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Vasyl Stefanyk Precarpathian National University

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M.S. Kukurudziak[1,2]

Influence of Surface Resistance of Silicon *p-i-n* Photodiodes n^+-Layer on their Electrical Parameters

[1]*Rhythm Optoelectronics Shareholding Company, Chernivtsi, Ukraine,* mykola.kukurudzyak@gmail.com
[2]*Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine,*

Silicon quadrant *p-i-n* photodiodes of different concentrations of diffused phosphorus in the n^+- layer were fabricated. The experimental curve of phosphorus impurity distribution along the depth of the diffusion layer is obtained. The influence of charge carrier concentration in this layer on the dark currents of responsive elements and the guard ring was studied. Volt-ampere characteristics of photodiodes were measured. It was seen that when the surface resistance of the n^+-layer decreases, the dark currents decrease, the samples with a surface resistance of 1.9 – 2.4 Ω/□ have approximately the same level of dark currents of responsive areas, i.e. further increase in charge carrier concentration makes no change. As to dark currents of photodiode guard rings, it was found that for the most part they depend on the state of the periphery of the crystal (outside the guard ring) but not on the level of doping. The influence of the surface resistance of the n^+-layer on interconnection resistance between the responsive areas and the protective ring, and no influence on the capacitance of the photodiodes were revealed.

Key words: photodiode, surface resistance, dark current, guard ring.

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Introduction

Along with the technical development of optoelectronic devices and systems, the requirements for parameters of their structural elements, photodetector preamplifier modules (PPM), in particular, are increasing. Silicon *p-i-n* photodiodes (PD) are widely used. They are employed for both civilian and military purposes: to measure distances (rangefinders) in geodesy or construction, in missile technology, etc.

In modern production PD are made by diffusion-planar technology [1], diffusion being the determining operation. It is the diffusion on the surface of silicon wafers that forms responsive elements (RE). When creating RE, the task arises to introduce such a concentration of dopant, which would provide a high level of responsivity at minimum values of dark currents. After all, when doping the surface n^+-layer of the substrate, its absorption coefficient increases, which is a negative phenomenon, because in the manufacture of PD you need to ensure maximum absorption of radiation in the high-impedance p-region of the substrate. Therefore, determining optimal concentration of the dopant, which would make low dark currents (and other electrical parameters) available with minimal loss of responsivity, is an urgent scientific and technical task.

A review of this problem in scientific sources has shown that the effect of the concentration of phosphorus dopant on *p-i-n* PD parameters has not been studied, and most of scientific papers are devoted to the study of silicon solar cells. Thus, in [2] causes and mechanisms of surface influence on the inverse characteristics of *p-n* structures are considered. A review of technological methods of structures of semiconductor devices treatment, including methods of gettering to prevent influence of surface effects on electric parameters of devices, was made. In [3] mechanisms of dark current formation in *p-i-n* PD and the guard ring (GR) principle of operation are considered. The influence of voltage across the guard ring on the dark current of the RE at different modes of operation of the guard ring has been studied. However, detailed data on the effect of doping on PD characteristics cannot be found in literature on the subject.

Based on the above, the purpose of this article is to study the effect of phosphorus concentration in the n^+-layer of silicon *p-i-n* PD on their electrical parameters, dark currents, in particular.

I. Experiment details

The investigation was performed on silicon four-element *p-i-n* PDs with a GR (Fig. 1, 2) with operating supply voltage $U_{op} = 120$ V and wavelength $\lambda_{op} = 1.064$ µm.

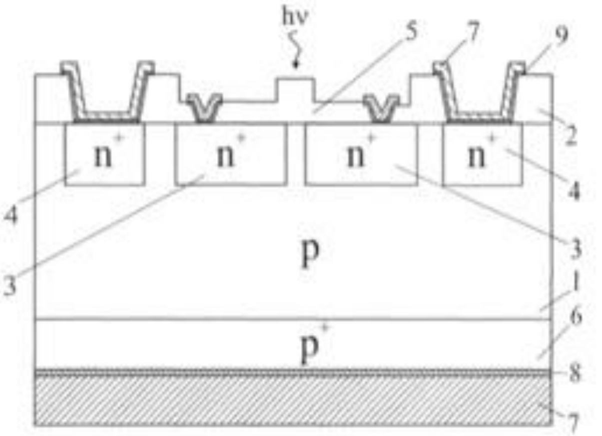


Fig.1. Cross section of a four-segment photodiode crystal: 1 – *i*-region; 2 – masking SiO_2 layer; 3 – responsive areas; 4 – guard ring; 5 – anti-reflecting SiO_2 layer; 6 – area, getterated by boron; 7 – layer of gold; 8, 9 – sublayer of chromium on the reverse and front side, respectively.

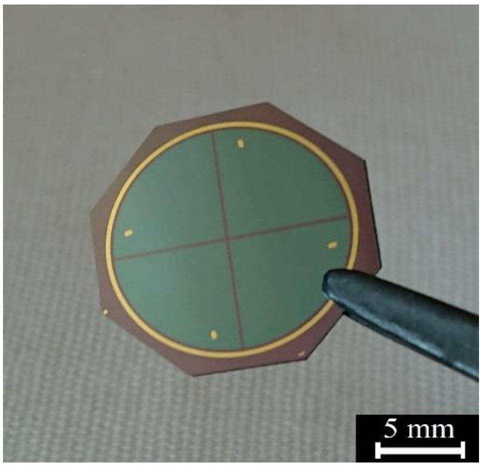


Fig. 2. Photodiode crystal.

Thermal processes, diffusion, in particular, were carried out using a diffusion system such as SDO-125/3 - 12.

Control of dark currents I_d was performed at $U_{bias} = 120$ V. Next, the current density J_d in nA/cm² will be indicated, which is calculated by formula (1).

$$J_d = \frac{I_d}{A_{RE}} \qquad (1)$$

where A_{RE} is the effective area of the RE.

Surface resistance (R_S) was measured by the four-probe method [4].

II. Experimental

Single-crystalline *p*-type silicon with a specific resistance of $\rho \approx 18$ kOhm·cm is used in the production, which corresponds to the concentration of the impurity $N_b \approx 7{,}7 \cdot 10^{11}$. PDs were manufactured by diffusion-planar technology using two-stage diffusion to make responsive elements and a guard ring of n^+-type conductivity. Initially, predeposition was carried out – it’s a short diffusion from an unlimited source at $T = 1353$ K in a nitrogen atmosphere, and a thin diffusion layer in the substrate was obtained. Next, drive-in was performed at $T = 1423$ K in an oxygen atmosphere, while the diffusion layer was a source with a limited amount of impurities. After each of these operations, R_S control was performed. By changing the predeposition time, different values of R_S were obtained. The drive-in duration was always the same for growing the like antireflecting coating and obtaining the same depth of the *p-n* junction in each PD series.

All the results were obtained in commercial production of photodiodes. But for the purity of the experiment and no influence of various factors, an experimental batch was conducted in which all wafers were oxidized in a single process, further the series was divided into subseries, and phosphorus was predeposited with different durations, followed by a single drive-in and diffusion of boron.

For convenience, the description of the investigation will indicate the surface resistance of the obtained samples, because this parameter is most often used in practice. The R_S values of the obtained samples are shown in Table 1.

Table 1

The value of the surface resistance of the obtained FD at different predeposition durations.

t [s] – predeposition duration	R_S [Ω/□] – after the predeposition	R_S [Ω/□] – after the drive-in
300	12.7	8.1
600	8.4	5.0
1200	5.4	3.3
1800	4.1	2.7
2400	3.7	2.4
3000	3.3	2.2
3600	3.1	1.9

But often in the manufacture and research of electronic devices with *p-n*-junctions, there is a need to predetermine the depth of the heterojunction (in this case, the n^+-*p*-junction x_{n+-p}) and the distribution of the concentration of impurities to obtain the given values ($N_{x,t}$). These parameters can be determined both by the calculation method and experimentally on control samples. Thus, x_{n+-p} after predeposition, according to [5], can be estimated by formula (2):

$$x_{n+-p} = 5{,}4\sqrt{D_1 t_1} \qquad (2)$$

where D_1 is the diffusion coefficient at T=1323 K,

$D_1=2\cdot10^{-13}$ cm^2/s [6]; t_1 – duration of predeposition.

The depth of the heterojunction was also determined experimentally by the oblique section method [7]. The experimental and calculated graphs of the dependence of x_{n+-p} on the duration of predeposition are shown in Fig. 3.

As we can see from Fig. 3 experimental values are well verified with theoretical ones with some deviation.

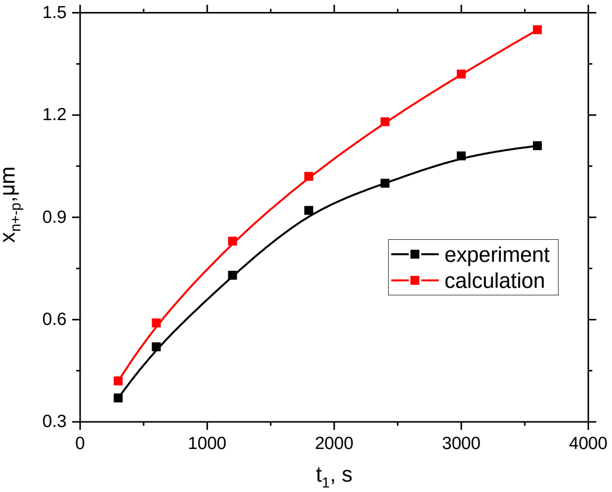


Fig. 3. Experimental and calculated graphs of the dependence of the depth of the heterojunction on the duration of the predeposition.

The surface concentration of introduced impurities (N_0) can be determined from the conductivity formula of an *n*-type semiconductor (3) [8], expressing electrical conductivity in terms of resistivity:

$$\sigma = \frac{1}{\rho} = en\mu_n \qquad (3)$$

where σ – electrical conductivity of a semiconductor; ρ – resistivity; e – the charge of an electron; n – electron concentration; μ_n – mobility of electrons.

Assuming that all introduced phosphorus impurities are ionized and $N_0=n$, we obtain for the surface concentration:

$$N_0 = \frac{1}{e\rho\mu_n} \qquad (4)$$

Accordingly, to determine N_0, need to know ρ after phosphorus predeposition, which can be determined from the formula [8]:

$$R_S = \frac{\rho}{x_{n+-p}} \qquad (5)$$

The results of the calculation of the surface concentration and specific resistance and their dependence on the surface resistance are shown in Fig. 4.

Knowing the surface concentration of Phosphorus after distillation, it is possible to determine the distribution of the impurity concentration along the depth of the *p-n* junction $N_{x,t}$ according to the formula [5]:

$$N_{x,t} = N_0 erfc\frac{x}{2\sqrt{D_1 t_1}} \qquad (6)$$

where *erfc (x)* is an additional error function.

This characteristic of the heterojunction in two-stage diffusion serves only to assess the uniformity of a limited diffusant source. We will calculate for one version of the duration of diffusion, for example, at t_1=2400 s. The results of the calculation of the distribution of impurities after predeposition are shown in Fig. 5.

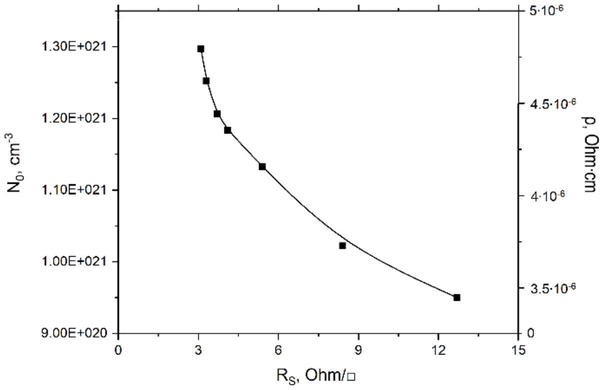


Fig. 4. Dependence of surface concentration and specific resistance on surface resistance.

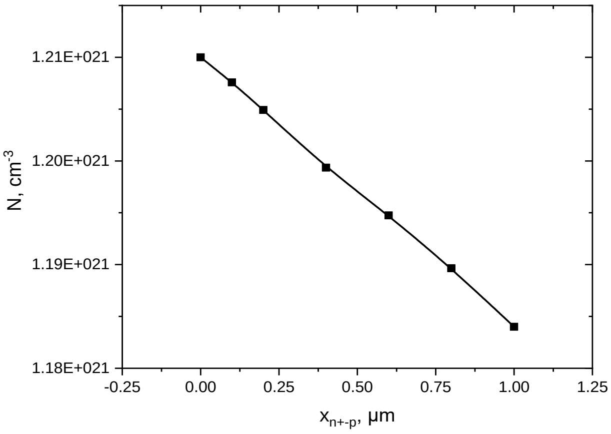


Fig. 5. Calculated graph of distribution of phosphorus after predeposition with a duration of t_1=2400 s.

Far more important parameters of the *p-n* junction of photodiodes are the final depth of the heterojunction and the final distribution of the impurity concentration in the n^{+}-layer. Note that after the phosphorus drive-in, diffusion of boron to the rear side of the crystal is carried out at T=1223 K. But during our study of x_{n+-p} changes before and after the last thermal operation, no increase in the depth of the p-n junction was observed, since:

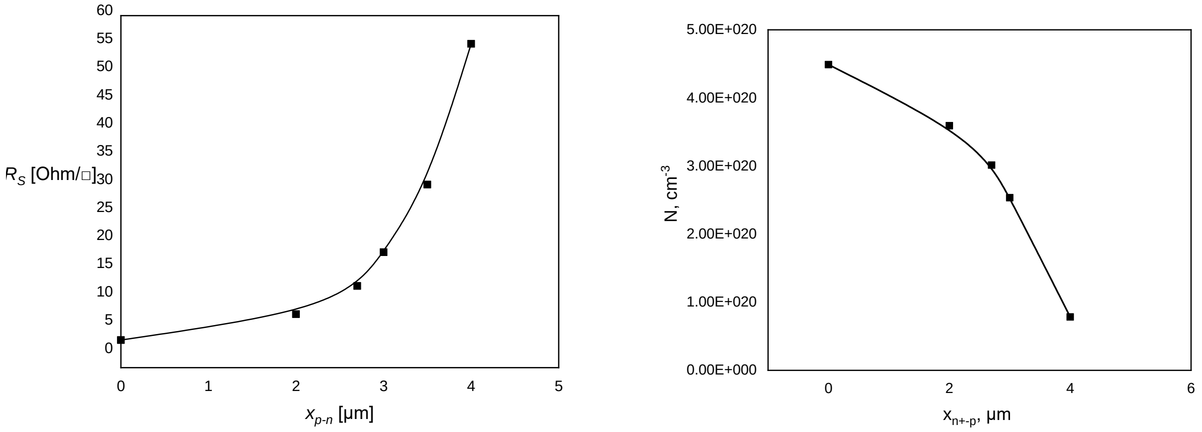
$$D_3 t_3 \ll D_2 t_2 \qquad (7)$$

where D_2 – phosphorus diffusion coefficient at T=1423 K, $D_2=10^{-12}$ cm^2/s [6]; t_2 – duration of phosphorus drive in, t_2=5100 c; D_3 – phosphorus diffusion coefficient at T=1223 K; t_3 – duration of boron diffusion.

Accordingly, the ultimate depth ($\boldsymbol{x'_{n+-p}}$), in this case, is formed by the phosphorus drive-in. This parameter can be estimated by the formula [5]:

$$x'_{n+-p} = 2\sqrt{D_1 t_1}\cdot\sqrt{ln\frac{Q}{N_b\sqrt{\pi D_2 t_2}}} \qquad (8)$$

where Q – doping dose (amount of impurity entering



a) b)

Fig.7. Experimental curves of phosphorus impurity distribution in the depth of the diffusion layer after the drive in: a) dependence of $R_S(x'_{n+-p})$; b) dependence of $N`(x'_{n+-p})$.

silicon during predeposition).

Doping dose can be determined from equation (9) [5]:

$$Q = 2N_0\left(\frac{D_1 t_1}{\pi}\right)^{1/2} \qquad (9)$$

A calculated graph of the dependence of x'_{n+-p} on the duration of predeposition according to (8) was obtained, and for comparison, the same graph was obtained experimentally (Fig. 6). From the figure, you can see the poor verification of calculated and experimental data. The first reason is the slow cooling of the plates after the drive-in, which increases the depth of the heterojunction, and this is not taken into account in (8). Also, a possible reason for the discrepancy is the empirical origin of some equations used to calculate diffusion processes, which were obtained for low-resistance silicon.

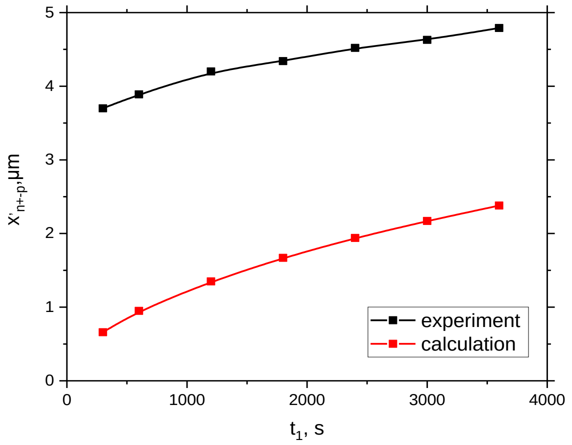


Fig. 6. Experimental and calculated graphs of the dependence of the depth of the heterojunction after the drive-in on the duration of predeposition.

As regards the concentration of impurities, it decreases with increasing depth of the diffusion layer. The distribution of impurities concentration in the depth of heterojunction ($N`_{x,t}$) in two-stage diffusion can be determined by formula [5]:

$$N'_{x,t} = \frac{2C_0}{\sqrt{\pi}}\sqrt{\frac{D_1 t_1}{D_2 t_2}}\exp\left(\frac{x^2}{4D_2 t_2}\right) \qquad (10)$$

It should be noted that there are some difficulties when calculating the distribution of impurity concentrations in our case. After all, when impurities are added to already doped silicon, the values of diffusion coefficients deviate from the constant value corresponding to the process temperature. Therefore, the value of the dependence $N`_{x,t}$ obtained experimentally.

To assess the distribution of impurities in the depth of the diffusion layer, the semiconductor substrate after diffusion of phosphorus *with* $R_S \approx 2.4$ Ω/□ was etched layer by layer in a slow etchant (HNO_3: HF: CH_3COOH= = 20: 1: 1) by chemodynamic polishing and surface resistance after each etching was measured. The results of the experiment are shown in Fig. 7.

From Fig. 2, as in formula (2), we can see the exponential dependence of the distribution of phosphorus in the depth of the diffusion layer. If the surface resistance was 2.4 Ω/□ ($4.5 \cdot 10^{20}$ cm^{-3}), then at x'_{n+-p}= 4 µm - $R_S \approx 55$ Ω/□ ($7.8 \cdot 10^{19}$ cm^{-3}).

III. Discussion and results

3.1. RE dark currents

Dark currents of responsive elements and guard rings were measured at two stages of production: a finished photoresponsive crystal and a finished PD. I_d values of PD responsive elements are about 10% higher than those of crystals. As for the guard rings, the level of their dark currents I_{GR} after welding the contact leads and hermetic sealing increased approximately twice as compared to the values of photoresponsive crystals. This can be explained by the influence of contact phenomena, measurement errors, or growth of the surface component of the dark current in the production process.

The results of measuring the I_d of photoresponsive crystals are presented in Table 2. To show a clear picture of dark currents figure of merit straggling on the responsive areas, I_d of the characteristic samples from each subseries is given.

As can be seen from Table 2, with increasing surface resistance (decreasing concentration), the dark currents of the RE increase. It can also be seen that samples with R_S = 1.9 – 2.4 Ohm/□ have approximately the same level of dark currents, i.e., a further increase in the concentration of charge carriers does not make any changes. Accordingly, to increase the duration of diffusion to further reduce I_d does not make sense. Decrease in dark current with increasing concentration of phosphorous may be explained by gattering of metal impurities and structure defects in the bulk of the samples. As the gettering effect increases with phosphorous concentration growth. It is known [9], that there is some maximum value R_S for the specified temperature the elevated value of wich will make the gattering inefficient. In this case, this is the value of R_S = 2.4 Ω /□.

Table 2.

Values of dark currents of photoresponsive crystals at different surface resistance (dark current density J_d will be indicated).

R_S [Ω/□] – after drive-in	J_d [nA/cm^2]				I_{GR}, μA/cm^2 – crystal
1.9 – 2.4	70.1	64.9	70.1	72.7	3.9
	77.9	77.9	75.3	75.3	4.0
	70.1	80.5	72.7	70.1	3.0
	67.5	64.9	64.9	62.3	2.3
	83.1	77.9	83.1	77.9	2.6
2.7	77.9	77.9	72.7	75.3	4.4
	85.7	83.1	75.3	90.9	3.8
	93.5	88.3	85.7	80.5	2.5
	72.7	90.9	80.5	83.1	2.7
	77.9	75.3	80.5	77.9	3.4
3.3	140.3	140.3	119.5	244.2	5.2
	174.0	93.5	132.5	127.3	3.0
	88.3	93.5	109.1	119.5	4.7
	200.0	142.9	124.7	98.7	3.8
	106.5	171.4	114.3	90.9	5.1
5.0	509.1	368.8	381.8	571.4	9.2
	335.1	368.8	322.1	296.1	6.6
	488.3	444,2	384,4	376,6	6.0
	293.5	290,9	355,8	280,5	4.7
	428.6	467,5	646,8	506,5	6.5
8.1	1298.7	1236.4	1485.7	1797.4	8.5
	963.6	1150.6	1007.8	859.7	5.3
	1207.8	974.0	898.7	1051.9	4.2
	1251.9	1041.6	1031.2	1324.7	5.5
	932.5	1176.6	1142.9	1246.8	5.2

It should be noted that with the increase of R_S, scatter of dark currents absolute values across the responsive areas increases, but the characteristic difference for all PD sub-batches of in percentage was about 10-20% relative to the average one. Note that twice scatter across PD responsive areas was considered a defect. Accordingly, it was seen that with decreasing levels of dark currents the percentage of defective products as to the criterion, increased.

In this case, as regards GR dark currents, the increase in I_{GR} with R_S rising is much smaller. So, when R_S changed from 1.9 – 2.4 Ω/□ to 8.1 Ω/□, I_d increased approximately 10-20 times, and I_{GR} doubled. This is due to the fact that PD GR dark current depends more on the state of the periphery of the crystal (charge states at Si-SiO$_2$ interface or the presence of defects in this region of the crystal), rather than the level of doping.

The volt-ampere characteristics (I–V) of back-biased PDs with different surface resistance (Fig. 8) have been studied, from which it can be seen that at U_{bias} = 60-80 V dark currents reach saturation. The curves for R_S = 1.9 – 2.4 Ω/□ actually coincide, and the curve for R_S = 2.7 Ω/□ is shifted by units of nanometers up the y-axis.

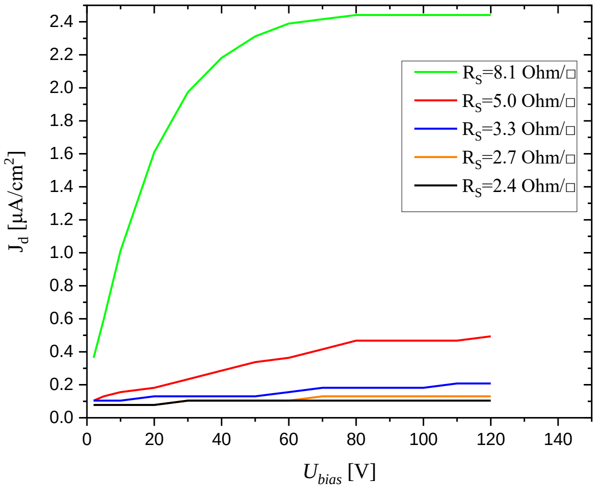


Fig.8. PD responsive elements I – V characteristics versus R_S.

It should be noted that the curves for R_S = 1.9 – 2.7 Ohm/□ have a minimal increase in dark currents with increasing U_{bias}.This indicates that with increasing electric field strength, mobility of charge carriers in heavily doped semiconductor layers increases to a lesser extent, which does not give rise to a significant growth in dark current. Other curves are characterized by a greater increment in dark current with increasing bias voltage. Thus, for samples with R_S=1.9 – 2.7 Ω /□ $I_{d,2V}$=77.9 nA/cm^2, $I_{d,120V}$=103.9 nA/cm^2, and for R_S=8.1 Ω/□ - $I_{d,2V}$=363.6 nA/cm^2, $I_{d,120V}$=2441.6 nA/cm^2.

3.2. GR dark currents

I – V characteristics of PD guard rings depending on R_S, randomly selected from each subseries, were also obtained, (Fig. 9). It can be seen from the figure that there is no increase in I_{GR} levels for GR with increasing R_S, and there is no pattern as in the case of RE. This confirms the fact that the dark current of the PD guard ring of the PD depends more on the state of the periphery of the crystal, than on the level of doping.

It can be seen from the figure that the GR I – V curves do not reach saturation in the range of studied voltages with increasing bias, and with further increase of the bias I_{GR} will grow to some maximum value. It is caused by increase in the space-charge region (SCR) of the guard ring with voltage growth toward the periphery of the crystal (Fig. 10). After all, the GR SCR is limited by the space charge region of the responsive element and the back side of the substrate (Fig. 10). Thus, if the thickness of the crystal is 420-470 μm, then at $U_{op} = 120$ V, according to [10], the width of the W_i reaches about 490 μm, which can be calculated by the formula:

$$W_i = \left(\frac{2\varepsilon\varepsilon_0\,(\phi_k - U_{op})}{eN_A}\right)^{\frac{1}{2}} \tag{11}$$

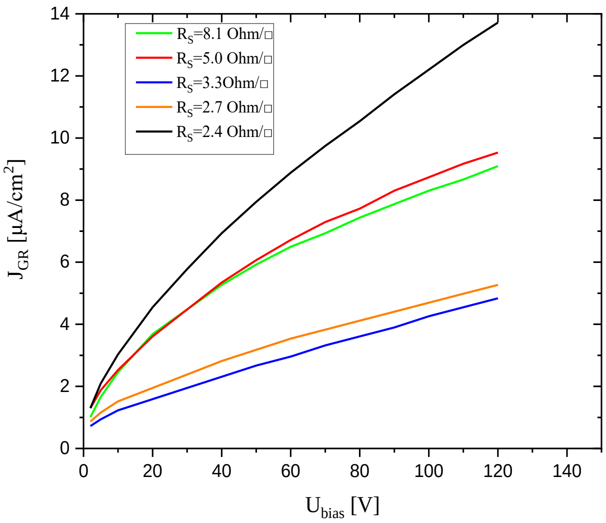


Fig. 9. *I – V* characteristics of PD guard rings at different R_S.

where ε, ε_0 are dielectric constants for silicon and vacuum, respectively; e is electron charge; φ_c is contact potential difference; U_{op} is bias voltage; N_A is impurity concentration in the substrate.

In Fig. 10 guard ring SCR on the periphery side is marked by a dotted line. Upon reaching the space charge region of the back side of the substrate, at a certain value of the bias voltage, the SCR with further growth of U_{bias} will grow towards the periphery, resulting in an increase in I_{GR}.

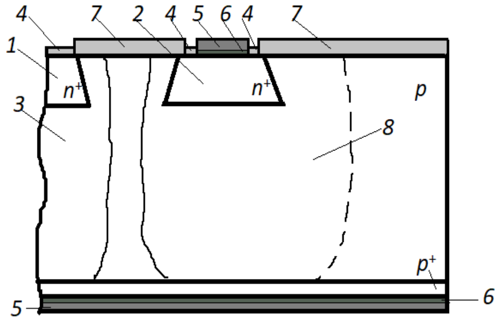


Fig.10. Schematic representation of the cross section of the PD crystal: 1 – RE; 2 - GR; 3 – RE SCR; 4 – SiO_2 antireflecting coating; 5 - a layer of gold; 6 - sublayer of chromium; 7 – masking SiO_2; 8 – GR SCR.

3.3. Dark currents at T = 85˚C, RE capacitance, interconnection resistance

To test the stability of the PD at elevated temperatures, dark currents were measured at $T = 85$˚C. This test is performed to a greater extent to assess I_{GR} at elevated temperatures, namely its stability. After all, sometimes there may be some instability of GR dark current, caused by charge states at Si-SiO_2 interface, which is not observed at room temperature [11]. This instability can be manifested as a slight slow increase in I_{GR} relative to the initial (from the moment of application of voltage) and uncontrolled avalanche-like growth. The results can be seen in Table 3 (2-3 columns).

It is known [12] that with PD temperature increasing by 10˚C, dark currents increase by 2-3 times. This fact is confirmed the values obtained.

Note: The range from the lowest to the highest values is specified.

Table 3.

RE and GR dark currents at $T = 85$˚C, capacitance and resistance of interconnection depending on different surface resistance and $U_{op} = 120$ V (the density of dark current J_d will be specified).

R_S, Ω/□	J_d, μA/cм^2	J_{GR}, μA/cм^2	C_{RE}, pF	$\sum R_{con}$, MΩ
1.9-2.4	18.7-24.7	606.5-866.4	11.9 – 13.4	10
2.7	19.5-34.8	563.2-895.3	12.3 – 13.2	10
3.3	21.0-42.1	462.1-953.1	12.1 – 13.3	10
5.0	56.9-103.9	722.0-1444.0	12.3 – 13.6	5-6.7
8.1	167.5-337.7	599.3-1588.4	12.4 – 13.2	4-5

Note: The range from the lowest to the highest values is specified.

As regards RE capacity (C_{RE}), the dependence on the surface resistance of the n^+-layer is not observed (Table 3, column 4). After all, C_{RE} depends on the applied voltage and RE area [10]:

$$C_{RE} = A_{RE}\left(\frac{\varepsilon\varepsilon_0 eN_A}{2(\phi_k - U_{op})}\right)^{\frac{1}{2}} \tag{12}$$

The resistance of the interconnection between RE and GR (R_{con}) was also measured (Table 3, column 5). In practice, the sum of the interconnection resistances between each photoresponsive area and GR ($\sum R_{con}$) is more often used. This parameter characterizes insulation resistance (SiO_2) and the n^+-type surface inversion channel between the responsive elements and the GR. The resistance of the interconnection must be high (of the order of MOhm). After all, as it is known [3], at back bias the guard ring "collects" the back current not only from its own area but also from the periphery of the crystal, including the ends and a half of the gap between the RE and GR, covered with an inversion layer. Accordingly, at low R_{con} there is a "flow" of dark current from the GR to the responsive areas, resulting in an increase in I_d.

Some dependence of $\sum R_{con}$ on R_S was observed, namely, with surface resistance increasing, the resistance of the interconnection decreases (Table 3, column 5). Given that PD were manufactured in a single technological cycle, then, accordingly, they are characterized by the same level of surface charge states, i.e., their contribution to the magnitude of dark currents is the same. From this we can conclude that $\sum R_{con}$ depends on the levels of dark currents (including I_{GR}) at the same levels of charge states.

Conclusions

Silicon four-element *p-i-n* photodiodes with guard ring of different R_S n^+-layers were obtained. The influence of phosphorus concentration in this layer on electrical parameters was investigated and determined:

1. As R_S decreases, responsive element dark currents decrease.
2. The optimal value of the surface resistance to obtain the minimum dark currents is $R_S \approx 2.4\ \Omega/\square$. With a further increase in the duration of diffusion, a decrease in I_d was not observed.
3. The effect of the surface resistance on the guard rings dark currents is much smaller. Thus, when the R_S changing from 1.9 – 2.4 Ω/□ to 8.1 Ω/□, I_d increased by about 10-20 times, and I_{GR} is doubled.
4. Responsive elements and guard ring I – V characteristics were obtained. However, it was seen that at U_{bias} = 60-80 V responsive elements dark currents reach saturation. With U_{bias} increasing, curves for R_S = 1.9 – 2.7 Ω/□ have a minimal increase in dark currents. The curves for R_S = 1.9 – 2.4 Ω/□ actually coincide.
5. The dependence of the RE capacitance on the surface resistance of the n^+-layer is not observed. After all, C_{RE} depends on the specific resistance of the substrate and the area of the RE only.
6. There is a slight dependence of $\sum R_{con}$ on R_S with surface resistance increasing, the resistance of the interconnection decreases.

Kukurudziak M.S. – engineer-technologist; Rhythm Optoelectronics Shareholding Company, Chernivtsi, Ukraine.

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М. С. Кукурудзяк[1,2]

Вплив поверхневого опору n^+-шару кремнієвих *p-i-n* фотодіодів на їх електричні параметри

[1]*Акціонерне товариство «Центральне конструкторське бюро Ритм» Україна, Чернівці,* mykola.kukurudzyak@gmail.com
[2]*Чернівецький національний університет імені Юрія Федьковича, Чернівці, Україна*

Виготовлено кремнієві квадрантні *p-i-n* фотодіоди з різною концентрацією дифундованого фосфору в n^+-шарі. Отримано експериментальну криву розподілу домішки фосфору по глибині дифузійного шару Вивчено вплив концентрації носіїв заряду в даному шарі на темнові струми фоточутливих елементів та охоронного кільця. Виміряно вольт-амперні характеристики фотодіодів. Побачено, що при зменшенні поверхневого опору n^+-шару, темнові струми зменшуються, зразки з поверхневим опором 1,9 – 2,4 Ω/□ мають приблизно однаковий рівень темнових струмів фоточутливих площадок, тобто подальше збільшення концентрації носіїв заряду не вносить ніяких змін. Для темнових струмів охоронних кілець фотодіодів побачено, що вони більшою мірою залежать від стану периферії кристалу, а не від степені легування. Виявлено вплив поверхневого опору n^+-шару на опір взаємозвязку між фоточутливими площадками та охоронним кільцем та відсутність впливу на ємність ФД.

Ключові слова: фотодіод, поверхневий опір, темновий струм, охоронне кільце, опір взаємозвя’зку.