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EFFECT OF STRUCTURAL DEFECTS ON PARAMETERS OF SILICON FOUR-QUADRANT *p-i-n* PHOTODIODES

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The article examines the influence of structural defects, in particular dislocations, on the electrical and photovoltaic properties of silicon four-quadrant *p-i-n* photodiodes. It was established that growth defects and defects formed during mechanical processing of plates can cross the entire substrate and deteriorate the parameters of photodiodes. This phenomenon is particularly negative due to the placement of defects in the space charge region. In this case, due to the presence of recombination centers in the space charge region, the life time of minor charge carriers decreases and the dark current and responsivity of photodiodes deteriorate. Often, the placement of defects is uneven, which provokes unevenness of parameters on responsive elements. It was also seen that the dislocation lines crossing the responsive elements and the guard ring worsen the insulation resistance of the specified active elements. A method of determining the final resistivity of silicon and the diffusion length of minor charge carriers by studying the pulse shape of the output signal is proposed.
Keywords: *Silicon; Photodiode; Point Defects; Dislocations; Dark Current; Sensitivity*
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Due to the dominance of silicon as the main electronics material, the issue of defect formation in single-crystal Si and the influence of structural defects on the parameters of electronics elements made on its basis is still open.

There are two possible approaches to the problem of the influence of crystallographic defects on the electrical properties of materials and devices. The first is to study the interaction of defects and impurities interacting with them and with each other on the charge transfer properties in a semiconductor. The second approach is to study the influence of impurities and defects on the performance of devices. The use of the second, more direct approach is an obligatory stage in the development of the so-called "defect-free" technology for manufacturing devices [1]. It is the second approach that will be the basis for this article.

It is known [2-4] that in the process of growing and processing, various crystallographic defects often occur in silicon wafers, the presence of which can have a significant impact on electrical phenomena in devices manufactured on the basis of such material. There are many so-called "gettering" methods that can reduce the harmful effects of crystallographic defects in silicon. These methods include the technology for obtaining defect-free material [5-7], the production of defect-free devices [8, 9], the "deactivation" of electrically active defects [10], and the structural use of defects deliberately introduced into certain areas of crystals [11], etc.

Despite the considerable number of works devoted to the influence of structural defects on the electrical properties of electronics elements in various fields of microelectronics, this problem remains relevant due to the wide variety of devices whose parameters can be affected by defects in different ways. Thus, in this work, we investigated the effect of dislocations on the electrical and photoelectric properties of four-quadrant silicon *p-i-n* photodiodes (PD). It should be noted that in [12] and [13] we investigated the mechanisms of defect formation on the surface of silicon wafers during the diffusion of phosphorus from planar solid-state sources and the liquid-phase diffuser PCl_3, and the effect of these defects on the dark currents of *p-i-n* photodiodes; in [14] we proposed a method for reducing the density of dislocations on the surface of photodiode responsive elements (RE). In [15], we also describe the effect of the chemical dynamic polishing on the structural perfection of the surface of silicon wafers and [16] indicates possible causes of the formation of point defects in the package during oxidation, the clusters of which can be the centres of generation of dislocation loops during subsequent thermal operations. However, in this work, we will not discuss the mechanisms of defect formation, but will focus on the effect of growth and acquired defects (in particular, dislocations) on the responsivity of the PD (S_{pulse}) (in particular, responsivity spread), the insulation resistance between the RE and guard ring (GR) (R_{con}), the dark currents of the RE (I_d) and their spread, the barrier capacity of the RE (C_{RE}), etc. The study of the effect of dislocations on the PD parameters is the purpose of this article. The information provided on the nature of the influence of these structural defects on certain parameters may be useful to specialists and technologists in the field of *p-i-n* photodiodes to determine the causes of degradation of certain parameters or failure of devices.

EXPERIMENTAL

The research was carried out in the manufacture of silicon 4Q *p-i-n* PDs with GR for operation at wavelength λ_{op} = 1.064 μm. PDs were made on the basis of single-crystal *p*-type silicon with resistivity $\rho \approx$ 18-22 kΩ·cm and [111]

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orientation. The samples were made by diffusion-planar technology according to the technological regimes given in [12]. The thickness of the crystals reached 500-510 μm.

During the serial production of photodiodes, it was found that dislocation lines and grids appear in certain areas of the used wafers (most often on the periphery), which can be seen with the naked eye and without selective etching (Fig. 1). These formations are not observed on the surface of the wafers before thermal operations, but become apparent after thermal operations. The resulting dislocation complexes are characterized by uneven distribution and localization (increased density in certain areas of the wafer). There may be several reasons for the formation of the indicated structural defects. The first is the relaxation of mechanical stresses in silicon during heat treatment. These stresses could be formed during ingot growth or machining. The other is the accumulation of point structural defects and microdefects, which are zones of dislocation loop generation during thermal operations [1, 17].

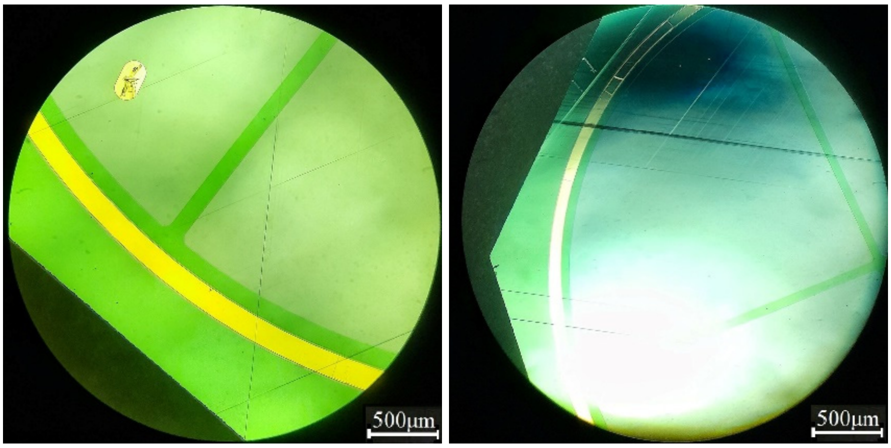


Figure. 1. Image of dislocation lines on the photodiode surface before selective etching

The crystals with the described surface formations had deteriorated parameters. A number of such crystals from different series were selected for the study.

The *I–V* characteristics of PDs were measured using a hardware-software complex implemented on the basis of the Arduino platform, an Agilent 34410A digital multimeter and a Siglent SPD3303X programmable power source, which were controlled by a personal computer using software created by the authors in the LabView environment.

Determination of R_{con} and was carried out according to the method shown in [18].

Monitoring of current monochromatic pulse responsitivity was carried out by method of comparing responsitivity 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 $1\cdot10^{-3}$ W; load resistance across the responsive element R_l= 10 kΩ,

To investigate the defective structure of the substrates chemical treatment was performed in selective Sirtle`s etchant [19] with the following composition: HF – 100 cm^3, CrO_3 – 50 g, H_2O – 120 cm^3. Then the surface was examined in microscopes of different magnifications.

RESULTS OF THE RESEARCH AND THEIR DISCUSSION

A) Influence of dislocations on the dark currents of photodiodes

The volt-ampere characteristics of each RE of the studied photodiodes were obtained (Fig. 2). For comparison, the *I-V* characteristics of one serial standard sample are given (PD_6).

As can be seen from Figure 2, the studied photodiodes had a significant variation in the dark currents of the RE. To determine the causes of the I_d unevenness, the PD crystals were processed in a Sirtle selective etchant (Fig. 3).

As can be seen from Figure 3, the photoiodines with a scatter of dark currents had an uneven density of dislocations on the surface of RE. In PD_1 and PD_2, in the areas of increased defectivity, the density of dislocations reached $N_{dis} \approx 10^{11}$-10^{13}cm^{-2} (Fig. 4a). In PD_3-PD_5, in the areas of increased defectivity, the density of dislocations reached $N_{dis}\approx10^8$-10^9 cm^{-2} (Fig. 4b). In serial PD_6 $N_{dis}\approx10^2$-10^3 cm^{-2} (Fig. 4c). However, we want to note that the dark current of a photodiode does not depend on the actual density of dislocations on the surface of RE, since the determining component of the dark current of a PD is the volumetric generation-recombination component (I_d^G)[1], which is much larger than the surface generation component [12]. Accordingly, the location of dislocations is crucial. And a significant influence on the value of the recombination current will be made by defects located in the space charge region (SCR).

$$\mathrm{I}_d^G = \mathrm{e}\frac{n_i}{2\tau}W_i A_{\mathrm{RE}}, \tag{1}$$

where *e* is electron charge; n_i is intrinsic concentration of charge carriers in the substrate; τ is lifetime of the minor charge carriers; W_i is width of the space charge region, A_{RE} is the area of responsive elements.

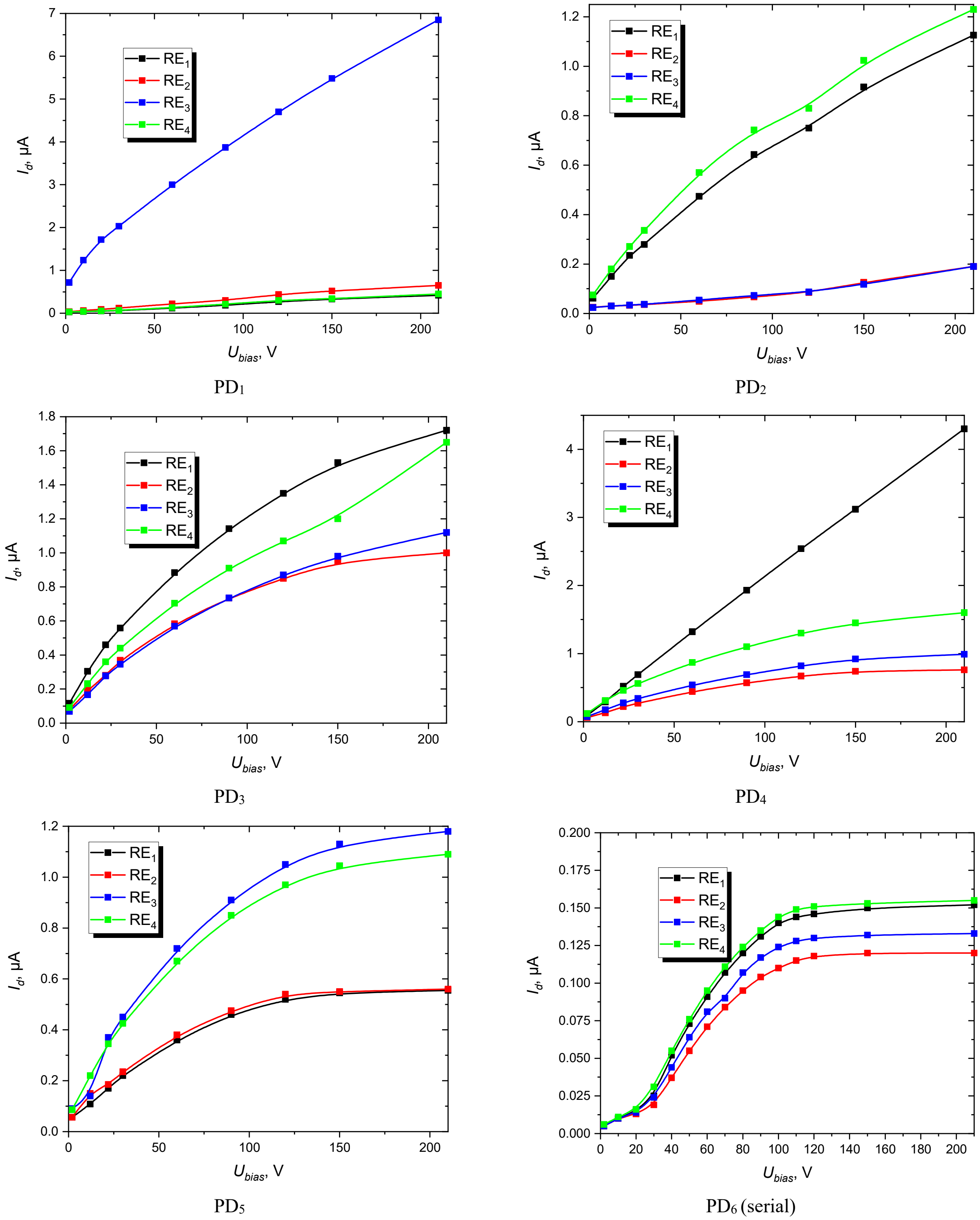
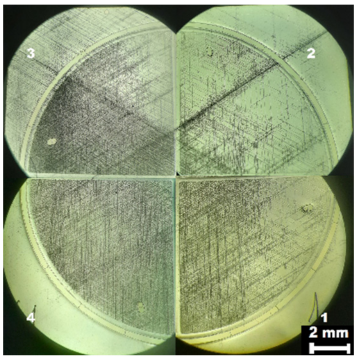
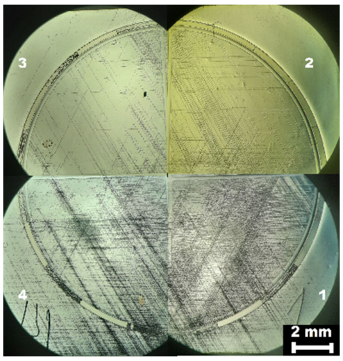


Figure 2. *I–V* characteristics of PDs

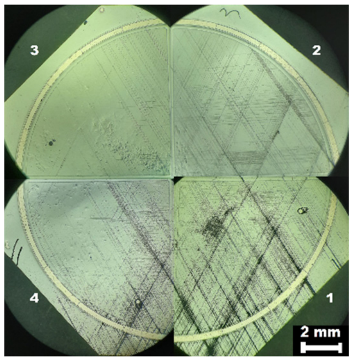
The depth of the dislocations can be determined by layer-by-layer silicon etching followed by selective etching. However, we found that the vast majority of dislocations formed as a result of phosphorus diffusion from planar solid-state sources are located in the diffusion layer. When doping substrates from liquid-phase phosphorus sources, dislocations may also be generated at some distance from the diffusion layer due to higher mechanical stresses caused by the high concentration of phosphorus atoms in the interstices of the silicon crystal lattice [13]. However, it is worth noting that dislocations formed as a result of growth defects or defects introduced during machining can cross the entire wafer and make a significant contribution to the value of dark currents by reducing the lifetime of minor charge carriers. In order to detect dislocations that cross the entire thickness of the silicon wafer, we also examined the reverse sides of the photodiode crystals under study (Fig. 5).



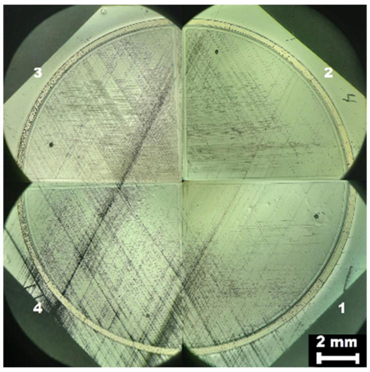
PD$_1$



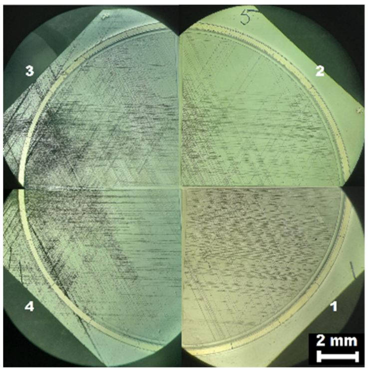
PD$_2$



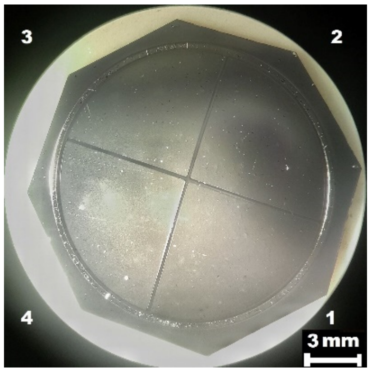
PD$_3$



PD$_4$



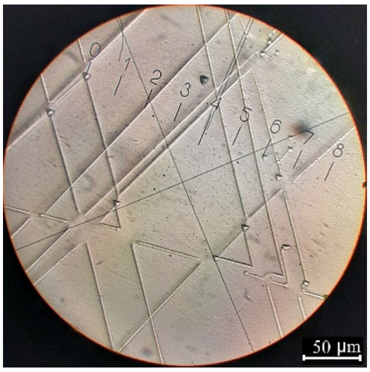
PD$_5$



PD$_6$

Figure 3. Image of dislocations on the surface of PD crystals after selective etching

a



b

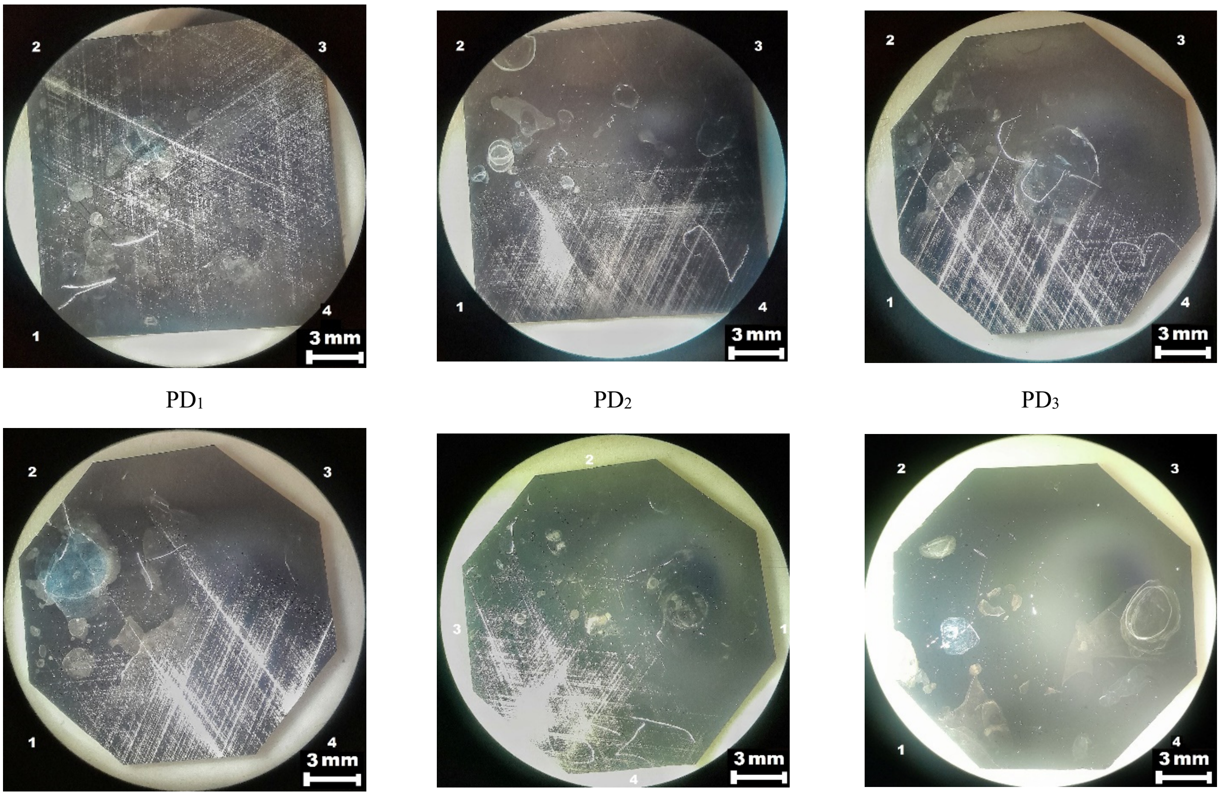
c

Figure 4. Zones of increased density of dislocations at a magnification of x500 for: a) PD$_1$ and PD$_2$; b) PD$_3$-PD$_5$; c) PD$_6$

As can be seen from Fig. 5, RE with high dark currents had dislocation grids of increased density in the projections to the back side of wafers. This indicated the presence of dislocations in the entire thickness of the SCR of the RE with increased I_d. The REs of the studied PDs, which were not characterised by increased dark currents, also had some dislocation density on the front side, but given the absence of these defects on the back side of these REs, it can be assumed that they are not distributed over the entire thickness of the SCR and are located in the diffusion zone or near it.

In the case of the serial PD$_6$, only a small density of dislocations was found on the reverse side (N_{dis}≤10^2 cm^{-2}), which is typical for silicon after technological treatments. The spread of the dark currents of the serial photodiode was up to 20%, in contrast to the defective samples under study, where the spread could reach 2 or more times.

The effect of dislocations on the electrical parameters of photodiodes and the properties of p-n junctions can be manifested in two ways: first, the presence of dislocations can lead to the appearance of band gap levels due to the elastic stress fields associated with dislocations. Dislocations can serve as areas of charge carrier recombination, and accordingly, the presence of recombination centers in the depleted region of the *p-n* junction will be manifested in an increase in the generation currents with a reverse shift of the *p-n* junction. Secondly, a more important effect is the influence of dislocations on the properties of *p-n* junctions due to the accumulation of impurities on and around dislocations, since dislocations can accumulate impurities due to their elastic fields, a dislocation decorated with impurities crossing a *p-n* junction will lead to the penetration of a high density of generation-recombination centers in the space charge region of the *p-n* junction, which again leads to an increase in the generation currents in the SCR at the reverse bias [1].



PD1 PD2 PD3 PD4 PD5 PD6

Figure 5. Dislocation structure of the back side of PD crystals

B) The influence of dislocations on the insulation resistance between REs and the GR

A table of the insulation resistance of each REs of the studied PDs and the GR was obtained (Table 1).

Table 1. Values of R_{con} of the studied PDs

	R_{con}, MΩ			
	RE_1	RE_2	RE_3	RE_4
PD_1	30.8	2.5	20	31.7
PD_2	20	40	26.7	12.5
PD_3	1.5	6.9	7.4	2.8
PD_4	3.6	6.7	6.7	1.4
PD_5	4.8	3.7	1.4	2.8
PD_6	8	6.7	7.1	8.3

As can be seen from Table 1, the PD_1-PD_5 had a certain scattering in the $R_{con.}$ It was found that the RE "connected" to the GR by dislocation lines have a reduced insulation resistance. No scattering of $R_{con.}$ was observed in the serial PD_6, since there are no dislocation lines crossing the RE and GR.

C) The influence of dislocations on the responsivity of PD

When measuring the responsivity of the photodiodes, we also observed some unevenness of this parameter across the REs. This phenomenon will be studied in more detail on the example of PD_5 and PD_6.The dependence of the responsivity of each photodiode RE on the bias voltage is shown at Fig. 6.

As can be seen from Figure 6, the S_{pulse} of each RE at a fixed voltage is different. It can also be seen that each curve reaches saturation at a different U_{bias}, although the maximum responsivity of the REs is approximately the same. Differences in responsivity values can be caused by differences in the lifetime of minor charge carriers due to different dislocation densities of each responsive element.

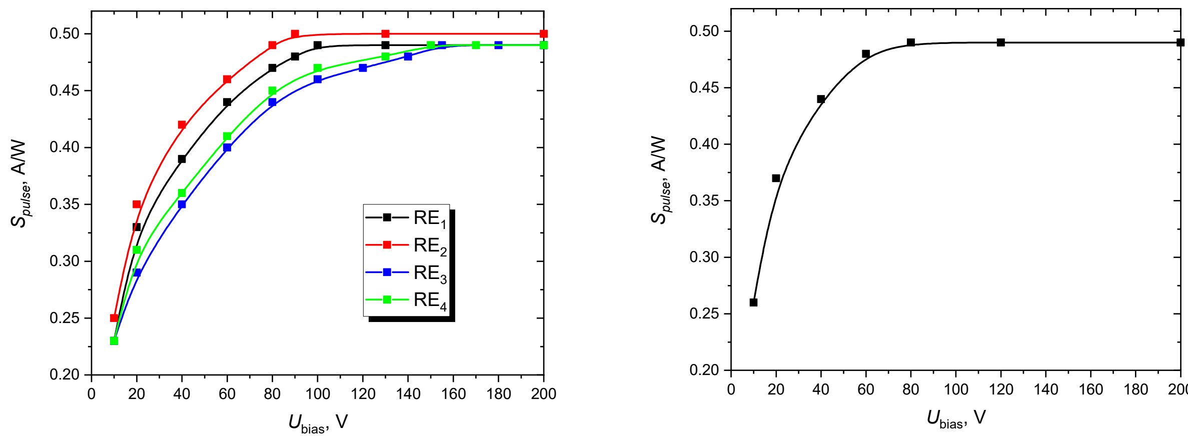
Note that the difference in the saturation voltage of responsivity can also be caused by the difference in the collection coefficient of minor charge carriers (γ) (2), which depends on the SCR width, which in turn depends on the material resistivity. The responsivity of the PD reaches saturation when the collection coefficient of the charge carriers reaches its maximum value, i.e. when all photogenerated charge carriers in the photodiode base are distributed by a *p-n* junction (3) [20].

$$\gamma = 1 - e^{-\alpha(W_i + L_n)}, \tag{2}$$

where α is the absorption index, L_n is diffusion length of electrons

$$S_\lambda = (1-R)TQ\sum\gamma\frac{\lambda_{op}}{1.24}, \tag{3}$$

where R is the reflection coefficient, T is the transmission coefficient of the input window or optical filter; Q is the quantum output of the internal photo effect.



a b

Figure 6. Dependence of the responsivity of RE on the bias voltage: a) PD_5; b) PD_6

The acquisition of the collection coefficient, and, accordingly, the responsivity, is possible when one of two conditions is met (4):

$$\begin{cases} X = L_n + W_i & (4.1) \\ X = W_i & (4.2) \end{cases}$$

where X is the thickness of the high-resistance region of the photodiode (base).

To be able to differentiate between these two cases, it is necessary to consider the impulse characteristic of the PD (Fig. 7). In the case (4.2), when the W_i is extended over the entire high-resistance region of the photodiode, the performance and inertial properties are determined by the drift mechanism of charge carrier transfer and the impulse characteristic will take the form shown in Fig. 7a.

Figure 7. The pulse shape of the PD output signal: a) the case when the SCR occupies the entire high resistivity region of the PD; b) the case when the sum of the width of the SCR and L_n is is equal to the *i*-region of the photodiode

Figure 7a shows the S_{pulse} characteristic of PD_5 RE_2 at U_{bias}=130 V. With a decrease in the reverse U_{bias}, the W_i decreases, but the responsivity does not decrease, since the diffusion mechanism of charge carrier transport begins to operate. The S_{pulse} will start to decrease when W_i+L_n is smaller than the *i*-region of the PD. In this case, the 4.1 condition is met at U_{bias}=90 V (Fig. 7b).

Knowing the thickness of the high-resistance region of the PD, which is W_i, formula (5)[21] can be used to determine the concentration of acceptors (N_A) in the *i*-region:

$$W_i = \left(\frac{2\varepsilon\varepsilon_0\,(\phi_c - U_{bias})}{eN_A}\right)^{\frac{1}{2}}, \tag{5}$$

where ε, ε_0 are dielectric constants for silicon and vacuum, respectively; φ_c is contact potential difference.

Knowing the concentration of acceptors, and assuming that all impurities are ionized at room temperature ($p=N_A$), it is possible to determine the resistivity of silicon from the formula for the electrical conductivity of a *p*-type semiconductor [22]

$$\sigma = \frac{1}{\rho} = eN_A\mu_p. \tag{6}$$

Knowing N_A, it is possible to determine W_i in the case corresponding to equation (4.1). For this, it is necessary to substitute the U_{bias} corresponding to case (4.1) in equation (5). The difference in the SCR corresponding to cases 4.1 and 4.2 is the diffusion length of the minor charge carriers.

Using the given method of determining the ρ and L_n, a table of data parameters for PD_5 was obtained (Table 2).

Table 1. Values of ρ and L_n each RE of PD_5

Parameter	RE_1	RE_2	RE_3	RE_4
ρ, kΩ	19.2	19.2	13.9	14.7
L_n, μm	60	80	35	30

As can be seen from Table 2, there is some variation in ρ and L_n of PD_5. If we compare the data obtained with the dislocation density in the same PD, we can see that the RE with a higher dislocation density have a lower L_n. This confirms the fact that the lifetime of minor charge carriers decreases with increasing dislocation density. It can also be seen from Table 2 that the L_n, of the RE are correlated with each other as dark current. It can also be seen that an increase in the dislocation density provokes a degradation of the resistivity. This, in turn, can contribute to the scattering of the C_{RE}, since the barrier capacity of a PD is determined by the N_A and, accordingly, the ρ of the Si (7)[21]:

$$C_{RE} = A_{RE}\left(\frac{\varepsilon\varepsilon_0 e N_A}{2(\phi_c - U_{bias})}\right)^{\frac{1}{2}}. \tag{7}$$

As for the serial PD_6, no responsivity variation was observed (Fig 6b). However, the S_{pulse} reached saturation at slightly lower reverse bias voltages, which indicates a moderate degree of resistivity degradation. In this case, according to the calculation by the above method $\rho \approx 20.8$ kΩ and $L_n \approx 90$ μm. This photodiode had a much lower defect density and, as a result, slightly better final electrophysical characteristics of silicon, which provided better parameters than the studied defective samples.

CONCLUSIONS

The effect of dislocations on the parameters of silicon four-quadrant *p-i-n* photodiodes was studied. The following conclusions were made during the research:

1) Mechanical stresses formed in plates formed during growth or mechanical processing of ingots provoke the formation of a high density of dislocations due to stress relaxation during thermal operations.

2) Formative defects are often placed unevenly on the plates and cause the unevenness of the parameters on the responsive elements.

3) The described defects often cross the entire wafer to form recombination centers in the space charge region of the photodiode.

4) The presence of recombination centers reduces the life time and diffusion length of minor charge carriers, as a result of which the parameters associated with the specified characteristics deteriorate.

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ВПЛИВ СТРУКТУРНИХ ДЕФЕКТІВ НА ПАРАМЕТРИ КРЕМНІЄВИХ ЧОТИРИКВАДРАНТНИХ *p-i-n* ФОТОДІОДІВ

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У статті досліджено вплив структурних дефектів, зокрема дислокацій, на електричні та фотоелектричні властивості кремнієвих чотириквадрантних *p-i-n* фотодіодів. Встановлено, що ростові дефекти та дефекти, які утворюються при механічній обробці пластин, можуть перетинати всю підкладку та погіршувати параметри фотодіодів. Це явище особливо негативне через розміщення дефектів в області просторового заряду. У цьому випадку через наявність центрів рекомбінації в області просторового заряду зменшується час життя неосновних носіїв заряду, погіршується темновий струм і чутливість фотодіодів. Часто дефекти розміщені нерівномірно, що провокує нерівномірність параметрів на фоточутливих елементах. Також було побачено, що дислокаційні лінії, які перетинають чутливі елементи та захисне кільце, погіршують опір ізоляції зазначених активних елементів. Запропоновано метод визначення кінцевого питомого опору кремнію та довжини дифузії неосновних носіїв заряду шляхом дослідження форми імпульсу вихідного сигналу.

Ключові слова: *кремній; фотодіод; чутливість; точковий дефект; дислокація; темновий струм*