Influence of low-energy proton irradiation on the effective lifetime in the space charge region of silicon $n^{+}$-$p$ junctions

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Abstract. The effect of low-energy proton irradiation on the pulse characteristics of silicon $n^{+}$-$p$-$p^{+}$ structures is analyzed. It is shown that irradiation with protons with an energy of 180 keV and a dose of $10^{15}$ cm$^{-2}$ creates a region with an effective lifetime of $5.5 \times 10^{-8}$ s in the space charge region of the $n^{+}$-$p$ junction. Such elements can be used to create high-speed photodiodes with an operating modulation frequency of 18 MHz.

1. Introduction

Technologies of proton irradiation of semiconductor devices allow selective introduction of recombination centers into silicon structures, reduction of the effective lifetime of charge carriers in hidden layers and creation of layers with hydrogen-containing centers [1]. The disturbed layer formed as a result of implantation of hydrogen ions is heterogeneous. The integral characteristics of the disturbed layer are studied in the work [2]. Reducing the lifetime of charge carriers in the local volume of the structure makes it possible to improve the totality of static and frequency characteristics of devices [3].

The influence of protons with energies $E_{p} = 40$ keV and $E_{p} = 180$ keV (irradiated samples were kept at temperatures $T_{p} = 83$ K and $T_{p} = 300$ K) on the parameters of the current-voltage (I–V) characteristics of silicon photovoltaic structures with a diffused $n^{+}$-$p$ junction with the depth $d_{n} = 0.45 \mu$m is shown in [4, 5]. Protons with an initial energy of 40 keV predominantly change the physical properties of the $n^{+}$-layer, and protons with an initial energy of 180 keV change the properties of the space charge region (SCR) in the $p$-layer.

Using the model of the formation of primary radiation defects (PRD) in silicon [6, 7], the depth distributions of the average number of interstitial silicon $G_{Si}$, vacancies $G_{V}$, divacances $G_{W}$ created by one proton per unit of the projective path length are calculated (figure 1).

Protons with an initial energy of $E_{p} = 40$ keV at temperatures $T_{p} = 83$ K and $T_{p} = 300$ K create primary radiation defects (PRD) in the $n^{+}$-layer at a distance of 0.41 $\mu$m from the surface. Protons with an initial energy of $E_{p} = 180$ keV create PRD in 1.51 $\mu$m in the entire of SCR $n^{+}$-$p$-junction. The number of radiation defects at the maximum of distribution in the $n^{+}$-layer at $E_{p} = 40$ keV, $T_{p} = 83$ K is much less than in the $n^{+}$-layer at $E_{p} = 40$ keV, $T_{p} = 300$ K and also in the $p$-layer at $E_{p} = 180$ keV, $T_{p} = 83$ K. Therefore, irradiation by protons with energy of 180 keV significantly reduces the effective lifetime of charge carriers [8].
Measurements of the photoconductivity decay are used to determine the lifetime [9, 10]. Measurements of the lifetime of minority carriers by the method of recording photoconductivity caused by microwave radiation are used to control the results of technological impacts [11]. Pulsed illumination is used to determine the effect of structural defects on the volume component of the lifetime of minority carriers and the recombination rate in the p-n junction in a two-sided polycrystalline silicon solar cell [12]. In order to exclude the time dependence of the photocurrent and photoconductivity used in the methods [9–12], the transient voltage in unlit silicon n+-p-p+n- structures irradiated with low-energy protons was measured in this work.

The aim of the work is to analyze the effect of low-energy proton irradiation on the pulse characteristics and lifetime of silicon structures with n+-p junction.

2. Research methods

Experimentally investigated the n+-p-p+n- structure of silicon grown by the Czochralski method, with a volume resistance of the p-type base $\rho = 10 \, \Omega \cdot cm$ and the concentration of equilibrium holes $p_0 \approx 10^{15} \, \text{cm}^{-3}$, the depth of diffusion of the n+-p and p-p+n- junctions $d_n \approx d_p \approx 0.45 \, \mu m$, thickness $L \approx 200 \, \mu m$. The surface concentrations of phosphorus and boron were $N_p \approx 10^{20} \, \text{cm}^{-3}$ and $N_B \approx 10^{20} \, \text{cm}^{-3}$. Samples with an area of $S \approx 1 \, \text{cm}^2$ were obtained by laser separation of plates using a solid-state YAG-laser in pulsed mode.

The samples were irradiated from the side of n+-layer by a proton flux with energy of $E_p = 40 \, \text{keV}$, $180 \, \text{keV}$ and with dose $F_p = 10^{15} \, \text{cm}^{-2}$ at sample temperatures $T_p = 300 \, \text{K}, T_p = 83 \, \text{K}$ on the implantator Extrion/Varian: no. 1 – $E_p = 180 \, \text{keV}, T_p = 83 \, \text{K}$; no. 2 – $E_p = 40 \, \text{keV}, T_p = 83 \, \text{K}$; no. 3 – $E_p = 40 \, \text{keV}, T_p = 300 \, \text{K}$. Control sample no. 4 was not irradiated.

The pulse characteristics were measured using a digital oscilloscope DSOX2022A, that includes the functions of a voltage pulse generator and a multimeter. The basic electrical diagram is shown in figure 2. To determine the switching time, bipolar rectangular voltage pulses with constant amplitude of 10 mV and a frequency of 200 kHz were used. The dependence of the voltage $U$ on time $t$ for the studied samples was measured in the dark (shown in figure 3).
Figure 2. Basic electrical diagram: 1 – voltage pulse generator, 2 – cable resistance $R = 0.1$ Ohm, 3 – high-frequency sensor $f_{\text{max}} = 300$ MHz, 4 – oscilloscope, 5 – studied sample.

Figure 3. Pulse characteristics at a pulse frequency of 200 kHz: 1 – sample no. 1, 2 – sample no. 2, 3 – sample no. 3, 4 – sample no. 4.

3. Analysis of the research results
The functions $U(t)$ (figure 3) are approximated with sufficient accuracy by the one-exponential dependence of the voltage on time (equation 1) for samples no. 2, no. 3, no. 4, and two-exponential dependence (equation 2) for sample no. 1.

$$U(t) = 2\Lambda \exp\{- (t - t_0)/\tau\} - A,$$

$$U(t) = 2\Lambda \left[ a_1 \exp\{- (t - t_0)/\tau_1\} + a_2 \exp\{- (t - t_0)/\tau_2\}\right] - A,$$

where $\Lambda = \pm 10$ mV – the amplitude of the bipolar voltage pulse, $t_0$ – the beginning of the countdown, $\tau, \tau_1, \tau_2, a_1, a_2$ – parameters determined as a result of the approximation.
The dependences $U(t)$ for samples no. 2, no. 3, no. 4 are close to each other. The following switching time values were found for these samples: no. 2 $- \tau = 6.6 \times 10^{-7}$ s, no. 3 $- \tau = 6.3 \times 10^{-7}$ s, no. 4 $- \tau = 6.4 \times 10^{-7}$ s. Two values were found for sample no. 1: $\tau_1 = 4.2 \times 10^{-7}$ s, $\tau_2 = 5.5 \times 10^{-8}$ s.

The values of the switching time can be explained using the depth distributions of the average number of primary radiation defects (PRD), shown in figure 1.

The number of PRDs created in the $n^*$-layer at a distance of 0.41 $\mu$m from the surface by protons with $E_p = 40$ keV at $T_p = 83$ K and at $T_p = 300$ K differs from each other by several times. However, the values of $\tau$ in the irradiated samples no. 2, no. 3 and unirradiated sample no. 4 are close and, therefore, cannot be the lifetime of holes in the $n^*$-layer. These values are much smaller than the lifetime of the electrons in the $p$-type base. Therefore, we assume that the measured dependences of $U(t)$ are determined by the voltage drop in the SCR of the $n^*$-$p$ junction, and the values $\tau$ are the effective lifetimes of charge carriers in this region.

The presence of two values $\tau_1$ and $\tau_2$ for sample no. 1 indicates that structure of the SCR of sample no. 1 has changed, there are two regions with different values of the effective lifetime. The value $\tau_2$ refers to the region with a high concentration of radiation defects near the Bragg peak, located at $x = 1.48$ $\mu$m (figure 1).

4. Conclusion

In the silicon structure, protons with energy of 180 keV create PRD in a layer with a thickness of 1.51 $\mu$m, and protons with energy of 40 keV create PRD in a layer with a thickness of 0.41 $\mu$m. At the irradiation temperature of the samples of 83 K, the amount of PRD in the distribution peak at the end of the projective path of a proton with $E_p = 40$ keV is much less than for a proton with $E_p = 180$ keV, which is due to the difference in the separation processes of Si, $V$ pairs silicon of $n$- and $p$-types of conductivity [4, 5]. Irradiation with protons with $E_p = 180$ keV changes the physical properties of the high-doped $n^*$-type layer and the entire SCR of the $n^*$-$p$ junction. Protons with $E_p = 40$ keV change the properties of the $n$-type layer without affecting the SCR if the depth of the $n^*$-$p$ junction exceeds the average length of the proton's projective path.

As a result of irradiation with protons with energy of 180 keV and a dose of $10^{15}$ cm$^{-2}$, the properties of the SCR $n^*$-$p$ junction changed so that the switching time decreased to $5.5 \times 10^{-8}$ s. Such elements can be used to create high-speed structures with an operating modulation frequency of 18 MHz.

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