Effects of 5.4 MeV Alpha-particle Irradiation on the Electrical Properties of Nickel Schottky Diodes on 4H-SiC

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ABSTRACT

Current-voltage, capacitance-voltage and conventional deep level transient spectroscopy at temperature ranges from 40-300 K have been employed to study the influence of alpha-particle irradiation from an ^{241}Am source on Ni/4H-SiC Schottky contacts. The nickel Schottky barrier diodes were resistively evaporated on n-type 4H-SiC samples of doping density of 7.1×10^{15} cm^{-3}. It was observed that radiation damage caused an increase in ideality factors of the samples from 1.04 to 1.07, an increase in Schottky barrier height from 1.25 to 1.31 eV, an increase in series resistance from 48 to 270 Ω but a decrease in saturation current density from 55 to 9×10^{-12} Am^{-2} from *I-V* plots at 300 K. The free carrier concentration of the sample decreased slightly after irradiation. Conventional DLTS showed peaks due to four deep levels for as-grown and five deep levels after irradiation. The Richardson constant, as determined from a modified Richardson plot assuming a Gaussian distribution of barrier heights for the as-grown and irradiated samples were 133 and 151 Acm^{-2}K^{-2}, respectively. These values are similar to literature values.

Keywords: Irradiation, DLTS, SiC, Defects, Schottky, alpha-particles

1. Introduction

SiC is a promising semiconductor with a wide band-gap of 3.26 eV [1]. Because of its wide band-gap, SiC is a suitable substrate for developing devices that are capable of operating at high temperature as well as in harsh radiation fields [2, 3]. The electrical and thermal properties of SiC make it suitable devices in the electronics operating at high power, high temperature and high frequency [4]. Irradiation is used to introduce defects in semiconductors in order to investigate the defects' properties by means of deep-level transient spectroscopy (DLTS) on Schottky diodes. Effects of radiation and temperature on semiconductors are technologically important for radiation to sensing applications as well as manufacturing processes and high temperature and high power applications [5].

It has been reported by many researchers that some wide band-gap semiconductors such as SiC and GaN are radiation hard which make them suitable for use in harsh radiation environments [3]. Effects of electron, proton, fast electron and fast neutron irradiation on SiC have been investigated by different researchers [3, 6-8]. To the best of our knowledge, the effect of alpha-particles irradiation on Ni/4H-SiC has not been reported.

In this work, the change in electrical properties of Ni/4H-SiC due to alpha-particle irradiation has been investigated by means of current-voltage (*I-V*), capacitance-voltage (*C-V*) and DLTS measurements. The major aim was to determine the effect of 5.4 MeV alpha-particles irradiation on the electrical properties and diode performance of n-type 4H-SiC.

2. Experimental Procedure

The Schottky diodes were fabricated on the Si face of chips cut from an *n*-type (nitrogen doped) 4H-SiC wafer, double polished with resistivity of 0.02 Ω-cm and doping density of 7.1×10^{15} cm^{-3}, supplied by CREE Res. Inc. Samples were degreased by boiling for 5 minutes each in trichloroethylene, acetone and methanol, followed by a 1 minute rinse in de-ionized water. They were etched in 40% hydrogen fluoride for 30 seconds, then rinsed in de-ionized water and followed by blowing dry with nitrogen gas prior to thermal evaporation of the nickel ohmic contact on the back surface of the samples. The ohmic contact with a thickness of 3000 Å was deposited at a rate of 0.4 Å

s^{-1}. The samples were annealed in a tube furnace under flowing argon gas at 950 ℃ for 10 minutes to form nickel silicides [9]. Hereafter, the samples were cleaned in an ultrasonic bath for 3 minutes each in trichloroethylene, acetone and methanol, followed by a 1 minute rinse in de-ionized H$_2$O. They were also blown dry with nitrogen gas before the fabrication of nickel Schottky diodes. The nickel Schottky contacts were deposited through a metal contact mask and had an area of 2.4×10^{-3} cm^2 and a thickness of 1000 Å deposited at a rate of 0.2 Ås^{-1} under a vacuum of approximately 1×10^{-5} Torr.

The current-voltage (*I-V*) and capacitance-voltage (*C-V*) measurements of the sample were carried out at room temperature to test the qualities of the contacts. The *I-V* and *C-V* measurements were carried out by HP 4140 B pA meter/DC voltage source and HP 4192A LF Impedance Analyzer, respectively. DLTS was used to characterize the defects present in the sample before and after alpha-particles irradiation.

The sample was irradiated with alpha-particle by placing an ^{241}Am source on top of the Schottky diodes. The irradiation was carried out at room temperature and lasted for 2 hours. The sample received the fluence of 5.1×10^{10} alpha-particles-cm^{-2} from the foil fluence rate of 7.1×10^6 alpha-particles-cm^{-2}-s^{-1}. The characterization of the sample was repeated.

3. Results and Discussion

3.1. I-V characteristics at room temperature
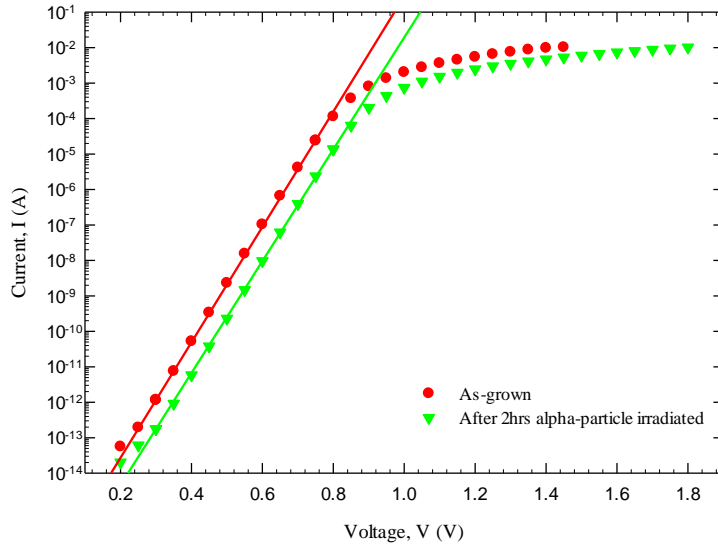
Fig. 1. Forward *I-V* characteristics of Ni/4H-SiC Schottky diodes before and after irradiation measured at 300 K.

Fig. 1 shows the forward semi-logarithmic *I-V* characteristics of the Schottky barrier diode measured at 300 K before and after irradiation. The effect of irradiation on the Ni/4H-SiC diode can be quantified in terms of the ideality factor (*n*), Schottky barrier height (SBH), saturation current (*I*$_s$) and series resistance (*R*$_s$) obtained from the plot. Measurements on the Schottky contacts were taken before and after the samples were irradiated. Table 1 compares the properties of the sample before and after irradiation at 300 K. The SBH of the contacts were determined from the *I-V* characteristics analysed by using the thermionic emission model [10, 11]. The *I*$_s$ was derived from the straight line intercept of *lnI-V* plot at $V = 0$

$$I_S = AA^* \exp(-\frac{\phi_{I-V}}{kT}) \tag{1}$$

where *A* is the effective diode area, A^* is the effective Richardson constant, ϕ_{I-V} is the effective SBH at zero bias, *k* is the Boltzmann constant and *T* is absolute temperature in Kelvin.

From the Eq. 1, SBH, ϕ_{I-V} is given as:

$$\Phi_{I-V} = \frac{kT}{q} ln(\frac{AA^*T^2}{I_s})\tag{2}$$

and n is given as:

$$n = \frac{q}{kT}\left(\frac{dV}{d(lnI)}\right)\tag{3}$$

which is unity for an ideal diode (i.e current flows entirely due to thermionic emission). But, n is always greater than one, which describes the deviation of the experimental lnI-V data from the ideal thermionic model. From Table 1, n, ϕ_{I-V} and R_s increases with radiation, but I_s decreases with radiation.

Table 1
Comparison of some electrical parameters of Ni/4H-SiC before and after alpha-particle irradiation estimated from I-V and C-V characteristics at 300 K.

Samples	n	I_s (A)	R_s (Ω)	V_{bi} (V)	N_t (cm^{-3})	ϕ_{I-V} (eV)	ϕ_{C-V} (eV)
As-grown	1.04	15.5×10^{-18}	48	1.07	7.8×10^{15}	1.25	1.36
Irradiated	1.07	2.6×10^{-18}	270	1.23	7.4×10^{15}	1.31	1.52

3.2. C-V characteristics at room temperature

Fig. 2 shows the plot of C^{-2} (pF^{-2}) as a function of voltage, V (V) before and after alpha-particle irradiation measured at 1 MHz frequency with the sample at room temperature. The capacitance increased with decreasing reverse voltage for both, but the capacitance after irradiation was lower. This is as a result of defects introduced into the sample during the irradiation process which traps electrons [12, 13]. The C-V parameters are tabulated in Table 1. The zero-bias barrier heights for both samples were determined from Eq. 4.

$$\Phi_{C-V} = V_{bi} + \frac{kT}{q} ln\frac{N_c}{N_d}\tag{4}$$
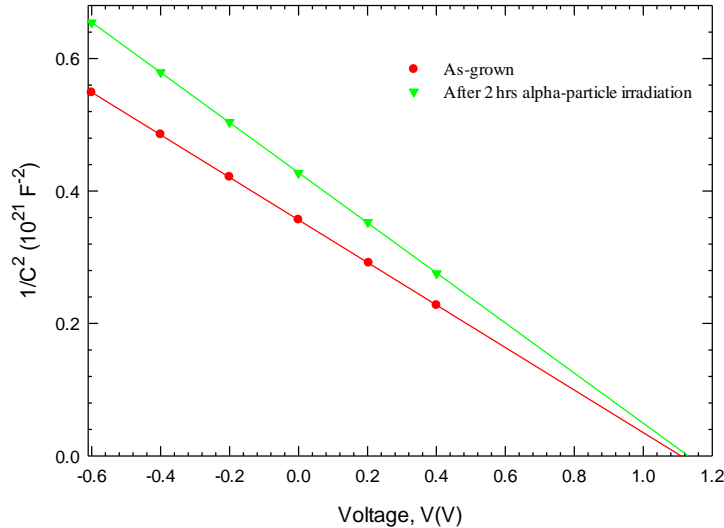
Fig. 2. $1/C^2$ as a function of voltage characteristics of Ni/4H-SiC before and after 5.4 MeV alpha-particles irradiation at 300 K.

From Fig. 2, the free carrier concentration of the sample before and after radiation was determined from the slope of the plots. The free carrier removal rate, η can be obtained from Eq. 5 below:

$$\eta = \frac{\Delta(N_D - N_A)}{\varphi}\tag{5}$$

where $\Delta(N_D - N_A)$ is the change in free carrier concentration before and after irradiation, φ is the fluence to which the sample was bombarded [14]. At room temperature (300 K), a fluence of 5.1×10^{10} alpha-particles-cm^{-2} resulted in a change in carrier concentration from 7.8×10^{15} to 7.4×10^{15} leading to a carrier removal rate of 7.8×10^{3} cm^{-1}.

Comparing the SBH for *I-V* and *C-V* measurements, it was observed experimentally that the SBH's do not agree. The SBH increased after irradiation for both *I-V* and *C-V*, but greater for *C-V* measurements. This is in confirmation with what has been reported in literature [15, 16]. The causes for a difference in this parameters are deep impurity level, surface inhomogeneity, quantum mechanical tunnelling, interfacial layer and states, image force lowering, and edge leakage currents [17].

3.3. I-V Characteristics at Temperature range 40-300 K

Fig. 3 shows the semi-logarithmic forward bias *I-V* characteristics for both as-grown and irradiated Ni/4H-SiC Schottky barrier diodes measured from temperature ranges 40-300 K in other to determine the effect of temperature on the electrical properties of the samples.
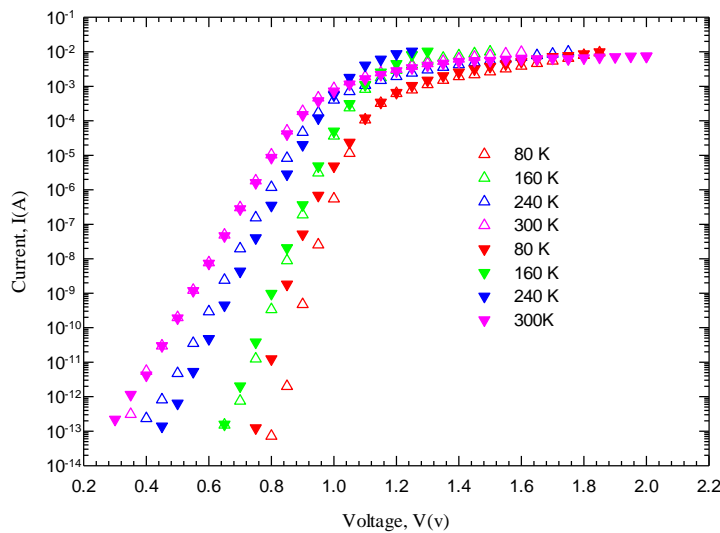
Fig. 3. The current versus voltage characteristics of Ni/4H-SiC before and after irradiation measured at temperature range 40-300 K. The solid symbols represent after irradiation.
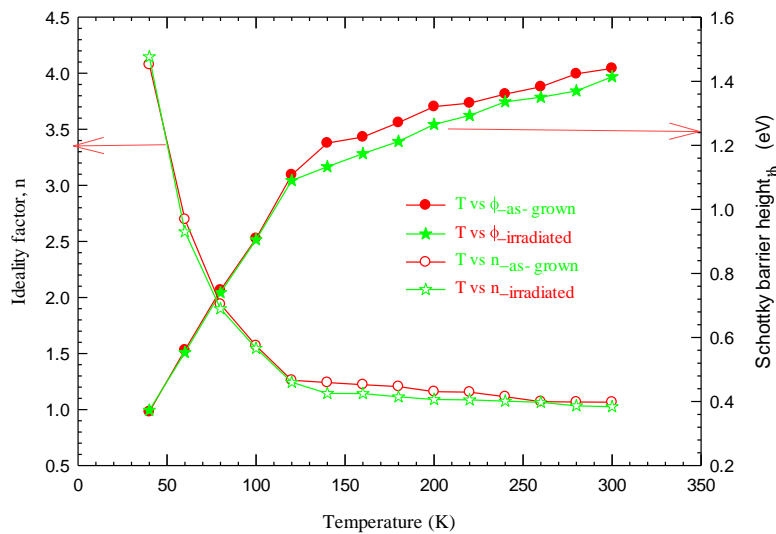
Fig. 4. Ideality factors and Schottky barrier heights as function of temperature before and after irradiation, measured at temperatures range 40-300 K.

Fig. 4 shows a gradual change in the idealit factor and the SBH before and after irradiation for SBD from temperature above 120 K. It can also be deduced from the plot that there is sporadic deviation of electrical behaviours of SBD from thermionic emission theory at lower temperature (below 120 K). The ideality factor and the SBH of the Ni/4H-SiC have strong reciprocal temperature dependence at lower temperatures. There was no noticeable change in the ideality factors and SBH at temperature 120 K and above, for before and after irradiation.

3.4. The Richardson and the Modified Richardson plots

The Richardson's plots of $\ln\left(\frac{I_S}{T^2}\right)$ as a function of $\frac{1}{T}$ are shown in Figs. 5 and 6 for SBD before and after irradiation. We can re-write Eq. 1 as shown below;

$$\ln\left(\frac{I_S}{T^2}\right) = \ln AA^* - \frac{q}{k}\phi_{BO}.\frac{1}{T} \tag{6}$$

The linear part of temperature range 120-300 K of the plots show in the graph. The Richardson constants before and after irradiation were estimated from the intercept of the plot to be 4.1×10^{-8} and 1.2×10^{-11} Acm^{-2}K^{-2}, respectively. The values are extremely small compared to the theoretical value of effective Richardson constant of 146 Acm^{-2}K^{-2} [18, 19], which indicate that the active area is smaller than the device area. The mean barrier heights for both were deduced from the slope of the plot to be 1.63 and 0.72 eV. It has been reported earlier by many researchers that the deviation of the Richardson constants from theoretical value may be as result of effect of the barrier inhomogeneity at the metal-semiconductor (MS) interface and some other factors such as crystal defects, potential fluctuation, etc [20]. Since the deviation cannot be explained by thermionic emission diffusion model, the Gaussian distribution model of barrier height can be used.

The Gaussian distribution model has been used to correct the deviation that cannot be explained with thermionic emission diffusion which occurred as a result of barrier height inhomogeneities. The deviation between experimental and theoretical values of the Richardson constants was described by the modified Richardson plot according to the aforementioned model.

Eq. 7 is obtained by combining Eq. 2 with Eq. 6.

$$\ln\left(\frac{I_S}{T^2}\right) - \left(\frac{q^2\sigma^2}{2k^2T^2}\right) = \ln(AA^{**}) - \frac{q\phi_{Bm}}{kT} \tag{7}$$
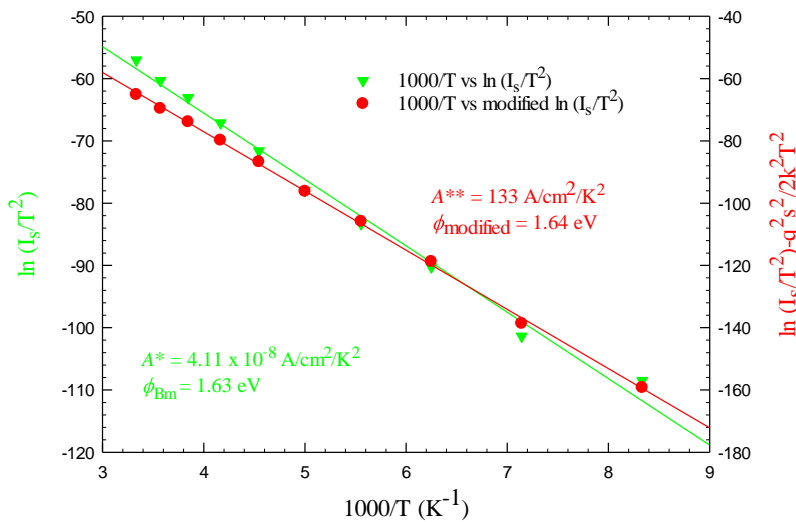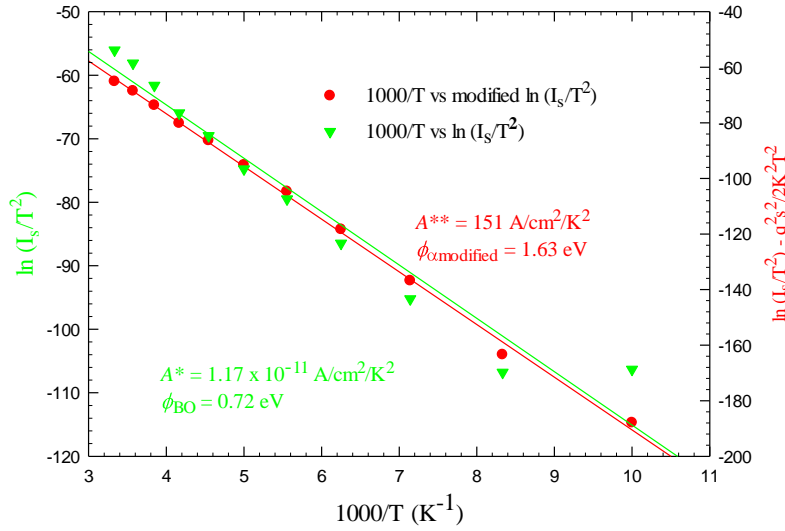

**Fig. 5.** The Richardson plot and the modified Richardson for as-grown Ni/4H-SiC.

Fig. 6. The Richardson plot and the modified Richardson for Ni/4H-SiC after 2 hours irradiation.

The standard deviation, σ, (which its square was calculated to be 1.08×10^{-2} and 1.21×10^{-2} for as-grown and after irradiation) plays major role in estimating the modified Richardson constant, A^{**}. Figs. 5 and 6 show the plot of $\ln(I_s/T^2) - (q^2\sigma^2/2k^2T^2)$ as function of $1000/T$. The A^{**} before and after irradiation were determined from the intercept of the straight line to be 133 and 151 Acm^{-2}K^{-2}, respectively. The values were in good agreement with the theoretical value. The mean barrier height before and after irradiation were estimated from the slope of the straight line as 1.64 and 1.63 eV, respectively. There was no significant change in the value of barrier height after irradiation.

3.5. DLTS analysis

Fig. 7 shows the DLTS spectra for the samples before and after alpha-particle irradiation. The measurements were obtained at temperatures range 22-350 K, at a quiescent reverse bias of −5.0 V, filling pulse of 1.0 V, filling pulse width of 1.0 ms and a rate window of 200 s^{-1}. Fig. 8 shows the Arrhenius plots of each defect. The *signatures* of the defects in term of activation energies, E_n and apparent capture cross sections, σ_n were determined from Fig. 8. The activation energy of each defect was determined from the slope, and the corresponding apparent capture cross section was calculated from the intercept of the Arrhenius plot of log (T^2/e_n) versus *1/T* as earlier reported by Auret *et al* [21]. The sample revealed the presence of four defects before irradiation, and five defects after alpha-particle irradiation as shown in Table 2. Defects with energy levels labelled as $E_{0.09}$, $E_{0.11}$, $E_{0.16}$ and $E_{0.65}$ were obtained before irradiation, and $E_{0.06}$, $E_{0.11}$, $E_{0.15}$, $E_{0.62}$ and $E_{0.67}$ after irradiation, where 'E' refers to an electron trap and the subscript 0.09 refers to an energy level below the conduction band. The properties and attributes of each defect were tabulated in Table 2. The $E_{0.09}$ has been attributed to nitrogen impurities that occupy cubic site and occupy hexagonal site when the activation enthalpy is approximately 0.06 eV [22, 23]. The defects $E_{0.11}$ and $E_{0.16}$ are related to transitional metal (titanium) [24, 25]. The $E_{0.11}$ and $E_{0.16/0.15}$ have been reported earlier that the two levels could be a single defect occupying different geometric positions in material [26]. The $E_{0.62}$ was the only defect introduced by alpha-particle irradiation, and was attributed to Z_1/Z_2.[22, 27]. It has been previously reported that $E_{0.67/0.65}$ could be a defect complex composed of several energy levels [28, 29]. The dominant of these energy levels is Z_1/Z_2 and is possibly a di-carbon or silicon interstitial next to a nitrogen atom or a hydrogen related intrinsic defect [23]. There was a shift in temperature of $E_{0.67}$ from 332 K to 326 K. This was as a result of $E_{0.62}$ defect emanated after irradiation. The peak height of $E_{0.67}$ increases after irradiation as well. The formation of a new defect and the increase in intensity of some of the defects causes changes in *I-V* and *C-V* characteristics and the parameters of the Schottky contacts.
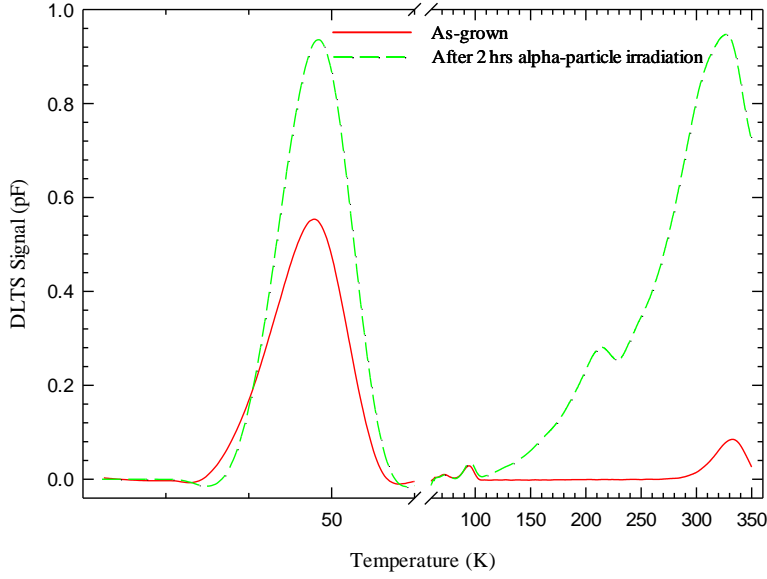
Fig. 7. DLTS spectra for the Ni/4H-SiC before and after alpha-particles irradiation. The temperature range 60-350 K scaled up to 10
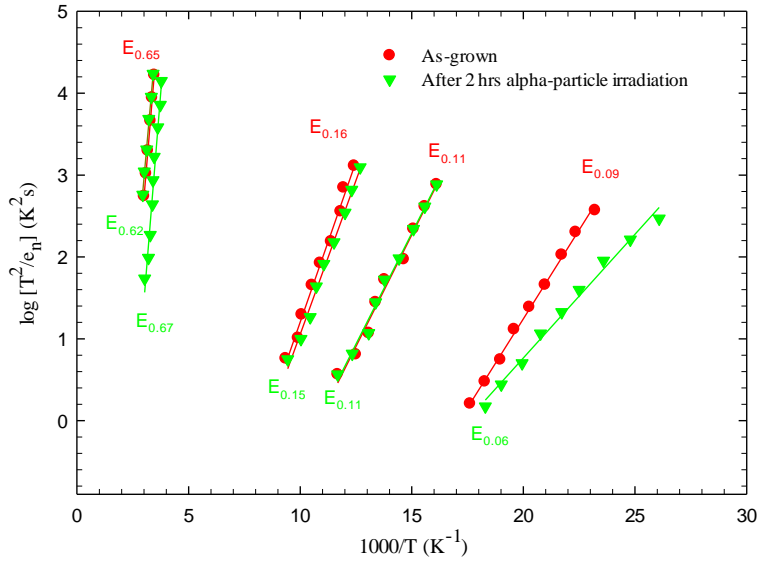
Fig. 8. The Arrhenius plots for the DLTS of as-grown and after irradiation Ni/4H-SiC.

Table 2
Electronic properties of defects detected by DLTS in as-deposited and 5.4 MeV alpha-particles irradiation of Ni/4H-SiC.

As-grown				After alpha-particle irradiation				Attribution
Defect	E_T (eV)	σ_a (cm^2)	T_{peak} (K)	Defect	E_T (eV)	σ_a (cm^2)	T_{peak} (K)	
$E_{0.09}$	E_c–0.09	8×10^{-15}	47	$E_{0.06}$	E_c–0.06	6×10^{-17}	48	N impurity [22]
$E_{0.11}$	E_c–0.11	2×10^{-16}	72	$E_{0.11}$	E_c–0.11	2×10^{-16}	74	Ti impurity [25]
$E_{0.16}$	E_c–0.16	1×10^{-15}	94	$E_{0.15}$	E_c–0.15	9×10^{-16}	95	Ti impurity [24]
–	–	–	–	$E_{0.62}$	E_c–0.62	1×10^{-13}	213	Z$_1$/Z$_2$ [22, 27]
$E_{0.65}$	E_c–0.65	4×10^{-15}	332	$E_{0.67}$	E_c–0.67	8×10^{-15}	326	Z$_1$/Z$_2$ (C/Si vacancy [24, 29]

NOTE: The T_{peak}(K) was taken at rate window of 200s^{-1}

4. Conclusions

In conclusion, the Ni/4H-SiC Schottky contacts have been successfully fabricated by resistive evaporation technique. The effects of 5.4 MeV alpha-particles irradiation measured at different temperatures on Ni/4H-SiC SBD have been investigated using I-V, C-V and conventional DLTS. The I-V and C-V measurements at 300 K before and after fluence of 5.1×10^{10} alpha-particles-cm^{-2} irradiation revealed good Schottky contacts. From I-V measurements, n, SBH, R_s increases with irradiation but I_s decreases with irradiation measured at 300 K. C-V measurements reveal decreases in free carrier concentration. The I-V measurements were also repeated at temperature range 40-300 K. The electrical behaviour of SBD deviated from thermionic emission theory at temperatures below 120 K. The modified Richardson constants before and after alpha-particle irradiation are 133 and 151 Acm^{-2}K^{-2}, respectively, by using Gaussian distribution method. The values of A** were in good agreement with the theoretical value. The electrical properties of Ni/4H-SiC SBDs show little response to 5.4 MeV alpha-particle irradiation with free carrier removal rate of 7.8×10^3 cm^{-1} which corroborate its uses in radiation harsh environments.

Acknowledgement

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