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High energy electron radiation effect on Ni/4H-SiC SBD and Ohmic contact*

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The Ni/4H-SiC Schottky barrier diodes (SBDs) and transfer length method (TLM) test patterns of Ni/4H-SiC Ohmic contacts were fabricated, and irradiated with 1 MeV electrons up to a dose of 3.43×10^{14} e/cm^{-2}. After radiation, the forward currents of the SBDs at 2 V decreased by about 50%, and the reverse currents at −200 V increased by less than 30%. Schottky barrier height ($\phi_{\rm B}$) of the Ni/4H-SiC SBD increased from 1.20 eV to 1.21 eV under 0 V irradiation bias, and decreased from 1.25 eV to 1.19 eV under −30 V irradiation bias. The degradation of $\phi_{\rm B}$ could be explained by the variation of interface states of Schottky contacts. The on-state resistance ($R_{\rm s}$) and the reverse current increased with the dose, which can be ascribed to the radiation defects in bulk material. The specific contact resistance ($\rho_{\rm c}$) of the Ni/SiC Ohmic contact increased from 5.11×10^{-5} Ω·cm^2 to 2.97×10^{-4} Ω·cm^2.

Keywords: silicon carbide, Schottky barrier diode, Ohmic contact, electron radiation
PACC: 6180, 8750G, 7850G, 7340S

1. Introduction

Silicon carbide (SiC) has outstanding properties such as wide bandgap, higher thermal conductivity, high critical breakdown field and high bond dissociation energy (435 kJ/mol), and it has been used to fabricate sensors and high-temperature and high-power electronic devices in the nuclear power industry and satellite-based system.[1] SiC Schottky contact and Ohmic contact are main factors for obtaining excellent performance of SiC-based devices like high-voltage rectifiers and metal-semiconductor-field-effect-transistors (MESFET).[2] Investigation of the radiation effect is important for the SiC device application in the intense radiation environment. The radiation effects of high-energy proton[3−6] and gamma ray[7,8] on SiC SBD have been reported, but the high-energy electron radiation effect has rarely been investigated. Also the radiation effect on SiC Ohmic contact has not been reported.

High-energy electrons are one of the main penetrating particles that are responsible for the degradation of electronic devices and circuits in space aircraft. Similar to protons, high-energy electrons (≥200 keV) can also introduce permanent defects in the SiC material, such as vacancies, interstitials and other related defects. These defects act as traps and generation-recombination centers in the SiC material. So they increase the resistivity of the SiC bulk material and introduce recombination current in the depletion layer, leading to the degradation of SiC devices. However, the radiation defects will not disappear unless by high-temperature annealing.[9−11]

The previously reported radiation study of SiC SBDs were generally performed at zero bias during irradiation, which is usually different from the practical application. In the MESFET, UV or radiation detector, the SiC Schottky contacts often work under reversed bias.

In this paper, 1 MeV electrons are used to investigate the radiation effect on Ni/4H-SiC SBDs and Ohmic contacts. The highest total dose is up to 3.43×10^{14} e/cm^2. The 0 V and –30 V bias are applied to the SBDs during irradiation.

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2. Experiment

A 4H-SiC wafer was prepared by homoepitaxial growth with a commercial low-pressure, hot wall CVD (LP-HW-CVD) reactor (Epigress VP508 system) using the $SiH_4/C_3H_8/H_2$ system. The n-type SiC epitaxial layer was grown on the surface (0001) of a 4H-SiC substrate with 8° off axis. The substrate was purchased from the SiCrystal.AG. The epilayer was formed by unintentionally doping, with a thickness of 10 μm, and the net carrier concentration is approximately 6.4×10^{14} cm^{-3}.

Metal films Ni/Pt (450/50 nm) were deposited on the backside of the SiC wafer by electron beam evaporation and subsequently annealed at 1000 °C in N_2 for 2 min to form Ohmic contacts, followed by electron beam evaporated Cr/Au (50/200 nm) on them. Circular Schottky contact was deposited by electron beam evaporating Ni/Cr/Au (200/50/200 nm) on the substrate and patterned by lift off. Ni metal is chosen in this investigation because it is one of the most widely used metals for Schottky contacts and Ohmic contacts in SiC devices. The cross section of the Ni/4H-SiC SBD is shown in Fig.1. Then the sample was cut into single devices by laser cutting for packaging. Aluminium wire was used to connect the pin to the pad.

The radiation experiment was operated at room temperature and performed with an ELV-8 type electron accelerator at the Northwest Institute of Nuclear Technology. The dose rate was 6.85×10^{10} e/cm^2·s, the highest total dose is up to 3.43×10^{14} e/cm^2.

A Laboratory DC power supply (Model MPS-3005LP-3) was used to supply the 0 V and –30 V bias to samples under irradiation. I–V characteristics were measured using HP4156A precision semiconductor parameter analyzer and Agilent Technology 34980A multifunction switch/measurement unit. In the process of the experiment, there was no obvious temperature rise observed for the samples.

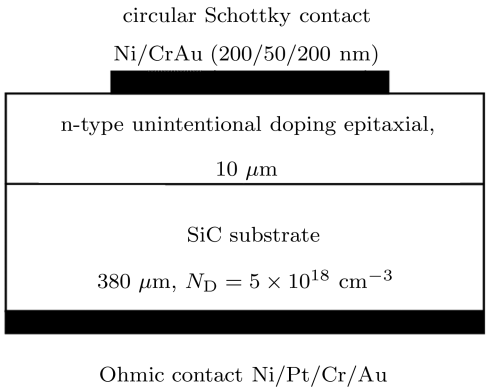


Fig.1. Schematic cross section of the Ni/4H-SiC SBD.

3. Results and discussion

3.1. Forward characteristics

Figure 2 shows the forward characteristics of the Ni/4H-SiC SBDs pre- and post-radiation. A noticeable and repeatable phenomenon is observed that the diodes showed different degradation trends under different irradiation bias. Under 0 V irradiation bias, the forward current decreases after radiation; however, under −30 V irradiation bias the forward current increases at low bias voltage (< 1.2 V) and decreases at higher forward voltage. The forward current at 2 V decreases by 50.3% and 50.7% after electron dose of 3.43×10^{14} e/cm^2 under 0 V and −30 V irradiation biases, respectively.

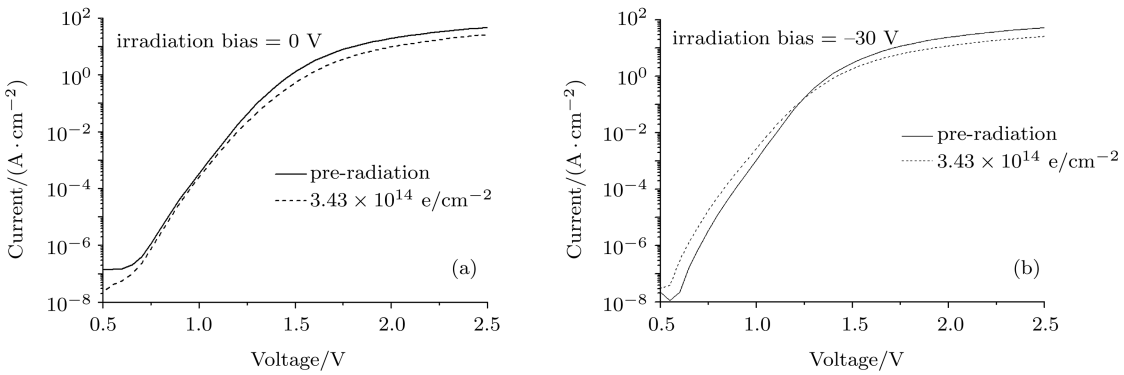


Fig.2. Forward I–V characteristics of the 4H-SiC SBDs before and after radiation.

Based on the thermionic emission theory, the forward current running through the SiC SBD can be expressed as[2]

$$I_{\rm F} = I_{\rm S}\left\{\exp\left[\frac{q}{nkT}(V - I_{\rm F}R_{\rm S})\right] - 1\right\}, \quad (1)$$

$$I_{\rm S} = AA^*T^2\exp(-q\phi_{\rm B}/kT), \quad (2)$$

where n is the ideality factor, $I_{\rm S}$ is the reverse saturation current, $R_{\rm s}$ is the on-state resistance, $\phi_{\rm B}$ is Schottky barrier height and A^* is Richardson's constant (146 A·cm^{-2}·K^{-2}).

In Eq.(2) n can be obtained by ignoring the voltage drop in the linear region of current,

$$n = \frac{q}{kT}\frac{\partial V}{\partial \ln I}. \quad (3)$$

At a high forward voltage, $R_{\rm S}$ can be given by

$$R_{\rm S} = \left(1 - \frac{\partial \ln I_{\rm F}}{\partial V}\frac{nkT}{q}\right) \Big/ \left(\frac{\partial I_{\rm F}}{\partial V}\right). \quad (4)$$

By calculating from Fig.2, we obtain the variation of n and $\phi_{\rm B}$ with electron dose as shown in Fig.3. The $\phi_{\rm B}$ of the SBD under 0 V irradiation bias increases from 1.20 eV to 1.21 eV, and decreases from 1.25 eV to 1.19 eV under −30 V bias.

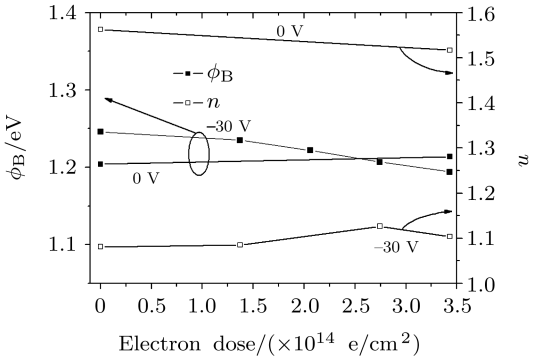


Fig.3. Variation of n and $\phi_{\rm B}$ with electron dose for 4H-SiC SBD.

Figure 4 shows the calculated $R_{\rm S}$ as a function of the electron dose. The $R_{\rm S}$ increases from 15.6 Ω to 21.6 Ω under 0 V irradiation bias, and increases from 17.9 Ω to 27.8 Ω under −30 V irradiation bias.

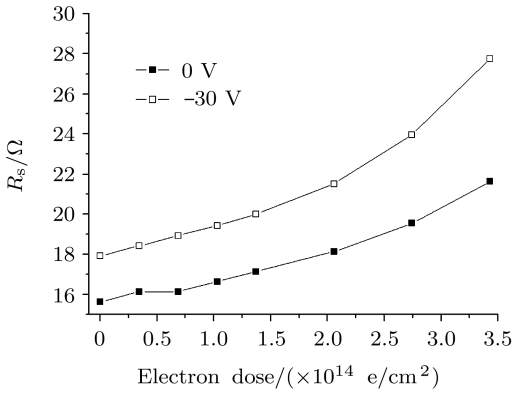


Fig.4. Variation of $R_{\rm s}$ with electron dose for 4H-SiC SBD.

After radiation, the diodes were annealed at room temperature. After one week, the measurement results showed that the values of $\phi_{\rm B}$ of the Ni /4H-SiC SBDs under 0 V and −30 V bias have completely recovered to the value before radiation. However, the values of $R_{\rm s}$ did not completely recover after four months. It can be explained by the fact that the degradation is caused by carrier and mobility removal effects due to radiation-induced defects in the SiC bulk material.[3,5,12]

The degradation of $\phi_{\rm B}$ could be explained by interface state changes of the Schottky contacts due to radiation.[13,14] The different degradation trend of $\phi_{\rm B}$ under different radiation bias needs further study.

3.2. Reverse characteristics

Figure 5 shows reverse characteristics of the Ni/4H-SiC SBDs at different electron doses. Under

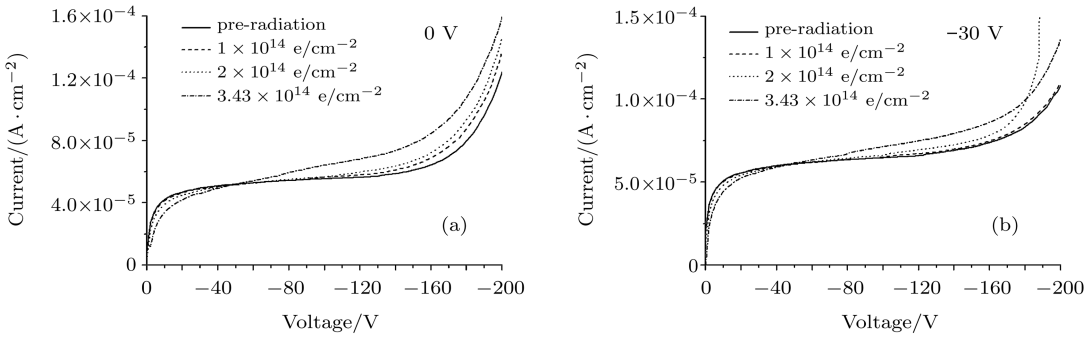


Fig.5. Reverse I–V characteristics of the 4H-SiC SBDs at different electron doses.

different irradiation bias, reverse characteristics show variations similar to the forward characteristics. Reverse current increases slightly with increasing electron dose. The reverse current at −200 V is increased from 1.24×10^{-4} A·cm^{-2} to 1.59×10^{-4} A·cm^{-2} under 0 V irradiation bias, and increased from 1.08×10^{-4} A·cm^{-2} to 1.36×10^{-4} A·cm^{-2} under −30 V irradiation bias.

After the sample was kept for two weeks on a shelve at room temperature, no obvious change of reverse currents can be observed, showing that reverse current is not influenced by the degradation of ϕ_{B}. The degradation of the reverse current could be ascribed to the generation-recombination centers created by the high-energy electrons.[3,15]

3.3. Ohimc contact

The scanning electron microscopy (SEM) image of the TLM pattern used in this study is shown in Fig.6. The interspaces of six rectangular N^+ regions are 8, 16, 24, 32 and 40 μm.

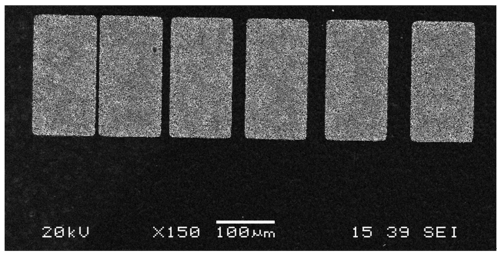


Fig.6. SEM image of TLM structure.

Figure 7 shows the variation of total resistance R_{T} between adjacent TLM pads with gap spacing L before and after radiation, which is measured by TEKET370B semiconductor parameter analyzer.

By assuming that the length of each contact is long enough, the total resistance R_{T} can be expressed as follows:

$$R_{\mathrm{T}} = 2R_{\mathrm{C}} + \frac{R_{\mathrm{sh}}L}{W}, \tag{5}$$

where W is the width of the contacts, $2R_{\mathrm{c}}$ is the y-interception of the linear curve. The specific contact resistance ρ_{c} is given by:

$$\rho_{\mathrm{C}} = \frac{(R_{\mathrm{C}}W)^2}{R_{\mathrm{sh}}}. \tag{6}$$

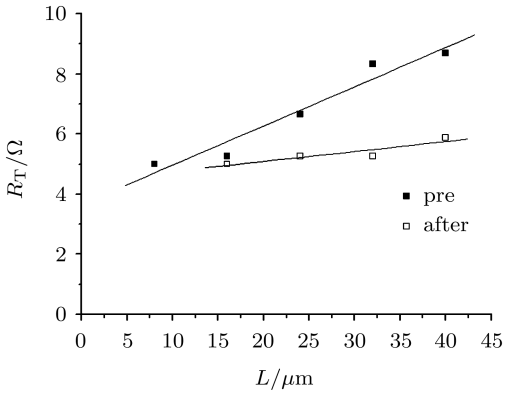


Fig.7. TLM total resistance versus gap spacing of the nickel silicide contacts.

The specific contact resistance of the Ni/4H-SiC Ohmic contact was 5.11×10^{-5} Ω·cm^2 before radiation, and increased to 2.97×10^{-4} Ω · cm^2 after radiation. Sheet resistance R_{sh} is W multiplied by the slope $\mathrm{d}R_{\mathrm{T}}/\mathrm{d}L$ obtained from Fig.7. The value for sheet resistance R_{sh} of the SiC substrate contact is about 26.12 Ω/□ before radiation and 6.6 Ω/□ after radiation. The degradation mechanism of the Ohmic contacts needs further study. Considering the above results, we can ascribe the degradation of the Ni/SiC Ohmic contact to changes in the barrier height between nickel silicide and SiC.[16]

4. Conclusion

In this paper Ni/4H-SiC SBDs and Ohmic contacts have been fabricated, and irradiated with the highest dose up to 3.43×10^{14} e/cm^{-2} of 1 MeV electrons. When 0 V and −30 V bias voltages were applied to the SBDs during irradiation, the diodes kept good rectifying characteristics, and showed excellent radiation-resist capability even after raidation. The R_{s} and the reverse current of the Ni/4H-SiC SBDs increased with increasing dose, which can be ascribed to the radiation defect; and ϕ_{B} increased under 0 V irradiation bias, but decreased under −30 V irradiation bias. The specific contact resistance ρ_{c} of the Ni/SiC Ohmic contact was increased after radiation.

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