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ARTICLE

Analysis of the Effect of Radiation Defects by Low-energy Protons on Electrophysical Properties of Silicon N^+-P-P^+ Structure

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ABSTRACT

Nowadays, radiation engineering is a promising direction in the creation of semiconductor devices. The proton irradiation is used to controllably change the optical, electrical, recombination, mechanical and structural properties of the semiconductors. Low-energy protons make it possible to purposefully change material properties near the surface where the n^+-p junction is located. In this paper, the impact of low-energy protons on the electro physical parameters of n^+-p-p^+ silicon photoelectric converters (SPC) is analyzed. The current-voltage characteristics and switching time of these SPCs are measured. The switching time is determined using rectangular bipolar voltage pulses with an amplitude of 10 mV, a frequency of 200 kHz, or a frequency of 1 MHz. A theoretical and experimental analysis of the obtained results is performed. The comparison of experimental data with the results of calculations shows that protons with an energy of 180 keV and a dose of 10^{15} cm^{-2} create two regions in the space charge region of the n^+-p junction with different switching times of 4.2×10^{-7} s and 5.5×10^{-8} s. SPC frequency characteristics have been improved by reducing the effective lifetime by 5-10 times. This effect can be used to create high-speed photodiodes with an operating modulation frequency of 18 MHz.

Keywords: Silicon; n^+-p junction; Lifetime; Proton; Pulse characteristic

1. Introduction

The relevance of studies of the effects of ionizing radiation on the properties of semiconductor materials and devices is increasing due to the increasing use of these processes in industrial technologies un-

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der controlled exposure, as well as the use of devices under uncontrolled environmental exposure [1-6].

The electrophysical characteristics of semiconductor structures with an n^+-p junction depend on the volume and surface recombination rates, the impurities and radiation defects distributions. The parameters of volume and surface recombination were measured by the photoconductivity decay method [7,8]. Methods for determining recombination parameters are being improved. Pulsed illumination was used to determine the effect of structural defects on recombination parameters in the bulk of polycrystalline silicon and the p-n junction [9]. Measuring recombination parameters using the photoconductivity method, which is recorded using microwave radiation, allows you to monitor the results of technological processes [10].

The transient characteristics of semiconductor devices can be improved by irradiating them with protons [11]. The influence of irradiation with low-energy protons and the temperature of irradiated samples on the parameters of current-voltage characteristics (CVC) of silicon photoelectric converters (SPC) and the distribution of radiation defects is shown in articles [12,13]. As a result of irradiation with low energy protons, the switching time of SPC decreases [14]. The authors of the article [15] draw attention to the relevance of numerical modeling of the effects of irradiation with light and ionizing particles in semiconductor devices.

From a scientific and practical point of view, it is necessary to study the change in the electrical properties of SPCs under the influence of low-energy protons and evaluate the possibility of reducing their switching time in a dynamic mode.

2. Research methods

Photoelectric converters are a wide class of devices that convert the energy of electromagnetic radiation into electrical energy [16-18]. These devices include the semiconductor photoelectric converter that performs the functions of a primary converter. The frequency characteristics of photovoltaic converters depend on the switching time of the semiconductor photoelectric converters.

The subject of the study is the properties of n^+-p-p^+ SPCs. The samples' parameters: concentration of equilibrium holes in the base—$p_0 \approx 10^{15}$ cm^{-3}, thickness of diffusion n^+-p and p-p^+ layers—$d_n \approx d_p \approx$ 0.45 μm, base thickness—$L \approx 200$ μm, area—S » 1 cm^2, phosphorus concentration on the surface of n^+ layer—$N_P \approx 10^{20}$ cm^{-3}, boron concentration on the surface of p^+ layer—$N_B \approx 10^{20}$ cm^{-3}.

Proton irradiation was performed from the n^+ layer side. Radiation dose $F_p = 10^{15}$ cm^{-2}. Sample irradiation conditions (proton energy E_p, sample temperature Tp): N1 – E_p = 180 keV, Tp = 83 K; N2 – E_p = 40 keV, Tp = 83 K; N3 – E_p = 40 keV, T_p = 300 K. The control group of 7 samples with very similar electrophysical characteristics N4 was not irradiated.

The dark CVC of the SPC was measured using an IPP1 device at a temperature T = 300 K [12,13] (**Figure 1**).

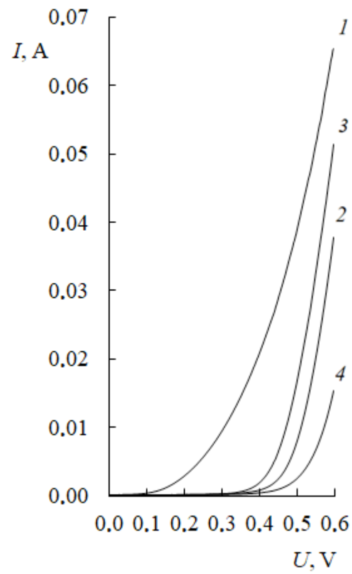

Figure 1. CVC of the studied SPC.

Note: 1—N1, 2—N2, 3—N3, 4—N4.

Transient characteristics were measured in the dark using a DSOX2022A digital oscilloscope, including the functions of a voltage pulse generator and a multimeter [14], using bipolar rectangular voltage pulses with a constant amplitude Um = 10 mV and a frequency f = 200 kHz and f = 1 MHz. The measured dependences of voltage U on time t are shown in **Figures 2 and 3**.

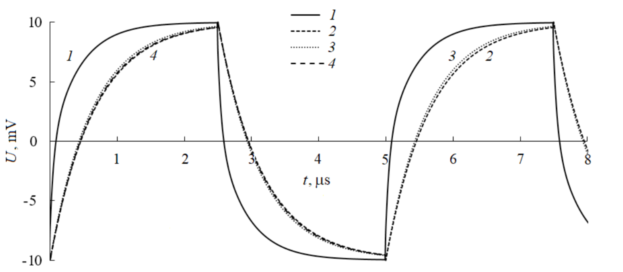

Figure 2. Transient characteristics of the SPC at a frequency 200 kHz.

Note: 1—N1, 2—N2, 3—N3, 4—N4.

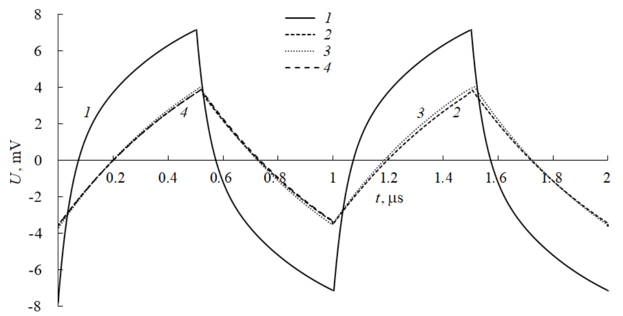

Figure 3. Transient characteristics of the SPC at a frequency 1 MHz.

Note: 1—N1, 2—N2, 3—N3, 4—N4.

3. Analysis of the research results

The depth distributions of the average number of interstitial silicon G_{Si}, vacancies G_V, and divacancies G_W created by one proton per unit of the projective path length were calculated using the model of the formation of primary radiation defects (PRD) [19] (**Figure 4**). The rate of formation of radiation defects depends on the concentration of impurities and the temperature of the samples [12,13,19,20].

Protons with E_p = 40 keV create PRDs in the n^+ layer at a depth of 0.41 μm. In this case, the number of PRDs at T_p = 300 K is several times greater than at T_p = 83 K, as well as the number of PRDs created by protons with E_p = 180 keV at T_p = 83 K (**Figure 4**). Protons with E_p = 40 keV change the properties of the n^+ layer, so the CVC of the irradiated samples N2, N3 and the unirradiated sample N4 are different (**Figure 1**). However, the transient characteristics of these samples differ little. Consequently, they do not depend on the electrical properties of the n^+ layer.

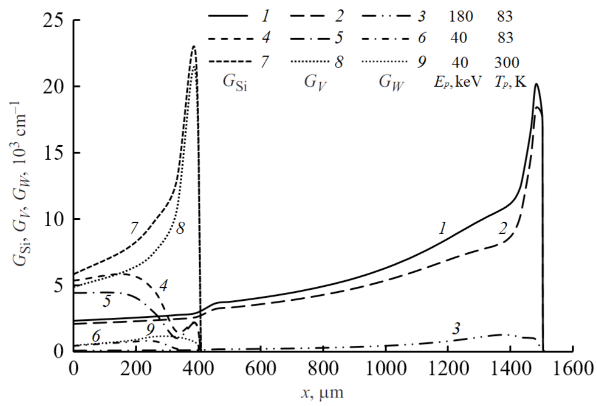

Figure 4. The distributions of PRD created by a proton with energy E_p at the temperature T_p of the irradiated SPC.

Protons with E_p = 180 keV create PRDs in the SCR of the n^+-p junction up to 1.51 μm (**Figure 4**). PRDs are absent in the base of SPC under these irradiation conditions. The transient characteristics of SPC N1 differ from the transient characteristics of SPC N2, N3, N4 (**Figures 2 and 3**), therefore the transient characteristics of the SPCs are determined by the parameters of the radiation-damaged SCR of the n^+-p junction. The CVC of SPC N1 differs from the CVC of SPC N2, N3, N4 (**Figure 1**), which is explained by a change in the electrophysical characteristics of the SCR of SPC N1 under proton irradiation.

Shockley [21] proposed the fundamental system of differential equations (FSDE) for the analysis of the transport of charge carriers in semiconductors with n^+-p junction.

$$\begin{cases} \vec{j}_n = \mu_n n \vec{\nabla}\varphi - D_n \vec{\nabla} n \\ \vec{j}_p = -\mu_p p \vec{\nabla}\varphi - D_p \vec{\nabla} p \\ \dfrac{\partial n}{\partial t} + \left(\vec{\nabla}\,;\vec{j}_n\right) = G - R \\ \dfrac{\partial p}{\partial t} + \left(\vec{\nabla}\,;\vec{j}_p\right) = G - R \\ \Delta\varphi = -\dfrac{q}{\varepsilon\varepsilon_0}\left(p - n + N_D^+ - N_A^-\right) \end{cases} \quad (1)$$

The system of equations, (1) contains unknown variables: n—the concentrations of electrons, p—the concentrations of holes, $\vec{j}_n$—the density of the electron flow, $\vec{j}_p$—the density of the hole flow, φ—the potential of the internal electric field; specified silicon parameters: μ_n—mobility of the electrons, D_n—diffusion coefficient of the electron, μ_p—mobility of the holes, D_p—diffusion coefficient of the hole, G—the rate of volume generation of the electron-hole pairs, R—the rate of volume recombination of the electron-hole pairs, N_D^+—concentration of the ionized donors, N_A^-—concentration of the ionized acceptors, q—elementary charge, ε—permittivity, ε_0—dielectric constant.

From the system of equations, (1) follows the dependence of the electric current I on the voltage U_{np} at the n-p junction of the following form [22].

$$I = I_0\left[\exp\left(\frac{qU_{np}}{kT}\right) - 1\right] + I_r\left[\exp\left(\frac{qU_{np}}{akT}\right) - 1\right] + \frac{U_{np_s}}{R_{sh}} \quad (2)$$

$$U_{np} = U - IR_s \quad (3)$$

where I_0—reverse saturation current due to quasineutral n^+ layer and base; I_r—recombination current due to SCR; a—the coefficient of nonideality of the n-p junction; R_{sh}—shunting resistance of the n-p junction; U—electrical voltage at the contacts; R_s—concentrated sequential resistance; k—Boltzmann constant. It is necessary to determine which region of the SPC gives the main contribution to the experimental dependences CVC. For this purpose, the experimental dependencies $I(U)$ (**Figure 1**) must be approximated by a theoretical dependence (4).

$$I = I_0\left(\exp\left\{\frac{e(U - IR_s)}{akT}\right\} - 1\right) + \frac{U - IR_s}{R_{sh}} \quad (4)$$

The parameters of CVC calculated as a result of the approximation are given in the table. The nonideality coefficient of the n-p junction a = 1.6 for the non-irradiated sample N4 (table). It means that the SCR gives the main contribution to the CVC at the voltage U < 0.6 V [22].

Radiation defects created by protons with energy 180 keV disrupt the structure of the SCR and reduce the lifetime of the electrons and holes. Therefore, the contribution of the SCR to the CVC and the nonideality coefficient increase, so that a = 2.6 for sample N1 (table).

Radiation defects created by protons with energy 40 keV change the properties of the n-region so that the concentration of the electrons, the diffusion length and the lifetime of the holes are reduced. As a result, the contribution of the n-region to the CVC increases. The quasineutral region contributes to the CVC with a non-ideality coefficient a = 1 [22]. Therefore, for samples N2 and N3 the coefficient of nonideality a is close to 1 (table).

The value of I_{0r} in sample N2 is an order of magnitude less than in sample N3 (table), because G_{Si}, G_V, created in the n-region at T_p = 83 K, are smaller than at T_p = 300 K (**Figure 4**).

The irradiated SPCs have less value of R_s than the non-irradiated ones, which is apparently due to a decrease in the resistance of surface. The decrease of R_{sh} in irradiated SPCs may be caused by an increase in the number of surface states at the ends of the n-p junction.

When measuring the pulse characteristics, the condition of the small amplitude of the voltage at the contacts was fulfilled (5).

$$qU_m/kT < 1 \quad (5)$$

Inequality (5) means that a mode of low injection of nonequilibrium electrons and holes in the n^+ and p regions is realized. According to the experimental conditions, there is no light generation of electrons and holes G = 0. Then the FSDE (1) is simplified so that the solution for the concentration of electrons and holes has the form (6).

$$n = n_0 + \delta n, p = p_0 + \delta p \quad (6)$$

where n_0 and p_0 are the solution of the system (1) under the equilibrium conditions $\vec{j}_n = 0$, $\vec{j}_p = 0$. To determine δn, δp we use substitution.

$$\delta n\,(x, t) = \sum_i \left[A_{ni}\,(x) - B_{ni}\,(x)\cdot\exp\left(-\frac{t - t_0}{\tau_i}\right) - 1\right] \quad (7)$$

$$\delta p\,(x, t) = \sum_i \left[A_{pi}\,(x) - B_{pi}\,(x)\cdot\exp\left(-\frac{t - t_0}{\tau_i}\right) - 1\right] \quad (8)$$

where $t_0 < t < t_m$, $t_m - t_0 = (2f)^{-1}$. The functions $A_{ni}(X)$, $B_{ni}(X)$, $A_{pi}(X)$, $B_{pi}(X)$ are the solution of FSDE in quasi-neutral p, n^+ regions and SCR.

The range of switching time values $\tau_j \in (2\Delta t, (4f)^{-1})$ is determined by the duration of the bipolar voltage pulses $(2f)^{-1}$ and the signal sampling step Δt. The SPC SCR makes the main contribution to the voltage drop U [22]. Thus, electrical voltage relaxation processes occur in the SPC with an effective lifetime τ_j depending on the processes in the SCR.

$$U(t) = \sum_j \left[D_j \cdot \exp\left(-\frac{t - t_0}{\tau_j} \right) - C_j \right], \text{ when } t_0 < t < t_m. \quad (9)$$

When using the dependence (9), the approximation of the pulse characteristics (**Figures 2 and 3**) gives close values of the effective lifetime in the SCR for the samples N2, N3, N4 (**Table 1**). Two values $\tau_1 = 4.2 \times 10^{-7}$ s, $\tau_2 = 5.5 \times 10^{-8}$ s were found for sample N1.

Consequently, the structure of SPC was changed by protons with an energy of 180 keV so, there are two regions in SCR with different values τ_1 and τ_2. The lifetime τ_2 belongs to the region with a high concentration of the PRD near the Bragg peak at $x = 1.48$ mm (**Figure 4**).

The transient response simulation results are shown in **Figures 5-7**. A decrease of lifetime τ at a given pulse frequency $f = 10$ MHz causes a change in the shape of the transient response. Transient characteristics have a triangular shape with a smaller amplitude and equal length front and rear wave fronts (**Figure 5**) at the values of the parameters $\tau = 2.5 \times 10^{-7}$ s and $\tau = 5 \times 10^{-7}$ s.

A decrease of the τ value at the frequency $f = 10$ MHz reestablishes the shape of the transient characteristics: A reduction of 10 times gives the transient characteristics shown in **Figure 6**, and 50 times the transient characteristics shown in **Figure 7**.

Table 1. Electrophysical parameters of SPC.

Sample, N	I_{0r}, A	a	R_s, Ohm	R_{sh}, Ohm	t, s
1	1.6×10^{-4}	2.6	3.1	1.2×10^{5}	4.2×10^{-7}; 5.5×10^{-8}
2	1.6×10^{-9}	1.2	2.3	1.1×10^{5}	6.6×10^{-7}
3	1.5×10^{-8}	1.3	2.2	1.1×10^{5}	6.3×10^{-7}
4	1.6×10^{-8}	1.6	4.2	3.4×10^{5}	6.4×10^{-7}

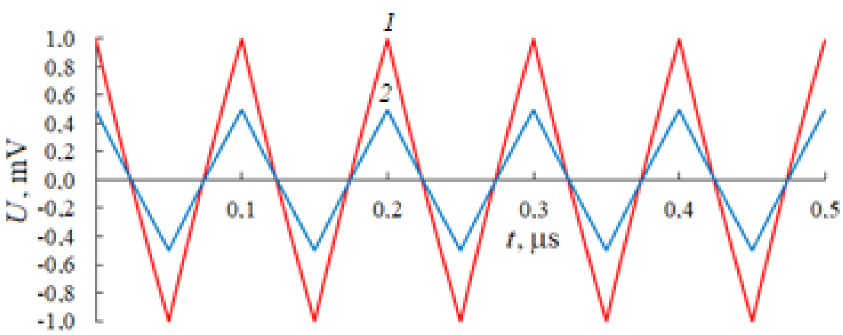

Figure 5. The transient characteristics at pulse frequency $f = 10$ MHz. The lifetime in SCR is *1 – τ = 2.5 × 10*$^{-7}$ *s, 2 – τ = 5 × 10*$^{-7}$ *s.*

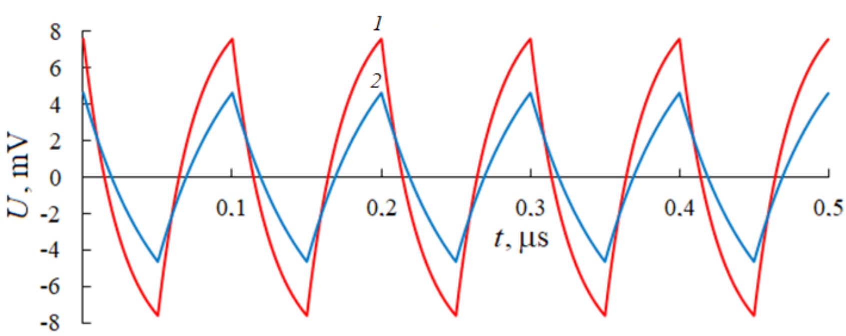

Figure 6. The transient characteristics at pulse frequency $f = 10$ MHz. The lifetime in SCR is *1 – t = 0.25 × 10*$^{-7}$ *s, 2 – t = 0.5 × 10*$^{-7}$ *s.*

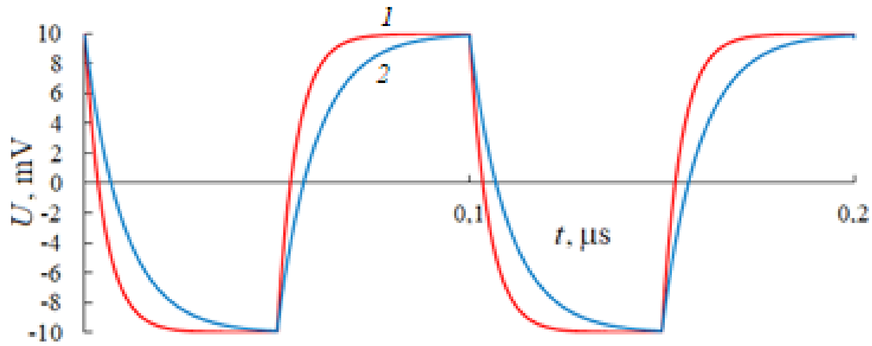

Figure 7. The transient characteristics at pulse frequency f = 10 MHz. The lifetime in SCR is *1* – $\tau = 0.05 \times 10^{-7}$ *s, 2* – $\tau = 0.1 \times 10^{-7}$ *s.*

4. Conclusions

Proton irradiation makes it possible to locally create the electrically and recombinationally active defects in semiconductors with a maximum concentration in the Bragg peak region. Radiation defects created by protons with an energy 180 keV and a dose 10^{15} cm^{-2} disrupt the structure of the SCR of the n^+-p junction of silicon devices and reduce the lifetime of charge carriers, which leads to a significant increase in the contribution of SCR to the dark electric current in stationary mode. It was found that two regions with different values of effective lifetimes $\tau_1 = 4.2 \times 10^{-7}$ s, $\tau_2 = 5.5 \times 10^{-8}$ s were formed in the SCR under the exposure of the proton irradiation. The value of τ_2 is an order of magnitude less than in non-irradiated devices.

Based on the results of the simulation of transient characteristics, it can be concluded that in order to improve the frequency characteristics at a frequency 10 MHz the effective lifetime should be reduced by 5 ÷ 10 times. However, in this case, an increase in the dose by 10 times will not lead to an inversely proportional decrease in the effective lifetime. The reason is that the concentration of formed PRDs in the Bragg peak region is much higher than the concentration of the main impurities in silicon grown by the Czochralski method (phosphorus, boron, oxygen, carbon) and other defects interacting with PRD at the stage of formation of secondary radiation defects (SRD). Therefore, direct or indirect annihilation of interstitial silicon and vacancies limits the concentration of recombination active SRDs. Consequently, the task of improving of the frequency characteristics of semiconductor devices cannot be solved only by increasing the radiation dose, but must be solved in combination with the formation of the semiconductor structure and impurity composition.

Author Contributions

Bogatov N. M.—problem statement, research management, article writing.

Grigoryan L. R.—transient response measurement.

Kovalenko M. S.—modeling and calculations.

Volodin V. S.—CVC measurement.

Conflict of Interest

The authors declare no conflict of interest.

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