Neutron radiation effect on 4H-SiC MESFETs and SBDs*

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Abstract: 4H-SiC metal Schottky field effect transistors (MESFETs) and Schottky barrier diodes (SBDs) were irradiated at room temperature with 1 MeV neutrons. The highest neutron flux and gamma-ray total dose were 1×10^{15} n/cm^2 and 3.3 Mrad(Si), respectively. After a neutron flux of 1×10^{13} n/cm^2, the current characteristics of the MESFET had only slightly changed, and the Schottky contacts of the gate contacts and the Ni, Ti/4H-SiC SBDs showed no obvious degradation. To further increase the neutron flux, the drain current of the SiC MESFET decreased and the threshold voltage increased. ϕ_B of the Schottky gate contact decreased when the neutron flux was more than or equal to 2.5×10^{14} n/cm^2. SiC Schottky interface damage and radiation defects in the bulk material are mainly mechanisms for performance degradation of the experiment devices, and a high doping concentration of the active region will improve the neutron radiation tolerance.

Key words: silicon carbide; metal semiconductor field effect transistor; Schottky barrier diode; neutron radiation
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1. Introduction

Silicon carbide (SiC) has outstanding properties and can be used to fabricate electronic devices in the nuclear power industry and in satellite-based systems[1]. Among various SiC electronic devices, the 4H-SiC MESFET and SBD have shown their maturity and been widely applied in high frequency and high power systems. Investigation of the neutron radiation effect is important for SiC device application in the intense radiation environment. The radiation effects of high-energy changing particles[2−7] and gamma ray[8, 9] on SiC MESFETs and SBDs have been reported, but the neutron radiation effect has rarely been investigated. In this paper, 1 MeV neutrons were used to investigate the radiation effect on 4H-SiC MESFETs. The highest neutron flux is up to 1×10^{15} n/cm^2.

2. Experiment

4H-SiC MESFETs were fabricated on a 4H-SiC semi-insulating substrate. A low doped p-type buffer layer and a 0.3 μm n-type channel layer with 3×10^{17} cm^{-3} were grown. The gate length and width were 1.2 μm and 1 mm, respectively. 4H-SiC SBDs were fabricated on an unintentionally doped n-type 4H-SiC epilayer with 10 μm thickness grown on a 4H-SiC high doped substrate. The net carrier concentration of the epilayer layer was about 6.4×10^{14} cm^{-3}. Ni metal was deposited for the backside of the SiC wafer and annealed to form an ohmic contact. A circular Schottky contact was formed by Ni/Cr/Au or Ti/Cr/Au on the top of the epilayer layer.

The radiation experiment operated at room temperature was performed in the Xi'an pulse reactor at the Northwest Institute of Nuclear Technology. The neutron flux and gamma dose rate were 8.1×10^7 n/(cm^2·kW·s) and 0.245 rad(Si)/(kW·s), respectively. The reactor operated at 200 kW produced the neutron flux of 1×10^{13} n/cm^2, then operated at 1 MW to produce the 1×10^{15} n/cm^2 flux. The highest neutron flux corresponding gamma total dose was 3.3 Mrad(Si). All the devices had zero bias during irradiation.

Direct current characteristics were measured at different neutron fluxes, using an HP4156A precision semiconductor parameter analyzer and an Agilent Technology 34980A multifunction switch/measurement unit. To avoid the activation effect of neutron radiation, on-line measurement was performed to obtain the device characteristics. A 40 m long data line was used to connect the devices and the measurement equipment.

3. Results and discussion

During measurements of the samples, it was found that noticeable and repeatable results were obtained. Figure 1 shows the typical output characteristics of a 4H-SiC MESFET at different neutron flux.

In Fig. 1(a), only slightly changes in $I-V$ are observed after neutron flux of 1×10^{13} n/cm^2, while an obvious decrease in the drain current is noticed for 1×10^{14} n/cm^2. The drain current at $V_{ds} = 20$ V and $V_{gs} = -7$ V decreased by 18.9% and 68.3% after neutron flux of 1×10^{14} n/cm^2 and 1×10^{15} n/cm^2, respectively.

The degradation of the drain current was mainly caused by carrier and mobility removal effects due to neutron radiation induced defects in the channel layer[10−12], and the negative surface charge above the channel region introduced by gamma-

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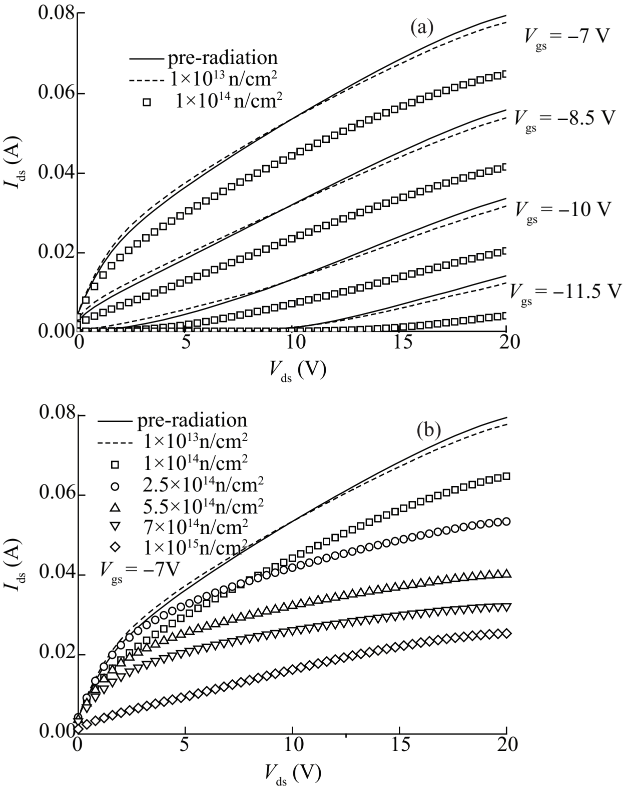

Fig. 1. Output characteristics of a 4H-SiC MESFET at different neutron flux.

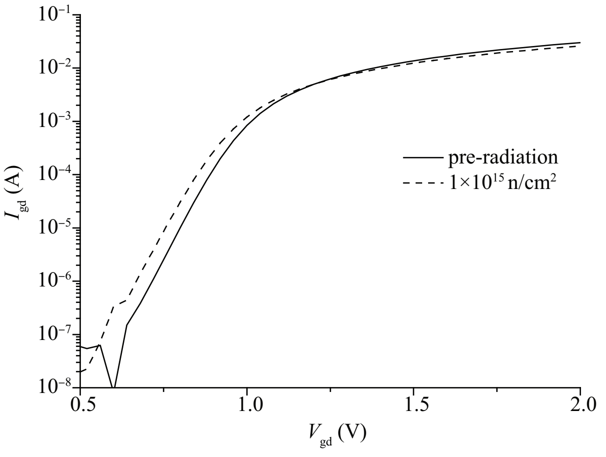

Fig. 2. Schottky gate characteristic of a MESFET in before and after radiation.

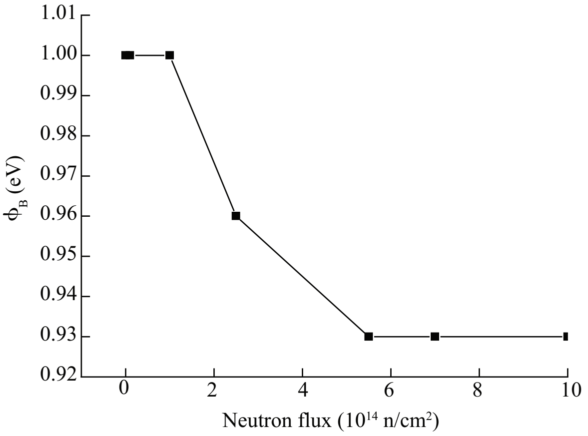

Fig. 3. ϕ_B of gate Schottky contact at different neutron flux.

rays also probably made the drain current decrease[3, 5, 13].

From Fig. 1(b), a slight drain current increased in the low V_{ds} (< 7 V) at a neutron flux of 2.5×10^{14} n/cm^2 compared to the flux of 1×10^{14} n/cm^2. In addition to the conductance of the channel layer, the drain current was influenced by Schottky gate contact. Figure 2 shows V_{gd} versus I_{gd} (other contacts are floated) both before and after radiation.

As can be seen from Fig. 2, after radiation, the gate current (I_{gd}) is increased at low V_{gd} and decreased at higher V_{gd}. Based on the thermionic emission theory, the forward current I_F running through the Schottky contact can be expressed as Eqs. (1) and (2)[14],

$$I_F = I_S\left\{\exp\left[\frac{q}{nkT}(V - I_F R_S)\right] - 1\right\}, \tag{1}$$

$$I_S = AA^* T^2 \exp\left(-\frac{q\phi_B}{kT}\right), \tag{2}$$

where n is the ideality factor, I_S is the reverse saturation current, R_s is the on-state resistance, A is the gate contact area and A^* is Richardson's constant (146 A/(cm^2·K^2)).

With the calculation from Fig. 2, the Schottky barrier heights of ϕ_B of the gate Schottky contact at different neutron flux are shown in Fig. 3. ϕ_B is 1.00 eV before radiation, decreasing to 0.93 eV after neutron flux of 1×10^{15} n/cm^2. ϕ_B basically remains at the same value when the neutron flux is less than or equal to 1×10^{14} n/cm^2, but begins to decrease at the flux of 2.5×10^{14} n/cm^2. This result is consistent with the degradation trend of the drain current. In a higher neutron flux, degradation of the channel layer is the dominant factor in the degradation mechanism.

Reference [9] reported that 4 Mrad(Si) gamma-ray radiation will not degrade the ϕ_B of 4H-SiC Schottky contact. In this paper, the highest gamma-ray total dose was 3.3 Mrad(Si), so the degradation mechanism of the gate Schottky contact can be explained by the SiC Schottky contact or bulk material damage introduced by neutron radiation. Considering that the carrier concentration of the bulk material decrease will cause ϕ_B to increase, the degradation mechanism of ϕ_B could be explained by Schottky interface damage caused by neutron radiation.

Figure 4 shows the transfer characteristics and transconductance of the 4H-SiC MESFET at different neutron flux from 1×10^{13} to 1×10^{15} n/cm^2 at V_{ds} = 15 V. The threshold voltage increased with increasing neutron flux. After radiation of 1×10^{14} n/cm^2, the threshold voltage increased from –12.5 to –11.5 V, as shown in Fig. 4(a). From Fig. 4(b), in the high reverse gate voltage, i.e., less than –10 V, transconductance decreased with increasing neutron flux. No more data were obtained in the lower gate voltage limited by the measurement conditions. The degradation of threshold voltage and transconductance can be explained by the carrier removal effect in the channel layer caused by neutron radiation.

Figure 5 shows the forward characteristics of Ni and Ti/4H-SiC SBDs at different neutron flux. In the low bias voltage, the

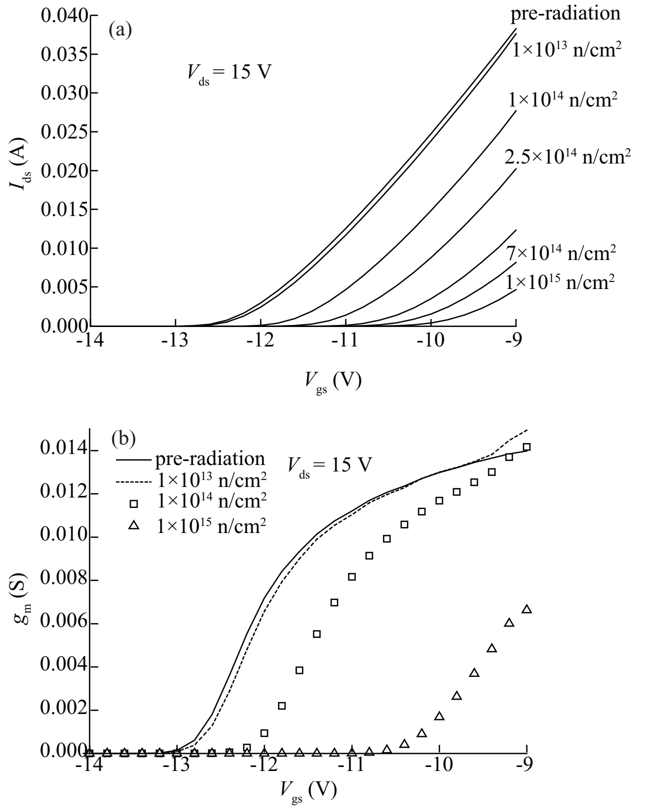

Fig. 4. (a) Transfer characteristics and (b) transconductance of a 4H-SiC MESFET at different neutron flux.

forward current of both SBDs shows no obvious change after a neutron flux of 1×10^{13} n/cm^2, but is only decreased a little bit in the higher bias voltage.

With the calculation from Fig. (2), ϕ_{B} of the Ni and Ti/4H-SiC SBDs are 1.02 eV and 0.82 eV. ϕ_{B} basically remained at the same value after a neutron flux of 1×10^{13} n/cm^2.

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

$$R_{\mathrm{S}} = \left(1 - \frac{\partial InI_{\mathrm{F}}}{\partial V}\frac{nkT}{q}\right) \Big/ \frac{\partial I_{\mathrm{F}}}{\partial V}. \tag{3}$$

R_{S} is increased from 21.8 to 22.9 Ω for Ni/4H-SiC SBD, and from 18.6 to 21.5 Ω for Ti/4H-SiC SBD. The degradation mechanism of R_{S} is similar to the drain current of the MESFET.

As can be seen from Fig. 5, after neutron flux of 1×10^{14} n/cm^2, the forward currents of both SBDs become worse because the epilayer of the SiC SBDs has become a high resistance layer due to the carrier removal effect. Compared with the gate contact of the SiC MESFET, the SiC SBD showed lower neutron radiation tolerance, which can be ascribed to the low carrier concentration of the active region. So the high doping concentration of the active region will improve the neutron radiation tolerance.

4. Conclusion

In this paper, the neutron radiation effect on a 4H-SiC MESFET and Ni, Ti/4H-SiC SBDs are investigated with the flux up to 1×10^{15} n/cm^2. After a neutron flux of 1×10^{13} n/cm^2, the current characteristics of the MESFETs and SBDs exhibit no obvious change, and they show excellent radiation-resistance capability. With increasing neutron flux, the drain current of the MESFET decreased and the threshold voltage increased. No obvious degradation of ϕ_{B} of the gate Schottky contacts of the Ni and Ti/4H-SiC SBDs was observed at the neutron flux of 1×10^{13} n/cm^2, but it decreased at a flux of 2.5×10^{14} n/cm^2 for the gate Schottky contacts. The result in this paper shows that a high doping concentration of the active region will improve the neutron radiation tolerance.

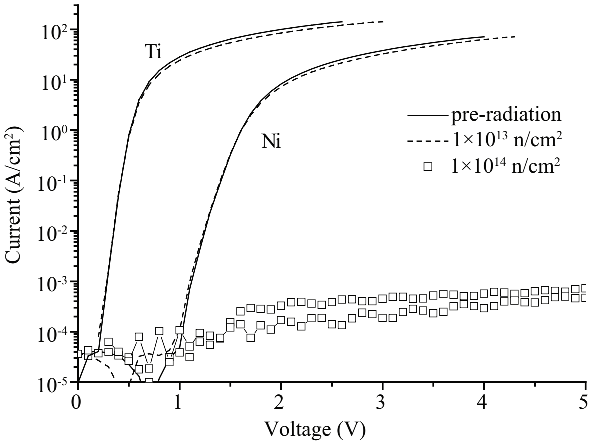

Fig. 5. Forward characteristics of Ni, Ti/4H-SiC SBDs at different neutron flux.

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References

[1] Zhang Y M. Study of silicon carbide material and devices. PhD Dissertation, Xidian University, 1998 (in Chinese)

[2] Nigam S, Kim J, Ren F, et al. High energy proton irradiation effects on SiC Schottky rectifiers. Appl Phys Lett, 2002, 81: 2385

[3] Luo Z Y, Chen T B, Ayayi C, et al. Proton radiation effects in 4H-SiC diodes and MOS capacitors. IEEE Trans Nucl Sci, 2004, 51: 3748

[4] Harris R D, Frasca A J, Patton M O. Displacement damage effects on the forward bias characteristics of SiC Schottky barrier power diodes. IEEE Trans Nucl Sci, 2005, 52: 2408

[5] Scheick L, Selva L, Becker H. Displacement damage-induced catastrophic second breakdown in silicon carbide Schottky power diodes. IEEE Trans Nucl Sci, 2004, 51: 3193

[6] Zhang Lin, Zhang Yimen, Zhang Yuming, et al. High energy electron radiation effect on Ni and Ti/4H-SiC Schottky barrier diodes at room temperature. Chinese Physics B, 2009, 18(5): 1931

[7] Zhang Lin, Zhang Yimen, Zhang Yuming, et al. High energy electron radiation effect on Ni/4H-SiC SBD and ohmic contact. Chinese Physics B, 2009, 18(8): 3490

[8] Kim J, Ren F, Chung G Y, et al. Comparison of stability of WSi$_X$ /SiC and Ni/SiC Schottky rectifiers to high dose gamma-ray irradiation. Appl Phys Lett, 2004, 84: 371

[9] Sheridan D C, Chung G, Clark S, et al. The effects of high-dose gamma irradiation on high-voltage 4H-SiC Schottky diodes and the SiC–SiO$_2$ interface IEEE Trans Nucl Sci, 2001, 48: 2229

[10] Shang Yechun, Zhang Yimen, Zhang Yuming. The electrical characteristics and neutron irradiation response model of 6H-SiC

JFET. Nuclear Electronics & Detection Technology, 2000, 20(6): 424 (in Chinese)

[11] McLean F B, McGarrity J M, Scozzie C J, et al. Analysis of neutron damage in high-temperature silicon carbide JFETs. IEEE Trans Nucl Sci, 1994, 41(6): 1884

[12] Scozzie C J, McGarrity J M, Blackburn J, et al. Silicon carbide FETs for high temperature nuclear environments. IEEE Trans Nucl Sci, 1996, 43(3): 1642

[13] Zhang Lin, Zhang Yimen, Zhang Yuming, et al. Ni/4H-SiC gamma-ray radiation effect on Ni/4H-SiC SBD. Acta Physica Sinica, 2009, 58(4): 288

[14] Wang Shouguo, Zhang Yimen, Zhang Yuming. Parameter extraction for a Ti/4H-SiC Schottky diode. Chinese Physics, 2003, 12(1): 94