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Radiation effects on ohmic and Schottky contacts based on 4H and 6H-SiC

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ABSTRACT

A systematic study of Ni based ohmic and Schottky contacts (SCs) onto the n-4H-SiC and n-6H-SiC under relatively low-dose (1×10^{12} e$^-$ cm^{-2}) and high-energy (6, 12, 15 MeV) electron irradiation (HEEI) has been introduced. Lower specific contact resistivity has been reached for Ni based ohmic contact structures on both 4H and 6H-SiC after each electron irradiation. This finding has been explained by the displacement damage produced by the collision of electrons with atoms of Ni contact material. It has been observed that the HEEI caused to increase in the ideality factors of both SCs indicating deviation from thermionic emission theory in current transport mechanism. While the Schottky barrier height (SBH) for Ni/4H-SiC SC remains nearly constant, an increase has been observed for the Ni/6H-SiC SC. Donor concentrations for both diodes have decreased with increasing electron energy probably due to the trapping effect of the irradiation induced defect(s).

1. Introduction

SiC is an indirect wide band gap compound semiconductor which has many important electrical, chemical, thermal and mechanical properties such as high thermal conductivity, high breakdown field, high saturation electron drift velocity, high chemical stability and strong mechanical strength as reviewed by the authors [1,2]. Because of these excellent properties, it is preferred to use in semiconductor devices and materials which are operated in harsh environments such as radiation, high temperature, high pressure and high corrosion, etc. In order to use SiC in semiconductor device arena under these mentioned harsh environments, high quality ohmic and Schottky contact properties is required.

So far, many different metals have been used as both ohmic and SC material such as Ni, Al, Co, Ti, Au and W. In addition, because of its superior advantages such as refractory nature, producing low ohmic contact resistivity [3–11] and high SBH [12–15], Ni has been generally chosen as the contact material both for ohmic and SCs in SiC [3–16]. The effects of high-energy proton irradiation and high-dose gamma ray irradiation on 4H-SiC Schottky rectifiers have been investigated by Nigam et al. and Kim et al. respectively, [17,18]. Although both Ni ohmic and SC properties for 4H-SiC have been reported by Perez et al. [11], there is no information for the performance of Ni both for ohmic and SC for 6H-SiC and also its performance under electron irradiation has not been reported for 4H and 6H-SiC samples.

In this study, Ni based ohmic and Schottky contacts onto the 4H- and 6H-SiC were characterized in terms of their electrical parameters under high-energy (6, 12, 15 MeV) and relatively low-dose (1×10^{12} e$^-$ cm^{-2}) EI. Transmission line method (TLM) and, *I–V* and *C–V* measurements were performed before and after each irradiation for ohmic contacts and SCs, respectively. The effects of HEEI on Ni ohmic and SC parameters were discussed in detailed for both 4H- and 6H-SiC materials.

2. Experiment

Silicon carbide bulk wafers used in this study were purchased from University Wafer. Both wafers are two sides polished and have <0001> crystalline orientation. In order to ensure the sample homogeneity, four adjacent pieces with dimensions of $5 \times 5 \times 0.5$ mm^3, two of them are the reference samples and the other two are the samples to irradiate, were cut out from both 4H and 6H-SiC wafers. All wafers were subjected to the well known Si cleaning process. 5N Ni was chosen as the ohmic and Schottky contact element because of becoming one of the most popular materials used in SiC metallization [7]. 5N Au element is used for cap layer in order to prevent the oxidation of Ni contacts. Both metals were evaporated through shadow masks

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sequentially as produced previously in our study [19], in a Univex-300 Pump system with a pressure of 4×10^{-5} Torr. In order to obtain good contact properties, ohmic contacts were annealed in a homemade furnace under dry N_2 gas flow at 950 °C for 10 min [20].

Radiation effects on the electrical parameters of the Au/Ni/n-4H-SiC and Au/Ni/n-6H-SiC ohmic contact structures were investigated by means of the TLM measurements. Before HEEI, TLM measurements were performed on these ohmic contacts. Then, both ohmic contacts were irradiated sequentially high energetic (6, 12, 15 MeV) electrons. After each irradiation step, the TLM measurements were repeated. The details of TLM measurements and a SEM image of the shadow mask used in transferring the ladder pattern to the sample surface can be found in our earlier reports [21,22]. In order to perform *I–V* and *C–V* measurements Keithley-487 picoampermeter and HP-4192 A impedance analyzer (at 50 kHz) were used, respectively.

By using the thermionic emission theory, Schottky contact parameters such as SBH, ideality factor and Fermi level energy position have been determined using the formulation given by our earlier reports [23,24].

Each Schottky contact was irradiated with high-energy (6, 12, 15 MeV) and flux of $3 \times 10^7\ e^- cm^{-2} s^{-1}$. The total dose of the all contacts were arranged to be $1 \times 10^{12}\ e^- cm^{-2}$. All irradiation experiments were carried out at room temperature for approximately 5 min. EI was made by Siemens-Primus linear electron accelerator which allows one to accelerate the electrons up to 21 MeV energy electrons. This dose of irradiation corresponds to the nearly one year period of fluence in the inner zone of the earth's trapped-electron radiation belts [25].

3. Results and discussion

3.1. Ohmic contacts; TLM measurements

Specific contact resistivity, ρ_c, of Ni contacts produced onto the 4H and 6H-SiC were calculated before the HEEI as $(17.1 \pm 7.1) \times 10^{-5}$ and $(5.4 \pm 2.89) \times 10^{-5}\ \Omega\,cm^2$, respectively. Nearly three times lower value of specific contact resistivity has been reached for 6H-SiC with respect to 4H-SiC. Table 1 shows the Ni based ohmic and SC properties obtained from the literature. A close match can be found between values obtained from the present study and the literature given in Table 1.

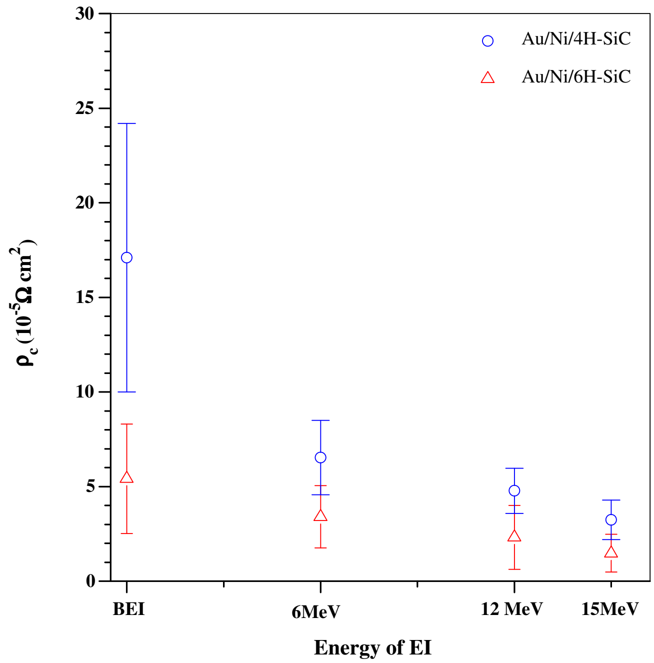

Fig. 1. The variation of ρ_c values with respect to the electron irradiation energy of the Au/Ni/n-4H-SiC and Au/Ni/n-6H-SiC ohmic contacts. The huge error bars could be resulted from the instrumentation problems.

Fig. 1 shows HEEI effects on the ρ_c of Ni based 4H and 6H-SiC ohmic structures. As can be seen from the plot, the specific contact resistivity for Au/Ni/n-4H-SiC and Au/Ni/n-6H-SiC was decreased with increasing electron energy. After the last electron irradiation of 15 MeV, almost five times decrease in ρ_c has been observed for both Au/Ni/n-4H-SiC and Au/Ni/n-6H-SiC structures. It is mostly expected that the particle irradiation gives rise to the displacement damage in semiconductor materials and devices. Therefore, this decrease in ρ_c may be resulted from the diffusion of Ni atoms into the semiconductor with the influence of collision between energetic electrons–atoms of the contact material. Furthermore, heat which emerged due to the electron–lattice interaction can cause a kind of annealing effect and thus diminishes the ohmic contact resistivity drastically.

Table 1
Literature values for the electrical parameters of Ni based ohmic and SCs onto both 4H and 6H-SiC samples.

References	Ohmic contacts		Schottky contacts			
	ρ_c (Ω cm^2)		n	ϕ_B (eV)	n	ϕ_B (eV)
	4H-SiC	6H-SiC	4H-SiC		6H-SiC	
Present study	17.1×10^{-5}	5.4×10^{-5}	1.55	0.91	1.12	0.67
La Via et al. [3]	4.8×10^{-5}	–	–	–	–	–
Pecz [4]	3.0×10^{-6}	–	–	–	–	–
Roccaforte et al. [5]	–	3.9×10^{-5}	–	–	–	–
Machác et al. [6]	–	3.8×10^{-4}	–	–	–	–
Marinova et al. [7]	–	2.8×10^{-6}	–	–	–	–
Kakanakova et al. [8]	2.8×10^{-6}	–	–	–	–	–
Saxena et al. [9]	–	8.2×10^{-5}	1.05	1.59	–	–
Yang et al. [10]	1.4×10^{-5}	–	–	–	–	–
Perez et al. [11]	3.0×10^{-5}	–	2.10	0.77	–	–
Nava et al. [12]	–	–	1.05	1.74	–	–
Vassilevski et al. [13]	–	–	1.10	1.45	–	–
Aboelfotoh et al. [14]	–	–	–	–	1.06	1.08
Sefaoğlu et al. [15]	–	–	–	–	1.25	1.00
Kazukauskas et al. [16]	–	–	1.05	0.74	–	–

3.2. Schottky contacts

In order to understand the radiation effects on Ni/n-4H-SiC and Ni/n-6H-SiC SDs, the accelerated electrons were directed onto the Schottky faces of the samples. Fig. 2(a) and (b) show the *I–V* characteristics of Ni/n-4H-SiC and Ni/n-6H-SiC SCs taken before and right after each irradiation, respectively. Before HEEIs, ideality factors of both Ni/n-4H-SiC and Ni/n-6H-SiC SCs were calculated to be 1.55 and 1.12 and SBHs as 0.91 eV and 0.67 eV, respectively, using the forward bias *I–V* characteristics. In calculations, the dielectric constant, $\varepsilon_s\varepsilon_0$ is taken to be 50.44×10^{14} F cm^{-1} for both samples. The density of states for conduction band, N_c and the Richardson constant, A^* have been taken to be 1.7×10^{19} cm^{-3}, 146 A cm^{-2} K^{-2} for 4H-SiC and 8.9×10^{19} cm^{-3}, 156 A cm^{-2} K^{-2} for 6H-SiC, respectively [26,27].

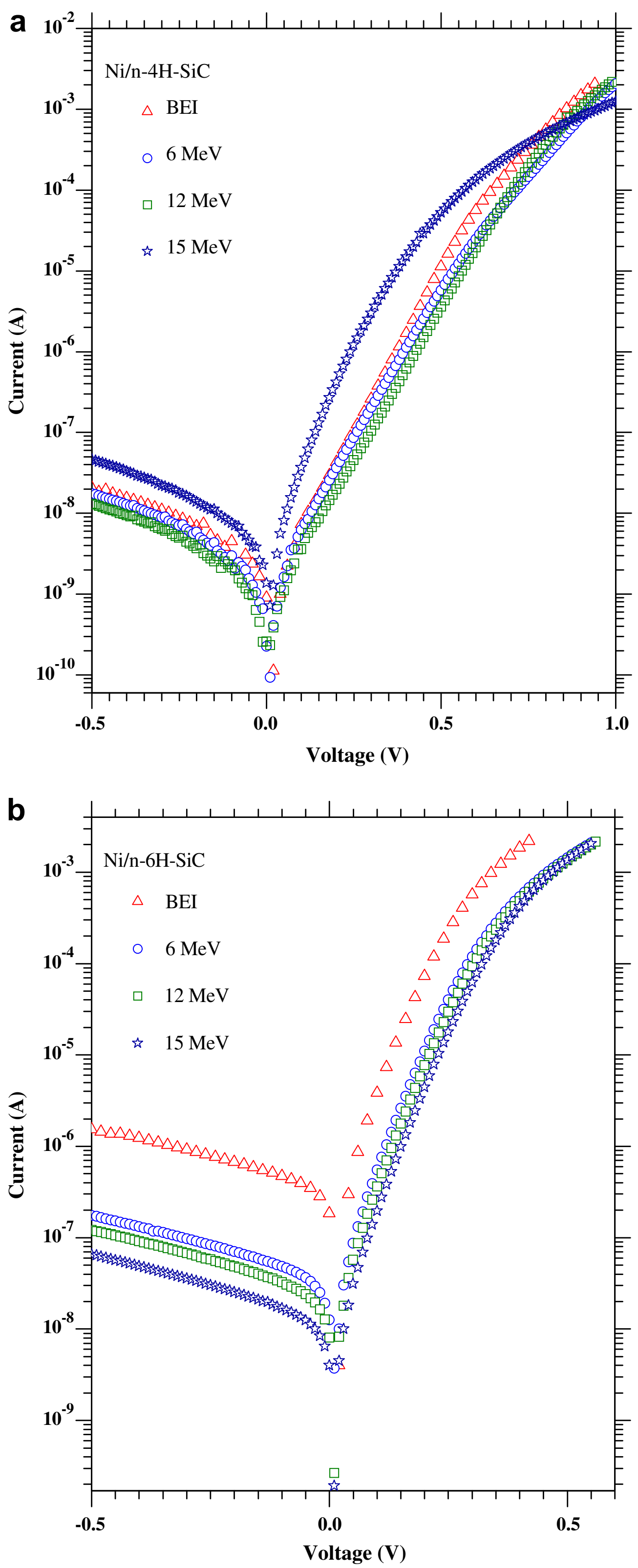

Fig. 2. The *I–V* characteristics of Schottky diodes (a) Ni/n-4H-SiC (b) Ni/n-6H-SiC.

Low value of ideality factor of Ni/n-6H-SiC SC depicts that the current transport mechanism is dominated by thermionic emission. However, relatively high ideality factor of the Ni/n-4H-SiC SC indicates that another mechanism might be possible in current transport. It has been previously reported that high ideality factors might be resulted from the deviation from the thermionic emission in current transport mechanism [24,28,29]. Table 2 gives the variation of the major electrical parameters of Ni/n-4H-SiC and Ni/n-6H-SiC SCs before and after each HEEI. It can be clearly seen from the table that HEEI caused to an increase in ideality factor of both SCs. These results are evidence of some tunneling mechanism becoming dominant in current transport due to the irradiation induced defect states formed at contact interface. The same result can be deduced from the decreasing donor concentration of SCs after HEEIs indicating carrier trapping effect of the defects formed due to the HEEI. These states that prevail at the interface can compensate the pre-existing donors at the interface by lowering the N_d and dislocates the position of Fermi level with respect to the conduction band (see Table 1).

The SBH of the Ni/n-4H-SiC SC does not show considerable change after exposed to the HEEI except for the last irradiation (Table 1). Fig. 2(a) shows the variation in the *I–V* characteristics and also the increase in reverse-bias current after 15 MeV EI. Thus, SBHs of the Ni/n-4H-SiC SC are slightly decreased after the last irradiation of 15 MeV. However, the SBHs of Ni/n-6H-SiC SC are shown to increase because of the decrease in the reverse-bias current with increasing electron irradiation energy as shown in Fig. 2(b). Similarly, Kazukauskas et al. found that particle irradiation caused to an increase in SBHs of Au/4H-SiC SC [16]. On the other hand, Fig. 3 shows the *C–V* and $1/C^2$–*V* (inset) plots for both SCs indicating the decreasing of the capacitance for both SCs with increasing electron energy. This may be resulted from the reduction of carrier concentrations of both materials due to the trapping effect of the irradiation induced defects. Before EI, donor concentrations for 4H- and 6H-SiC SCs have been calculated to be 2.12×10^{15} and 1.09×10^{15} cm^{-3}. It has been found that the increasing EI energy results in a decrease of approximately 20% in donor concentration for the 4H-SiC and 3% for the 6H-SiC after the last EI with respect to those obtained before HEEI. This should suggest that the Ni/n-6H-SiC SC is more radiation resistant to the HEEI as compared to the Ni/n-4H-SiC SC.

4. Conclusion

The effects of relatively low-dose (1×10^{12} e$^-$ cm^{-2}) and HEEI (6, 12, 15 MeV) on Ni based ohmic and Schottky structures onto the n-4H-SiC and n-6H-SiC have been investigated. TLM measurements have shown that the ohmic contact resistivity for both Au/Ni/n-4H-SiC and Au/Ni/n-6H-SiC structures decreased approximately five times after HEEI. These results have been interpreted based on the assumption of that the atoms of the contact elements diffused into the semiconductor material with the influence of radiation-matter interaction and subsequent annealing effects. Both Ni/n-4H-SiC and Ni/n-6H-SiC SCs are shown to increase in ideality with increasing electron energy because of the deviation

Table 2
Major electrical parameters of Ni/n-4H-SiC and Ni/n-6H-SiC Schottky diodes obtained before and after each electron irradiation. The SBH (Φ_b) and ideality (n) have been calculated from I–V characteristics and donor concentration (N_d), Fermi energy (E_F) from C–V measurements.

EI energy	Ni/n-4H-SiC				Ni/n-6H-SiC			
	Φ_b (eV)	n	N_d ($\times 10^{15}$ cm^{-3})	E_F (eV)	Φ_b (eV)	n	N_d ($\times 10^{15}$ cm^{-3})	E_F (eV)
Before EI	0.91	1.55	2.12	0.232	0.67	1.12	1.09	0.293
6 MeV	0.94	1.58	1.94	0.235	0.71	1.25	1.09	0.289
12 MeV	0.93	1.80	1.92	0.235	0.72	1.27	1.06	0.296
15 MeV	0.791	1.85	1.70	0.238	0.73	1.29	1.05	0.296

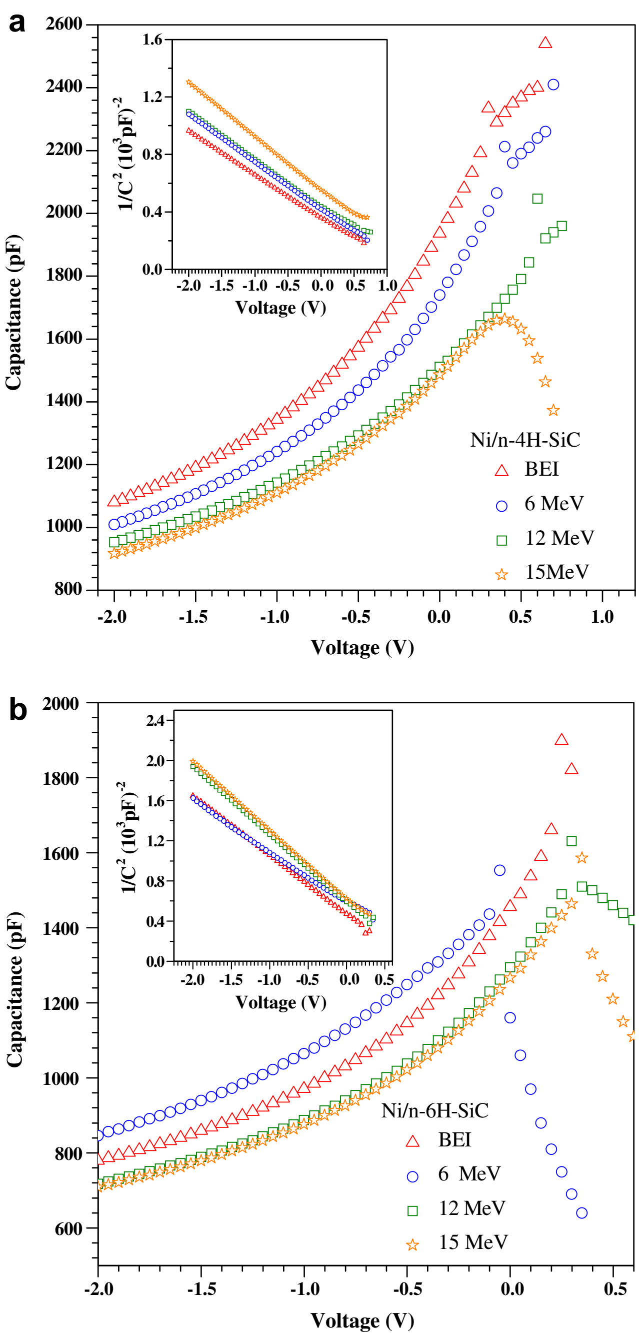

Fig. 3. The C–V characteristics of Schottky diodes (a) Ni/n-4H-SiC (b) Ni/n-6H-SiC.

from the thermionic emission to the tunneling mechanism by the irradiation induced traps at the interface. The current–voltage (I–V) measurements have shown that the SBH of Ni/n-4H-SiC SC remained nearly constant whereas SBHs for Ni/n-6H-SiC SC are shown to increase slightly due to the lower reverse-bias current after HEEIs. This should suggest that the Ni/n-6H-SiC SC is more radiation resistant to the HEEI as compared to the Ni/n-4H-SiC SC. These results may have practical as well as fundamental significance, because the high energetic particles are often encountered in space applications.

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