The effects of high-energy proton irradiation on the electrical characteristics of Au/Ni/4*H*-SiC Schottky barrier diodes

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Abstract

Au/Ni (20:80) Schottky barrier diodes (SBDs) were resistively evaporated on nitrogen-doped *n*–type 4*H*-SiC. Current-voltage (*I*-*V*) and capacitance-voltage (*C*-*V*) characteristics of the SDBs were investigated before and after bombardment with 1.8 MeV proton irradiation at a fluence of 2.0×10^{12} cm^{-2}. The measurements were carried out in the temperature range 40 – 300 K in steps of 20 K. Results obtained at room temperature (300 K) showed highly rectifying devices before and after bombardment. It was observed that the proton irradiation induced an increase of ideality factor from 1.05 to 1.13, a decrease in Schottky barrier height from 1.40 to 1.22 eV, an increase in series resistance from 10 to 66 Ω and a noticeable increase of the saturation current from 3.0×10^{-21} to 6.8×10^{-17} A. The increase in saturation current after proton irradiation was attributed to the presence of interfacial states created by irradiation-induced defects. Thermionic emission dominated the *I*-*V* characteristics in the temperature range 120 – 300 K but the *I*-*V* characteristics deviated from thermionic emission theory at temperatures below 120 K for devices both before and after irradiation. The variation of the SBDs characteristics with temperature was attributed to the presence of lateral inhomogeneities of the SBH. Modified Richardson constants were determined from a Gaussian distribution of barrier heights to be 133 and 165 A cm^{-2} K^{-2} before and after irradiation, respectively.

Keywords: Richardson constant, proton irradiation, 4*H*-SiC, SBD

1. Introduction

A Schottky barrier diode (SBD) is a metal semiconductor device that is widely used where diodes with low forward voltage drop, junction capacitance and very fast switching speeds are required. This makes SBDs ideal for use as rectifiers in photovoltaic systems, high-efficiency power supplies and high frequency oscillators [1]. In addition, SBDs have important use in optoelectronics, high frequency and bipolar integrated circuits applications [2]. The reliability of the diodes depends on the quality of the metal-semiconductor (M-S) junction [3]. The performance of SBDs may be quantified experimentally in terms of ideality factor, Schottky barrier height (SBH), saturation current and series resistance. Among these properties of the M-S interface, SBH plays a major role in the successful operation of many devices in transporting electrons across the M-S junction [4]. To extract the SBH from the *I-V* characteristics, the value of the Richardson constant is needed.

The Richardson constant is one of the most important parameters in the thermionic emission theory of current transport across M-S junctions. Here, it is the proportionality constant in the relationship between the current and the voltage for the flow of electrons across the M-S junction. The theoretical value of the effective Richardson constant of 4*H*-SiC reported in literature is 146 $\mathrm{Acm^{-2}K^{-2}}$ [5], which differs significantly from the experimentally observed values due to various factors. The factors responsible for deviation may be small active area of devices and atomic or barrier inhomogeneities at the M-S interface, which are caused by defects, multiple phases and grain boundaries.

The 4*H* polytype of SiC has a wide band gap of 3.26 eV [6], and a promising material for vertical type high-voltage devices due to its higher bulk mobility and smaller anisotropy. Due to its capability to operate at a very high temperature, high power and high frequency, it is a suitable substrate material for producing high power, high frequency electronic devices. Also, due to its radiation hardness, SiC has many applications in radiation harsh environments, such as space, accelerator facilities and nuclear power plants [7]. The effects of radiation and temperature on semiconductor devices are scientifically significant for radiation sensing applications, as well as technologically important for manufacturing processes and high temperature and high power applications [8].

Experimental and theoretical studies of defects in semiconductors have been reported [8-12], but room temperature *I-V* and *C-V* measurements characteristics alone cannot provide comprehensive information about the mechanisms responsible for the formation of a barrier at the junction of the M-S and electrical properties of SBDs [13]. More information about diodes is revealed by characterising them over a wide temperature range (40 – 300 K).

In the previous studies, the radiation hardness of some wide bandgap semiconductors, such as SiC, ZnO and GaN, that make them suitable for use in radiation environments has been studied [14]. We have reported the influence of alpha-particle and high energy electron irradiation on the electrical characteristics of 4*H*-SiC measured at different temperatures [8, 12]. To the best of our knowledge, the effect of 1.8 MeV proton irradiations at fluence of 2.0×10^{12} cm^{-2} on Au/Ni/4*H*-SiC SBDS has not been reported.

In this work, we report the effect of 1.8 MeV proton bombardment on the electrical characteristics of nitrogen-doped, *n*-type 4*H*-SiC SBDs measured over a wide temperature range (40 – 300 K). The major aim of this work was to determine the extent to which the characteristics of Au/Ni contacts on *n*-type 4*H*-SiC would be affected by proton irradiations with 1.8 MeV measured at different cryogenic temperatures.

2. Experimental details

A nitrogen-doped, *n*-type 4*H*-SiC wafer supplied by Cree Research Inc. was used for this study. The epilayer was grown by chemical vapour deposition. It was polished on both sides with the Si-face epi ready with resistivity of 0.02 Ω-cm and doping density of 1.6×10^{16} cm^{-3}. Samples were cut into smaller sizes from the wafer. Before metallization of the ohmic contact on highly doped side (1.0×10^{18} cm^{-3}) of the sample, the degreasing and etching were carried out as described in *refs* [8, 12, 15, 16]. Nickel ohmic contacts of 300 nm in thickness were thermally evaporated at a deposition rate of ~0.09 nm s^{-1} and vacuum pressure of ~2×10^{-5} mbar. The ohmic contacts were annealed in a quartz tube heated by a Linderberg Hevi-Duty furnace in flowing Ar at 950 °C for 10 minutes to reduce the contact (metal-semiconductor) resistance by the forming of nickel silicide. Prior to Schottky contact evaporation on the front (epi-layer) side of the samples, the samples were degreased as reported in *refs* [8, 12, 15, 16]. Au/Ni Schottky contacts, 0.6 mm in diameter with a thickness of 200/800 nm, were thermally evaporated through a metal contact mask at very low deposition rate of ~0.02 nm s^{-1} and vacuum pressure of ~1×10^{-5} mbar.

The suitability of the contacts was tested immediately after evaporation by characterizing them using an *I-V* and *C-V* system comprising an HP 4140 B pA Meter/DC Voltage Source and an HP 4192A LF Impedance Analyzer, respectively. The characterization of the samples was done at room temperature and in the dark.

Thereafter, the sample was placed under vacuum in a closed cycle helium cryostat and the *I-V* and *C-V* measurements were carried out on a particular SBD in the temperature range of 40 – 300 K in intervals of 20 K under control of a program written in Labview™.

After *I-V* and *C-V* measurements, the same SBD was bombarded at room temperature under a high vacuum with 1.8 MeV protons from a Van de Graaff accelerator. The diode received a fluence of 2.0×10^{12} cm^{-2}. Immediately after proton irradiation, the contact quality was evaluated using current-voltage-temperature and capacitance-voltage-temperature measurements. The experiment was repeated on other diodes for confirmation of the results observed.

3. Results and Discussion

3.1. Current-Voltage Characteristics

The suitability of the Au/Ni/4*H*-SiC contacts for temperature dependent *I-V* studies before and after proton irradiation was confirmed from the results obtained at room temperature as shown in Figs. 1. Some of the important electrical parameters such as ideality factor (n), Schottky barrier height ($\phi_{I\text{-}V}$), series resistance (R_s) and saturation current (I_s) were obtained from the measurements are summarized in Table 1. The ideality factor determined from the slope of the linear region of the log $I - V$ characteristics was close to unity and the SBH evaluated from the intercept was relatively high, which shows that thermionic emission (TE) model sufficiently described the current flow from Au/Ni to 4*H*-SiC. We concluded that the Au/Ni/4*H*-SiC SBDs were highly rectifying and thus suitable for temperature dependent measurements. A significant deviation was observed after proton irradiation at fluence of 2.0 $\times 10^{12}$ cm^{-2}. The deviation was as a result of the increase of deep level defect density at the interface with irradiation [8, 12, 15, 17].

Fig. 1 shows the semi-logarithmic forward bias *I-V* characteristics of the SBDs before and after proton irradiation measured over the temperature range 40 – 300 K. The plots before and after proton irradiation was linear up to a current of ~10^{-4} A, but deviated below 80 K. The deviation of the plots from linearity at high forward voltages may be due to series resistance caused by the interfacial layer between Au/Ni and 4*H*-SiC and the bulk of the material. From Fig. 1, the *I-V* plots show lower current at lower temperature, which is in accordance with thermionic emission-diffusion theory [18]. It was also observed that the decrease of the forward bias current with decrease in temperature was less pronounced after irradiation, which was attributed to the presence of interfacial states created by irradiation-induced defects [15, 19].

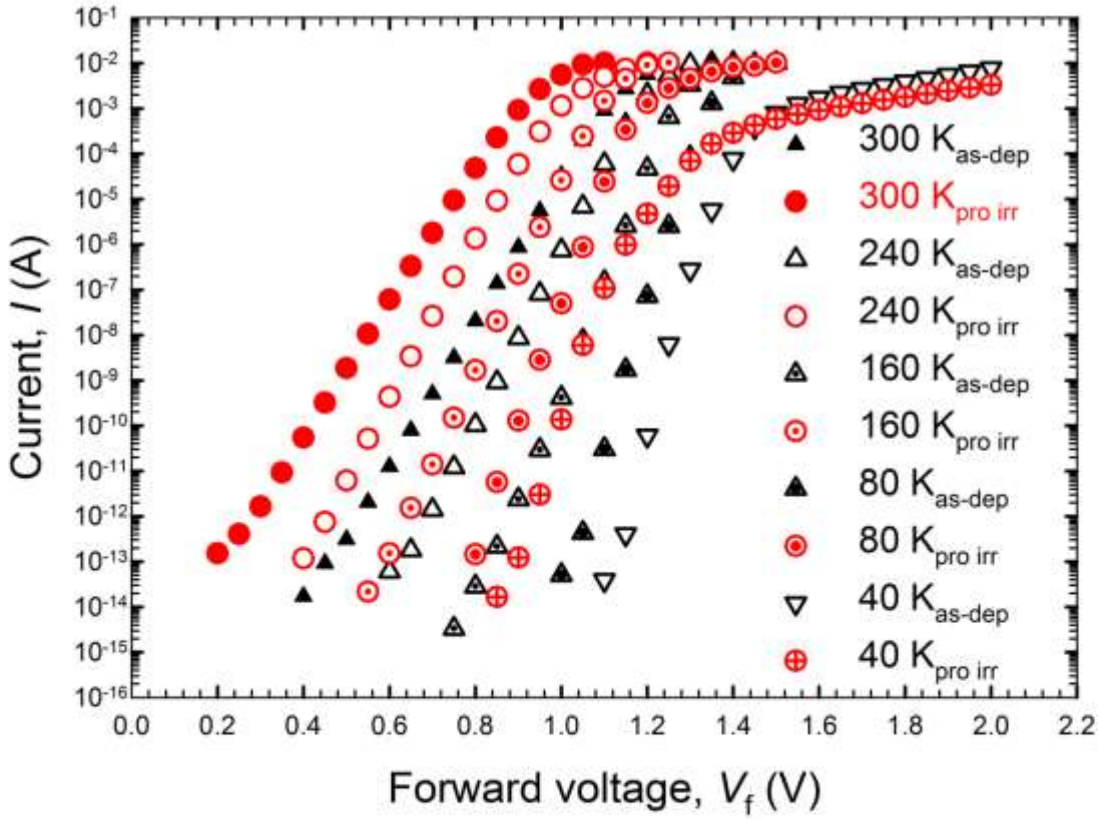

Fig. 1. Semi-logarithmic forward *I-V* characteristics of Au/Ni/4*H*-SiC Schottky diodes before and after proton irradiation at a fluence of 2.0× 10^{12} cm^2, measured at different temperatures between 40 K and 300 K.

The linear part of the plots was fitted over the forward voltage range where thermionic emission was the dominant transport mechanism. From the fits, the important electrical parameters that give better understanding of the devices performance at different temperatures were determined according to Eqs 1 and 2 as reported in *refs* [3, 8, 12, 20-22].

$$I = I_s\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \quad (1)$$

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

where I is the current flowing through the diode in forward voltage, I_s is the saturation current measured at zero voltage, q is the electronic charge, V is the applied voltage, n is the ideality factor, k is the Boltzmann constant, is the temperature in Kelvin, A is the area of

Schottky barrier diode, $A*$ is effective Richardson constant and ϕ_{ap} is the experimental apparent SBH.

Table 1 compares the results obtained from the SBDs at 300 K and 40 K before and after irradiation.

Table 1. Electrical properties of Au/Ni/*n*-type 4*H*-SiC SBDs before and after 1.8 MeV proton irradiation determined from *I-V* and *C-V* characteristics at 40 and 300 K, respectively.

SBD	n	I_s (A)	R_s (Ω)	N_d–N_a ($\times 10^{16}$ cm^{-3})	V_{bi} (V)	ϕ_{I-V} (eV)	ϕ_{C-V} (eV)
As-deposited (300K)	1.05	3.0×10^{-21}	10	1.68	1.16	1.40	1.42
As-deposited (40 K)	3.51	2.9×10^{-45}	66	1.30	2.68	0.45	2.71
Proton irradiation (300 K)*	1.13	6.8×10^{-17}	25	1.62	1.04	1.22	1.30
Proton irradiation (40 K)*	4.45	5.4×10^{-39}	160	1.22	3.23	0.34	3.26

* at fluence of 2.0×10^{12} cm^{-2} (300K)

Gradual changes in ideality factor and SBH$_{I-V}$ before and after irradiation were observed from 120 to 300 K but the temperature dependence became more significant below 120 K as shown in Fig. 2. This temperature dependence of the ideality factor and SBH$_{I-V}$ is in agreement with what was observed after alpha-particle and high-energy electron irradiation [8, 12], and is ascribed to deviation from thermionic emission theory at lower temperatures (< 120 K). This deviation may be ascribed to an inhomogeneous barrier at the interface. The deviation from ideality was more pronounced after irradiation, which was due to the presence of additional deep level defects induced by irradiation as already observed in *refs* [8, 12].

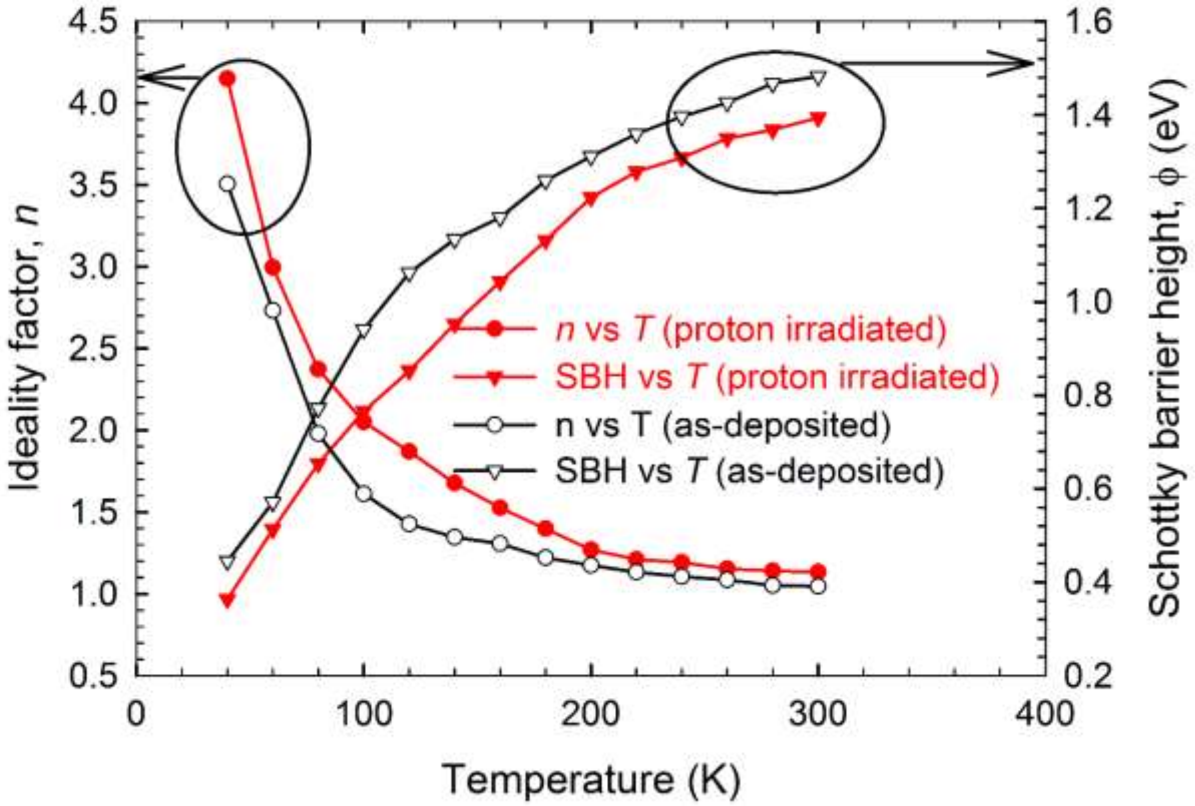

Fig. 2. Comparison of ideality factor, *n*, and Schottky barrier height, *ϕ*, as function of temperature before and after 1.8 MeV proton irradiation at fluence of 2.0×10^{12} cm^2 at temperature range 40-300 K.

3.2. Capacitance-Voltage Characteristics

Fig. 3 shows the plot of $1/C^2$ versus voltage of the SBDs before and after proton irradiation at fluence of 2.0×10^{12} cm^{-2} measured at 1 MHz at temperature of 40, 80 and 300K. These temperatures were chosen since there was little or no significant change from 100 to 300 K before and after irradiation. As seen from Fig. 3, at room temperature, the capacitance of the irradiated diodes was less than that of the unirradiated diodes. At lower temperatures, the capacitance decreased and the difference between the irradiated and unirradiated samples increased. The electrical parameters such as $SBH_{C\text{-}V}$ (determined from the intercept), net donor concentration, $N_d - N_a$ (determined from the slope) and built voltage, V_{bi} (evaluated from the intercept of x-axis) were calculated from the plots of $1/C^2$ vs V according to *refs* [3, 8, 12, 20, 21] and are shown in Table 1. As listed in Table 1, the $SBH_{C\text{-}V}$ increases with decreasing temperature though lower after irradiation. The values of $SBH_{C\text{-}V}$

obtained were higher than those of SBH_{I-V} which can be attributed to inhomogeneity in the interface oxide layer composition, non-uniformity of the interfacial layer thickness, distribution of interface charges, impurity level and quantum mechanical tunnelling among other reasons [8]. In addition, the net donor concentration decreases slightly with decreasing temperature. The values SBH_{C-V} were lower after irradiation which might be as a result of an increased tapping of charge due to the induced deep level defects.

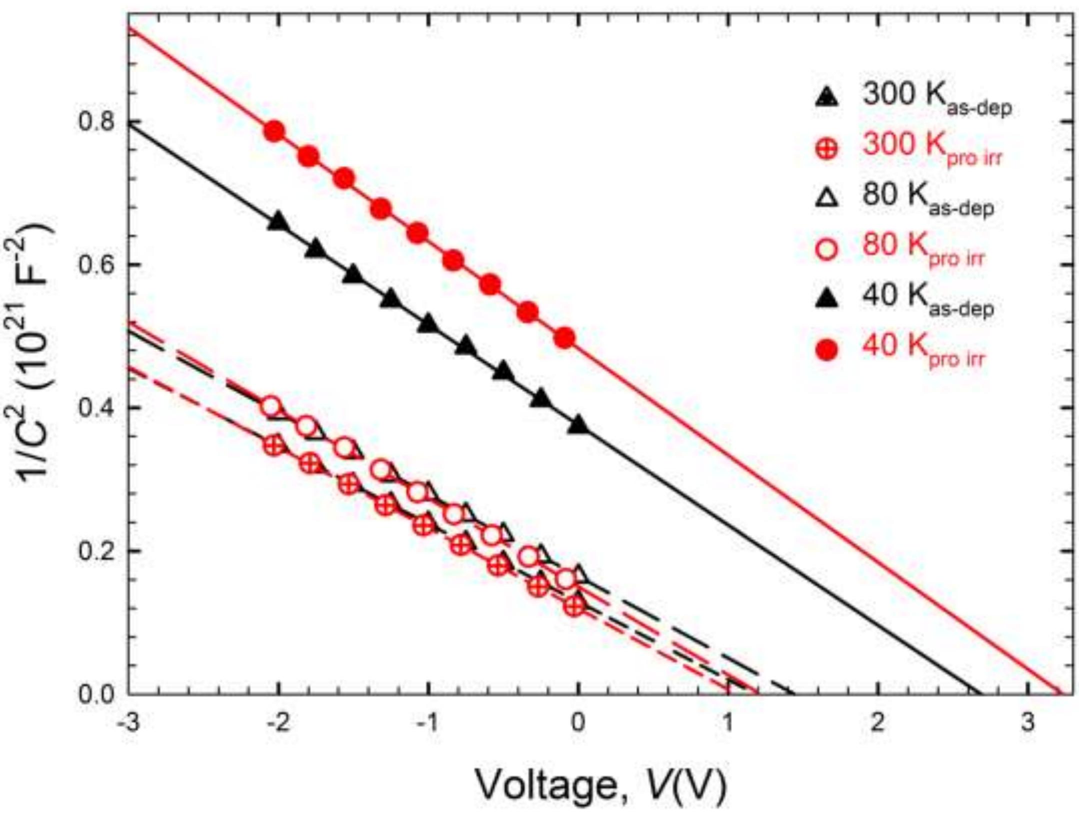

Fig. 3. Graph of C^{-2} as a function of voltage of a Au/Ni/4*H*-SiC SBD before and after 1.8 MeV proton irradiation at fluence of 2.0×10^{12} cm^2 measured at different temperatures between 40 and 300 K.

The room temperature change in carrier concentration, $\Delta(N_d - N_a)$, of the SBD determined before irradiation (1.68×10^{16} cm^{-3}) and after proton irradiation (1.62×10^{16} cm^{-3}) was calculated to be 6×10^{14} cm^{-3}. The carrier removal rate, η, after the fluence, φ, of 2.0×10^{12} cm^{-2} was calculated according to Eq. 3 [8, 12].

$$\eta = \frac{\Delta(N_d - N_a)}{\varphi} \quad (3)$$

From Eq. 3, the carrier removal rate due to proton irradiation of the SBDs with energy of 1.8 MeV was calculated to be 300 cm^{-1}.

3.3. Barrier height inhomogeneities analysis

The anomalous behaviour (i.e. increase in SBH with increasing temperature) that occurred in the forward *I-V* measurements at different temperatures has been reported [8, 12, 23]. Werner and Guttler suggested that the non-ideal behaviour can be best explained by spatial distribution of the SBH at the interface of M-S Schottky contacts. This anomalous can be described by assuming the Gaussian distribution, $P(\phi_B)$, with a standard deviation, σ_s, and a mean SBH, $\overline{\phi}_B$, as written in Eq. 4 [24].

$$P(\phi_B) = \frac{1}{\sigma_s\sqrt{2\pi}} exp\left(-\frac{(\phi_B - \phi_{B0})^2}{2\sigma_s^2}\right) \quad (4)$$

From the Gaussian distribution of the SBH, the experimental apparent SBH ϕ_{ap} at zero bias can be expressed as:

$$\phi_{ap} = \phi_{B0}(T = 0) - \frac{q\sigma_{s0}^2}{2kT} \quad (5)$$

where $\phi_{B0}(T = 0)$ is the mean SBH at zero bias which was evaluated from the intercept of Fig. 4 (i.e. is the SBH extrapolated to zero temperature), σ_{s0} is the standard deviation at zero bias which was determined from the slope of Fig. 4 [25].

Fig. 4 shows the plot of experimental value of ϕ_{ap} as a function of $1/(2kT)$ before and after proton irradiation. From the plot, the $\phi_{B0}(T = 0)$ was determined from the intercept to be 1.71 and 1.44 eV, and the σ_{s0} (which is a measure of barrier homogeneity) was estimated from the slope as 0.116 and 0.113 eV before and after irradiation, respectively. The value of σ_{s0} describes the magnitude of the SBH's homogeneity at the interface of the diodes [4]. Since the values of σ_{s0} is not small compared to the values of $\phi_{B0}(T = 0)$, we conclude the presence of barrier inhomogeneity at the interface of Au/Ni/4H-SiC SBDs [4]. This barrier inhomogeneity influence low temperature *I-V* characteristics, as low barrier regions conduct a greater fraction of the current at lower temperatures, thereby causing a lower barrier to be measured.

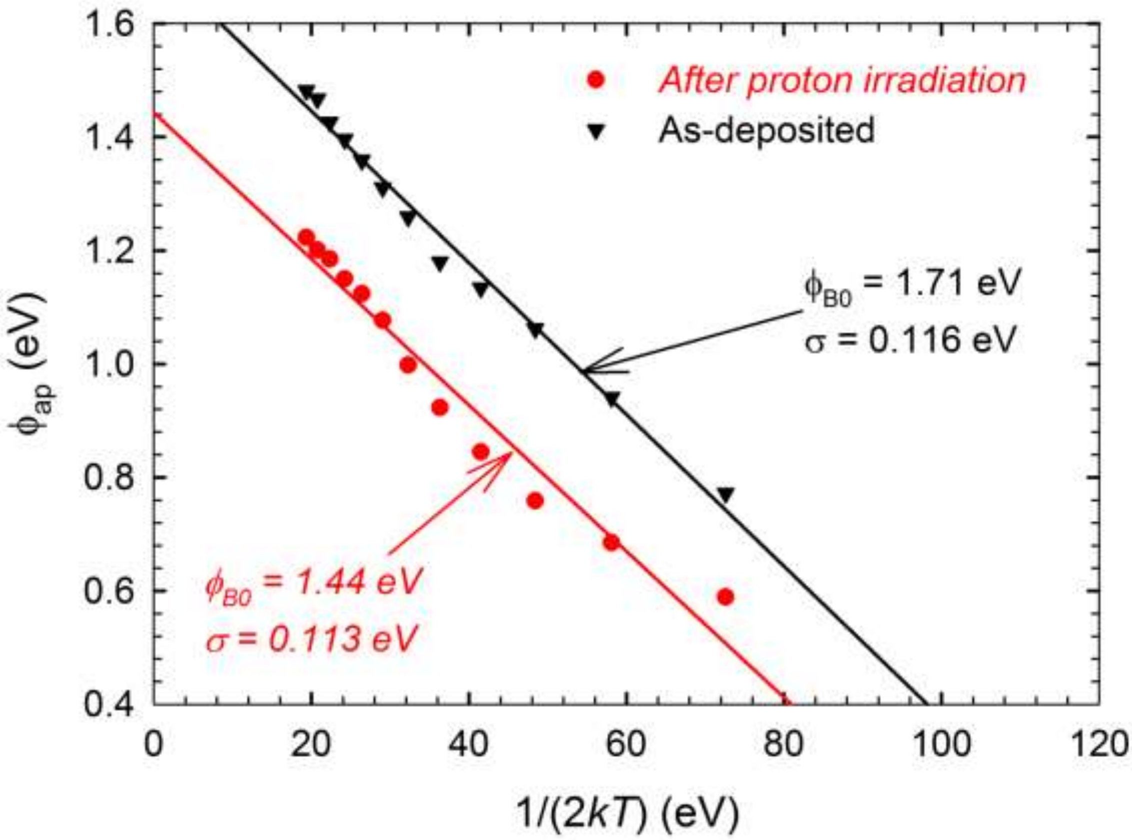

Fig. 4. The zero bias apparent barrier height versus 1/2kT for the Au/Ni/4*H*-SBDs before and after proton irradiation. The insert shows the plot of $(1/n_{ap})$–1 versus 1/2kT.

The inhomogeneous barrier height and deviation from thermionic emission and diffusion theory have been predicted from the temperature dependent behaviour of the ideality factor and SBH plotted in Fig. 4. The standard deviation of the barrier height, σ_{s0}, plays a major role in correcting the values of Richardson constant determined from the conventional Richardson's plot as reported in *ref.* [8]. The conventional (homogeneous SBH) Richardson constant and barrier height can be determined by re-written Eq. 2 as given in Eq. 6.

$$\ln\left(\frac{I_s}{T^2}\right) = \ln(AA^*) - \frac{q\Phi_B}{kT} \tag{6}$$

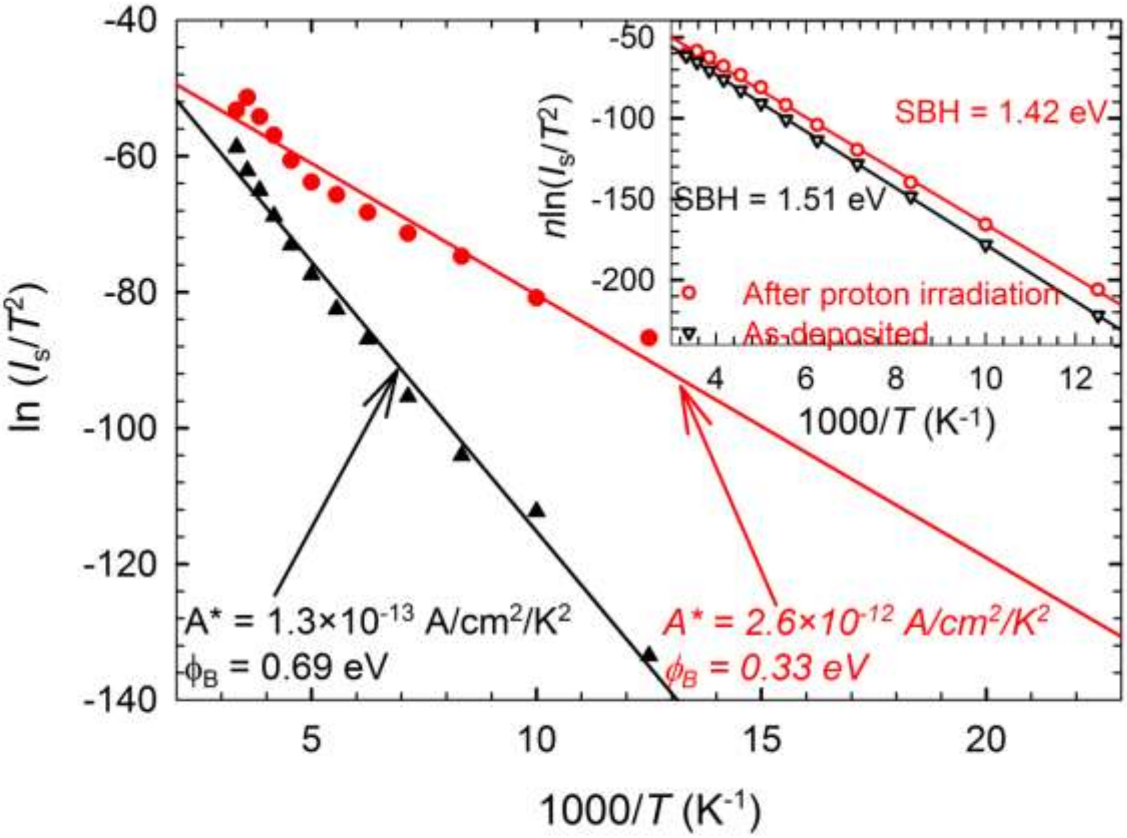

Fig. 5. The Richardson plot, $\ln(I_s/T^2)$ versus 1000/*T* for Au/Ni/4*H*-SiC before and after 1.8 MeV proton irradiation at of fluence of 2.0 × 10^{12} cm^2. The insert shows the plot of $n[\ln(I_s/T^2)]$ versus 1000/*T* to linearize the main plot.

Fig. 5 depicts the plot of $\ln(I_s/T^2)$ as a function of $1000/T$, where the effective Richardson constant and SBH were determined. We calculated the effective Richardson constant, A*, from the intercept of the plot to be 1.3 × 10^{-13} and 2.6 × 10^{-12} Acm^{-2}K^{-2} before and after proton irradiation, respectively. These experimental values were very small compared to the theoretical value of effective Richardson constant of 146 Acm^{-2}K^{-2}. This deviation may be due to the effect of Schottky barrier inhomogeneity at the interface between metal and semiconductor as well as crystal defects and potential fluctuation. It may also be an indication that the active area is smaller than the actual devices area, but this effect could not explain such a large deviation.

The extremely small value of the Richardson can be corrected by taking the inhomogeneity of the SBH into account, in which case Eq. 6 becomes:

$$\ln\left(\frac{I_s}{T^2}\right) - \left(\frac{q^2\sigma_{s0}^2}{2k^2T^2}\right) = \ln(AA^{**}) - \frac{\Phi_{Bmodified}}{kT} \quad (7)$$

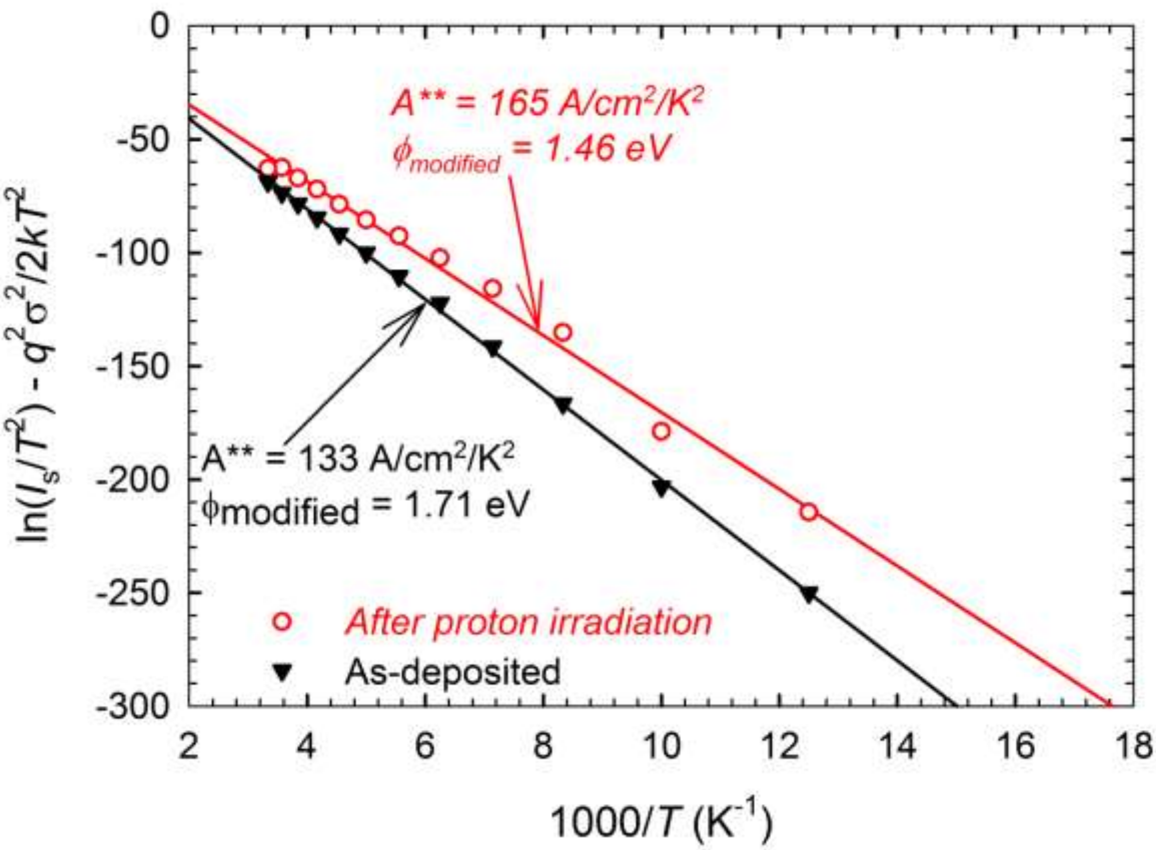

Fig. 6. **The modified Richardson plot for the Au/Ni/4*H*-SiC SBDs before and after proton irradiation.**

From Eq. 7, modified Richardson plot of $\ln(I_s/T^2) - (q^2\sigma^2/2k^2T^2)$ versus $1000/T$ before and after proton irradiation were obtained and plotted in Fig. 6. The mean barrier height, ϕ_{B0}, was calculated by equating the gradient to $q\phi_B/k$. After substitution, the values of $\phi_{Bmodified}$ were determined to be 1.71 and 1.46 eV for as deposited and proton irradiated SBDs, respectively. As noticed, the modified mean barrier heights calculated were approximately equal to those obtained from the plot of ϕ_{ap} vs $1/2kT$ in Fig. 4. In addition, the modified Richardson constants, A^{**}, were determined by equating the intercept to $\ln(AA^{**})$. The values of A^{**} for Au/Ni/4H-SiC SBDs before and after proton irradiation were calculated to be 133 and 165 A cm^{-2} K^{-2}, respectively, which is in good agreement with the theoretical value. The values of A^{**} obtained were in line with what has been observed during alpha-particle [12] and high-energy electron irradiation [8]. In addition, the calculated results of ϕ_{B0} and A^{**} before and after irradiation as shown in Table 2, revealed the extent to which

Au/Ni/4*H*-SiC SBDs could be affected by high-energy proton irradiation at fluence of 2.0×10^{12} cm^{-2}. From these results, a conclusion was reached that 4*H*-SiC is a radiation hard semiconductor that is suitable to operate at high radiation harsh environments.

Table 2. The characteristics of Ni/Au SBDs on *n*-4H-SiC before and after 1.8 MeV proton irradiation.

Samples	σ_{so}(eV) ±0.001	$\Phi_{B0}(T=0)$ (eV) ±0.01	$\Phi_{Bmodified}$ (eV) ±0.01	A^* (Acm^{-2}K^{-2})	A^{**} (Acm^{-2}K^{-2})
As-deposited	0.116	1.71	1.71	1.3×10^{-13}	133
After proton irradiation	0.114	1.44	1.46	2.6×10^{-12}	165

4. Summary and conclusions

We have successfully fabricated highly rectifying Au/Ni/4*H*-SiC SBDs by thermal evaporation techniques. The influence of proton irradiation at a fluence of 2.0×10^{12} cm^{-2} on the Schottky contacts has been investigated by *I-V* and *C-V* characteristics at cryogenic temperatures from 40 to 300 K. The electrical behaviour of the devices before and after proton irradiation revealed good Schottky contacts that support the suitability of SiC in high radiation environments. The performance of the devices deviated from thermionic emission at temperatures below 120 K. This deviation could be well explained by barrier inhomogeneities that formed at the interface of Au/Ni and 4*H*-SiC which were described by assuming a Gaussian distribution of SBHs. The deviation was more pronounced after proton irradiation because of deep level defects induced into the Schottky barrier diodes as a result of bombardment. By using a Gaussian distribution of barrier heights, the modified Richardson constants before and after high-energy proton irradiation were 133 and 165 Acm^{-2}K^{-2}, respectively, which is much closer to the theoretical value obtained when a homogeneous barrier height is assumed. It has been confirmed from our findings that the Richardson constant is not dependent on the Schottky barrier height and active devices only, but also depend on the irradiation types. The findings revealed that the Richardson constant might be influenced by irradiation. We conclude that the *I-V* characteristics of both irradiated and unirradiated Au/Ni/4H-SiC Schottky diodes are well described a Gaussian distribution of Schottky barrier height.

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