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Effect of high temperature irradiation with 15 MeV protons on characteristics of power SiC Schottky diodes

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ABSTRACT

The effect of high-temperature irradiation with 15 MeV protons on the parameters of high-voltage 4H-SiC Schottky diodes has been studied at irradiation temperatures of 23–500 °C and doses in the range from 7×10^{13} to 2×10^{14} cm^{-2}. After the irradiation with a dose of 10^{14} cm^{-2} at room temperature, the forward current at a forward voltage $U = 2$ V decreases by ~10 orders of magnitude. In this case, the cutoff voltage U_c, equal to ~0.6 V in unirradiated devices, decreases to $U_c \approx 0.35$ V. By contrast, irradiation with the same dose at a temperature of 500 °C leads to an increase in U_c up to $U_c \approx 0.8$ V. At the same reference value of the forward voltage $U = 2$ V, the decrease in current, compared to the value in unirradiated devices, was smaller by ~4 orders of magnitude. In the entire range of doses and irradiation temperatures under study, the forward current–voltage characteristic of diodes at $U > U_c$ is linear up to $U \leq 2$ V.

1. Introduction

In recent years, high-power high-voltage silicon carbide-based Schottky diodes (JBS - junction barrier Schottky diodes) have become one of the main components of radiation-hard and high-temperature electronics. The radiation hardness of the diodes with respect to proton irradiation is frequently determines the possibility of using power 4H-SiC JBS in such applications as electronic systems of nuclear reactors and spacecraft electronics. The response of SiC JBS to high-energy proton irradiation is also very important because of the applications in satellites, especially in a study of the Earth's radiation belts.

The effect of room-temperature proton irradiation ("cold" proton irradiation) on the properties of 4H-SiC JBS has been extensively studied (see, e.g., [1–9] and references therein). The effect of proton irradiation at elevated temperatures ("hot" proton irradiation) on the properties of 4H-SiC JBS was examined, as far as we know, only in [10,11]. The results obtained in these studies are contradictory. Thus, in accordance with the data of [10] obtained for epitaxial CVD 4H-SiC p-n structures, the electron removal rate from the conduction band, η, depends very weakly and nonmonotonically on the irradiation temperature T_i. By contrast, according to the data of [11] obtained for the commercial CPW3-1700SO10 Schottky diodes, the value of η decreases monotonically and very significantly with increasing T_i. In addition, the effect of the proton irradiation was examined in both studies only at low doses Φ, when the concentration in the conduction band decreases linearly with increasing dose.

In the present study, the effect of the temperature of irradiation with 15 MeV protons on the characteristics of high-power high-voltage (blocking voltage 1700 V) 4H-SiC JBS was examined for the first time at irradiation temperatures T_i in the range from 23 to 500 ^{0}C and doses Φ of 7×10^{13} to 2×10^{14} cm^{-2}.

2. Experimental

Commercial 4H-SiC CPW3-1700-S010B-WP (Cree/Wolfspeed) Schottky diodes with blocking voltage of 1700 V were irradiated in pulse mode by protons with energy of 15 MeV. The pulse duration was 2.5 ms, and the pulse repetition rate 100 Hz. The irradiation doses were in the range of 7×10^{13} –2×10^{14} cm^{-2}. The temperature T_i at which the samples were irradiated ranged from 23 to 500 °C. For high-temperature irradiations, a special target chamber was designed. The chamber gives an opportunity to perform irradiation at temperatures in the range from

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room temperature to 650 °C. During the irradiation, the temperature of an irradiated sample was maintained within ± 5 °C. The mean free path of 15 MeV protons, calculated using the SRIM program [12], was 1 mm. Thus, the distribution of defects introduced by irradiation can be considered uniform with high accuracy.

The initial concentration of electrons in the base layer of unirradiated diodes, n_0, determined from C-V measurements, was 3.4×10^{15} cm^{-3}. The forward current–voltage characteristics at currents in the range 10^{-12}–2×10^{-3} A were measured in a double-shielded chamber. At currents of 2×10^{-3}–1 A, measurements were made in the pulse mode. The pulse length was 5 μs and the pulse repetition rate 100 Hz.

3. Results and discussion

Fig. 1 shows the forward current–voltage characteristics of the diodes under study after the irradiation with protons at a dose of $\Phi = 1 \times 10^{14}$ cm^{-2} at three irradiation temperatures T_i.

In unirradiated diodes, the forward current I at the reference forward voltage $U = 2$ V is $I \approx 12$ A [13]. As seen from Fig. 1, after the irradiation with a dose of $\Phi = 1 \times 10^{14}$ cm^{-2} at room temperature, the current I at $U = 2$ V is $\approx 10^{-8}$ A, i.e. it decreases by about 9 orders of magnitude. Note that to obtain a similar effect upon electron irradiation of epitaxial SiC layers with a close initial electron concentration $n_0 = 7.2 \times 10^{15}$cm^{-3}, the required dose Φ was 1.9×10^{18} cm^{-2} (at an electron energy of 400 keV) [14].

At $T_i = 300$ °C, the forward current at $U = 2$ V is 8×10^{-5} A. When T_i is raised to 500 °C, the forward current is even approximately ~ 80 times higher. However, it should be borne in mind that the heating of the JBS above 370C leads to the in-diffusion and alloying of the metal (Ni) into the SiC surface [15].

As shown below, the "saturation" portion of the curves in Fig. 1 actually corresponds to the linear dependence of the forward current on forward bias. In unirradiated diodes, the voltage of the transition from the exponential part of the $I(U)$ dependence to the linear current–voltage characteristic (cutoff voltage, U_c) is $U_c \sim 0.6$ V. The cutoff voltage in irradiated diodes depends on the irradiation temperature (Fig. 2)

Fig. 2 shows the forward current–voltage characteristic at $U \geq U_c$ after the irradiation with a dose of $\Phi = 1 \times 10^{14}$ cm^{-2} at room temperature. The inset shows a similar dependence for $T_i = 500$ °C.

In the linear portion of the forward current–voltage characteristic, the differential resistance $R_d \approx 9.5 \times 10^7$ Ohm. The initial value of R_d in unirradiated diodes at a forward bias of ~ 1 V is ~ 0.2 Ohm [13,16]. Thus, irradiation with a dose of $\Phi = 1 \times 10^{14}$ cm^{-2} at room temperature makes R_d more than 8 orders of magnitude higher. Despite such a high resistance, the $I(U)$ dependence at voltages in the range $0.7 \text{ V} \leq U \leq 2$ V is linear with very good accuracy. No indications of the influence exerted by the space charge limited current (SCLC, [17]) are observed. As seen from Fig. 2, the cutoff voltage after the irradiation with a dose of 1×10^{14} cm^{-2} at $T_i = 23$ °C is $U_C \approx 0.35$ V, which is noticeably smaller than $U_C \approx 0.6$ V in unirradiated diodes.

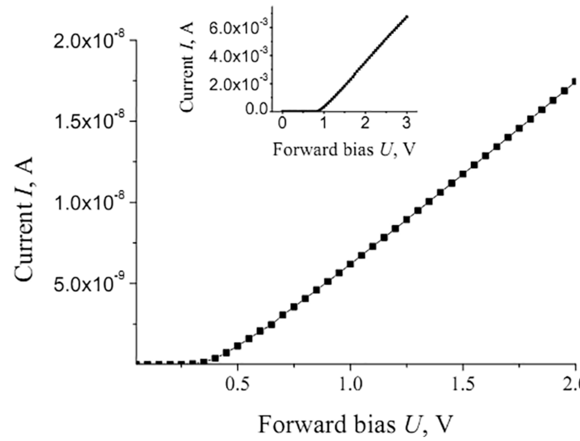

Fig. 2. Forward current–voltage characteristic of the diode after the irradiation with 15 MeV protons at $T_i = 23$ °C. The inset shows a similar dependence for $T_i = 500$ °C. $\Phi = 1 \times 10^{14}$ cm^{-2}.

The inset to Fig. 2 shows the dependence $I(U)$ after the irradiation with a dose of $\Phi = 1 \times 10^{14}$ cm^{-2} at $T_i = 500$C. The resistance $R_d \approx 300$ Ohm in this case. The cutoff voltage U_C is ≈ 0.8 V, that is, it is noticeably higher than the U_C in unirradiated devices.

Since the cutoff voltage is determined by the height of the Schottky barrier, it should be concluded that the proton irradiation with high doses of protons noticeably affects the spectrum of surface states at the metal–semiconductor interface. A noticeable effect of the proton irradiation on surface states at the oxide–semiconductor interface has been obtained for lateral SiC MOSFETs [18,19]. By contrast, irradiation with high doses of electrons has nearly no effect on the height of the Schottky barrier in a wide range of T_i [20].

Fig. 3 compares the dependences of the base resistivity ρ on inverse temperature $1/T_i$ for diodes irradiated with 15 MeV protons (dose $\Phi = 1 \times 10^{14}$ cm^{-2}) and 0.9 MeV electrons (dose $\Phi = 1.3 \times 10^{17}$ cm^{-2}). Curve 2 (electron irradiation) was plotted using the data reported in [20].

Both the curves in Fig. 3 correspond to the doses Φ at which the shallow donor level that determines the electron concentration in the base of unirradiated diodes is completely depleted due to the acceptor levels created by the irradiation. The residual concentration of electrons, which determines the base resistivity, is governed by the thermal generation of electrons from levels created by the irradiation (see, for

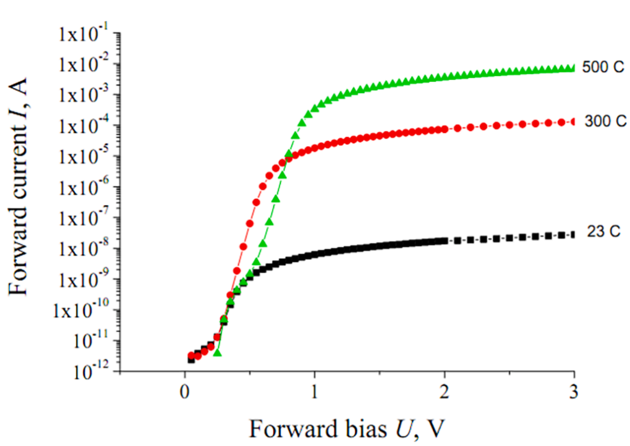

Fig. 1. Forward current–voltage characteristics of diodes after irradiation with 15 MeV protons at three different irradiation temperatures T_i. Dose $\Phi = 1 \times 10^{14}$ cm^{-2}.

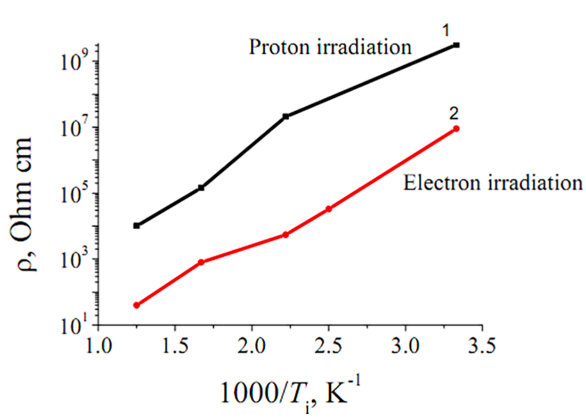

Fig. 3. Dependences of the base resistivity ρ on inverse temperature $1/T_i$ after the irradiation with 15 MeV protons (dose $\Phi = 1 \times 10^{14}$ cm^{-2}) and 0.9 MeV electrons (dose $\Phi = 1.3 \times 10^{17}$ cm^{-2}).

example, [21] and references therein).

Although both the electron and proton irradiations create numerous (and partially identical) local levels in the SiC band gap, the residual electron concentration for both types of irradiation is apparently determined mainly by the thermal generation from the $Z_{1/2}$ level having an activation energy of ~ 0.6 eV [14,22,23].

The fact that curves 1 and 2 in Fig. 3 are practically parallel serves as an additional convincing argument in favor of the statement that, under electron and proton irradiations, the residual concentration of electrons in the base is determined by the thermal generation from the same level.

Fig. 4 shows the current–voltage characteristics of diodes irradiated with three doses Φ at a temperature $T_i = 300$C

The differential resistance R_d in the linear portion of the current–voltage characteristic are 2.4 Ohm, 4.1 $\times$ 10^3 Ohm, and 2 $\times$ 10^4 Ohm for $\Phi = 7 \times 10^{13}$ cm^{-2}, 1×10^{14} cm^{-2}, and 2×10^{14} cm^{-2}, respectively.

When the diodes are irradiated at room temperature, the concentration of electrons in the base of the diodes, *n,* decreases both under the electronic and proton irradiations linearly with increasing Φ at low doses [5,7,23,24] . When the shallow level (nitrogen), which determines the initial level of *n* in the base, is completely depleted, the decrease in concentration of electrons with a further increase in the dose becomes much sharper [14,22]. The corresponding dependences $n(\Phi)$ under "hot" irradiation have not yet been examined. The data presented in Fig. 4, give reason to believe that, upon irradiation at $T_i = 300$ °C, the transition from a linear to a much sharper dependence $n(\Phi)$ lies in the range $7 \times 10^{13} < \Phi < 1 \times 10^{14}$ cm^{-2}.

The above-presented experimental data on the monotonic decrease in base resistance with increasing irradiation temperature T_i indicate obviously decrease in the steady-state concentration of radiation defects responsible for the compensation of the base conductivity of the Schottky diodes under study.

The main radiation defects that create deep acceptor levels in *n*-SiC are carbon vacancies [14,23]. The generation rate of primary defects (vacancies and interstitial atoms) in the T_i range under study is nearly independent of the irradiation temperature [25,26]. However, the process of secondary defect formation may depend on T_i quite significantly. With increasing temperature, the mobility of vacancies grows. The radius of recombination of a vacancy with a genetically related interstitial atom also becomes larger. Therefore, the fraction of vacancies that have escaped recombination and created deep acceptor levels may significantly decrease with increasing T_i.

There is one more possible reason for the dependence of the parameters of the irradiated devices on the temperature T_i. The spectrum of secondary defects itself may depend on the irradiation temperature. Such dependences have been previously observed under hot electron irradiation of silicon and III-V materials [27,28].

Complete characterization of changes in device parameters under influence of radiation, as a rule, includes comparison *C-V* dependences and reverse *I-V* characteristics before and after irradiation. However, as noted in the Ref. [1], with an increase in the radiation dose, an increase in the base resistance makes it impossible to measure the capacitance, since the measured capacitance ceases to depend on the applied voltage. Besides, at high radiation doses used in this study, when practically full compensation is realized, the base capacity is simply equal to the "geometric" value, which is determined by the diameter and thickness of the base. This situation is realized even at zero reverse voltage. The behavior of the reverse current–voltage characteristics at high irradiation doses was investigated under "cold" proton irradiation in Refs. [29,30]. It was demonstrated that the forward high voltage JBS current–voltage characteristics are much more sensitive to proton irradiation, especially at high dose, than parameters of reverse *I-V* characteristics.

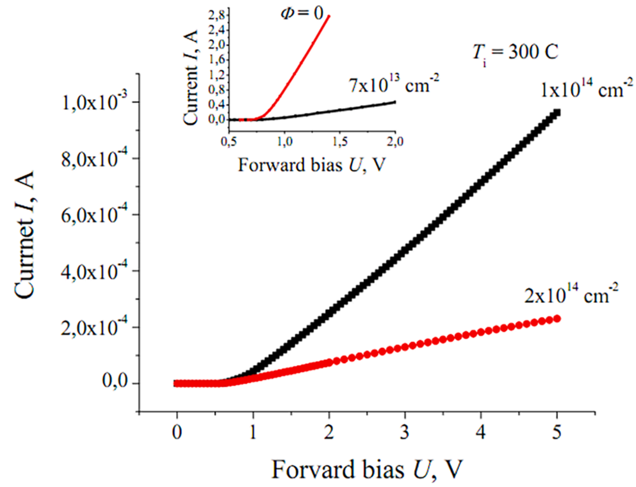

Fig. 4. Forward current–voltage characteristics of diodes after the proton irradiation at $T_i = 300$ °C for two doses $\Phi = 1 \times 10^{14}$ cm^{-2} and $\Phi = 2 \times 10^{14}$ cm^{-2}. The inset shows $I(U)$ characteristics for an unirradiated diode ($\Phi = 0$) and for that irradiated with a dose $\Phi = 7 \times 10^{13}$ cm^{-2}.

4. Conclusion

The effect of a high-temperature proton irradiation on the properties of high-voltage (1700 V blocking voltage) 4H-SiC Schottky diodes was studied. The influence of irradiation with 15 MeV protons was examined at doses Φ in the range from 7×10^{13} to 2×10^{14} cm^{-2} and irradiation temperatures T_i from room temperature to 500 °C. So, after the irradiation with a dose $\Phi = 1 \times 10^{14}$ cm^{-2} at $T_i = 23$ °C, the forward current at the reference value of the forward voltage $U = 2$ V decreases by ~ 9 orders of magnitude. After the irradiation with the same dose at $T_i =$ 500 °C, the current decreases at the same value of U by a lesser amount, 6 orders of magnitude. In contrast to the electron irradiation, the proton irradiation noticeably changes the Schottky barrier height estimated from the cutoff voltage U_c. Irradiation at room temperature with a dose of $\Phi = 1 \times 10^{14}$ cm^{-2} leads to a decrease in U_c from 0.6 V in unirradiated devices to $U_c \approx 0.35$ V. By contrast, irradiation with the same dose at T_i = 500 °C leads to an increase in the cutoff voltage to $U_c \approx 0.8$ V.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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