High energy electron radiation effect on Ni and Ti/4H-SiC Schottky barrier diodes at room temperature

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This paper reports that Ni and Ti/4H-SiC Schottky barrier diodes (SBDs) were fabricated and irradiated with 1 MeV electrons up to a dose of $3.43 \times 10^{14}$ e/cm$^2$. After radiation, the Schottky barrier height $\phi_B$ of the Ni/4H-SiC SBD increased from 1.20 eV to 1.21 eV, but decreased from 0.95 eV to 0.94 eV for the Ti/4H-SiC SBD. The degradation of $\phi_B$ could be explained by interface states of changed Schottky contacts. The on-state resistance $R_S$ of both diodes increased with the dose, which can be ascribed to the radiation defects. The reverse current of the Ni/4H-SiC SBD slightly increased, but for the Ti/4H-SiC SBD it basically remained the same. At room temperature, $\phi_B$ of the diodes recovered completely after one week, and the $R_S$ partly recovered.

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

1. Introduction

Silicon carbide (SiC) has outstanding properties such as wide bandgap, higher thermal conductivity, high breakdown field and high radiation tolerance, and has been used to fabricate high operating temperature, high power, and high radiation hardness devices.[1] The SiC Schottky barrier diode (SBD) can be made by a simple process and has superior performances to sustain high critical breakdown electric field and high temperature operation, high switching speed and low power loss, and has been used as a high voltage rectifier, ultraviolet and radiation detector. Also, SiC SBD is a key component of many SiC-based power devices like metal semiconductor field effect transistors (MESFET) and static induction transistors (SIT).[2]

There is great interest in the response of SiC SBD to high-energy particle radiation because of the potential applications in space, nuclear power industry and military areas. High-energy particles such as proton, neutron and electron radiation can create vacancies, interstitials, and their associated defects. These radiation-induced defects act as traps and generation-recombination centres in the SiC material. So they make the resistivity increase in the SiC and enhance the recombination current, leading to the degradation of SiC devices. However, the radiation defects will not disappear without high temperature annealing.[3-5]

In the past several years, high energy proton[6,7] and neutron[8,9] radiation effects on SiC SBD have been reported, but the high energy electron radiation effect has rarely been investigated.

In this paper, the radiation effect on Ni and Ti/4H-SiC SBDs is investigated with 1 MeV electron irradiation. Then the annealing effect of the diodes at room temperature is observed.

2. Experiment

The 4H-SiC wafer was prepared by homoepitaxial growth with a commercial low-pressure, hot wall chemical vapour deposition (CVD) (LP-HW-CVD) reactor (Epigress VP508 system) using the SiH$_4$/C$_2$H$_6$/H$_2$ system. The n type SiC epitaxial layer was grown on the Si-face (0001) 4H-SiC substrate with 8° off axis, which was purchased from SiCrystal AG. The growth process lasted for 2 hours at 1580 °C. A typical growth rate was 5 μm/h, and the thickness of the epilayer was approximately 10 μm. The epi-
layer was formed by an unintentionally doped process, with measured net carrier concentration about \(6.4 \times 10^{14} \text{cm}^{-3}\).

The Ni/Pt (450/50 nm) was deposited on the backside of the SiC wafer by electron beam evaporation and annealed at 1000 °C in \(N_2\) ambience for 2 min to form ohmic contacts, followed by electron beam evaporated Cr/Au (50/200 nm). Circular Schottky contact was deposited by electron beam evaporation Ni/Cr/Au or Ti/Cr/Au (200/50/200 nm) and patterned by lift off. The Ti and Ni metals in this investigation were chosen because they are the most widely used metals for Schottky contacts in SiC devices. The cross section of the Ni or Ti/4H-SiC SBD is shown in Fig.1. Then the sample was sliced into a single device by laser cutting for packaging with aluminium wire bonding.

The radiation experiment was performed at room temperature with the ELV-8 type electron accelerator at the Northwest Institute of Nuclear Technology. The highest total dose was up to \(3.43 \times 10^{14} \text{e}/\text{cm}^2\) with a dose rate of \(6.85 \times 10^{10} \text{e}/(\text{cm}^2 \cdot \text{s})\). Meanwhile, all diodes were with zero bias during irradiation.

The \(I-V\) characteristics were measured by using an HP4156A precision semiconductor parameter analyser and an Agilent Technology 34980A Multifunction Switch/Measurement Unit. During the experiment, there was no obvious sample temperature rise to be observed.

Based on thermionic emission theory, the forward current \(I_F\) running through the SiC SBD can be expressed as:

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

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

where \(n\) is the ideality factor, \(I_S\) is the reverse saturation current, \(R_S\) is the on-state resistance, \(\phi_B\) is the Schottky barrier height and \(A^*\) is the Richardson’s constant (146 A cm\(^{-2}\) K\(^{-2}\)).

Ignoring the voltage drop at the linear region of current, we can obtain \(n\) from Eq.(1),

\[
n = \frac{q}{kT} \frac{\partial V}{\partial \ln I}, \quad I = \frac{I_F}{I_S}.
\]

At a high forward voltage, \(R_S\) can be given by

\[
R_S = \left( 1 - \frac{\partial \ln I_F}{\partial V} \frac{nkT}{q} \right) \left( \frac{\partial I_F}{\partial V} \right).
\]

With calculation from Eq.(2), \(\phi_B\) and \(n\) of the Ni/4H-SiC SBD are changed from 1.20 eV to 1.21 eV and 1.56 to 1.51, and that of Ti/4H-SiC SBD decreased from 0.95 eV to 0.94 eV and 1.14 to 1.12 respectively.

Figure 3 shows the \(R_S\) as a function of the electron dose. After radiation, \(R_S\) is increased from 15.6 Ω to 21.6 Ω for Ni/4H-SiC SBD, and increased from 8.16 Ω to 13.7 Ω for Ti/4H-SiC SBD. The increase of \(R_S\) can be explained by the carrier removal effect and the mobility removal effect of the electron radiation.\(^{[10]}\)
3.2. Reverse characteristics

Figure 4 shows reverse characteristics of the Ni and Ti/4H-SiC SBDs before and after radiation. The reverse current of the Ni/4H-SiC SBD is slightly increased from $1.24 \times 10^{-4} \text{A} \cdot \text{cm}^{-2}$ to $1.59 \times 10^{-4} \text{A} \cdot \text{cm}^{-2}$ at $-200 \text{V}$ after radiation. The generation-recombination centres created by the high energy electrons are the main mechanism for the increased reverse current.\[6\] But the reverse current of the Ti/4H-SiC SBD basically remained the same; perhaps this is because the reverse current is much bigger than the recombination current component introduced by radiation defects.

3.3. Annealing effect

After radiation, the diodes were annealed for two weeks at room temperature. The measurement results showed that the reverse characteristics did not have obvious changes in two weeks, but an obvious recovery effect of the forward characteristics was observed. Annealing results are shown in Fig.5. After one week, $\phi_B$ of the Ni and Ti/4H-SiC SBDs had completely recovered to the value before radiation, and $R_S$ had partly recovered. The annealing of $\phi_B$ showed that the degradation could be explained by interface states of their Schottky contacts changed by electron radiation.\[11,12\] The mechanism of the recovered effect on $R_S$ needs further study. But considering the radiation induced defects in SiC material will not recover without high temperature annealing, the recovery effect of the $R_S$ perhaps for the charged state of the radiation induced traps changed.

4. Conclusion

In this paper, the high energy electron radiation effect on Ni and Ti/4H-SiC SBDs is investigated by electron irradiation with a highest dose up to $3.43 \times 10^{14} \text{e/cm}^2$ of 1 MeV electrons. After radiation, both diodes have kept a good rectifying characteristic, and show excellent radiation-resistance capability. The $\phi_B$ of the Ni/4H-SiC SBD is slightly increased, but slightly decreased for the Ti/4H-SiC SBD. The $R_S$ values of both diodes are increased with the electron dose. The reverse current of the Ni/4H-SiC SBD is slightly increased, but basically remained the same for the Ti/4H-SiC SBD. At room temperature, visible recovery effects of $\phi_B$ and $R_S$ have been observed.
References


