The effects of electron irradiation and thermal dependence measurements on 4H-Sic Schottky diode

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In this paper the effects of high energy (3.0 MeV) electrons irradiation over a dose ranges from 6 to 15 MGy at elevated temperatures 298 to 448 K on the current-voltage characteristics of 4H-SiC Schottky diodes were investigated. The experiment results show that after irradiation with 3.0 MeV forward bias current of the tested diodes decreased, while reverse bias current increased. The degradation of ideality factor, n, saturation current, I_s, and barrier height, Φ_b, were not noticeable after the irradiation. However, the series resistance, R_s, has increased significantly with increasing radiation dose. In addition, temperature dependence current–voltage measurements, were conducted for temperature in the range of 298 to 448 K. The Schottky barrier height, saturation current, and series resistance, are found to be temperature dependent, while ideality factor remained constant.

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1. Introduction

Device reliability and radiation hardness are very important for electronic applications in radiation hard environment. Due to its superior electrical and thermal properties such as wide band gap, high thermal conductivity and high critical breakdown field, 4H-Silicon Carbide (4H-SiC) is currently known to be the most promising material for electronic devices in such environment. This makes it attractive in many applications such as satellite-based systems, detectors and high-temperature electronics in nuclear power industry [1–4]. Therefore, over the last decade, many papers have presented their experimental results and theoretical analysis of electron radiation effects, especially on self-grown 4H-SiC Schottky diodes. Only a few researchers such as Ohyama et al. [5] reported on the electron radiation effects of commercial 4H-SiC Schottky diodes. In this paper, the effects of electron radiation on current-voltage ($I-V$), and temperature dependence current-voltage ($I-V-T$), characteristics of commercial 4H-SiC Schottky diodes were investigated.

2. Experimental details

Diodes used in this experiment are high-voltage, high-speed switching 4H-SiC Schottky diodes fabricated by ROHM with reverse blocking voltage of 650 V. The part number of the tested diodes is SCS220AGC.The diodes were irradiated at Malaysian Nuclear Agency (MNA) using EPS-3000 electron beam machine with 3.0 MeV energy. Four different irradiation dose levels (6, 9, 12 and 15 MGy) were used in this experiment and all diodes were labeled accordingly. Experiment for each dose level was conducted on three devices. Room temperature and temperature dependence $I-V$ measurements, were performed using Keithley 4200 Semiconductor Characterization System (Keithley 4200-SCS). The $I-V-T$ measurements were carried out on a copper heat stage and 3 runs were performed for each measurement for repeatability.

3. Results and discussion

3.1. $I-V$ measurements of the commercial 4H-SiC Schottky diode

All of the results presented in this subsection were obtained from the measurement of 12 commercial 4H-SiC Schottky diodes to assess the quality of the diodes before and after irradiations. Diodes that were irradiated with the same dose level show similar results. Fig. 1 shows the forward and reverse semi-logarithmic $I-V$ characteristics of the tested Schottky diodes before and after irradiation with 6, 9, 12 and 15 MGy. It can be seen from Fig. 1, a that the forward bias (FB) $I-V$ curves exhibit linear behavior at lower voltages and dominated by series resistance at higher voltages (> 0.6 V). After irradiation with 15 MGy, the FB current of the diodes decreased — down to 7 orders of magnitude at 0.9 V. The decreases in the FB current magnitude can be attributed to the introduction of radiation-induced trap levels. These trap levels in the forbidden gap are responsible for the capture of the free carriers and the increase of series resistance correspondingly [2,6–9].

Meanwhile, Fig. 1, b shows the measurement of reverse leakage current from 0 to 100 V. After the irradiation, the reverse bias (RB) leakage current of the tested diodes increased more than one order of magnitude at −100 V. The increment of the leakage current is believed to be due to irradiation-induced defects which create traps at the interface. These traps behave as generation-recombination (G–R) centers which are responsible for emission and capture processes affecting the RB leakage current [10]. Paradzah et al. [11] reported that, the directly proportional relationship between reverse leakage current and reverse

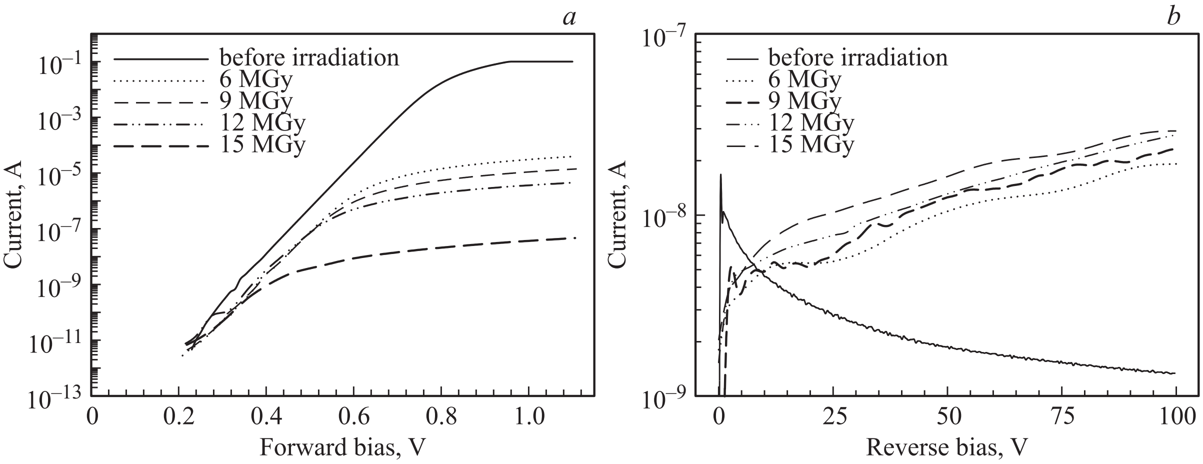

Figure 1. Semi-logarithmic $I-V$ characteristics of commercial 4H-SiC Schottky diodes at different radiation dose level: a — forward bias, b — reverse bias.

voltage is due to the lowering of Schottky barrier. When we increase the reverse voltage, the electric field E will also increase and cause the Schottky barrier to become lower, hence increasing the reverse leakage current.

An interesting result observed at reverse bias measurements, where the $I-V$ characteristics of the tested diodes exhibited a current overshoot signal before irradiation as can be seen in Fig. 1, b at lower bias. However, this current overshoot did not occur after irradiation. It is believed that the observed anomaly is due to the thermal release of captured electrons on shallow traps at low voltage [12]. In order to analyze $I-V$ characteristics of the tested diodes, the ideality factor, n, saturation current, I_s, and series resistance, R_s, have been determined by fitting the linear and high injection region of the FB $I-V$ curves using ideal diode equation:

$$I = I_s \left[\exp\left(-\frac{q(V - IR_s)}{nkT} \right) - 1 \right],$$

where

$$I_s = AA^* T^2 \left(-\frac{q\Phi_b}{kT} \right). \quad (2)$$

In the above equations, I_s is the saturation current, T is the temperature in K, q is the electron charge, V the forward-bias voltage, k is the Boltzmann constant, A is the effective diode area, A^* is effective Richardson, Φ_b is the effective barrier height at zero bias, and n is the ideality factor which measures deviation of practical diodes from ideal thermionic emission theory, R_s, is series resistance of a diode.

The value of the fitted ideality factor, saturation current, series resistance, and calculated barrier height, before and after irradiation are tabulated in Table 1. After the bombardment of 15 MGy of electrons, the ideality factor, increased only from 1.04 to 1.1, remaining close to unity, which confirm that thermionic emission remains as the major transport mechanism during irradiation process [11]. Note also that R_s increased from 1.3 Ω to 15 MΩ, I_s decreased from $4.2 \cdot 10^{-15}$ to $1.4 \cdot 10^{-15}$ A, while Φ_b increased from 1.20 to 1.23 eV. It can be concluded that degradation of ideality factor, saturation current, and barrier height, are not significant after irradiation. However, after irradiation, series resistance, increased significantly. This increment is believed to be due to the same argument before, where the decrement in effective dopant density is caused by radiation-induced traps.

Table 1. Electrical parameters of commercial 4H-SiC Schottky diodes extracted from $I-V$ characteristics at different dose levels

Irradiation dose, MGy	Ideality factor, n	Barrier height, Φ_b (eV)	Saturation current, I_s (A)	Series Resistance, R_s (kΩ)
Before irradiation	1.04	1.20	$4.2 \cdot 10^{-15}$	0.0013
6	1.05	1.24	$8.5 \cdot 10^{-16}$	11
9	1.05	1.24	$8.5 \cdot 10^{-16}$	33.2
12	1.09	1.22	$2.1 \cdot 10^{-15}$	109
15	1.10	1.23	$1.4 \cdot 10^{-15}$	15 000

3.2. Temperature dependence measurements of the commercial 4H-SiC Schottky Diodes

Temperature dependence $I-V$ measurements ($I-V-T$), were conducted for both non-irradiated and irradiated diodes. The measurements were carried out in the temperature range of 298 to 448 K with a step of 25 K. Fig. 2, a and b show the FB and RB $I-V-T$ characteristics of the non-irradiated commercial diode respectively. It can be observed that at low voltages, the FB current of the diodes showed linear behavior and increased up to 6 orders of the magnitude with increasing temperature. Whilst from Fig. 2, b it can be observed that the RB leakage current showed similar behavior to the FB current where the current increased with the increasing temperature. The increment in the RB leakage current ranges from $2.6 \cdot 10^{-10}$ (at 298 K) to $2.6 \cdot 10^{-5}$ A (at 448 K) at 200 V. In both cases, increase of the current at high temperatures are related to the rise in the number of generated free carriers which increase with temperature.

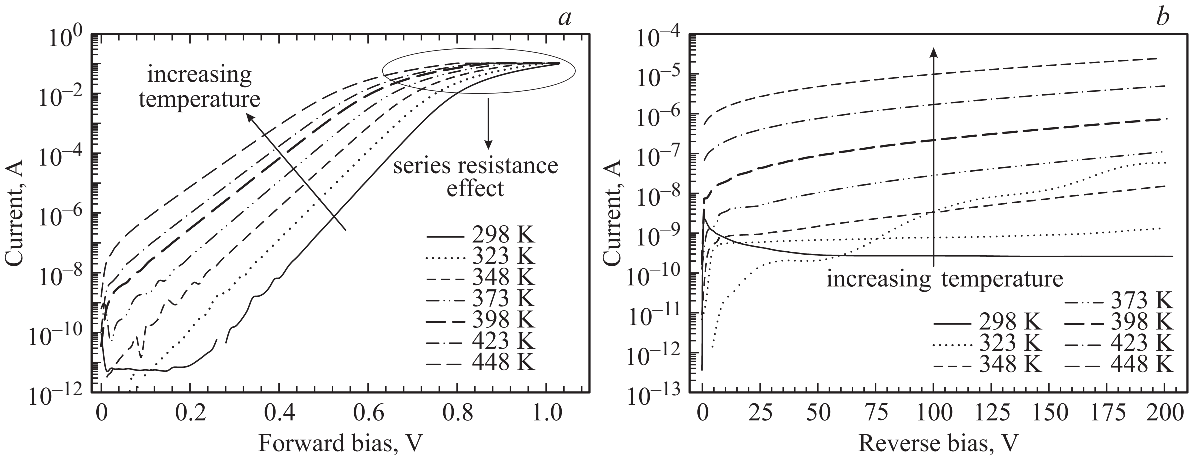

Figure 2. Semi-logarithmic $I-V$ characteristics of non-irradiated commercial 4H-SiC Schottky diode at different temperatures: a — forward bias, b — reverse bias.

To further analyze the $I-V-T$ characteristics of the non-irradiated diodes, ideality factor, saturation current, and series resistance, were determined by fitting the linear region and high injection region of the forward bias $I-V$ curve using Eq. (1). The resulting I_s values were then computed by Eq. (2) to obtain the barrier height, Φ_b.

The values of above mentioned fitted parameters for non-irradiated sample are given in Table 2. The fitting results indicate that the saturation current, is strongly dependent on the temperature increasing 10^6 times from $2.8 \cdot 10^{-15}$ (at 298 K) to $6.2 \cdot 10^{-9}$ A (at 448 K). However, the effect of high temperature on ideality factor, n, and series resistance, R_s, are not significant. It was found that ideality factor, and series resistance, of non-irradiated diode increased from 1.04 to 1.07 and from 1.95 to 2.03 Ω, respectively. As reported by V. Lakshmi Devi et al. the rise of the series resistance, is most probably due to decrease of the electron mobility with elevated temperature in the drift layer of the Schottky contact [13]. Moreover, it was found that with the increases in temperature, the barrier height, Φ_b, of the non-irradiated diode decreased from 1.21 to 1.19 eV. We believe that the reduction of the barrier heights is mainly attributed to the reduction of interfacial defects densities. The reduction of the interfacial defect density by annealing may change the pinning at the Fermi level, resulting in a decrease of the barrier heights Φ_b [14].

Table 2. Electrical parameters of non-irradiated commercial 4H-SiC Schottky diodes extracted from $I-V$ characteristics for different temperatures

Temperature, T (K)	Ideality factor, n	Barrier height, Φ_b (eV)	Saturation current, I_s (A)	Series Resistance, R_s (Ω)
298	1.04	1.21	$2.8 \cdot 10^{-15}$	1.95
323	1.04	1.20	$1.4 \cdot 10^{-13}$	2.03
348	1.06	1.19	$5.1 \cdot 10^{-12}$	2.02
373	1.08	1.17	$1.0 \cdot 10^{-11}$	2.02
398	1.08	1.16	$1.3 \cdot 10^{-9}$	2.04
423	1.07	1.18	$5.3 \cdot 10^{-9}$	2.03
448	1.07	1.19	$6.2 \cdot 10^{-9}$	2.03

Table 3. Electrical parameters of irradiated commercial 4H-SiC Schottky diodes extracted from $I-V$ characteristics for different temperatures

Temperature, T (K)	Ideality factor, n	Barrier height, Φ_b (eV)	Saturation current, I_s (A)	Series Resistance, R_s (Ω)
298	1.09	1.22	$2.1 \cdot 10^{-15}$	109000
323	1.08	1.22	$7.7 \cdot 10^{-14}$	185000
348	1.08	1.23	$1.1 \cdot 10^{-12}$	51000
373	1.08	1.23	$1.7 \cdot 10^{-11}$	17000
398	1.08	1.23	$1.7 \cdot 10^{-10}$	595
423	1.07	1.23	$1.5 \cdot 10^{-9}$	225
448	1.07	1.25	$1.3 \cdot 10^{-8}$	92

In addition, the FB and RB $I-V-T$ characteristics of the irradiated commercial diode are shown in Fig. 3, a and b respectively. As it was observed earlier for the non-irradiated diode, at low voltages, the RB current increased up to 6 orders of magnitude with temperature. However, for the irradiated diodes, as can be seen in Fig. 3, b, the increase in temperature up to 398 K does not affect the RB leakage current significantly. This may be due to the lack of electrons with sufficient energy to escape from radiation-induced traps. Furthermore, there is a significant increases in the leakage current at the temperature greater than 423 K. This result further strengthens the hypothesis that the increase in RB current is due to increase in the number of electrons that have enough energy to be released from traps at high temperature.

Table 3 shows fitted values of ideality factor, saturation current, series resistance, and barrier height, of the irradiated diode at high temperature. It was found that, the degradation of ideality factor, n, of irradiated diodes due to high temperature is insignificant and decreased from 1.09 at 298 K to 1.07 at 448 K, while barrier height, Φ_b, increased

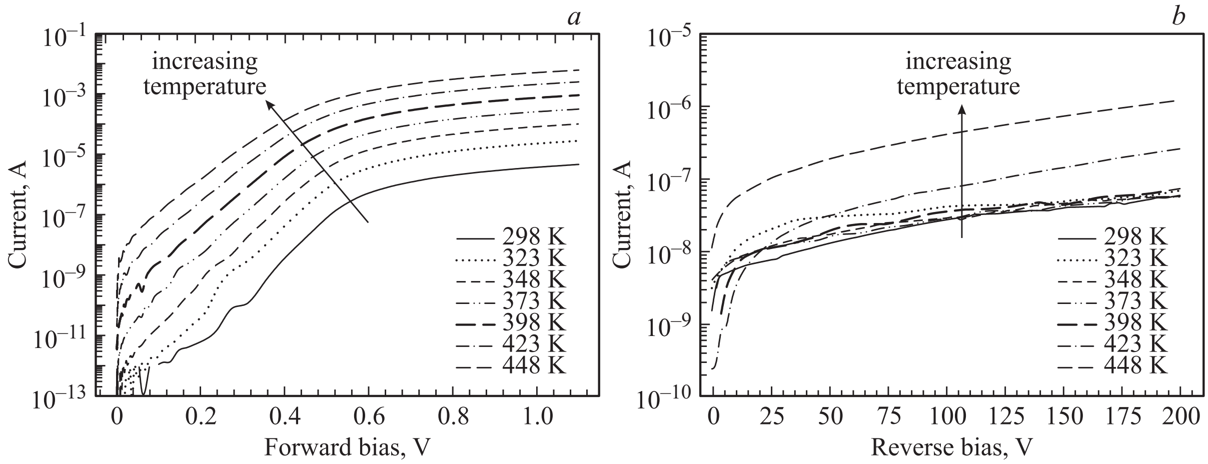

Figure 3. Semi-logarithmic $I-V$ characteristics of irradiated commercial 4H-SiC Schottky diode at different temperatures: a — forward bias, b — reverse bias.

from 1.22 at 298 K to 1.25 eV at 448 K. The observed increment in the barrier height, is due to barrier inhomogeneities at the Schottky contact. It is known that the current transport across the metal-semiconductor interface is a temperature-activated process, and at low temperature, electrons are able to pass over the lower barriers. Therefore, current transport will be dominated by current flowing through the area of lower barrier. As the temperature increase, the number of electrons that have sufficient energy to surmount the higher barrier increase. Correspondingly, the dominant barrier height increase with temperature [15].

Moreover, it can be seen from Table 3 that series resistance, of irradiated diode strongly changed with temperature. In contrast to the non-irradiated diode R_s of irradiated diode decrease at high temperature. The decrease of R_s in the irradiated diode is due to the radiation-induced defects in the bulk of 4H-SiC. These defects can interact electrically with the dopant, leading to its deactivation and finally to the reduction of free-carriers. Therefore, the high value of R_s at low temperatures is believed due to lack of free charge carriers [14,15]. As temperature increase, the number of electrons which have sufficient energy to be released from the traps also increase. Eventually, it results in a reduction of series resistances, R_s.

4. Conclusion

In conclusion, the effects of electron radiation and high temperature on the $I-V$ characteristics of commercial 4H-SiC Schottky diodes were investigated. All devices were irradiated with 3.0 MeV electron radiation at four different dose levels. Experiment results show that after irradiation, the forward bias current of the tested diodes decreased, while reverse bias current increased. It is found that degradation of ideality factor, n, saturation current, I_s, and barrier height, Φ_b, was not noticeable after irradiation. However, the series resistance, R_s, increased significantly with radiation dose level. This is believed to be a result of decrease in the effective dopant density due to radiation-induced traps. Moreover, effects of high temperature on the electrical characteristics of the diodes in the range of 298 to 448 K were also investigated. The Schottky barrier height, Φ_b, saturation current, I_s, and series resistance, R_s, are found to be temperature dependent, while ideality factor, n, almost remained constant.

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