Electrical characterization of high energy electron irradiated Ni/4*H*-SiC Schottky barrier diodes

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The effect of high energy electron (HEE) irradiation on Ni/4*H*-SiC Schottky barrier diodes was evaluated by current-voltage (*I-V*) and capacitance-voltage (*C-V*) measurements at room temperature. Electron irradiation was achieved by using a radioactive strontium source with peak emission energy of 2.3 MeV. Irradiation was performed in fluence steps of 4.9×10^{13} cm^{-2} until a total fluence of 5.4×10^{14} cm^{-2} was reached. The Schottky barrier height determined from (*I-V*) measurements was not significantly changed by irradiation while that obtained from (*C-V*) measurements increased with irradiation. The ideality factor was obtained before irradiation as 1.05 and this value did not significantly change as a result of irradiation. The series resistance increased from 47 Ω before irradiation to 74 Ω after a total electron fluence of 5.4×10^{14} cm^{-2}. The net donor concentration decreased with increasing irradiation fluence from 4.6×10^{14} cm^{-3} to 3.0×10^{14} cm^{-3} from which the carrier removal rate was calculated to be 0.37 cm^{-1}.

Key words: *n*-type 4*H*-SiC, Schottky barrier diodes, carrier removal rate, electrical characterization and high energy electron irradiation

INTRODUCTION

Silicon carbide is a wide bandgap semiconductor with high electron mobility, high electron saturation drift velocity and high thermal conductivity.[1-3] These properties make SiC a suitable semiconductor for fabrication of devices that can operate at high power, high frequency and high temperatures. [2, 3] Additionally, SiC is also a radiation hard material and this makes it a suitable semiconductor for devices that can operate both in high radiation environments and at high temperatures. [4, 5]

Although it is radiation hard, SiC is not totally resistant to irradiation damage. If exposed to radiation particles such as electrons, neutrons, alpha particles and protons with a certain minimum energy called the threshold displacement energy, radiation damage can be manifest in the material. [6] To produce carbon displacement damage in 6*H*-SiC, electron energy of ~ 108 ± 7 keV is required. [7] For silicon displacement damage, more particle energy is required. Irradiation by particles with at least the minimum displacement energy can thus lead to degradation of devices, such as radiation detectors, that operate in radiation harsh environments.

If a material is to be successfully used in the fabrication of devices for radiation detection, it is important to have a profound understanding of the effect of radiation both on Schottky diodes and on the semiconductor in general.

The effect of particle irradiation on SiC has been studied by several researchers.[8-12] Nava *et al*. [8] performed high energy (8.2 MeV) electron irradiation in addition to proton and gamma ray irradiations on SiC diodes. Their study focused on testing the radiation hardness of SiC and determined the charge collection efficiency to be hundred percent. The effect of irradiation was also observed to affect the Schottky barrier height and reverse leakage current although this was correlated with the micropipe density of the samples used. The effect of electron irradiation on defect formation and determination of carrier lifetimes has also been studied in SiC. [9-12] Study of defects induced by irradiation is very important as many of these defects have acceptor-like properties hence they reduce the semiconductor net donor concentration.

In this study high-energy electron (HEE) irradiation is performed using small and increasing fluences so the change in the diode characteristics can be closely monitored. This allows for the monitoring of changes in the net donor concentration from which the carrier removal rate is determined.

I-*V* and *C*-*V* measurements are used in the analysis of the effect of HEE irradiation on SiC. Changes in the diode ideality factor (n), Schottky barrier height (Φ_b), series resistance (R_S) and reverse leakage current (I_L) can be used to quantify the effect of particle irradiation on diode. Changes in the bulk of the semiconductor are analysed by monitoring the changes in the net donor concentration.

EXPERIMENTAL PROCEDURE

Fabrication of diodes

Nitrogen doped epilayer SiC samples with a doping density of 3.4×10^{14} cm^{-3} were used in this study. The back side of the sample had a high doping density of 1×10^{18} cm^{-3} for the fabrication of ohmic contacts.

The samples were cleaned by first degreasing in boiling trichloroethylene for five minutes followed by boiling in acetone for five minutes and lastly boiling them in methanol for a further five minutes. The samples were then rinsed in de-ionised water followed by a thirty seconds rinsing in 40% concentrated hydrofluoric acid. Samples were then rinsed in de-ionised water again before nitrogen gas was used to dry the samples.

The 300 nm thick nickel ohmic contacts were evaporated by resistive evaporation of nickel onto the backside of the samples. The ohmic contacts were annealed in argon ambient at 950 °C for 15 minutes.

Prior to Schottky barrier diodes fabrication, the ohmic contacts were cleaned in the same way as before except that instead of five minute boiling in each of the three solvents, the samples were only rinsed ultrasonic bath for three minutes in the same solvents at room temperature. The 100 nm thick nickel Schottky barrier diodes with a diameter of ~0.6 mm were deposited by resistive evaporation.

Measurements

The *I-V* measurements were carried out using a Hewlett Packard pA Meter / DC Voltage Source 4140B instrument. The instrument allows current measurement from 10^{-15}A with an accuracy of 0.5%. Measurements were carried out in a closed station to ensure there was no light illumination. Ideality factor values, Schottky barrier height, and series resistance values were obtained from *I-V* measurements.

The *C-V* measurements were carried out in the same closed station using a 4192A LF Impedance Analyzer capable of measuring in the 5 Hz to 13 MHz frequency range. The measurements were performed at a constant frequency of 1 MHz. *C-V* measurements were used to determine the values of the Schottky barrier height and the net donor concentration. The carrier removal rate was calculated from the changes in the net donor concentration with fluence.

High-energy electron irradiation

The HEE irradiation was performed by using radioactive strontium disc. Strontium decays to yttrium with an emission of ~0.5 MeV and then to zirconium with the emission of ~2.3 MeV. The electrons emitted from the strontium source therefore have a continuous energy distribution, with more than 70% having energy above 0.25 MeV. More information on the radioactive source can be obtained from Auret *et al*. [13] The radioactive disc was placed on top of the sample in a way that the emitted electrons were directed onto the diodes as shown in Fig. 1.

The electrons were emitted from the radioactive strontium disc at a fluence rate of 6.8×10^{9} cm^{-2} s^{-1}. This fluence rate is for HEEs with above threshold energy for damage in SiC. The samples were irradiated in steps of 2 hours (= 4.9×10^{13} cm^{-2} fluences) until a total cumulative time of 22 hours (= 5.4×10^{14} cm^{-2} fluences) was reached. *I-V* and *C-V* measurements were carried out after each irradiation.

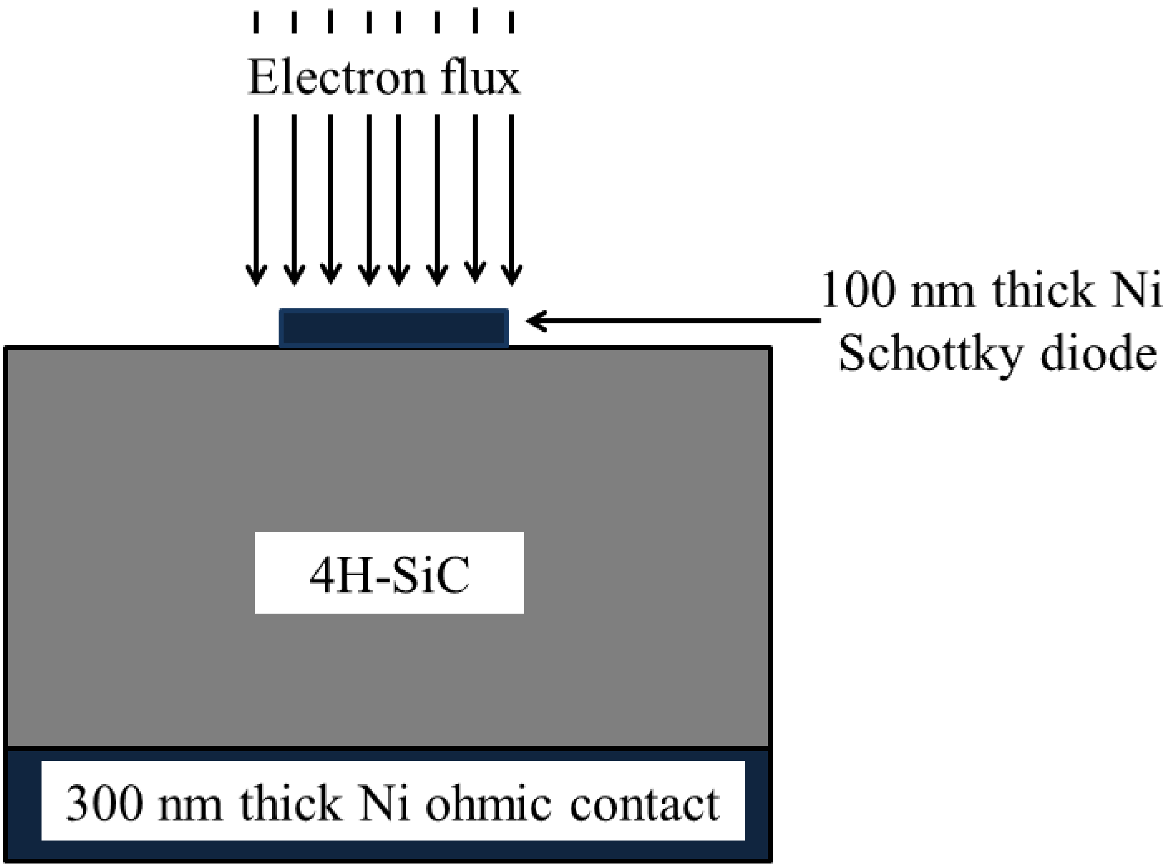

Fig. 1. Cross sectional schematic diagram of a diode being irradiated by electrons.

RESULTS AND DISCUSSION

I-V Results

Forward *I-V* characteristic obtained before and after irradiation are shown in Fig. 2. The thermionic emission model, Eq. 1 was used to analyse the experimental data. [14, 15]

$$I = I_s[\exp(q(V - IR_s)/nk_BT) - 1] \quad (1)$$

I_S is the saturation current, T is the temperature at which the measurements are made, q is the electron charge, n is the ideality factor, k_B is the Boltzmann constant, V is the applied voltage and R_S is the diode series resistance. The expression for I_s is given by equation:

$$I_S = AA^*T^2 \exp(-q\Phi_{b0}/nk_BT) \quad (2)$$

A is the diode area, Φ_{b0} is the zero bias barrier Schottky height and A^* is the Richardson constant. The theoretical A^* value for 4*H*-SiC is 146 $\mathrm{Acm^{-2}K^{-1}}$.[16] From Eqs 1 and 2, the expressions for the n and the Φ_b are respectively obtained as [14]:

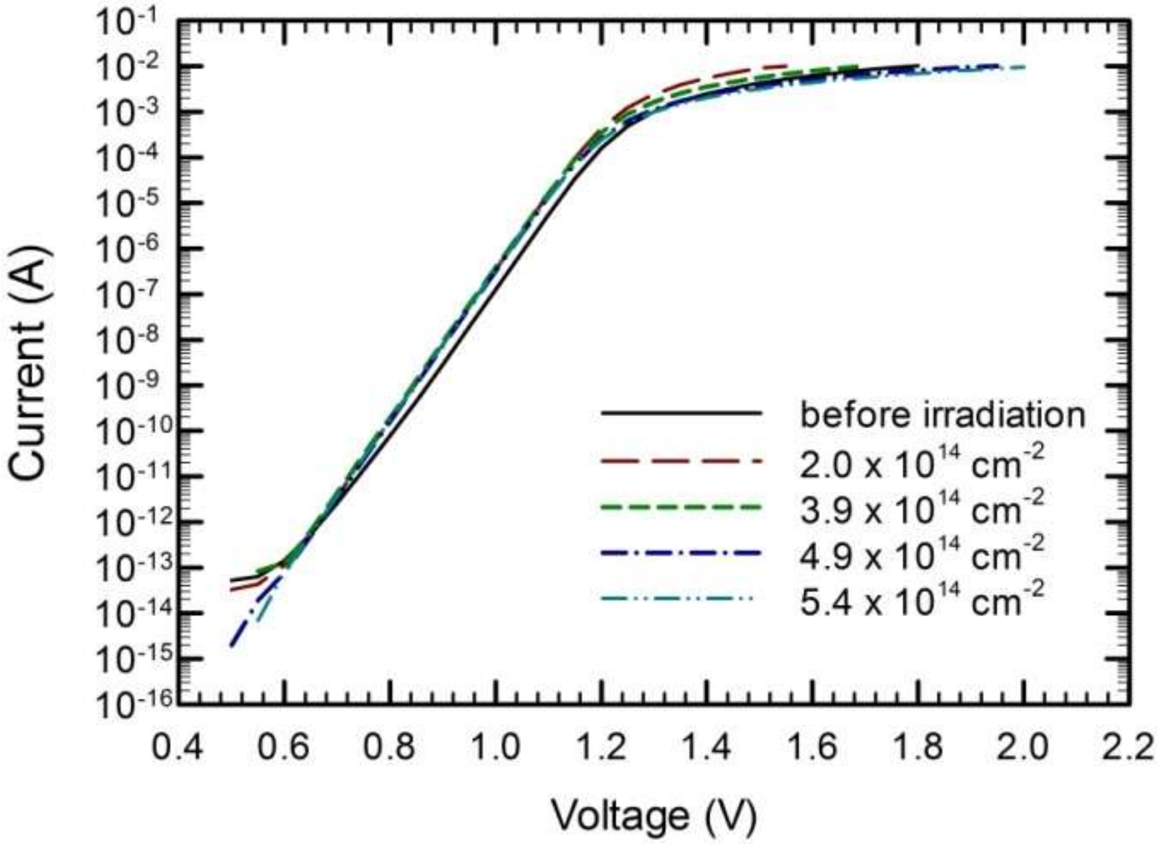

Fig. 2. Semi-logarithmic *I-V* curves as a function of electron irradiation fluence up to a fluence of 5.4×10^{14} cm^{-2}**.** All steps were measured although only certain measurements are shown in this plot.

$$n = q/k_B T\,(dV/d\ln I) \tag{3}$$

and

$$\Phi_b = (k_B T/q)\ln(AA^* T^2/I_s) \tag{4}$$

Before irradiation, the ideality factor was obtained as 1.05. This value is fairly close to unity thus confirming that the thermionic emission process is indeed the main current transport mechanism across the metal-semiconductor junction. During irradiation there was no significant increase in the values of the ideality factor. This is an indication that thermionic emission remains the dominant current transport mechanism during the irradiation process. HEE irradiation induces defects in SiC. [17-19] Some defects may lead generation recombination current leading to higher ideality factors. Fig. 2 shows that there is a small increase in the forward current at low voltages comparing the un-irradiated diodes with the irradiated diodes. This is an indication that defects were induced by irradiation and contribute to the electron current transport across the

Schottky barrier. However the non-increasing ideality factor indicates that thermionic emission remains the dominant current transport mechanism although generation recombination is also present.

The Schottky barrier height from *I-V* measurements was obtained, before irradiation as 1.62 eV. According to the Schottky–Mott theory, [20] an ideal Schottky barrier height, Φ_{b0} is given by $e\Phi_{b0} = e(\Phi_m - \chi_{sc})$, where Φ_m is the metal work function and χ_{sc} is the semiconductor electron affinity. Considering the metal work function of nickel, 5.35 eV [21] and the electron affinity of SiC, 3.10 eV [22], the ideal Schottky barrier for Ni/4*H*-SiC would be 2.25 eV. The smaller Schottky barrier height value obtained is possibly due to the presence of interface states, or the inhomogeneity of the metal-semiconductor interface. [23] The Schottky barrier height did not significantly change as a result of electron irradiation.

cm^{-2}**.** All steps were measured although only certain measurements are shown in this plot.

The reverse leakage current was measured from 0 V to –50 V, Fig. 3. Only very small increases in the reverse leakage current with irradiation are observed at voltages greater than –10 V. This increase is attributed to the creation of generation-recombination centres as a result of irradiation induced atomic displacements. At

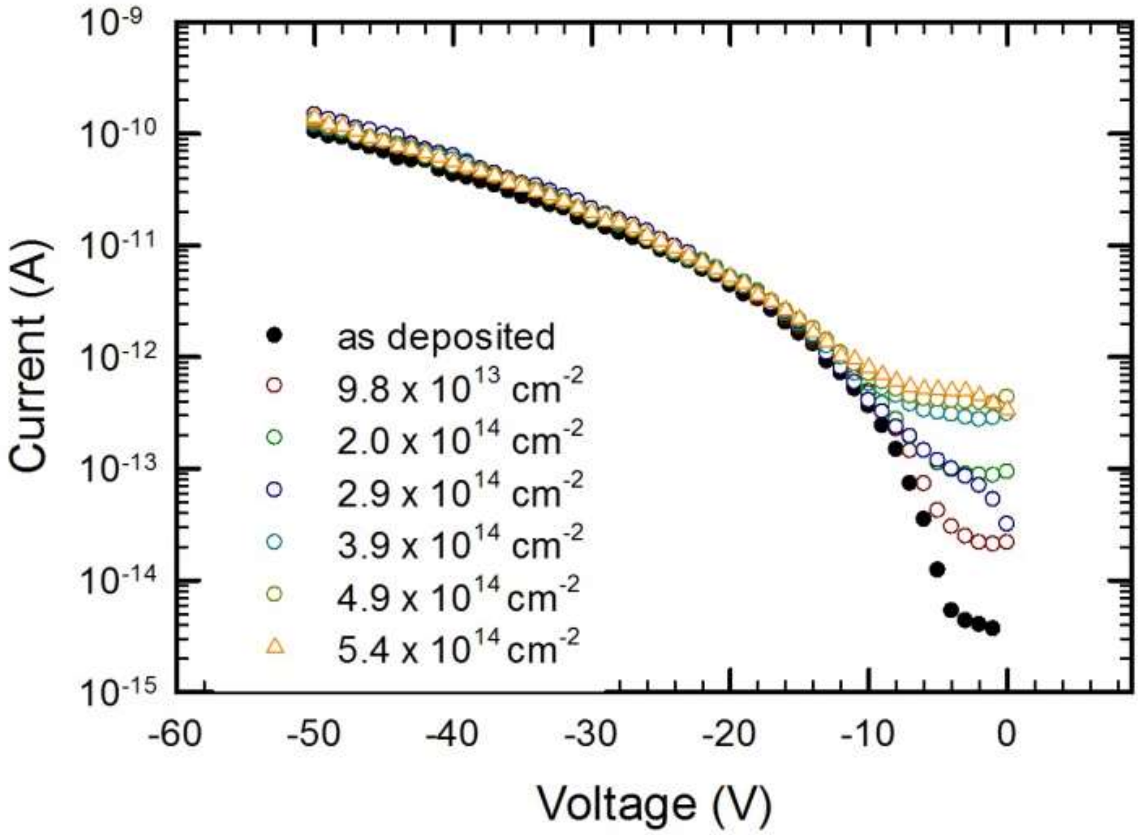

Fig. 3. Semi-Logarithmic curves of the reverse leakage current measured up to **–**50V as function of electron irradiation up to a fluence of 5.4 × 10^{14}

voltages between –10 V and –50 V, there is no difference in the reverse leakage current between the un-irradiated diodes characteristics and the irradiated diodes characteristics. In both cases the current increased approximately by four to five orders of magnitude with decreasing applied voltage.

The increase in the reverse leakage current with increasing reverse voltage is attributed to the Schottky barrier lowering, $\Delta\varphi$. [15] As the reverse voltage increases, the electric field, $\bar{E}$ increases leading to Schottky barrier lowering. The barrier lowering directly depends on the electric field according the equation [24]:

$$\Delta\varphi = \sqrt{q\bar{E}/4\pi\epsilon_s} = 2\bar{E}x_m \tag{5}$$

where x_m is the position of the image force lowering, and ϵ_s is the permittivity of the semiconductor.

The dependence of the electric field, $\bar{E}$ on the voltage is given by the relation [25]:

$$\bar{E} = \sqrt{[2qN_D/\ \epsilon_S](V + V_{bi})} \tag{6}$$

where N_D is the semiconductor doping concentration and V_{bi} is the Schottky diode built in voltage. The effect of the Schottky barrier lowering is more effective such that any changes in the reverse leakage current that may be due to irradiation are not noticed.

Before irradiation, the series resistance was obtained following Eq. (1) as 47 Ω, a low value which indicates desirable Schottky diodes. After irradiation to fluence of 9.8×10^{13} cm^{-2}, the series resistance decreased to 25 Ω before increasing to 74 Ω at fluence of 5.4×10^{14} cm^{-2}. The initial decrease in the series resistance with irradiation still remains to be investigated. The change in the series resistance with irradiation is shown in Fig. 4. The ideality factor, Schottky barrier height and series resistance values obtained before and after irradiation for selected fluences are summarised in Table I.

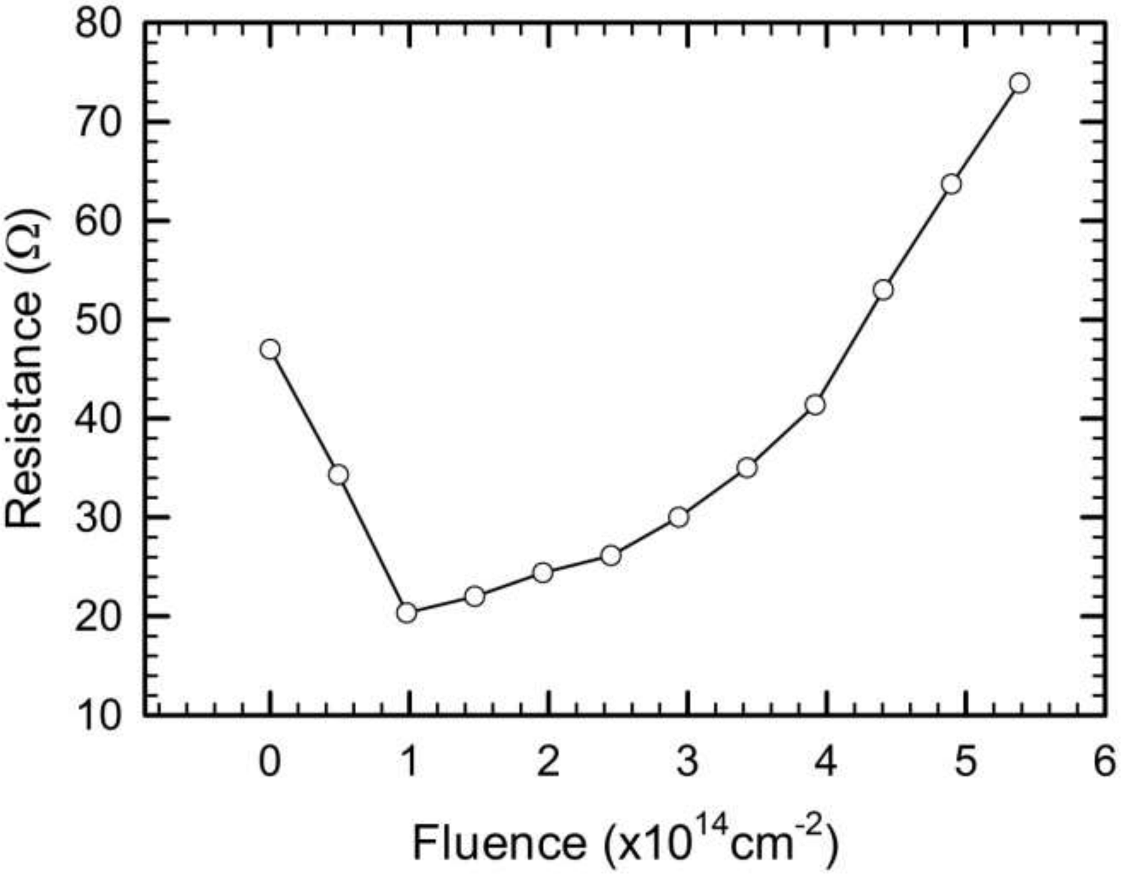

Fig. 4. The variation of series resistance with HEE irradiation to fluence of 5.4×10^{14} cm^{-2}.

Table I. *I-V* parameters obtained from room temperature measurements for as deposited diodes and with irradiation to a fluence of 5.4×10^{14} cm^{-2}. Not all values are presented in this table.

Fluence (cm^{-2})	n (±0.02)	Φ_b (±0.02 eV)	Rs (±5 Ω)	I_L (A) at -5V
0	1.05	1.62	47	1.2×10^{-14}
9.8×10^{13}	1.05	1.59	25	4.2×10^{-14}
2.0×10^{14}	1.04	1.61	34	1.1×10^{-13}
2.9×10^{14}	1.05	1.60	36	1.1×10^{-13}
3.9×10^{14}	1.04	1.60	41	3.2×10^{-14}
4.9×10^{14}	1.04	1.60	63	4.1×10^{-14}
5.4×10^{14}	1.04	1.60	74	5.2×10^{-14}

***C-V* Results**

The effect of HEE irradiation on the Schottky barrier height and on the net donor concentration was evaluated from *C-V* measurements. The carrier removal rate was also determined from the changes in the net donor concentration with irradiation. Curves of $1/C^2$ vs. V_{ext} obtained before and after irradiation are shown in Fig. 5.

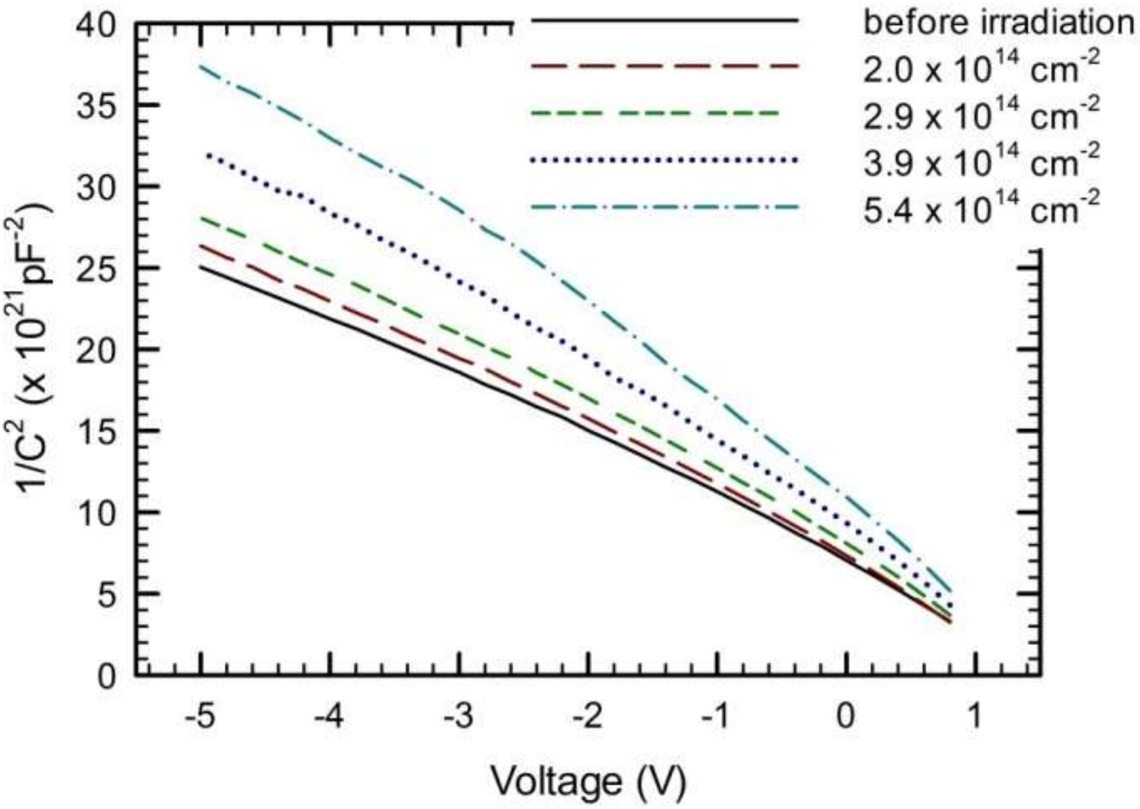

Fig. 5. Curves of $1/C^2$ against Voltage obtained after different HEE irradiation fluences.

The Schottky barrier height and the net donor concentration values were obtained from the curves following the relation [26, 27]:

$$1/C^2 = 2\,(V_{bi} - k_B T/q - V)/A^2 q N_D \epsilon_S \quad (7)$$

Before irradiation the Schottky barrier height was obtained as 2.13 eV, a larger value compared to that obtained from *I-V* measurements. The difference can be explained by the presence of an inhomogeneous metal semiconductor interface hence the Schottky barrier height obtained from *I-V* measurements is lower. As can be seen from Fig. 5, there is a small but progressive increase in the voltage intercept hence increasing Schottky barrier height with irradiation. After irradiation to fluence of 5.4×10^{14} cm^{-2}, the Schottky barrier height increased to 2.19 eV. The small increase is evidence that there was very limited degradation in the diode characteristics, where possibly irradiation introduced defects trap carriers leading to a higher Schottky barrier height.

The net donor concentration was obtained from the gradient of the curves of Fig. 5. Before irradiation the net donor concentration was obtained as 4.6 × 10^{14} cm^{-3} and decreased to ~ 3.0 × 10^{14} cm^{-3} was observed after a total fluence of 5.4 × 10^{14} cm^{-2}. The decrease in the net donor concentration shows that irradiation introduced acceptor-like defects which traps / captures carriers. Using the relation $\Delta(N_D - N_A)/\emptyset$ [28], Fig. 6 was plotted from which the carrier removal rate was obtained.

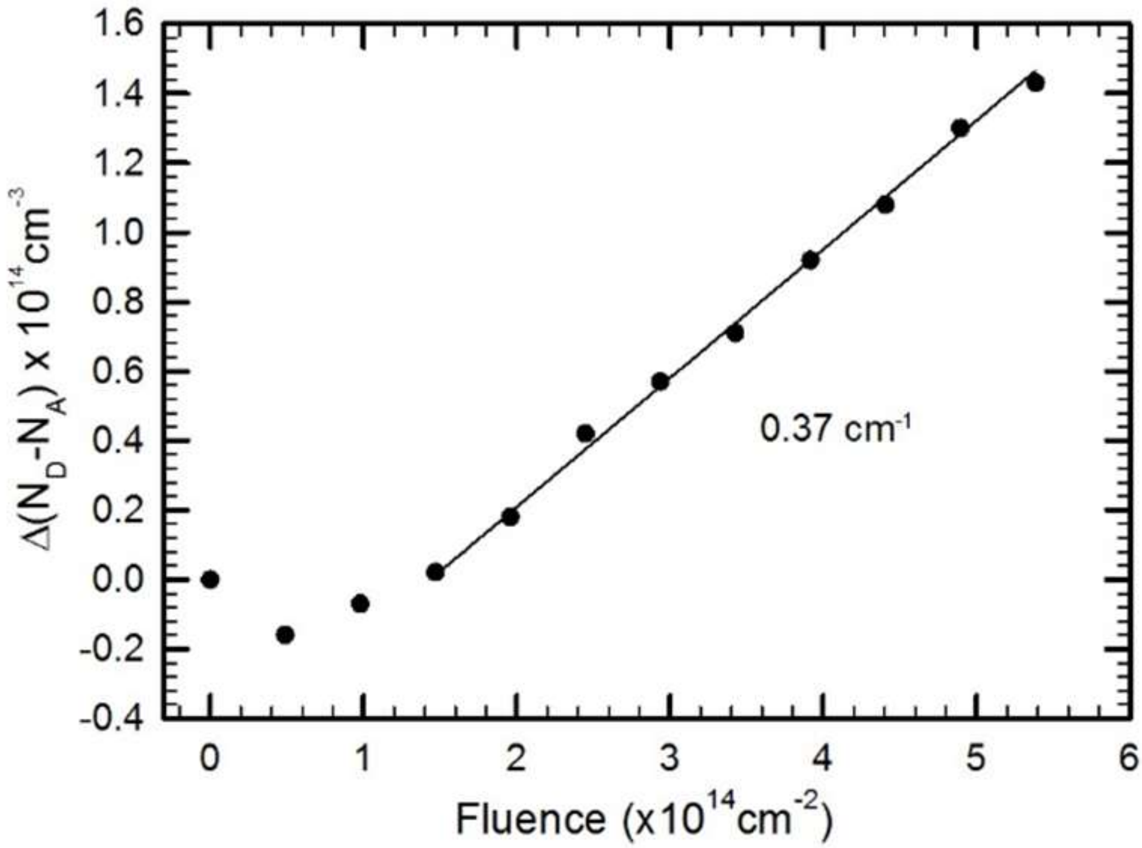

Fig. 6. Free carrier removal rate graph obtained from the linear region of ΔN_D versus fluence.

The carrier removal rate was obtained as 0.37 cm^{-1}. This is a very low value which shows that SiC is a radiation hard semiconductor. We have also calculated the carrier removal rate for SiC samples with a doping density of 7.1 × 10^{15} cm^{-3} to be 1.67 cm^{-1} after HEE irradiation. [29] After 5.4 MeV alpha-particle irradiation, we obtained a large carrier removal rate of 15 × 10^{1} cm^{-1}. [30] This is because high energy alpha particles were used. Additionally, alpha particles are heavier than electrons hence a higher carrier removal rate. Kozlovski *et al*. [31] similarly observed very low carrier removal rates for SiC and proved SiC to have high radiation tolerance compared to silicon. Since electron irradiation is expected to introduce defects in semiconductors, it can be concluded from the small carrier removal rate obtained here that the introduced defects do not have a strong compensating effect. Another possibility is that the defects anneal out at room temperature hence the carrier removal rate is very low.

CONCLUSIONS

The effect of HEE irradiation on Ni/4*H*-SiC was investigated. Minimal degradation on the diode characteristics, *i.e*. on the ideality factor, reverse leakage current, Schottky barrier height and on the series resistance was observed as the electron fluence was increased. The effect of HEE irradiation on the reverse leakage current was only observed at low voltages while Schottky barrier lowering was more evident at higher reverse voltages leading to nearly equal reverse leakage current as the fluence was increased. The effect of HEE irradiation on the net donor concentration and subsequently on the carrier removal rate was also observed to be minimal. This is an indication that SiC is a radiation hard material especially considering that HEE irradiation was performed and at increasing fluence.

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