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# Impact of high temperature electron irradiation on characteristics of power SiC Schottky diodes

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ABSTRACT

Impact of high temperature electron irradiation on the characteristics of power silicon carbide-based semiconductor devices was studied for the first time. Commercial 4H–SiC integrated Schottky diodes (JBS) with blocking voltage of 1700 V were irradiated with 0.9 MeV electrons at temperatures from 23 to 500$^0$C in the fluence range $\Phi$ from $1 \times 10^{16}$ cm$^{-2}$ to $1.3 \times 10^{17}$ cm$^{-2}$. It was shown that ruggedness of the diodes during high temperature ("hot") irradiation significantly exceeds the ruggedness of diodes at room temperature ("cold") irradiation. With an increase in the irradiation temperature from 23 to 500 °C, the change in the base resistance at a fluence of $1.3 \times 10^{17}$ cm$^{-2}$ decreases by 6 orders of magnitude. In the entire investigated range of irradiation temperatures and fluences, irradiation does not change the height of the metal-semiconductor barrier even at the maximum fluence $\Phi$.

## 1. Introduction

Power 4H–SiC Schottky diodes (JBS - junction barrier Schottky diodes) have become one of the most important elements of high-temperature power electronics in recent years. They are widely used in space electronics, accelerator equipment, nuclear power plants, etc. The possibility of using these devices in high-temperature applications depends largely on their resistance to various types of irradiation at elevated temperatures. Particularly high requirements for radiation resistance are imposed on devices intended to operate during the unloading of spent fuel from nuclear reactors. The effect of room temperature electron irradiation on the properties of high-voltage 4H–SiC Schottky diodes has been studied in many works (see, for example (Castaldini et al., 2004; Danno and Kimoto, 2006; Kaneko and Kimoto, 2011; Kozlovski et al., 2014; Kozlovski et al., 2015; Omotoso et al., 2015; Kozlovski et al., 2017; Hazdra and Vobecký, 2019),). However, as far as we know, the effect of electron irradiation carried out at elevated temperatures still remains unexplored. Meanwhile, works carried out in the 90s of the last century on the study of electron irradiation A3B5 semiconductors at elevated temperatures showed that the radiation resistance can significantly increase with an increase in the temperature at which irradiation is performed (see, for example (Kozlovski et al., 1996),). The first studies of high-temperature proton irradiation on the properties of 4H–SiC Schottky diodes (Kozlovski et al., 2020) also showed that with an increase in the irradiation temperature, the radiation resistance of the diodes increases significantly.

In this paper, the effects of the high temperature electron irradiation on silicon carbide devices are studied for the first time. The effects were investigated on high-power (blocking voltage 1700 V, operating current 10 A) 4H–SiC Schottky diodes in the irradiation temperature range of 23–500 0C.

## 2. Experimental

We have studied commercial *CPW3-1700-S010B-WP* (Cree/Wolfspeed) Schottky diodes with a blocking voltage of 1700 V (https://www.digchip.com/d, 2101). Irradiation with 0.9 MeV electrons was carried out on a resonant transformer accelerator. The pulse repetition rate was 490 Hz, the pulse duration was 330 μs. The average electron beam current density was 12.5 μA cm-2. The mean free path of electrons with

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an energy of 0.9 MeV, λ, in SiC, is ~ 1.0 mm. Thus, at a diode base thickness $L \approx 20$ μm, defects were introduced uniformly over the sample volume.

To carry out high-temperature irradiation, a special target chamber was created. This chamber allowed irradiation in air in the temperature range from room temperature to 600 °C. The accuracy of maintaining the temperature of the sample during irradiation was ±5 °C. The heating rate of the samples was maintained equal to 0.5 deg/s.

## 3. Results and discussion

Fig. 1 shows the forward-voltage characteristics of diodes after irradiation with electrons with a fluence of $\Phi = 6 \times 10^{16}$ cm$^{-2}$ at three values of the temperature during irradiation $T_i$.

It can be seen that the slope of the exponential part of the current-voltage characteristic, following the usual dependence $I = I_s[\exp(qU/nkT - 1]$, does not depend on $T$i. Here $q$ is the elementary charge, $T$ is the absolute temperature, $n$ is the ideality factor, $k$ is the Boltzmann constant, and $I_s$ is the saturation current. The value of the ideality factor $n \approx 1.03$ coincides with the value of $n$ in unirradiated diodes [7, 11]. The saturation current values $I_s \approx 10^{-13}$ A for $T_i = 23$ and 300 °C practically coincide. Irradiation of the samples at $T_i = 500$ °C leads only to a slight increase in the saturation current.

The "saturation" part on the lg$I(U)$ dependence (Fig. 1) corresponds to a linear increase in current with voltage growth $U$ and is determined by the base resistance $R_b$. The $R_b$ value in unirradiated diodes is ~ 0.1 Ohm (Kozlovski et al., 2020; Shabunina et al., 2014). As can be seen from Fig. 1, after irradiation with a fluence of $\Phi = 6 \times 10^{16}$ cm$^{-2}$ at room temperature, the resistance is ~ $10^6$ Ohm. This result is in full agreement with the data of (Kozlovski et al., 2017). As shown in (Kozlovski et al., 2017), this situation corresponds to the case when the shallow donor level responsible for the initial electron concentration in the base of unirradiated diodes is completely depleted, and the "residual" electron concentration is determined by the generation of electrons from the $Z_{1/2}$ level with activation energy of ~ 0.65 eV.

After irradiation of the samples with the same fluence at a temperature of 300 °C, the characteristic value of the base resistance is ~ $10^2$–$10^3$ Ohm. An increase in $T_i$ to 500 °C reduces the $R_b$ value to ~ 1 Ohm.

The inset to Fig. 1 shows the dependence of the base resistivity, $\rho$ on the inverse temperature $T_i$ after irradiation with a fluence of $\Phi = 1.3 \times 10^{17}$ cm$^{-2}$. It can be seen that this dependence can be considered exponential with reasonable accuracy.

It should be noted that even if we assume that each electron, absorbed in the base, creates a charged defect, the total concentration of such defects is $\sim\Phi/\lambda \sim 10^{18}$ cm$^{-3}$. In this case, the electron mobility will decrease with respect to the initial value in unirradiated samples by only a few times (Levinshtein et al., 2001). Meanwhile, the range of variation $\rho$ in the inset to Fig. 1 is ~ 6 orders of magnitude. Therefore, the dependence shown in the inset characterizes with good accuracy the dependence of the conduction electron concentration on the irradiation temperature (at a fluence of $\Phi = 1.3 \times 10^{17}$ cm$^{-2}$)

Fig. 2 shows the current-voltage characteristics of diodes in the region of relatively large forward biases after electron irradiation with a fluence of $\Phi = 1.3 \times 10^{17}$ cm$^{-2}$ at two $T_i$ values.

The $I(U)$ dependences are linear with good accuracy in the range 1V $\leq U \leq$ 2V. Base resistances for two $T_i$ values differ by ~ 6 orders of magnitude. Nevertheless, the cutoff voltages for both $T_i$ values are practically the same and equal to ~ 0.6 V. Since the cutoff voltage is determined by the height of the Schottky barrier, it should be concluded that electron irradiation has practically no effect on the spectrum of surface states at the metal-semiconductor interface. This fact serves as additional confirmation that the main effect of electron irradiation at any irradiation temperature is an increase in the base resistance $R_b$.

Fig. 3 shows the forward current-voltage characteristics of the diode in the region of relatively large forward bias after irradiation at $T_i$ = 300 °C for three fluences $\Phi$.

At $\Phi = 3 \times 10^{16}$ cm$^{-2}$, the differential resistance of the diode in the linear part of the $I(U)$ dependence, $dU/dI \approx 10$ Ohm. For comparison, it can be indicated that when diodes are irradiated with the same fluence at room temperature (23 °C), $R_d = dU/dI \approx 2 \times 10^3$ Ohm. It should be noted that with an increase in the fluence $\Phi$, the influence of the irradiation temperature on the change in the base resistance increases very strongly (Fig. 4).

At relatively low values of $\Phi \leq 10^{16}$ cm$^{-2}$, an increase in the irradiation temperature from room temperature to 300 °C has a relatively weak effect on the electron removal rate. With an increase in the fluence, the difference in the resistivity of the base after irradiation at room temperature and at an elevated temperature increases monotonically, and $\Phi \approx 6 \times 10^{16}$ cm$^{-2}$ it exceeds three orders of magnitude. Under irradiation at room temperature, the dependence $\rho(\Phi)$ follows with a fairly good accuracy the law $\rho \sim\Phi^8$. This result is in satisfactory agreement with the data obtained in (Kozlovski et al., 2017). At the irradiation temperature $T_i$ = 300 °C, the dependence $\rho(\Phi)$ noticeably tends to saturation with increasing fluence. This fact may indicate that the spectrum of local levels introduced by electron irradiation depends significantly on the irradiation temperature $T_i$.

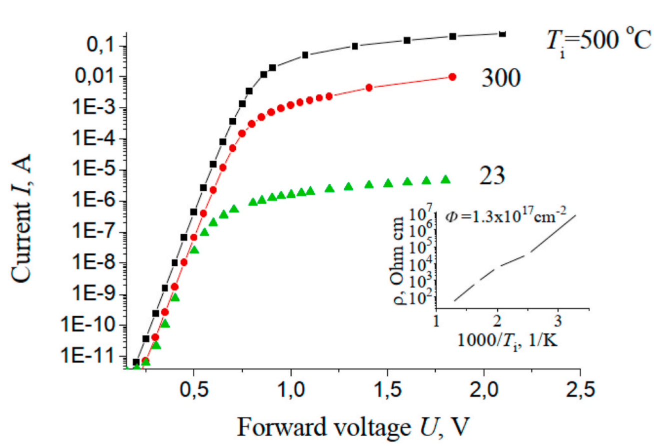


**Fig. 1.** Forward current-voltage characteristics of the diodes after irradiation with 0.9 MeV electrons at three different temperatures $T_i$. Measurements were made at room temperature. Fluence $\Phi = 6 \times 10^{16}$ cm$^{-2}$. Inset shows the dependence of the base resistivity, $\rho$ on the inverse temperature $T_i$ after irradiation with a fluence of $\Phi = 1.3 \times 10^{17}$ cm$^{-2}$.

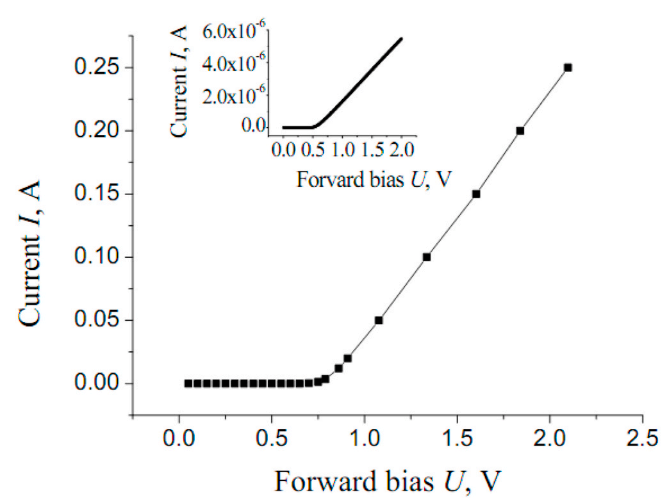


**Fig. 2.** Forward current-voltage characteristics of the diode after electron irradiation at $T_i$ = 500°C. The inset shows a similar dependence for $T_i$ = 23 °C. $\Phi = 1.3 \times 10^{17}$ cm$^{-2}$.

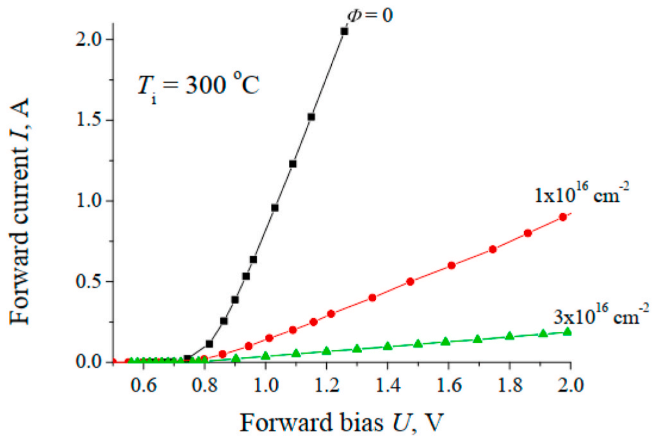


**Fig. 3.** Forward current-voltage characteristics of diodes after electron irradiation at $T_i$ = 300 °C for three fluences $\Phi$.

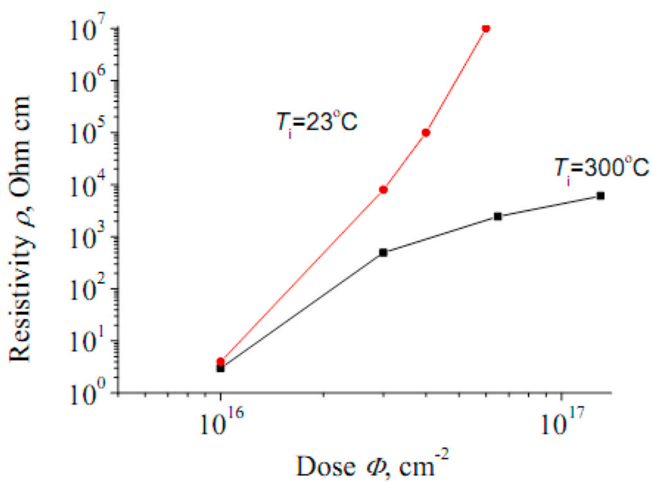


**Fig. 4.** Dependences of the base resitivity $\rho$ on fluence $\Phi$ for two values of irradiation temperature $T_i$.

The results obtained, apparently, require some revision of the existing concepts of radiation defect formation in *n*-type 4H–SiC. As before, it can be assumed that the primary radiation defects introduced by electron irradiation and causing the compensation of conductivity in *n*-type 4H–SiC are associated with the components of the Frenkel pair (vacancy and interstitial atom) only in one of the SiC sublattices, namely, in carbon sublattice (Li et al., 2019). During irradiation, these primary defects partially avoid recombination and are separated into single components. In accordance with the known results of electron irradiation at room temperature (Castaldini et al., 2004; Danno and Kimoto, 2006; Kaneko and Kimoto, 2011; Kozlovski et al., 2014, 2015, 2017; Omotoso et al., 2015; Hazdra and Vobecký, 2019), it was believed that these components form deep acceptor levels $Z_{1/2}$ and $EH_{6/7}$ with activation energies $E_c$ – 0.65 eV and $E_c$ – 1.55 eV, respectively (Kozlovski et al., 2017; Kawahara et al., 2014). The capture of electrons at these levels leads to an increase in the base resistivity. The results obtained in this work indicate, however, the possibility of generating other defects that do not arise upon irradiation at room temperature. The study of DLTS spectra and the study of the temperature dependences of the resistivity of diodes irradiated at high temperatures should clarify the problem posed in this work.

## 4. Conclusion

The effect of electron irradiation at elevated temperatures ("hot electron irradiation") on the characteristics of a silicon carbide-based semiconductor device has been studied for the first time. The change in the parameters of power 1700 V blocking voltage 4H–SiC Schottky diodes under the influence of irradiation with 0.9 MeV electrons was studied in the fluence range $\Phi$ from $1 \times 10^{16}$ cm$^{-2}$ to $1.3 \times 10^{17}$ cm$^{-2}$ and irradiation temperatures $T_i$ from 23 to 500$^0$C. Resistance to radiation damage monotonically increases with an increase in the irradiation temperature. Thus, at $\Phi = 1.3 \times 10^{17}$ cm$^{-2}$, irradiation at room temperature ("cold") irradiation leads to an increase in $R_b$ by ~ 6 orders of magnitude. Under irradiation with the same fluence at $Ti = 500^0$C, the $R_b$ value changes only several times. With an increase in the fluence $\Phi$, the influence of the irradiation temperature on the change in the base resistance increases very strongly. In the entire investigated irradiation temperature and fluences ranges, electron irradiation does not change the height of the Schottky barrier.

## CRediT authorship contribution statement

**A.A. Lebedev:** Conceptualization, Project administration. **V.V. Kozlovski:** Investigation, Data curation. **M.E. Levinshtein:** Investigation, Roles, Writing – original draft, Writing – review & editing. **A.E. Ivanov:** Investigation, Resources. **K.S. Davydovskaya:** Investigation. **V.S. Yuferev:** Investigation, Software. **A.V. Zubov:** Formal analysis.

## 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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