Effect of low-energy proton irradiation on parameters of silicon structures with n-p junction

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Abstract. The dependences of the separation probability of the Frenkel pair on the temperature and the position of the Fermi level in the band gap cause the dependences of primary radiation defects concentration on the irradiation temperature and impurity concentration. This conclusion is confirmed by study results of electrophysical and optical properties of silicon n$^+$-p-p$^+$ structures, irradiated by the proton flux with the energy of 40 keV and the fluence of $10^{15}$ cm$^{-2}$.

1. Introduction
Silicon electronics are used in conditions of increased exposure to ionizing radiation. A radiation defects formation affects parameters of electronic devices. Also, it is one of the reasons of silicon electronics parameters degradation in irradiation conditions [1–3].

Radiation defects in a silicon have electrical and recombinational activity. An increase in the number of radiation defects changes the concentration and the lifetime of electrons and holes, as a result, electrical characteristics of n-p-junctions change during device operation [4, 5]. Thus, a study of the radiation defects formation is an actual problem of semiconductor physics and technology [6, 7].

The paper [8] suggests a model of the radiation defects formation in a silicon irradiated by ionizing particles. The process of primary radiation defects (PRD) formation was calculated in [9] using the model [8]. The calculated dependence of the separation probability on the temperature and the position of the Fermi level in the band gap is a consequence of the existence of Frenkel pairs in the charged and neutral states. The separation probability increases with a decrease in the position of the Fermi level, so the concentration of primary radiation defects decreases with increasing donor concentrations. In n-type silicon, the separation probability decreases if the irradiation temperature decreases.

The objective of this paper is to carry out the experimental study of the effect of low-energy proton irradiation temperature on parameters of silicon structures with n-p junction.

2. The Model of Primary Radiation Defects Formation
A radiation defect forms as a result of exposure to ionizing radiation. Depending on a mechanism of formation, let us distinguish simple, primary and secondary radiation defects [10, 11]. The interaction
of ionizing radiation with a crystalline silicon lattice forms simple radiation defects: separated and bound Frenkel pairs. These defects consist of vacancy $V$ and self-interstitial silicon $Si_I$.

The following model describes the process of formation and separation of the Frenkel pairs during irradiation of silicon. An incident ionizing particle transfers the kinetic energy to a silicon atom. To get out of a crystal site, a silicon atom must overcome potential barrier $T_d$. A type of the Frenkel pair depends on the energy that a silicon atom received from an incident particle. The energy threshold of forming the bound Frenkel pair is $T_d = 12.9$ eV, and the separated Frenkel pair is $T_{dr} = 21$ eV [10, 11].

The bound Frenkel pair forms when a silicon atom in the crystal site receives energy $T_k$ ($T_k < T_d$; $T_{dr}$) after collision with an incident particle. The bound Frenkel pair exists only at the liquid helium temperature [12]. When temperature grows, an interstitial silicon atom may overcome an energy threshold and annihilate or overcome another energy threshold with the formation of the separated Frenkel pair.

The separation of the bound Frenkel pair is described by various models of metastable pairs [11–13]. There are neutral and charged bound Frenkel pairs. The probability of the charged state of a bound Frenkel pair is described by the formula:

$$\omega_f = \left[ 1 + g_e \exp \left( \frac{F - E_f}{kT} \right) \right]^{-1},$$

where $F$ – the Fermi level, $g_e = 0.5$, $E_f$ – Frenkel pair energy level in the silicon band gap, $E_f = E_c - 0.07$ eV [12], $k$ – the Boltzmann constant, $T$ – the temperature. The form of the potential barrier of a charged Frenkel pair varies so that it separates with probability 1.

The probability of a neutral pair separation is described by the formula:

$$\omega_n = \left[ 1 + \exp \left( \frac{T_d - T_{dr}}{kT} \right) \right]^{-1}. \quad (2)$$

The probability of the bound Frenkel pair separation taking into account charged and neutral states of a defect is determined by quantity $\omega_f$:

$$\omega_f = \omega_f \omega_n + (1 - \omega_f \omega_n)\omega_2,$$

where $\omega_n$ – the additional parameter that characterizes the probability of the displacement of a silicon atom into a spatial position permitting the charged state, $\omega_n = 0.00887$ [8]; $\omega_f = \omega_f \omega_n$ – the charged state probability of a silicon atom in an interstitial position (a charged Frenkel pair is divided), $\omega_2 = (1 - \omega_f \omega_n)\omega_2$ – the separation probability of bound Frenkel pair in the neutral state.

The probability of avoiding annihilation of separated $V$ and $Si_I$ placed at the distance of $r \leq r_{vi}$ ($r_{vi}$ – average reaction radius, $r_{vi} = 2.8 a$, where $a$ – lattice period) is $\omega_0 = 6\omega_f \omega_n$, since the charged state is formed with a vacancy in one of the six symmetrical directions of the symmetry group of tetrahedron $T_d$.

The average number of interstitial silicon atoms and vacancies created by a single ionizing particle per unit length of the projective range at $T_{dr} \leq T_k \leq T_m < 2T_{dr}$ ($T_m$ – the maximum energy transmitted by the incident particle to the atom in the crystal lattice node) is given by the formula:

$$G_v = G_i = N_0 \left( \omega_f \int_{T_1}^{T_f} \frac{d\sigma}{dT} dT + \omega_n \int_{T_1}^{T_f} \nu(T) \frac{d\sigma}{dT} dT \right), \quad (4)$$

where $N_0$ – the concentration of Si atoms in a crystal lattice; $d\sigma(E, T_k)$ – differential scattering cross section (characterizes the probability of transmission of energy $T_k$ to a site atom from an incident particle with energy $E$). Formula (4) differs from the analogous [11] by factor $\omega_f$.

The region of the displacement cascade arises when the energy of the recoil atom is $T_k \geq 2T_{dr}$. The average number of PRD created by a single ionizing particle per unit length of the projective range at $2T_{dr} \leq T_k \leq T_m \leq T_{do}$ is given by the formula:
\[
\begin{bmatrix}
G_{Si} \\
G_{V} \\
G_{W}
\end{bmatrix} = N_0 \int_{T_0}^{T_p} \frac{V_i}{V_v} d\frac{\sigma_d}{dT_k},
\]

where the average number: \(v_i\) – interstitial atoms, \(v_v\) – vacancies, \(v_w\) – divacancies avoided of the annihilation in the displacement cascade.

Figure 1 shows calculation results by formulas (1-5):

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Depth distribution of PRD created per unit length of projective range by one proton with \(E_p = 40\) keV in silicon with different phosphorous concentration \(N_D\): a – \(T = 300\) K, 1 – \(G_{Si}\) at \(N_D = 10^{15} \div 10^{17}\) cm\(^{-3}\), 2 – \(G_{V}\) at \(N_D = 10^{15} \div 10^{17}\) cm\(^{-3}\); 3 – \(G_{Si}\) at \(N_D = 10^{19}\) cm\(^{-3}\), 4 – \(G_{V}\) at \(N_D = 10^{19}\) cm\(^{-3}\); b – \(T = 83\) K, 1 – \(G_{Si}\) at \(N_D = 10^{15}\) cm\(^{-3}\), 2 – \(G_{V}\) at \(N_D = 10^{15}\) cm\(^{-3}\), 3 – \(G_{Si}\) at \(N_D = 10^{17} \div 10^{19}\) cm\(^{-3}\), 4 – \(G_{V}\) at \(N_D = 10^{17} \div 10^{19}\) cm\(^{-3}\).}
\end{figure}

3. Experiment results

Czochralski silicon n\(^-\)-p-p\(^+\) structures with double-sided photosensitivity were studied. Parameters of the structures: the resistivity of the p-type base is \(\rho = 10\ \Omega \cdot \text{cm}\); equilibrium holes concentration is \(p_0 \approx 10^{15}\) cm\(^{-3}\); the depth of diffusion junctions (n\(^-\)-p and p-p\(^+\)) is \(d_n \approx d_p \approx 0.45\ \mu\text{m}\); the thickness is \(L \approx 200\ \mu\text{m}\); phosphorous surface concentration is \(N_P \approx 10^{20}\) cm\(^{-3}\); boron surface concentration is \(N_B \approx 10^{20}\) cm\(^{-3}\); area \(S \approx 1\ \text{cm}^2\). Samples were obtained by laser separation of silicon plates using a solid-state YAG laser in a pulse mode.

The structures were irradiated by protons under the following conditions: protons energy is \(E_p = 40\) keV and fluence is \(F_p = 10^{15}\) cm\(^{-2}\); samples temperature is \(T_p = 300\) K and \(T_p = 83\) K; irradiated sample side – n\(^-\); irradiation source – Extrion/Varian implanter.

Current-voltage characteristics of silicon n\(^-\)-p-p\(^+\) structures were obtained on the semiconductor device parameter analyzer (IPPP-1) at the temperature of \(T = 300\) K. Dark I-V curves were approximated by a single exponential model:

\[
I = I_0 \left\{ \exp \left[ \frac{e(U - IR_s)}{a kT} \right] \right\} + \frac{U - IR_s}{R_{sh}},
\]

where \(e\) – elementary charge, \(I_0\) – the reverse saturation current, \(R_s\) – the lumped series resistance, \(a\) – the ideality factor of n-p junction space charge region, \(k\) – the Boltzmann's constant, \(T\) – the absolute temperature, \(R_{sh}\) – the bypass resistance. As a result of the approximation, parameters \(I_0, a, R_s, R_{sh}\) were determined.

Figure 2 shows experimental I-V curves of silicon n\(^-\)-p-p\(^+\) structures.
Figure 2. Current-voltage characteristics of silicon n⁺-p-p⁺ structures:

1 – \( T_p = 300 \) K; 2 – \( T_p = 83 \) K; 3 – unirradiated sample

Parameters calculated from model (1) are presented in table 1.

| Sample | \( I_0 \), A | \( a \) | \( R_s \), Ω | \( R_{sh} \), Ω |
|--------|-------------|-------|-------------|-------------|
| 1      | 1.5 \times 10^{-8} | 1.3   | 2.2         | 1.1 \times 10^5 |
| 2      | 1.6 \times 10^{-9} | 1.2   | 2.3         | 1.1 \times 10^5 |
| 3      | 1.6 \times 10^{-8} | 1.6   | 4.2         | 3.4 \times 10^5 |

The ideality factor is \( a = 1.6 \) for sample 3. It indicates that the main contribution to current-voltage characteristics in the voltage range of \( U < 0.6 \) V is given by a space charge region.

Protons with energy \( E_p = 40 \) keV have average projective range \( \approx 0.46 \) µm and therefore radiation defects produced by protons are located in the n-region. Consequently, the lifetime, the diffusion length of minority carriers and the concentration of majority carriers decrease. This increases the contribution of quasi-neutral part of the n-region to amperage \( I \) that is observed in the reducing of the ideality factor \( a \) for sample 1 \((T_p = 300 \) K\) is less than \( a \) for unirradiated sample 3.

The n-region gives the main contribution to the I-V characteristic of sample 2 \((T_p = 83 \) K\), as well as sample 1. This is confirmed by the factor \( a \) value close to 1. Unlike sample 1, value \( I_0 \) of sample 2 decreased by an order of magnitude. This is due to a much smaller number of radiation defects in the region of the maximum of distribution \( G_{Si} \), \( G_{V} \) produced in n-region at \( T_p = 83 \) K compared with \( T_p = 300 \) K (figure 1).

\( R_s \) is less for irradiated samples than for unirradiated samples. Perhaps this is due to a decrease in the surface resistance. \( R_{sh} \) is also less for irradiated samples. This can be caused by an increase in the density of surface states at the sample end faces.

The transmission spectra \( T_s(\lambda) \) in the IR region were measured at \( T = 300 \) K in the range of 1.3\( \pm \)27.1 µm by spectrometer BRUKER VERTEX 70.

The experimental transmission spectra \( T_s(\lambda) \) were approximated by the absorption model by free carriers in a heavily doped layer:
\[
T_i(\lambda) = \exp \left[ -C_0 \left( \frac{C_{n,\lambda} + C_{n} \lambda^{1/2} + C_{i} \lambda^{3/2}}{1 + \left( C_{n,\lambda} + C_{n} \lambda^{1/2} + C_{i} \lambda^{3/2} \right)^2} \right) \right] - \alpha_i.
\] (7)

parameters \( C_0, C_{n,\lambda}, C_{n}, C_{i}, \alpha_i \) were calculated numerically.

Figure 3 shows experimental transmission spectra \( T_i(\lambda) \) of studied structures. Calculated values of approximation parameters are shown in table 2.

![Figure 3. The experimental transmission spectra: 1 \( T_p = 300 \) K, 2 \( T_p = 83 \) K, 3 – unirradiated sample](image)

### Table 2. Parameters of the absorption model by free carriers

| Sample | \( C_0, \mu m^{-1} \) | \( C_{n,\lambda}, \mu m^{-1} \) | \( C_{n}, \mu m^{1/2} \) | \( C_{i}, \mu m^{3/2} \) | \( \alpha_i \) | \( \lambda_c, \mu m \) |
|--------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1      | 0.43                 | 0.0006               | 0.39                 | 0.001                | 1.34                 | 19.2                 |
| 2      | 0.47                 | 0.00055              | 0.39                 | 0.0011               | 1.07                 | 18.5                 |
| 3      | 0.51                 | 0                   | 0.39                 | 0.0009               | 1.48                 | 20.7                 |

Parameters of the absorption model by free carriers show that the absorption by free carriers with the scattering by acoustic phonons predominates over the absorption with the scattering by ionized impurities in the wavelength range of \( \lambda < \lambda_c \):

\[
C_{a} \cdot \lambda^{1/2} > C_{i} \cdot \lambda^{3/2}.
\] (8)

The contribution to the scattering by ionized impurities increases in the range of \( \lambda > \lambda_c \), so this process dominates.

Parameter \( C_0 \) reflects electron concentration decrease \( n_e \) in a heavily doped part of \( n^+ \)-region after a proton irradiation, where \( N_D(x) > 10^{18} \) cm\(^{-3} \), \( x < 250 \) nm. \( C_{n,\lambda} \) and \( C_i \) reflect the increase (due to radiation defects formation) concentration of neutral and ionized carrier scattering centers accordingly. Values of \( C_0 \) and \( C_{n,\lambda} \) for samples 1, 2 confirm the less radiation damage to the heavily doped part of \( n^+ \)-region of sample 2 by comparison with sample 1. This corresponds to smaller values \( G_{S_0}, G_{V} \) at \( T_p = 83 \) K compared at \( T_p = 300 \) K (figure 1).

Parameter \( C_a \) characterizes the absorption by free carriers due to the process of scattering by acoustic phonons. \( C_0 \) has not changed after an irradiation.

Factor \( \alpha_i \) characterizes the contribution of processes not related to the absorption by free carriers. The \( \alpha_i \) decrease in irradiated samples is due to a change in the optical properties of the silicon structures surface.
4. Conclusion
The PRD formation model, taking into account the neutral and charged state of the V-Si pair, explains changes in the parameters of the experimental volt-ampere characteristics and transmission spectra of silicon n⁺-p⁺-p⁺-p⁺ structures upon irradiation of the n⁺-layer by a proton flux with energy $E_p = 40$ keV, dose $F_p = 10^{15}$ cm⁻² and sample temperatures $T_p = 300$ K, $T_p = 83$ K.

The obtained results make it possible to draw the following conclusion: the low-energy proton irradiation of silicon n⁺-p⁺-p⁺-p⁺ structures with $E_p = 40$ keV at the temperature of samples equals to $T_p = 83$ K substantially reduces the amount of radiation defects (formed in the n⁺-layer) in the region of the distribution maximum of the PRD mean number at the depth of $x = 390$ nm compared to similar irradiation conditions at $T_p = 300$ K. This makes it possible to change electrophysical and optical properties of the n⁺-region at a distance of $x < 250$ nm from the surface.

This conclusion is not applicable to silicon p⁺-n⁻-n⁻ structures, since for silicon of p-type conductivity, as well as with a low concentration of donors and acceptors, the irradiation temperature over a wide range of values does not affect the probability of the PRD formation. Silicon structures with an n⁺-p junction have a higher radiation resistance than structures with a p⁺-n junction upon irradiation with low-energy protons.

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