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STUDY OF THE CHARGE CARRIER COLLECTION COEFFICIENT OF SILICON *p-i-n* PHOTODIODES

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The paper investigates the collection coefficient of minority charge carriers in silicon *p-i-n* photodiodes and the influence of certain technological factors on it. It has been found that the diffusion length of minority charge carriers and the resistivity of the material have a significant effect on the value of the collection coefficient, since the collection area of photogenerated charge carriers increases with increasing these parameters. It was also found that an effective method to increase the collection coefficient of photodiodes is to ensure that the thickness of the high-resistance region of the photodiode is equal to the sum of the diffusion length of minority charge carriers and the width of the space charge region. The effect of the concentration of dopants on the responsivity and collection coefficient is investigated. It was found that, in contrast to the calculated data, in which the collection coefficient increases with decreasing concentrations of phosphorus and boron, in the experimental data, with decreasing concentrations of impurities, the responsivity and, accordingly, the collection coefficient decrease due to a decrease in the degree of heterogenization and, as a result, a decrease in the width of the space charge region and the diffusion length of minority charge carriers.
Keywords: *Silicon; Photodiode; Responsivity; Charge carrier Collection coefficient; Barrier capacity*
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In semiconductor photovoltaic devices that convert radiation energy into electrical energy, it is necessary that most of the incident radiation is absorbed in the' semiconductor volume, since radiation reflected from the surface or passed through the semiconductor is wasted. One of the types of interaction between radiation and a semiconductor that underlies the principle of operation of most photovoltaic devices is the generation of charge carriers under the action of photons. That is, if the structure with a *p-n* junction is exposed to radiation in the wavelength range corresponding to the intrinsic absorption in the semiconductor, then electron-hole pairs are generated in the semiconductor volume under the influence of radiation. If all the electron-hole pairs created by the radiation incident on the device are separated by the *p-n* junction field and create a current in the external circuit, the current conversion efficiency will be maximized. The efficiency of the radiation penetrating into the semiconductor is characterized by the charge carrier collection coefficient (γ), which is the ratio of the number of charge carriers separated by the *p-n* junction field to the number of photons penetrating the semiconductor (1):

$$\gamma = \frac{I_{sc}}{eN}, \tag{1}$$

where I_{sc} is the short-circuit current of the external circuit of the photodetector; e is the electron charge, N is the number of photons.

In this case, it is assumed that one photon creates one electron-hole pair in the semiconductor, i.e., the quantum yield of the photoconversion is equal to one. For an ideal photodetector, the collection coefficient is equal to one over the entire wavelength range to which a given semiconductor is sensitive. In real devices, due to various losses, it is less than unity; this difference is also caused by the fact that some of the carriers created by radiation recombine with each other or on impurity centers before reaching the *p-n* junction [1]. Carrier losses due to recombination depend on the structure of the photodetector, geometric thicknesses of the n- and p-regions, impurity concentration distribution in the *n*- and *p*-regions, diffusion lengths of non-basic charge carriers, etc. [2].

The responsivity and photocurrent of photodetectors, as their main parameters, are a function of the charge carrier collection coefficient. With the development of optoelectronics and photoelectronics, there is an increasing need to manufacture photodetectors with maximum responsivity and, accordingly, with the maximum collection coefficient. A review of scientific sources shows that many works have been devoted to the problems of ensuring high values of the collection coefficient in photodetectors with a *p-n* junction. For example, [3] shows that in organic photodetectors, an indium oxide and gold electrode with modified output operation acts as a resonator mirror, improving the collection coefficient and at the same time providing an extremely selective cathode, sharply suppressing the dark current. In [4], methods for improving the efficiency of photodetectors based on low-halide perovskite materials were investigated and it was shown that the best device characteristics were obtained by optimizing the thickness of the absorbing layer, doping, and defect density of the buffer and absorbing layers. However, it should be noted that the sources provide rather little information on methods for increasing the collection coefficient of photodetectors with a *p-i-n* structure, in particular silicon *p-i-n* photodiodes (PD).

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However, a well-known method of increasing the collection coefficient of *p-i-n* photodiodes is the use of side illumination of the photodetector, which ensures the absorption of radiation in the high-resistance *i*-region bypassing the doped low-resistance *n*- and *p*-regions [5]. This is also possible with the use of mesa-structures [6, 7], but this method requires precise beam focusing and is not possible in the manufacture of large-area PDs. Another effective method of increasing the photosensitivity and collection coefficient is the use of anti-reflective coatings [8, 9]. A common method of increasing the collection coefficient is to ensure double passage of radiation through the thickness of the semiconductor, which is ensured by using a mirror (usually gold) layer on the back of the device, but this is possible at a high depth of radiation absorption and relatively small thickness of the devices [10]. The disadvantage of this method is the low adhesion of gold to silicon, which requires the use of adhesive layers, in particular, a chromium sublayer.

Taking into account the advantages of *p-i-n* PDs in speed, low barrier capacity, and photosensitivity over *p-n* PDs or other types of photodetectors, the establishment of methods to increase the charge carrier collection coefficient in this type of PD is an urgent scientific and technical task, which is the purpose of this article. In particular, we will investigate silicon PDs and pay special attention to the degree of doping of *n*- and *p*-regions of *p-i-n* PDs.

EXPERIMENTAL

The research was carried out in the manufacture of silicon four-element *p-i-n* PDs for operation at supply voltage U_{bias} = 2 V and operating wavelength λ_{op} = 1.064 μm. PDs were made on the basis of single-crystal dislocation-free *p*-type silicon with resistivity $\rho \approx$ 18-20 kΩ·cm.

The samples were made by diffusion-planar technology according to the technological regimes given in [11]. The thickness of the crystals reached $X \approx$ 500-510 μm.

The photodetector with a *p-i-n* structure consisted of two thin low-impedance n^+- and p^+-regions between which a long high-impedance layer depleted of free carriers was placed. On the reverse side of the crystal, a gold layer was formed with an adhesive sublayer of chromium. The thickness of the chromium sublayer reached 10 nm. The thickness of the n^+-layer was $x_{n^+-p} \approx$ 4-5 μm. The thickness of the p^+-layer was $x_{p^+-p} \approx$ 1-2 μm. Samples were made with different surface concentrations of phosphorus and boron (surface resistance R_S) of the n^+- and p^+-layers, respectively. The surface resistance of n^+-layers reached the range $R_S \approx$ 2.1-8.1 Ω/□. The surface resistance of the p^+-layers was in the range $R_S \approx$ 16-40 Ω/□. The surface resistance was measured by the four-probe method.

To determine the transmittance of the doped layers at λ_{op} at different concentrations of the impurity, the transmission spectra were measured. It should be noted that the transmission spectra were measured on silicon wafers of the same thickness with only n^+- or p^+-layers.

Investigation of the transmission spectra were performed using NIKOLET 6700 and SF-2000 spectrophotometers at room temperature, the total wavelength range was 0.2-26 μm.

The transmission spectra were used to theoretically determine the charge carrier collection coefficient and responsivity. The theoretical responsivity was compared with the experimentally obtained one with the same photodiode characteristics used in the calculations.

Monitoring of current monochromatic pulse responsivity (S_{pulse}) was carried out by method of comparing responsivity of the investigated PD with a reference photodiode certified by the respective metrological service of the company. Measurements were performed when illuminating the PD with a radiation flux of a power of not over $1 \cdot 10^{3}$ W; load resistance across the responsive element R_l = 10 kΩ, at the bias voltages of U_{bias} = 2 V and pulse duration τ_i = 500 ns.

CALCULATIONS

To be able to determine the charge carrier collection coefficient, it is necessary to determine what radiation intensity (I) (in absolute units) is absorbed in the semiconductor thickness equal to the sum of the width of the space charge region (W_i) and the diffusion length of the minority charge carriers (L_n), since the photogenerated charge carriers will be separated by the electric field in this region. A schematic diagram of a photodiode with its various layers is shown in Figure 1.

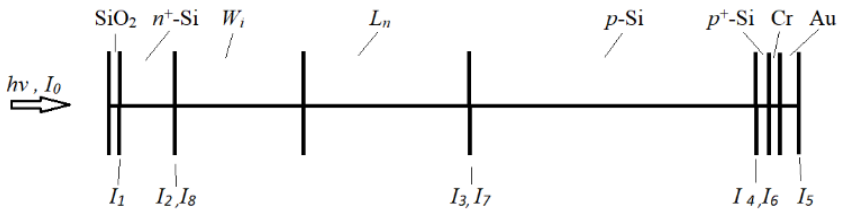

Figure 1. Layer-by-layer schematic representation of a *p-i-n* photodiode.

We determine the radiation intensities according to the Bouguer-Lambert-Beer law [12]:

$$I(x) = I_0[1 - R]e^{-\alpha x}, \tag{2}$$

where $I(x)$ is the intensity of light that has passed through a layer of substance with thickness of x, - the I_0 intensity of light at the entrance to the substance, R is the reflection coefficient, α is the absorption index.

First, it is necessary to determine the transmittance of the n^+- and p^+-layers (Figs. 2, 3).

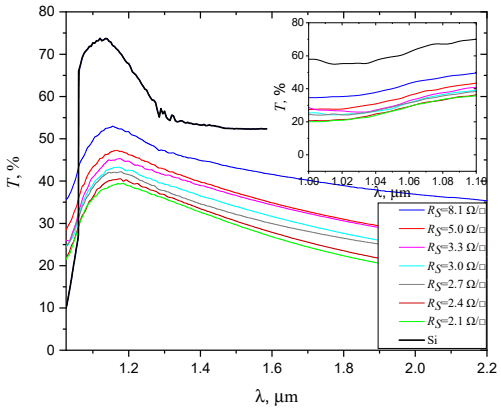

Figure 2. Transmittance of silicon substrates with n^+-layer at different phosphorus concentrations

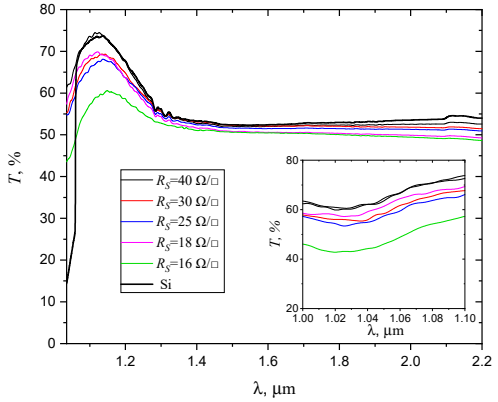

Figure 3. Transmittance of silicon substrates with p^+-layer at different boron concentrations

In [11] and [13], we found that the optimal values of the surface resistance of phosphorus and boron are R_S = 2.7 Ω/□ and R_S = 18 Ω/□, respectively. We present the calculations of the charge collection coefficient at these values.

The surface of the PD receives radiation I_0, the intensity of which, after passing through the anti-reflective coating, will be I_1:

$$I_1 = I_0(1 - R), \tag{3}$$

where R = 5% [14].

In the n^+-layer, determining the amount of absorbed radiation using the exponential Bouguer's law is a difficult technical task. Since this layer is unevenly doped, the degree of radiation absorption by this layer is determined experimentally by measuring the transmission spectrum. Figure 2 shows that at R_S = 2.7 Ω/□, the transmittance of the substrate decreases by 32% ($T_{n+} \approx 32\%$ at λ_{op}) relative to the transmittance of silicon ($T_{Si} \approx 64$ %). That is, 32 % of the radiation was additionally absorbed by the n^+-layer. Therefore, to determine the radiation intensity that will pass through this layer, the transmission coefficient of the n^+-layer must be subtracted from the intensity found by the Bouguer's law. Accordingly, the radiation intensity that enters the spatial charge region is equal to I_2:

$$I_2 = 0.68 \cdot I_1 e^{-\alpha \cdot x_{n+-p}}. \tag{4}$$

To determine the intensity of radiation absorbed in the thickness of a crystal equal to the sum of W_i+L_n, it is necessary to know their individual thicknesses. To determine the value of W_i and L_n of end products, it is necessary to know the resistivity of their high-resistance *i*-region, or the concentration of acceptors (N_A) in this region. The value of N_A can be determined by knowing the barrier capacity of responsive elements (C_{RE}). In the investigated case, the capacitance was measured at a bias voltage of U_{bias} = 120 V and reached C_{RE} = 12.1 pF. From the formula for the barrier capacitance [15], we can determine N_A:

$$C_{RE} = A_{RE}\left(\frac{\varepsilon\varepsilon_0 e N_A}{2(\phi_c - U_{bias})}\right)^{\frac{1}{2}}, \tag{5}$$

where A_{RE} is the area of responsive elements; ε, ε_0 are dielectric constants for silicon and vacuum, respectively; φ_c is contact potential difference.

In this case, $N_A \approx 1.4 \cdot 10^{12}$ cm^{-3}.

Next, it is necessary to determine the voltage at which the responsivity or dark current of the PD reaches saturation. In this case, we measured the dependence of pulsed monochromatic responsivity on voltage (Fig. 4). The saturation of the responsivity means that the sum of the width of the space charge region and the diffusion length of the minority charge carriers is equal to the thickness of the high-resistance region of the PD crystal, and further responsivity growth is not possible. At saturation, the value of W_i+L_n is:

$$W_i + L_n = X - \left(x_{n+-p} + x_{p+-p}\right). \tag{6}$$

From Fig. 4, we can see that at U_{bias} = 100 V, the responsivity reaches saturation. Knowing N_A, it is possible to determine W_i from the formula (at U_{bias} =100 V) [15]:

$$W_i = \left(\frac{2\varepsilon\varepsilon_0 (\phi_c - U_{bias})}{eN_A}\right)^{\frac{1}{2}}. \tag{7}$$

From formula (7) $W_i \approx 310$ μm, respectively, from formula (6) $L_n \approx 180$ μm.

Further, knowing N_A, we can determine the value of W_i at U_{bias} = 2 V from formula (7). After performing these calculations, you can see that at U_{bias} = 2 V the value of W_i+$L_n \approx 233$ μm.

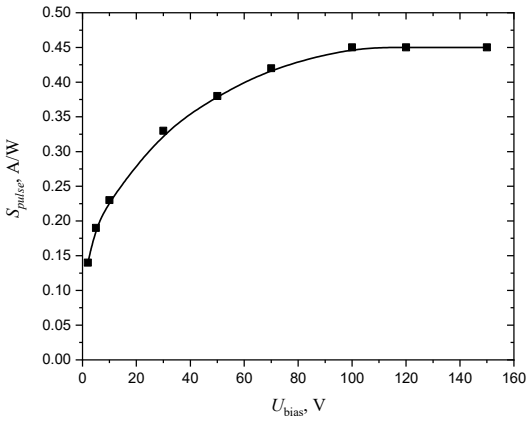

Figure 4. Dependence of the responsivity of the PD on the bias voltage.

Knowing these parameters, you can determine the radiation intensity that will be absorbed in this layer:

$$I_3 = I_2 e^{-\alpha(W_i+L_n)}. \tag{8}$$

Next, it is necessary to determine how much radiation intensity will be emitted in the «inactive» high-resistance region:

$$I_4 = I_3 e^{-\alpha\left(X-(W_i+L_n+x_{n+-p}+x_{p+-p})\right)}. \tag{9}$$

Next, it is necessary to determine how much the radiation flux will be attenuated after passing through the p^+-layer and the adhesive sublayer of chromium. Figure 3 shows that the presence of a p^+-layer on the surface of a silicon substrate with a R_S = 18 kΩ/□ decreases the transmittance by 4 %. Therefore, by analogy with the n^+-layer, it is necessary to subtract the following 4% from the radiation intensity found by the Bouguer's law. Also, in [10], we found that a 10 nm thick chromium film absorbs 4% ($T_{Cr} \approx 96\%$) of the radiation of the operating wavelength. Accordingly, the radiation intensity after passing through these layers will be:

$$I_5 = 0.96 \cdot T_{Cr} I_4 e^{-\alpha \cdot x_{p+-p}}. \tag{10}$$

The intensity of the radiation after reflection from the gold layer and passing through the adhesive layer of chromium and the p^+-layer will gain value:

$$I_6 = 0.96 \cdot T_{Cr} R_{Au} I_5 e^{-\alpha \cdot x_{p+-p}}, \tag{11}$$

were R_{Au} is reflection coefficient of gold at λ_{op} is R_{Au} = 98.3% [16].

The intensity of radiation after passing through the «inactive» *i*-region after reflection from gold will reach:

$$I_7 = I_6 e^{-\alpha\left(X-(W_i+L_n+x_{n+-p}+x_{p+-p})\right)}. \tag{12}$$

The radiation intensity absorbed in the crystal layer W_i+L_n after reflection from the gold will reach:

$$I_8 = I_7 e^{-\alpha(W_i+L_n)}. \tag{13}$$

The collection coefficient of minority charge carriers will be determined by the formula [17]:

$$\gamma = 1 - e^{-\alpha x}. \tag{14}$$

Taking into account the change in radiation intensity, this formula will take the form:

$$\gamma_1 = I_3\left(1 - e^{-\alpha(W_i+L_n)}\right) \approx 0.106, \tag{15}$$

where γ_1 is coefficient of collection of minority charge carriers at the first passage through the crystal thickness.

$$\gamma_2 = I_8\left(1 - e^{-\alpha(W_i+L_n)}\right) \approx 0.042, \tag{16}$$

where γ_2 is coefficient of collection of minority charge carriers at the second passage through the crystal thickness.

The responsivity was determined using the formula [18]:

$$S_\lambda = (1-R)TQ\sum\gamma\frac{\lambda_{op}}{1.24} \approx 0.12\ A/W, \tag{17}$$

where T is the transmission coefficient of the input window or optical filter (consider that T = 100%); Q is the quantum output of the internal photoeffect (consider that Q = 1).

RESULTS OF THE RESEARCH AND THEIR DISCUSSION

The value of responsivity obtained by the calculated method correlates well with the experimental one, which reached S_{pulse} = 0.12-0.14 A/W.

As can be seen from the calculations, the charge carrier collection coefficient provided by the reflected radiation from the gold "mirror" is about 40 % of the collection coefficient provided by the first passage of radiation through the photodiode crystal or 28 % of the total collection coefficient. The decrease in this parameter is caused by the absorption of radiation by the semiconductor thickness, p^+-layer, and chromium sublayer. It is possible to increase the collection coefficient by increasing the resistivity of the material, which will increase the W_i, and by increasing the L_n. This will ensure the expansion of the collection area of the charge carriers. To ensure the maximum values of these parameters, it is necessary to use silicon with high resistivity and lifetime of minority charge carriers and to use a technology that ensures minimal degradation of these characteristics during the production process, for example, it can be a mesa-technology [6, 7].

An effective method of γ of low-voltage PDs is to reduce the crystal thickness to minimize the area of the semiconductor in which there is no "charge carrier collection". In this case, the ideal PD is a crystal variant in which the W_i+L_n region covers the entire high-resistance region of the substrate. Such a case is provided in high-voltage photodiodes, but to realize it in low-voltage PDs, it is necessary to reduce the crystal thickness.

Thus, if we calculate the collection coefficient according to the methodology given in the previous section with the same initial data, but assuming that the crystal thickness is less by the value of:

$$X_1 = X - \left(W_i + L_n + x_{n+-p} + x_{p+-p}\right), \tag{18}$$

where X_1 is the thickness of the crystal region in which there is no charge carrier collection, $X_1 \approx 257$ μm.

We obtain that $\gamma_2 \approx 0.07$, which is about 66 % of the collection coefficient provided by the first passage of radiation through the photodiode crystal or 40 % of the total collection coefficient. With the obtained value of the collection coefficient, it will be possible to increase the responsivity of the product by about 16% and obtain S_λ = 0.14 A/W. In practice, a significant reduction in the substrate thickness is a difficult technological task due to the reduced mechanical strength of the wafers. However, it is possible by forming thinnings on the back side of the crystal by chemical-dynamic polishing [19] in a shape that corresponds to the responsive element, provided that the proper thickness of the crystal periphery is ensured, which will play the role of stiffeners [20]. The described thinning on the back side of the substrate can be seen in Figure 5.

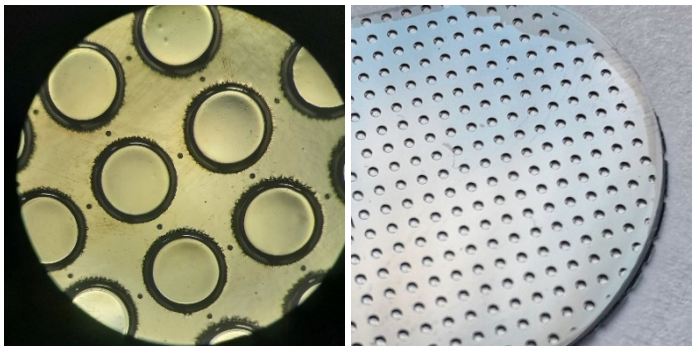

Figure 5. Etched thinning on the back side of the substrate

It should be noted that according to Figure 1, the transmittance of the substrates at different phosphorus concentrations differs, which may affect the final value of the collection coefficient and responsivity. Let's calculate these parameters according to the above methodology with the specified initial data, taking into account only the change in the transmittance of the n^+- layer (Table 1).

Table 1. Calculations of the collection coefficient of minority charge carriers and responsivity at different phosphorus concentrations in the n^+-layer

R_S, Ω/□	T_{n+}, %	∑γ, abs.	S_λ, A/W	S_λ, A/W (U_{bias}=120 V), exp.
8.1	45	0.16	0.13	0.42-0.43
5.0	37	0.152	0.124	0.42-0.44
3.3	34	0.151	0.122	0.45-0.47
3.0	33	0.149	0.121	0.46-0.47
2.7	32	0.148	0.12	0.46-0.47
2.4	31	0.147	0.119	0.4-0.41
2.1	31	0.147	0.119	0.38-0.4

As can be seen from Table 1, with increasing phosphorus concentration in the n^+-layer, the transmittance of this region decreases. When the surface resistance value R_S = 3.3 Ω/□ is reached, the transmittance changes minimally and at R_S = 2.4 Ω/□ it does not decrease anymore. The same pattern was observed with the collection coefficient and

responsivity. From the calculations, we can see that the lowest value of R_S corresponds to the highest value of responsivity. But in practice, the situation is quite different. We measured the S_{pulse} at U_{bias} = 120 V at different R_S (Table 1, 5 column). We obtained the value of high-voltage responsivity to be able to estimate of this parameter in saturation, since at low voltages the responsivity may differ minimally.

As can be seen from the experimental data, there is no correlation between them and the calculations for the dependence of responsivity on phosphorus concentration, which is caused by the different degree of substrate gettering during phosphorus diffusion, respectively, at different duration of gettering, the diffusion length of minority charge carriers and resistivity differed, which was reflected in the responsivity values. The decrease in responsivity at R_S = 2.1-2.4 Ω/□ is caused by the formation of structural defects, in particular dislocations due to high phosphorus concentration, which in turn can reduce of the diffusion length of charge carriers due to their recombination on crystallographic defects (provided they are placed in the space charge region) [21]. Accordingly, in the methodology for calculating the collection coefficient, it is necessary to provide other initial data of the capacitance, resistivity, and diffusion length of minority charge carriers, which are characteristic of each case, since they completely depend on the degree of gettering. The absence of correlation between the calculations and the experiment is caused by the difference in these initial data

The same situation was observed in the case of the p^+-layer, since, as can be seen from the Figure 2, with a decrease in the boron concentration in the p-layer, the transmittance of this layer increases, which should ensure an increase in the collection coefficient. However, in practice, with a decrease in boron concentration, a decrease in responsivity was observed due to a decrease in the degree of boron gettering on the back side of the substrate [13].

CONCLUSIONS

The influence of technological factors on the collection coefficient of minority charge carriers of silicon *p-i-n* photodiodes is investigated. The following conclusions have been made:

1. The width of the space charge region and the diffusion length of the minority charge carriers have a significant effect on the collection coefficient, since these two parameters form the region in which the photogenerated charge carriers "collect" and will be separated by the p-n junction.
2. The maximum value of the collection coefficient is possible when the thickness of the high-resistance region of the photodiode is equal to the sum of the diffusion length of the minority charge carriers and the width of the space charge region.
3. The degree of doping of the n^+- and p^+-regions affects the value of the collection coefficient, since the transmittance of these regions decreases with increasing concentration. However, it should be noted that with a decrease in the concentration of dopants and a decrease in the duration of diffusion processes, the degree of crystal volume gettering decreases, which negatively affects the diffusion length of minority charge carriers and the resistivity of silicon (the width of the space charge region).
4. With an increase in the phosphorus concentration and with an increase in the duration of the gettering, there is a slight decrease in the responsivity and, accordingly, the collection coefficient due to the formation of structural defects on the surface of the substrate, which results in the recombination of photogenerated charge carriers on crystallographic defects. The optimum value of the surface resistance of the n-layer after phosphorus diffusion to ensure the maximum collection coefficient and responsivity is R_S = 2.7-3.0 Ω/□.

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ДОСЛІДЖЕННЯ КОЕФІЦІЄНТА ЗБИРАННЯ НОСІЇВ ЗАРЯДУ КРЕМНІЄВИХ *p-i-n* ФОТОДІОДІВ†

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В статті досліджено коефіцієнт збирання неосновних носіїв заряду кремнієвих *p-i-n* фотодіодів та вплив на нього окремих технологіних чинників. Встановлено, що значний вплив на значення коефіцієнта збирання має дифузійна довжина неосновних носіїв заряду та питомий опір матеріалу, оскільки при збільшенні даних параметрів зростає область збирання фотогенерованих носіїв заряду. Також встановлено, що ефективним методом підвищення коефіцієнта збирання фотодіодів є забезпечення товщини високоомної області фотодіода рівною сумі дифузійної довжини неосновних носіїв заряду та ширини області просторового заряду. Досліджено вплив концентрації легуючих домішок на значення чутливості та коефіцієнта збирання. Встановлено, що на відміну від розрахункових даних, в яких коефіцієнт збирання зростає при зниженні концентрації фосфору та бору, в експериментальних даних, при зниженні концентрації домішок, чутливість, а відповідно і коефіцієнт збирання зменшуються внаслідок зниження міри гетерування та, як наслідок, зниження ширини області просторового заряду та дифузійної довжини неосновних носіїв заряду.

Ключові слова: *кремній; фотодіод; чутливість; коефіцієнт збирання носіїв заряду; бар'єрна ємність*