Semiconductors, 2022, Vol. 56, No. 8

Electron irradiation hardness of high-voltage $4H$-SiC Schottky diodes in the operating temperature range

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Received May 19, 2022
Revised May 30, 2022
Accepted May 30, 2022

Effect of irradiation with 0.9 MeV electrons on the parameters of $4H$-SiC Schottky diodes with a limiting blocking voltage $U_b = 600$ and 1700 V was studied for the first time in the range of operating temperatures T_i (23 and 175°C). The range of fluences Φ was $1 \cdot 10^{16}-2 \cdot 10^{16}\,\text{cm}^{-2}$ for devices with $U_b = 600$ V and $5 \cdot 10^{15}-1.5 \cdot 10^{16}\,\text{cm}^{-2}$ for devices with $U_b = 1700$ V. Irradiation at room temperature increases significantly the differential resistance of the base of the diodes. Irradiation with the same doses at $T_i = 175^\circ$C — i.e. at limiting operating temperature of devices, does not affect practically the parameters of current-voltage characteristics. Nevertheless, the DLTS spectra demonstrate a significant increase in the concentration of deep levels in the upper half of the band gap not only after irradiation at room temperature, but also after irradiation at $T_i = 175^\circ$C.

Keywords: silicon carbide, Schottky diodes, electron irradiation, current-voltage characteristics, DLTS spectra.

DOI: 10.21883/SC.2022.08.54119.9891

1. Introduction

Presently, the silicon carbide integrated Schottky diodes (JBS) with the blocking voltage $U_b = 600$ and 1700 V are important components of the up-to-date electronics. They are used in the automobile and aerospace industries, reactive power compensators, solar power large-area panel converters, pulse power supplies, equipment of the nuclear power stations [1–5]. The radiation hardness of the instruments based on silicon carbide to various types of radiation is often an important criterion, which determines the applicability of corresponding electron components in the space and aviation electronics, the nuclear reactor equipment and in the accelerators of charged particles.

The influence of electron irradiation with the energies in the range $\sim 0.25-10$ MeV on the properties of the silicon carbide and the instruments based thereon has been studied in a number of the investigations (see, for example, [6–10] and the references therein). All those studies include the irradiation at the room temperature. Recently, the studies [11–13] have investigated the influence of the temperature of irradiation by electrons of the $4H$-SiC JBS diodes with the blocking voltage of 1700 V at the temperatures $T_i = 300$ and 500°C, which significantly exceed the limit operating temperature of the diodes. It is shown that the radiation hardness of the instruments is monotonically increasing with the increase in the irradiation temperature. It is demonstrated that at the high-temperature („hot") irradiation there are defects which are absent during irradiation at the room temperature.

However, the temperatures, at which the study [11–13] investigated the influence of the hot irradiation on the properties of the $4H$-SiC JBS structures, significantly exceed the limit operating temperature of the Schottky diodes with the blocking voltage $U_b = 600$ and 1700 V (175°C) [14,15].

The present study has compared the influence of irradiation by the electrons with the energy of 0.9 MeV, which was at the room temperature and the limit operating temperature, on the parameters of the $4H$-SiC JBS with the blocking voltage $U_b = 600$ and 1700 V.

2. Experimental conditions

The CPW3-0600S002.0 Schottky diodes with the blocking voltage 600 V (the average value of the rectified current 2 A) [14] and the diodes CPW3-1700-S010B-WP with the blocking voltage 1700 V and the average value of the rectified current 10 A have been investigated [15]. They have been irradiated by electrons with the energy of 0.9 MeV in the pulse mode with the pulse duration of $330\,\mu$s and the pulse repetition rate of 490 Hz. The radiation defects were generated in the base of the structures with a high degree of homogeneity [11–13]. The diodes were irradiated in a specially designed target chamber in air. The accelerated electrons were extracted from the vacuum accelerator volume through a titanium foil of the thickness of $\sim 50\,\mu$m. The temperature maintenance accuracy was ±5°C. The isothermal current-voltage characteristics of the diodes were measured at the room temperature in a mode of single pulses.

3. Results and discussion

Fig. 1 shows the forward current-voltage characteristics of the diode with the blocking voltage of 600 V. The curve *1* corresponds to the $I-V$-characteristic of the initial (unirradiated) CPW3-0600S002.0 diode within the relatively high shifts. With the small forward biases, in the area of the exponential part of the $I-V$-characteristic, the electron irradiation insignificantly affects the parameters of the current-voltage characteristics [10–12].

The difference resistance of the base R_d in the unirradiated diode was measured to be 0.076 Ohm. As a result of irradiation, the electrons from the conductivity band are captured to the generated acceptor centers, thereby resulting in the increase of the resistance of the base. The irradiation of the $\Phi = 1 \cdot 10^{16}\,\text{cm}^{-2}$ fluence at the room temperature results in the increase of R_d in 1.9 times, to the value $R_d \approx 0.145$ Ohm; after irradiation of the $\Phi = 2 \cdot 10^{16}\,\text{cm}^{-2}$ fluence the value R_d was ≈ 0.35 Ohm, i.e. it has increased in ~ 4.6 times. The initial value of the concentration n_0 is $\approx 10^{16}\,\text{cm}^{-3}$ [16]. With the same value of the mobility in the irradiate and initial diodes [17], removal rate of the electrons from the diode base under effect of radiation η_e is $\eta_e = (n_0 - n)/\Phi \approx 0.4\,\text{cm}^{-1}$ for the both values of the fluence. Here, n — the concentration after irradiation with the corresponding dose. This value is somewhat bigger than the value $\eta_e = 0.25\,\text{cm}^{-1}$, specified in the studies [18,19], but significantly less than the value $\eta_e = 1.67\,\text{cm}^{-1}$, measured in the study [9].

It should be noted that at $\eta_e = 0.4\,\text{cm}^{-1}$, the concentration of the electrons in the base n with the $\Phi = 2.5 \cdot 10^{16}\,\text{cm}^{-2}$ fluence is formally zero. This situation complies with the condition, when the irradiation creates in the semiconductor band gap acceptor centers, whose total concentration is equal to the initial concentration of the electrons in the base n_0. With this and higher values of Φ, the small residual concentration of the electrons in the base is determined by the thermal generation from quite deep levels [7,8,20]. In fact, when irradiating the samples at 23°C with the $\Phi = 3 \cdot 10^{16}\,\text{cm}^{-2}$ fluence, the resistance of the base R_d was $\approx 2 \cdot 10^4$ Ohm (see the insert of Fig. 1).

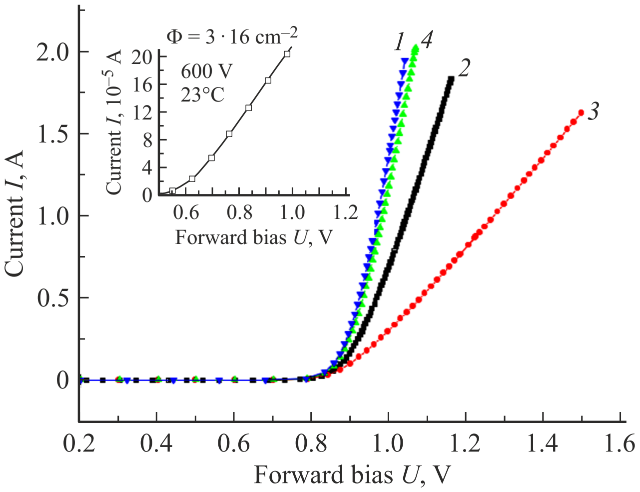

Figure 1. Forward current-voltage characteristics of the diode with the blocking voltage 600 V. *1* — the initial $I-V$-characteristic, *2* — after irradiation by the electrons of the $\Phi = 1 \cdot 10^{16}\,\text{cm}^{-2}$ fluence at the room temperature (23°C), *3* — after irradiation by the electrons of the $\Phi = 2 \cdot 10^{16}\,\text{cm}^{-2}$ fluence at the room temperature, *4* — after irradiation by the electrons with the $\Phi = 2 \cdot 10^{16}\,\text{cm}^{-2}$ fluence at the temperature of 175°C. The insert shows the current-voltage characteristics of the diode after irradiation of the $\Phi = 3 \cdot 10^{16}\,\text{cm}^{-2}$ fluence at 23°C.

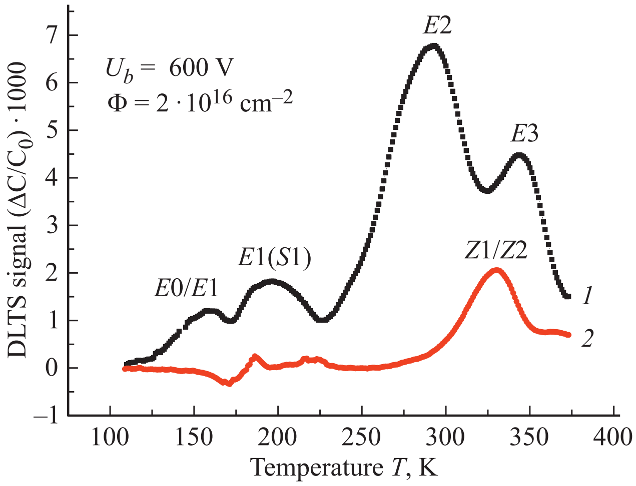

Figure 2. DLTS-spectra of the sample with the blocking voltage $U_b = 600$ V, irradiated by the $\Phi = 2 \cdot 10^{16}\,\text{cm}^{-2}$ dose. *1* — the irradiation temperature $T_i = 23$°C, *2* — $T_i = 175$°C. The rate window — $51\,\text{s}^{-1}$. The amplitudes of the maximums in the unirradiated sample ($\Phi = 0$) throughout the whole range of the temperatures is significantly less than the amplitudes of the maximums after irradiation.

The curve *4* is the $I-V$-characteristic of the diode after irradiation with the $\Phi = 2 \cdot 10^{16}\,\text{cm}^{-2}$ fluence at the temperature $T_i = 175$°C. In this case, the differential resistance of the base R_d was 0.084 Ohm. Thus, in comparison with the resistance of the unirradiated diode, the resistance has increased by $\approx 10\%$. It is quite obvious that the increase in the temperature T_i, at which the it is irradiated, radically increases the radiation hardness of the diodes even at the irradiation temperature within the allowable operating temperature.

Fig. 2 shows the DLTS-spectra recording the levels in the upper half of the band gap.

The designations of the maximums on the DLTS-spectra corresponds to the classification accepted in the study [10]. We note that the study [10] has investigated the DLTS-spectra after irradiation with the electrons with a close energy value (1.05 MeV) of the 4*H*-SiC JBS diodes with the blocking voltage of 1700 V.Nevertheless, the temperature position of the DLTS-peaks (Fig. 2) observed after irradiation at the room temperature quite well agrees with the position of the corresponding peaks observed in the study [10]. The concentrations of the acceptor levels determined from the DLTS-measurements are $N_t^{E2} = 1.4 \cdot 10^{14}\,\mathrm{cm}^{-3}$, $N_t^{E3} = 1.02 \cdot 10^{14}\,\mathrm{cm}^{-3}$, $N_t^{E1/S1} = 3.7 \cdot 10^{13}\,\mathrm{cm}^{-3}$ and $N_t^{E0/E1} = 2.35 \cdot 10^{13}\,\mathrm{cm}^{-3}$ for the $E2, E3, E1/S1$ and $E0/E1$ peaks, respectively.The „double" peak designations $E1/S1$ and $E0/E1$ are caused by the fact that at the relatively high value of the $\Phi = 2 \cdot 10^{16}\,\mathrm{cm}^{-2}$ fluence the unavoidable broadening of the lines result in the partial overlapping and merging of the close peaks. Besides, as it is noted in the study [10], the irradiation exhibits some shift of the peak position in relation to the conductivity band due to formation of the polytype $3C$ in a small concentration, which has a smaller band gap.

When evaluating the full concentration of the acceptor levels created by the irradiation, it is necessary to take into account the existence of the level $EH6/7$, observed int the DLTS spectra at the typical temperature $\sim 570\,\mathrm{K}$ [7,10]. In order to avoid the spontaneous annealing [8] for the studied samples, when measuring the DLTS-spectra, the maximum temperature was 400 K. In the reference samples, the DLTS spectra were studied up to the temperature of $\sim 630\,\mathrm{K}$. The concentration of the $EH6/7$ level was found to be equal to $\approx 10^{14}\,\mathrm{cm}^{-3}$. Thus, the total concentration of the acceptor centers observed in the upper half of the band gap during the irradiation at the room temperature with the $\Phi = 2 \cdot 10^{16}\,\mathrm{cm}^{-2}$ fluence was $N_t^{\Sigma} \approx 4 \cdot 10^{14}\,\mathrm{cm}^{-3}$.

Based on this, it could be expected that the resistance of the diode base would increase as a result of the irradiation only by $\sim 4\%$. Meanwhile, the resistance of the base R_d increases at the same fluence in ~ 4.6 times. Apparently, it should be assumed that in addition to the levels in the upper half of the band gap, the electron irradiation creates acceptor levels in the lower half of the band gap, too.

When irradiating at the temperature of $T_i = 175°\mathrm{C}$ (the curve *2* on Fig. 2), the peak with the maximum amplitude observed at $T \approx 330\,\mathrm{K}$, is identified as the $Z1/Z2$ level. The concentration of the $N_t^{Z2/Z2}$ level is $\sim 5 \cdot 10^{13}\,\mathrm{cm}^{-3}$. The concentrations of the levels corresponding to the maximums at the temperatures $T = 220, 185$ and $171\,\mathrm{K}$, are $N_{t220} \approx 5 \cdot 10^{12}$, $N_{t185} \approx 4.2 \cdot 10^{12}$, $N_{t171} \approx 9 \cdot 10^{12}\,\mathrm{cm}^{-3}$, respectively. Taking that the concentration of the $EH6/7$ level is equal to the concentration in $Z1/Z2$ [7,21], the total concentration N_t^{Σ} of the acceptor levels created by irradiation in the upper half of the band gap at $T_i = 175°\mathrm{C}$, can be evaluated as $N_t^{\Sigma} \approx 1.2 \cdot 10^{14}\,\mathrm{cm}^{-3}$. At this value, it should have been expected the increase in the resistance R_d by $\sim 1.2\%$. Meanwhile, as it is clear from Fig. 1, in this case R_d increases by $\sim 10\%$, i.e. in 7 times more strongly.

The qualitatively similar results were obtained when investigating the effect of irradiation on the diodes with the blocking voltage $U_b = 1700\,\mathrm{V}$ (Fig. 3).

The difference resistance of the base R_d in the unirradiated diode was measured to be 0.08 Ohm. After irradiation with the $\Phi = 5 \cdot 10^{15}\,\mathrm{cm}^{-2}$ fluence at the room temperature the value R_d was 0.145 Ohm (the increase in ~ 1.8 times). After irradiation with the $\Phi = 1.5 \cdot 10^{16}\,\mathrm{cm}^{-2}$ fluence, the value R_d was ≈ 0.23 Ohm (the increase in ~ 2.9 times). The initial value of the concentration n_0 in the studied structures is equal to $3.4 \cdot 10^{15}\,\mathrm{cm}^{-3}$ [10,13]. Thus, for the $\Phi = 1.5 \cdot 10^{16}\,\mathrm{cm}^{-2}$ dose the electron removal rate η_e is $\eta_e \approx 0.15\,\mathrm{cm}^{-1}$. This value coincides with the magnitude η_e, obtained for the diodes of the same type in the study [10] when irradiating with the electrons with a close energy value 1.05 MeV.

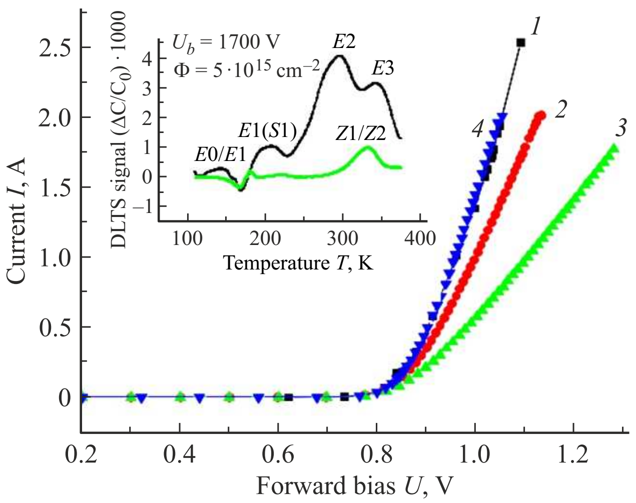

Figure 3. Forward current-voltage characteristics of the diode with the blocking voltage 1700 V. *1* — the initial $I{-}V$-characteristic, *2* — after irradiation by the electrons of the $\Phi = 5 \cdot 10^{15}\,\mathrm{cm}^{-2}$ fluence at the room temperature, *3* — after irradiation by the electrons of the $\Phi = 1.5 \cdot 10^{16}\,\mathrm{cm}^{-2}$ fluence at the room temperature, *4* — after irradiation by the electrons with the $5 \cdot 10^{15}\,\mathrm{cm}^{-2}$ fluence at the temperature of 175°C. The insert shows the DLTS-spectra of the sample with the blocking voltage $U_b = 1700\,\mathrm{V}$, irradiated by the $\Phi = 5 \cdot 10^{15}\,\mathrm{cm}^{-2}$ dose. *1* — the irradiation temperature $T_i = 23°\mathrm{C}$, *2* — $T_i = 175°\mathrm{C}$. The rate window — $51\,\mathrm{s}^{-1}$. The amplitudes of the maximums in the unirradiated sample ($\Phi = 0$) throughout the whole range of the temperatures is significantly less than the amplitudes of the maximums after irradiation.

When irradiating with the $5 \cdot 10^{15}\,\mathrm{cm}^{-2}$ fluence at the temperature 175°C (the curve *4* of Fig. 3), the current-voltage characteristic coincides, with the experimental accuracy, with the $I{-}V$-characteristic of the initial unirradiated sample. Nevertheless, the DLTS-spectra recording the levels in the upper half of the band gap (see the insert of Fig. 3) demonstrate substantial changes in the amplitudes of the corresponding peaks not only after the irradiation at the room temperature, but as a result of the irradiation at the temperature of 175°C (see the insert of Fig. 3).

As it can been seen from comparison of the insert of Fig. 3 with the data given on Fig. 2 the DLTS-spectra are quite similar in both the cases. As noted above, the positions of the peaks also quite well agree with the data given in the study [10] for the same CPW3-1700-S010B diodes irradiated by the electrons of the energy of 1.05 MeV with the $\Phi = 1.2 \cdot 10^{15}\,\mathrm{cm}^{-2}$ fluence at the room temperature. Thus, the temperature position of the $E2, E3$ and $E0/E1$ peaks at the insert of Fig. 3 (the curve *1*) corresponds to the values 290, 345 and 160 K, respectively. In the study [10], the corresponding values of the temperatures for these peaks are 260, 310 and 160 K respectively. As indicated above, some difference in the position of the maximums is explained by unavoidable broadening and partial overlapping of the lines with the significant increase in the fluence.

When irradiating at $T_i = 175°\mathrm{C}$ (the curve *2*), the peak with the maximum amplitude at $T = 317\,\mathrm{K}$ corresponds to the $Z1/Z2$ level with the concentration $N_{t317} \approx 1.2 \cdot 10^{13}\,\mathrm{cm}^{-3}$. The concentrations of the other two levels with a significantly smaller amplitude as observed at the temperatures $T = 180$ and 212 K, are $N_{t180} \approx 8 \cdot 10^{11}$ and $N_{t212} \approx 7.5 \cdot 10^{11}\,\mathrm{cm}^{-3}$. Assuming that at the $EH6/7$ level the concentration is approximately equal to $N_{Z1/Z2} \approx 1.2 \cdot 10^{13}\,\mathrm{cm}^{-}3$, we will find that the total concentration of the acceptor centers, N_t^{Σ}, observed in the upper half of the band gap when irradiating at $T_i = 175°\mathrm{C}$ with the $\Phi = 5 \cdot 10^{15}\,\mathrm{cm}^{-2}$ fluence, was $N_t^{\Sigma} \approx 2.6 \cdot 10^{13}\,\mathrm{cm}^{-3}$, i.e. $< 1\%$ of the initial concentration of the electrons in the unirradiated sample $n_0 = 3.4 \cdot 10^{15}\,\mathrm{cm}^{-3}$.

The obtained results indicate that it is possible to drastically improve the radiation hardness of the high-voltage carbide-silicon Schottky diodes in relation to the electron irradiation with maintaining the increased temperature of the irradiated diodes within the operating range of the temperatures.

4. Conclusion

For the first time, the effect of the irradiation with the electrons of the energy of 0.9 MeV within the operating range of the temperatures on the parameters of the high-voltage 4*H*-SiC Schottky diodes. It is demonstrated that the irradiation with the fluence resulting in the change of the resistance of the base in several times in irradiation at the room temperature, almost has no effect on the resistance of the base when irradiating with the same fluence at the limit operating temperature (175°C). Nevertheless, the DLTS changes demonstrate quite a noticeable increase in the amplitude of the peaks corresponding to the acceptor centers introduced by the irradiation. It is established that when the critical parameter is the radiation hardness, the heating during the irradiation to the relatively small temperature can radically increase the radiation hardness of the instruments.

Funding

This study was carried out under partial financial support of the RSF grant No. 22-12-00003.

Conflict of interest

The authors declare that they have no conflict of interest.

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