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Effect of proton irradiation on the properties of high-voltage integrated $4H$-SiC Schottky diodes at operating temperatures

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The effect of proton irradiation (proton energy 15 MeV) on the parameters of high-voltage $4H$-SiC integrated Schottky diodes (JBS) was studied for the first time in the operating temperature range Ti (23 and 175°C). The blocking voltage of the diodes under study, U_b, was 600 and 1700 V. For devices with $U_b = 600$ V, the fluence range was $5 \cdot 10^{13}-1 \cdot 10^{14}$ cm^{-2}; for devices with $U_b = 1700$ V, the fluence range was $3 \cdot 10^{13}-6 \cdot 10^{13}$ cm^{-2}. An increase in the irradiation temperature leads to a noticeable decrease in the effect of irradiation on the current-voltage characteristics of the diodes. The effect of annealing on the current-voltage characteristics of irradiated devices is studied.

Keywords: Silicon carbide, Schottky diodes, proton irradiation, current-voltage characteristics, annealing.

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1. Introduction

Powerful high-voltage silicon carbide integrated Schottky diodes based on $4H$-SiC ($4H$-SiC junction barrier Schottky diodes, JBS) have been playing an increasingly important role every year in applications such as automotive and space electronics, nuclear power plant equipment, power supplies, solar cell converters, etc., etc. The effect of proton irradiation on the properties of these devices was studied in a number of papers (see, for example, [1–6] and references in these papers). The range of proton energies used during irradiation was in the range 100 keV — 62.5 MeV, fluence values Φ were in the range of $5 \cdot 10^7-10^{14}$ cm^{-2}.

The irradiation at room temperature was used in an overwhelming number of works. In work [5], the maximum irradiation temperature T_i was 500°C. It is shown that the radiation resistance of the devices is monotonously increasing with the growth of T_i. It is established that the spectrum of defects occurring in SiC under high-temperature („hot") irradiation differs significantly from the spectrum of defects introduced during irradiation at a room temperature. The work [6] studied the proton irradiation under the temperature range of T_i 100–400 K. The study of the features arising from proton irradiation at low temperatures is of considerable interest both from the point of view of fundamental issues of defect formation and for understanding the features of the operation of instruments in near-Earth orbits and in space.

From a practical point of view, however, the study of the effect of irradiation in the temperature range from room temperature to the maximum permissible operating temperature for high-voltage Schottky diodes (175°C) [7,8] is of the greatest interest. The vast majority of diodes used in practice operate in this temperature range [9].

The impact of irradiation with protons with an energy of 15 MeV on the parameters of high-voltage $4H$-SiC JBS was studied in this paper for the irradiation temperature $T_i = 23$°C and the maximum operating temperature $T_i = 175$°C.

2. Experimental conditions

JBS structures with blocking voltage $U_b = 1700$ V (CPW3-1700SO10) and $U_b = 600$ V (GW3-S06010) were irradiated with protons with an energy of 15 MeV on the cyclotron MGTs-20 [10]. The initial concentration of uncompensated impurity (N_d-N_a) in the n-diode base with $U_b = 1700$ V was $3.4 \cdot 10^{15}$ cm^{-3}. The value (N_d-N_a) in the diode base with $U_b = 600$ V was equal to 10^{16} cm^{-3}. With a small forward bias of the exponential forward volt-ampere characteristic, both types of diodes were characterized by a near-ideal volt-ampere characteristic $I = I_o \exp(qU/\beta kT)$ [4,5] with the value of the ideality coefficient $\beta = 1.02-1.05$. With a small reverse bias, the leakage current amounted to $\sim 10^{-12}-10^{-11}$ A (here q — elementary charge, k — Boltzmann constant).

The samples were irradiated in a pulsed mode with a pulse repetition rate of 100 Hz at a pulse duration of 2.5 ms. The current density of the proton beam was 10–100 nA/cm^2. The temperature was maintained with an accuracy of ±5°C during the irradiation. The path length of protons with an energy of 15 MeV (calculated using the program SRIM [11]) was 1 mm. The distribution of the defects introduced by irradiation is uniform with very high accuracy with the diode base length of $L \leq 10$ microns.

The irradiated structures were annealed in the atmosphere of dry nitrogen at temperatures of 200 and 300°C for 60 min.

The voltage-ampere characteristics of the diodes before and after irradiation and after annealing were measured at room temperature in the single pulse mode ensuring the isothermal character of the measurements.

3. Results and discussion

Figure 1 shows the forward volt-ampere ($I-V$) characteristics of the sample with a blocking voltage of 1700 V (CPW3-1700SO10) in the region of direct voltages exceeding „cut-off voltage“, i.e., in conditions when the diode base is exposed to the overwhelming part of the applied voltage. With relatively small forward bias, neither electron nor proton irradiation has a noticeable effect on the parameters of forward volt-ampere characteristics in the region of exponential dependence of current on voltage [12,13].

The measured value of the differential resistance of the base $R_d = 0.092$ Ohm agrees very well with the manufacturer's data in an unirradiated diode (curve *1*) [8]. The resistance of R_d has increased to $R_d = 0.81$ Ohm after the irradiation with fluence $\Phi = 3 \cdot 10^{13}\,\text{cm}^{-2}$ at room temperature (23°C). The electron concentration in the irradiated diode decreased by ~ 8.8 times with the same amount of mobility in the initial and irradiated diodes [14]. The electron removal rate from the diode base due to the generation of acceptor centers [5,12], η_e is $\eta_e = (n_0 - n)/\Phi \approx 100\,\text{cm}^{-1}$ (n_0 — the electron concentration in an unradiated diode, n — the concentration after irradiation.) The obtained value η_e is reasonably consistent with the previously obtained results [13,15].

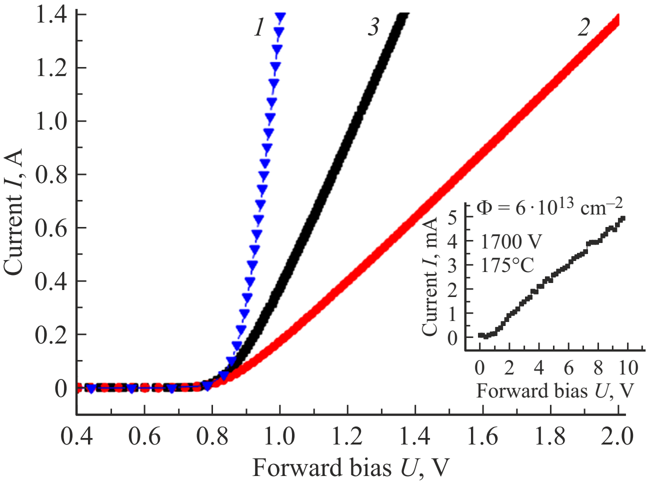

Figure 1. Forward volt-ampere characteristics of a diode with a blocking voltage of 1700 V. *1* — initial $I-V$-characteristic of an unirradiated diode, *2* — $I-V$-characteristic after irradiation with fluence protons $\Phi = 3 \cdot 10^{13}\,\text{cm}^{-2}$ at a room temperature ($T_i = 23°\text{C}$), *3* — same after irradiation with the same fluence at a temperature of $T_i = 175°\text{C}$. The volt-ampere characteristics of the diode after irradiation with fluence $\Phi = 6 \cdot 10^{13}\,\text{cm}^{-2}$ at $T_i = 175°\text{C}$ is shown on the insert.

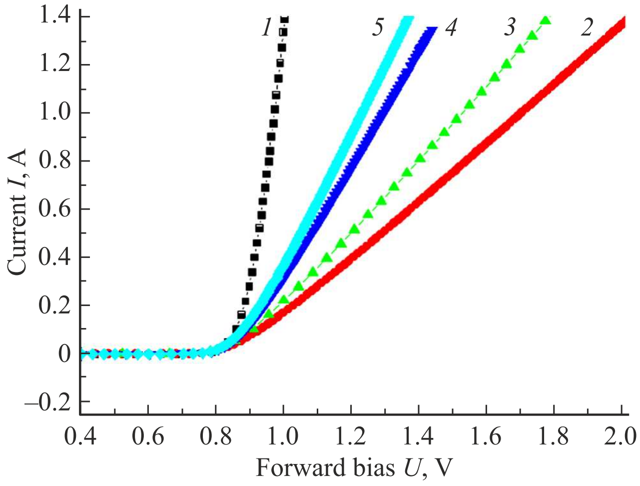

Figure 2. The forward volt-ampere characteristics of a diode with a blocking voltage of 1700 V. *1* — initial $I-V$-characteristic of an unradiated diode, *2* — $I-V$-characteristic after irradiation with protons by fluence $\Phi = 3 \cdot 10^{13}\,\text{cm}^{-2}$ at a room temperature (23°C), *3* — after subsequent annealing in a dry nitrogen atmosphere for 60 min at 200°C, *4* — after repeated annealing for 1 h at 300°C, *5* — volt-ampere characteristic of the diode after irradiation with fluence $\Phi = 3 \cdot 10^{13}\,\text{cm}^{-2}$ at $T_i = 175°\text{C}$ and two consecutive annealing for 1 h at 200 and 300°C.

Irradiation of diodes with the same dose at the maximum operating temperature of 175°C significantly reduces the value of η_e (curve *3*). The value of the differential resistance was $R_d = 0.37$ Ohm after the irradiation with fluence $\Phi = 3 \cdot 10^{13}\,\text{cm}^{-2}$ at $T_i = 175°\text{C}$ i.e., it decreased by ~ 2 times compared to the case of irradiation at a room temperature. The electron removal rate in this case is $\eta_e \approx 85\,\text{cm}^{-1}$

The electron concentration n formally becomes zero at the fluence value $\Phi_0 = n_0/\eta_e \approx 4 \cdot 10^{13}\,\text{cm}^{-2}$ in case of irradiation at 175°C ($\eta_e = 85\,\text{cm}^{-1}$). Physically, this means that at $\Phi > \Phi_0$, the total concentration of the acceptor levels introduced by irradiation exceeds the initial electron concentration of n_0. In this case, the resistance increases significantly more sharply than in the area of linear decline of the dependence $n(\Phi)$ with a further increase of Φ [4,5].

The inset to Fig. 1 shows the $I-V$ characteristic of the diode after irradiation of the diode at $T_i = 175°\text{C}$ with fluence $\Phi > \Phi_0 = 6 \cdot 10^{13}\,\text{cm}^{-2}$. In this case, the differential resistance of the base R_d is equal to 1850 Ohm, i.e. increases by $\approx 5 \cdot 10^3$ times with a twofold increase of the dose.

Fig. 2 shows the results obtained by annealing irradiated diodes with $U_b = 1700$ V.

The curves *1* and *2* in Figure 2 coincide with the corresponding curves in Figure 1. It can be seen that annealing

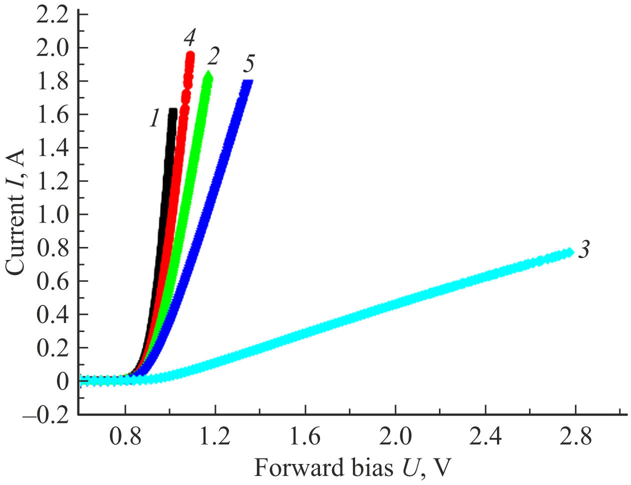

Figure 3. Forward volt-ampere characteristics of a diode with a blocking voltage of 600 V. *1* — initial $I-V$-characteristic of an unirradiated diode, *2* — $I-V$-characteristic after irradiation with protons by fluence $\Phi = 5 \cdot 10^{13}\,\mathrm{cm}^{-2}$ at $T_i = 23°\mathrm{C}$, *3* — same after irradiation at the same temperature with fluence $\Phi = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$, *4* — after irradiation with fluence $\Phi = 5 \cdot 10^{13}\,\mathrm{cm}^{-2}$ at $T_i = 175°\mathrm{C}$, *5* — after irradiation with fluence $1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ at 175°C.

for 60 min at $T_a = 200°\mathrm{C}$ (curve *3*) slightly reduces the differential resistance of the diode irradiated at a room temperature (from $R_d = 0.81$ Ohm to $R_d = 0.59$ Ohm). Subsequent annealing for 60 min at $T_a = 300°\mathrm{C}$ reduces the value of R_d to the value of $R_d = 0.41$ Ohm (curve *4*). However, even after such a double annealing, the value of R_d is still greater than the value of R_d after irradiation at $T_i = 175°\mathrm{C}$ ($R_d = 0.35$ Ohm, curve *5*). This result seems quite understandable: the complete annealing of defects generated by proton irradiation occurs at temperatures in the order of 1800–2100 K (see, for example, [16]). On the other hand, some of the defects are annealed already at temperatures of 500–650 K (200–350°C) [16].

No effective recovery of differential resistance is observed when annealing structures irradiated at $T_i = 175°$ C with a dose of $\Phi > \Phi_0$, i.e., resulting in „full compensation" (see insert on Fig. 1). This situation is similar to the result obtained by irradiating 1700 V diodes at a room temperature with electrons [17]

Double annealing of a diode irradiated at $T_i = 175°\mathrm{C}$ for an hour sequentially at temperatures of 200 and 300°C (curve *5*) has practically no effect on the value of the differential resistance of the base.

Fig. 3 shows the direct $I-V$ characteristics in the direct voltage region for a sample with a blocking voltage of 600 V (GW3-S06010).

The measured differential resistance of the base of an unirradiated diode is $R_d = 0.05$ Ohm. After irradiation at a room temperature with fluence $\Phi = 5 \cdot 10^{13}\,\mathrm{cm}^{-2}$ (curve *2*), the value of R_d was 0.12 Ohm. Irradiation at a room temperature with fluence $\Phi = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ results in the increase of R_d to $R_d = 2.29$ Ohm. Assuming, as before, the mobility is constant, we obtain at $\Phi = 5 \cdot 10^{13}\,\mathrm{cm}^{-2}$ for the electron removal rate $\eta_e = (n_0 - n)/\Phi$ the value $\eta_e \approx 110\,\mathrm{cm}^{-1}$, close to the value obtained for 1700 V diodes.

With $\eta_e \approx 110\,\mathrm{cm}^{-1}$ and with the initial carrier concentration in the non-irradiated diode of $n_0 = 1 \cdot 10^{16}\,\mathrm{cm}^{-3}$, the electron concentration in the base n formally becomes equal to zero when $\Phi_0 = n_0/\eta_e \approx 9 \cdot 10^{13}\,\mathrm{cm}^{-2}$. This value is very close to the value $\Phi = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$, which corresponds to the curve *3* fig. 3. The experimentally measured value of n at $\Phi = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ is less than the original value of n_0 in ~ 46 times. The discrepancy between the values of Φ_0 calculated and estimated from the experiment is $\sim 10\%$ and can be explained both by inaccuracy in the estimation of the experimental value of Φ and „by the" dependence of $n(\Phi)$ when approaching to the „threshold" value Φ_0. The possible mechanisms of such rejuvenation in relation to electron irradiation are considered in [19].

Irradiation at $T_i = 175°\mathrm{C}$ with fluence $\Phi = 5 \cdot 10^{13}\,\mathrm{cm}^{-2}$ (curve *4*) results in the increase of the differential resistance to $R_d = 0.09$ Ohm; after irradiation with fluence $\Phi = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ the value of R_d was 0.24 Ohm (curve *5*). Such values R_d correspond to the electron removal rate of $\eta_e = (n_0 - n)/\Phi \approx 90\,\mathrm{cm}^{-1}$ for $\Phi = 5 \cdot 10^{13}\,\mathrm{cm}^{-2}$ and $\eta_e \approx 80$ for $\Phi = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$. Based on the obtained values of η_e, it should be assumed that the condition „of full compensation", i.e., the situation when the electron concentration n in the base formally becomes zero, is realized for $T_i = 175°\mathrm{C}$ at $\Phi_0 = n_0/\eta_e \approx 1.25 \cdot 10^{14}\,\mathrm{cm}^{-2}$.

Figure 4 shows the results of annealing of 600 V diodes irradiated with doses of $\Phi = 5 \cdot 10^{13}\,\mathrm{cm}^{-2}$ and $1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ (see insert).

The curves *1* and *2* in Fig. 4 coincide with the corresponding curves in Fig. 3. Annealing after irradiation at a room temperature for 60 min at 200°C only slightly reduces the differential resistance (curve *3*). However, after subsequent annealing at 300°C (curve *4*), the volt-ampere characteristic coincides with very good accuracy with $I-V$-characteristic of a diode irradiated at a temperature of $T_i = 175°\mathrm{C}$ (curve *5*). Comparing the data shown in Fig. 2 and 4, it is easy to verify that annealing at a temperature of 300°C for 600 V diodes is more effective than for diodes with a blocking voltage of 1700 V.

It should be noted that raising the annealing temperature to values noticeably exceeding 300°C is apparently impractical. Heating to temperatures exceeding 370°C leads to acceleration and partial melting of metal (Ni) into the surface of silicon carbide [19].

Irradiation of the diode at a temperature of $T_i = 175°\mathrm{C}$ significantly reduces the rate of electron removal compared to irradiation with the same dose at a room temperature (cf. curves *2* and *5* Fig. 4). However, subsequent annealing, in contrast to the irradiation at a room temperature practically does not affect the volt-ampere characteristic of the diode irradiated at $T_i = 175°\mathrm{C}$.

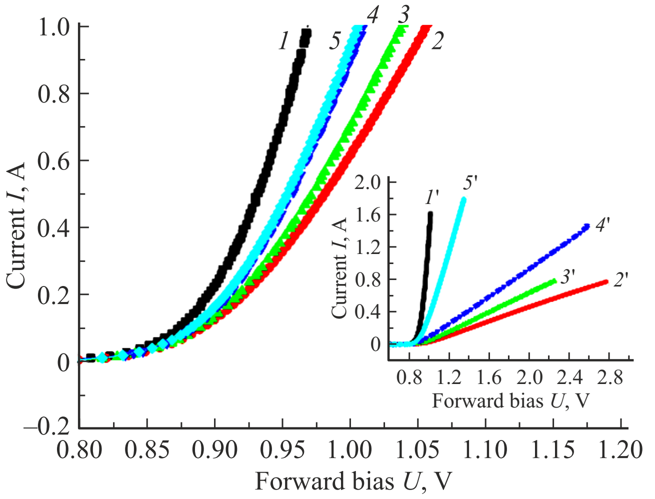

Figure 4. Forward volt-ampere characteristics of a diode with a blocking voltage of 600 V after irradiation with a dose of $\Phi = 5 \cdot 10^{13}\,\text{cm}^{-2}$ and subsequent annealing. *1* — initial $I{-}V$-characteristic of an unirradiated diode, *2* — $I{-}V$-characteristic after irradiation at $T_i = 23^\circ$C, *3* — after subsequent annealing in a dry nitrogen atmosphere for 60 min at 200°C, *4* — after repeated annealing for 1 h at 300°C. *5* — after irradiation at $T_i = 175^\circ$C and two consecutive annealings for 1 h at temperatures of 200 and 300°C. The insert shows data for a diode irradiated with a dose of $\Phi = 1 \cdot 10^{14}\,\text{cm}^{-2}$. *1′* — the initial $I{-}V$ is the characteristic of an unirradiated diode, *2′* — $I{-}V$ is the characteristic after irradiation at $T_i = 23^\circ$C. *3′* — after subsequent annealing (60 min at 200°C), *4′* — after repeated annealing (60 min at 300°C), *5′* — after irradiation at $T_i = 175^\circ$C and two consecutive annealing for 60 min at temperatures of 200 and 300°C.

The insert to Fig. 4 shows the results of annealing of 600 V diodes irradiated with a dose of $\Phi = 1 \cdot 10^{14}\,\text{cm}^{-2}$. When comparing the data shown in Fig. 4 and insert, first of all it should be noted that the results of annealing of structures irradiated with doses of $5 \cdot 10^{13}\,\text{cm}^{-2}$ and $1 \cdot 10^{14}\,\text{cm}^{-2}$, are radically different.

After irradiation with a dose of $\Phi = 5 \cdot 10^{13}\,\text{cm}^{-2}$ and double annealing for 60 min sequentially at 200 and 300°C $I{-}V$-the characteristic of the diode with good accuracy coincides with the volt-ampere characteristic of a diode irradiated with the same dose at $T_i = 175^\circ$C (Fig. 4). The differential resistance of the base, R_d, after such a double annealing is 0.12 Ohm and exceeds the value of R_d in an unirradiated structure in ~ 2.4 times.

At $\Phi = 1 \cdot 10^{14}\,\text{cm}^{-2}$ and after the same double annealing, the value of R_d is an order of magnitude greater and equals ~ 1.15 Ohm (curve *4′* on insert). This value is ~ 5 times higher than the value of R_d after irradiation with the same dose at $T_i = 175^\circ$C and ~ 23 times greater than the resistance of R_d of the unirradiated structure (Fig. 4).

This result serves as a convincing illustration of the very strong dependence of the results of annealing on the radiation dose. The annealing efficiency noticeably decreases even at doses of Φ_0, somewhat smaller, but close enough to the compensation threshold.

4. Conclusion

The paper studied the impact of the proton irradiation (with 15 MeV energy) on the parameters of high-voltage (blocking voltage, U_b, 600 and 1700 V) 4*H*-SiC Schottky diodes in the operating temperature range (23 and 175°C). The radiation resistance of the devices increases with an increase in the irradiation temperature. Even relatively short-term (60 min) annealing at a temperature of 300°C after irradiation can significantly reduce the differential resistance of the diode base R_d with relatively small fluence values Φ $(3 \cdot 10^{13}\,\text{cm}^{-2})$ for devices with $U_b = 1700$ V and $5 \cdot 10^{13}\,\text{cm}^{-2}$ for diodes with $U_b = 600$ V. The effect of annealing becomes practically insignificant in case of relatively large values of Φ, exceeding or even slightly less than the value of Φ_0, corresponding to the case when the concentration of electrons in the base of the diode formally becomes zero.

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Conflict of interest

The authors declare that they have no conflict of interest.

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