1 – The initial silicon p-i-n-structure chosen for simulation

In order to optimize physical and topological structure of multilayer silicon structures it was developed the program for spectral characteristics simulation.

Silicon photosensitive structures simulation was performed by solving the basic system of equations: Poisson equation, the continuity and the transfer of electrons and holes equations [12].

In the numerical solution of the basic equations of the original differential equations in partial derivatives are presented in the difference form.

Taking the boundary conditions at the fields' edges and wondering initial charge carrier distribution, it is obtained a system of nonlinear equations. Thus, instead of differential equations, it is necessary to solve a system of nonlinear algebraic equations.

If necessary, for the solution of linear algebraic systems with matrices, being nearly empty, i.e., containing some non-zero elements, passing method has been used successfully [13, 14].

The simulation program is developed using Borland Delphi 7 language.

The program gives opportunity to create new layers simulated structure specifying the number of layers, the material conductivity type, doping level and each layer thickness. The resulting structure is drawn in a separate window. Created structure can be stored in a special file, with the possibility of layer characteristics subsequent correction, including adding and removing layers. Next, for each layer it is setted its semiconductor and optical characteristics

3. RESULTS AND DISCUSSION

To determine the spectral dependence of the photosensitivity it was set the spectral range, and in every area of monochromatic spectral range it was determined the photocurrent. Moreover, in order to analyze the physical processes occurring in the structure, and optimizing the structure design it was determined separately photocurrents generated separately by p- and n- regions and the space charge region [15].

Setted radiation flux is recalculated into the power of the incident radiation power (W/cm^2) [16].

As a result, it was obtained the spectral sensitivity distribution in the units A/W.

In order to validate the simulation, by the developed program, it was compared the results of the usual calculations with the calculations by the program TCAD Sentaurus [16]. The results obtained showed a good agreement between the results of calculations using these two programs.

For further simulation it is advisable to use a developed program (Polisloi), allowing a more detailed analysis of the physical processes in order to optimize the developed photodetector structure.

Charge carriers mobility Influence and lifetime is the same, and affects the contribution of quasi-neutral regions into the sensitivity. When the mobility and lifetime are less, the fewer number of charge carriers reach the space charge region, therefore, the contribution of quasi-neutral regions is reduced. Mobility and lifetime of mobile charge carriers are reduced with increasing doping level, however, it varies the contact potential difference, and hence it will change the space charge region width. Therefore, to select only the lifetime change it will be changed the lifetime, without changing the doping level.

When the top p-layer thickness is less than 1 micron lifetime value little effects on the spectral sensitivity characteristics. Noticeable changes start at 10^{-8} s.

Much more noticeable influence change in the lifetime when the top layer depth increases ($d = 5$ μm) (Fig. 2).

In fact, the electrons produced near the surface (in the wavelength region of the spectrum), have to go a greater distance to the space charge region, so reducing the lifetime of electrons plays a more significant role.

This situation is due to the simultaneous influence of the surface recombination velocity. For small values of the top p-layer thickness of the electrons effective lifetime is determined mainly by the high surface recombination velocity. When reducing the surface recombination velocity up to 1 cm/s the influence the lifetime change effect is more significantly.

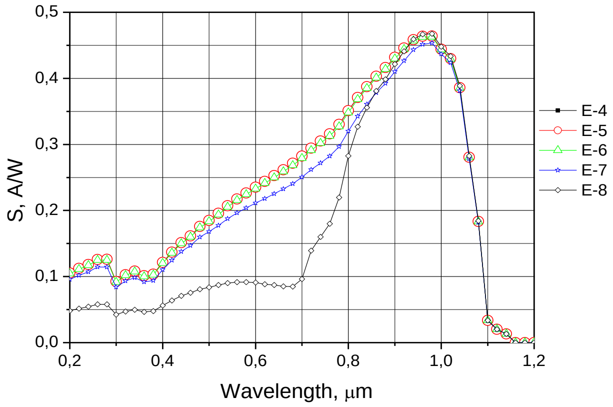

Fig. 2 – The structure spectral sensitivity dependence on the electron lifetime in p-type region ($\tau_n = 10^{-4} \div 10^{-8}$ s, $d = 5$ μm, $S = 10^4$ cm/s)

In terms of impact on the effective lifetime in the p-layer most effective influence is the influence on the spectral sensitivity in the wavelength region of the surface recombination velocity. The increase in surface recombination velocity reduces the structure sensitivity in the spectrum short-wavelength area the by reducing the electrons collection efficiency. Therefore, to simulate it was studied the effect of changes in the surface recombination velocity in the range $1 \div 10^5$ cm/s.

By increasing the level depth the surface effect is reduced, however, and the distance increases to be traveled to the photogenerated electron surface space charge region. As a result the surface recombination velocity influence is more significant.

Based on the simulation results and silicon structure characteristics and due to the various factors influence on the p-i-n-structure photosensitive parameters the parameter calculations was performed. The problems of design optimization, the doping level of the photodetector areas and modes of photodetector operation were discussed.

Effect of the top p-layer thickness is due to several factors, and especially, the incident optical radiation distribution. With increasing photon energy (decreasing wavelength) increases the absorption coefficient of the optical radiation. This means that photogenereated carriers will be formed closer to the surface. To take part in the photocurrent formation, mobile carriers must either be formed within the space charge region, or to reach the area of the quasi-neutral regions (electrons from the p-type region and holes from the n-region). In this case, the effectiveness of the contribution of the top p-layer is caused by some fraction of the electrons formed by optical radiation to reaching the space charge region. It is accordingly determined by the thickness of the upper layer, i.e., by the distance to the SCR, mobility and electron lifetime and surface recombination velocity.

Fig. 3 shows the top p-layer thickness effect on the structure spectral sensitivity characteristic.

For given parameters of the semiconductor thickness effect is negligible. There is a slight shift of the spectral sensitivity characteristics toward shorter wavelengths.

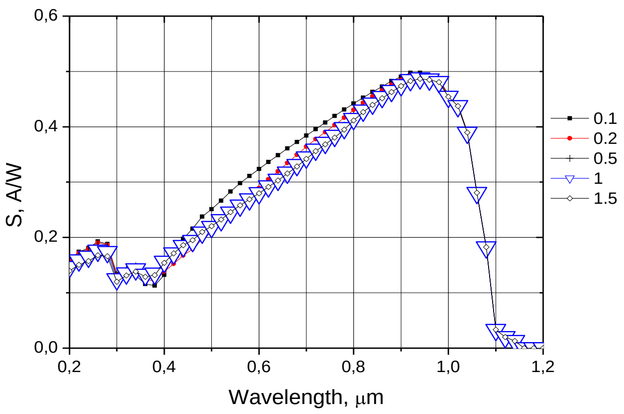

Fig. 3 – Influence of the top p-layer thickness on spectral sensitivity characteristic structure. ($d = 0.1 \div 1.5$ microns). The doping level of the p-region – 10^{17} cm^{-3}

At the same time as the p-layer thickness smaller proportion of short-wave quanta is absorbed in the SCR, therefore, the spectral sensitivity of the SCR is shifted to longer wavelengths, and the overall contribution of the SCR is reduced. The i-region contribution is not substantially changed.

By increasing the impurity concentration in the p-region, the effect of changing the top p-layer depth is more evident. This is due to the fact that when the concentration of the p-top layer 10^{19} cm^{-3}, the electron mobility decreases to 100 cm^2·V·s^{-1} and the lifetime of [17]. This leads to a noticeable change in the electrons contribution – with increasing the top layer depth is the number of less electrons formed by short-wave quanta (i.e. in the surface region) reach the space charge region. While the contribution of the space charge region remains virtually unchanged compared to the level of doping 10^{17} cm^{-3}.

Since the effect of lifetime was discussed previously, it is investigated 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. 4).

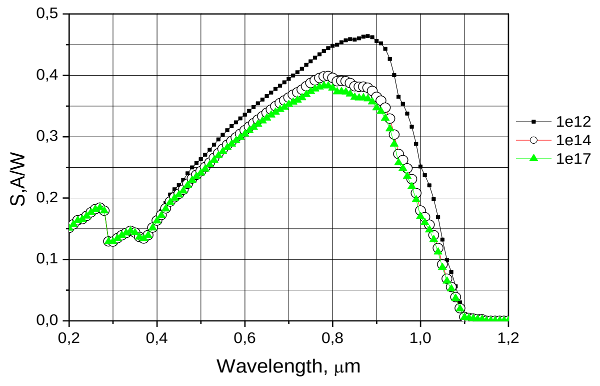

Fig. 4 – The effect of the doping level of the lightly doped n-region on the spectral sensitivity characteristics ($N_d = 10^{12} \div 10^{17}$ cm^{-3})

At the same time it is clear that a redistribution of the deposit space charge region and the n-region occurs – a decrease in the other contribution follows an increase in the contribution of one area. At increasing the n-region doping level space charge region decreases and at the same time the number of holes formed in the n-region increases.

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

Changing the applied bias slightly increases the spectral sensitivity characteristic in the area and slightly shifts it to longer wavelengths (Fig. 5), although the space charge region expands significantly in the lightly doped region.

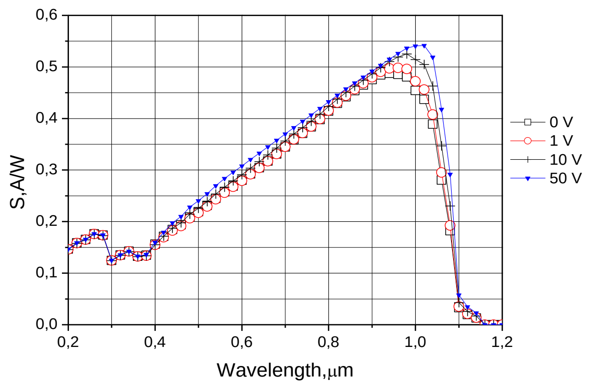

Fig. 5 – The effect of the reverse bias applied on the p-i-n-structure spectral sensitivity characteristics ($U = 0 \div 50$ B)

Such a change in the p-i-n-structure spectral sensitivity is due to the space charge region expansion the contribution of the space charge region increases, i.e., the long-wavelength photons increases contribution. Charge carriers generated by long-wavelength photons in the space charge region, are fully involved in the formation photosignal. There is a redistribution contribution to the photosensitivity between the region and the quasi-neutral charge space lightly doped n-region. The n-region contribution is reduced as the area itself is removed from the surface and the number of photons absorbed in it reduces.

This slight the spectral sensitivity expansion is due to the original n-region contributions to the spectral sensitivity was small, and the redistribution contribution to sensitivity between the n-region and the space charge region prevents substantial gain.

In order to extend the spectral sensitivity characterristics were discussed. It was assumed that the so-called "well" with the concentration of electrons 10^{12} cm^{-3} should provide the best collection of photogenerated carriers from the lightly doped n-region.

The next stage of the simulation was to study the influence of the lightly doped "well" thickness on the

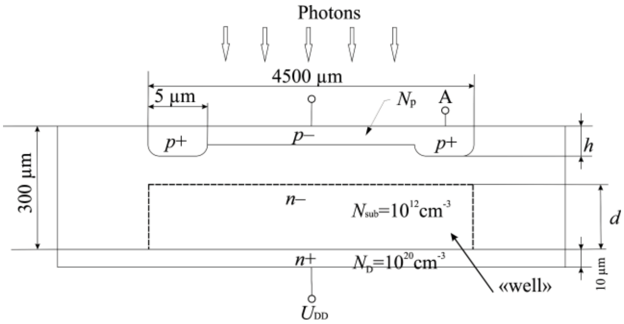

Fig. 6 – Silicon *p-i-n*-structure with high resistance "wells"

spectral sensitivity characteristics of pin-structure. The total thickness of the lightly doped layer was 300 microns. When the well thickness – 250 microns, the *n*-layer remainder thickness was 50 microns. It is assumed that the addition of the lightly doped region should provide increased sensitivity of the structure. Fig. 7 shows the change in sensitivity of pin-structures for different values of the structure thickness.

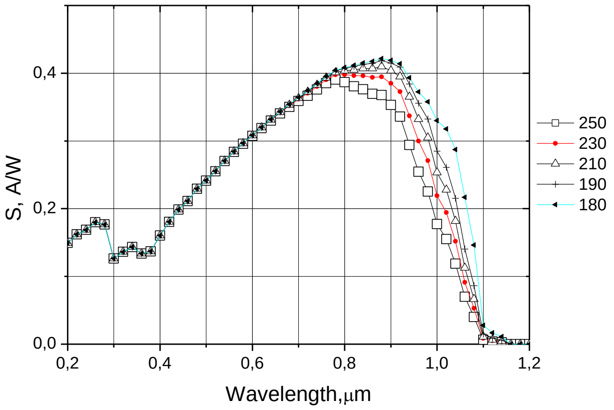

Fig. 7 – The dependence of p-i-n-structures the spectral sensitivity characteristics on the high resistance "well" thickness (180÷250 microns). The doping level of the *p*-region 10^{17} cm^{-3}

In fig. 7 it is seen that with decreasing thickness "well" maximum spectral sensitivity is increased, and the very characteristic is shifted towards longer wavelengths with a thickness of "well" less than 180 microns and spectral sensitivity characteristics is changed slightly. For comparison, it was carried out the calculations of the spectral sensitivity characteristics without the "well" with the doping level 10^{14} cm^{-3} and 10^{12} cm^{-3}. Fig. 8 shows calculations results of the structures spectral sensitivity characteristics with *p-i-n*-thick "well" 180 and 220 microns, and structures built without a "well".

Fig. 8 shows that in the structure without well and with a doping level *i*-region 10^{14} cm^{-3} spectral sensitivity characteristics, practically coincides with the spectral sensitivity characteristic at a "well" thickness 180 microns. That is, the spectral sensitivity characteristics maximum in the presence of "well" increases with decreasing "well" thickness and the very characteristics goes to specifications without "well". It also shows that the maximum sensitivity is achieved in a structure without well with doping level 10^{12} cm^{-3}.

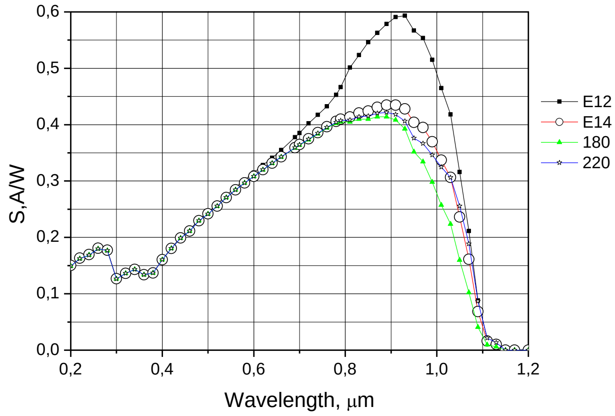

Fig. 8 – The *p-i-n*-structures spectral sensitivity characteristics with high resistance "wells" thickness of 180 and 220 microns, with and without wells doping level *i*-region 10^{12} and 10^{14} cm^{-3}

Thus the basic spectral characteristic change in sensitivity is due to the contribution of the lightly doped *n*-region.

A situation in which an increase in the size of "well" leads to a spectral sensitivity characteristics reduction, is explained as follows. The structure doping profile formation leads to the fact that there is an area on the border of the field which on the one hand prevents the holes diffusion from the lightly doped region in the space charge region, on the other hand creates a photogenerated holes flow from the n-region adjacent to the space charge region. Reducing the size of the "well" shifts the boundary in area where the holes generation almost does not occur, and hence the structure sensitivity from the long waves increases.

4. SUMMARY

It was investigated the various factors effect: the electrons and holes lifetime and mobility, surface recombination velocity on the *p-i-n*-structures spectral sensitivity characteristics.

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 areas of the structure.

It is shown that an increase of the reverse bias in the test structure does not lead to a significant increase in spectral sensitivity.

To increase the silicon photodetector structures spectral sensitivity characteristics toward shorter wavelengths it requires maximum approximation 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.

It is shown that the presence of lightly doped "well" in the structure reduces the structure sensitivity in the long-wave region. This is due to the appearance of a potential barrier for holes at the boundary of the lightly doped *n*-region and the "well". Maximum structure sensitivity is achieved at the absence of structure "well" and reducing the level of *n*-doped layer.

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