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Response of Ni/4H-SiC Schottky barrier diodes to alpha-particle irradiation at different fluences

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Irradiation experiments have been carried out on $1.9\times10^{16}\,cm^{-3}$ nitrogen-doped 4H-SiC at room temperature using 5.4 MeV alpha-particle irradiation over a fluence ranges from 2.6×10^{10} to $9.2\times10^{11}\,cm^{-2}$. Current–voltage (*I–V*), capacitance–voltage (*C–V*) and deep level transient spectroscopy (DLTS) measurements have been carried out to study the change in characteristics of the devices and free carrier removal rate due to alpha-particle irradiation, respectively. As radiation fluence increases, the ideality factors increased from 1.20 to 1.85 but the Schottky barrier height (SBH_{I-V}) decreased from 1.47 to 1.34 eV. Free carrier concentration, N_d decreased with increasing fluence from 1.7×10^{16} to $1.1\times10^{16}\,cm^{-2}$ at approximately 0.70 μm depth. The reduction in N_d shows that defects were induced during the irradiation and have effect on compensating the free carrier. The free carrier removal rate was estimated to be $6480\pm70\,cm^{-1}$. Alpha-particle irradiation introduced two electron traps ($E_{0.39}$ and $E_{0.62}$), with activation energies of 0.39 ± 0.03 eV and 0.62 ± 0.08 eV, respectively. The $E_{0.39}$ as attribute related to silicon or carbon vacancy, while the $E_{0.62}$ has the attribute of Z_1/Z_2.

1. Introduction

Metal-semiconductor (M-S) Schottky barrier diodes (SBDs) are widely used where diodes with low forward voltage drop, low capacitance and high switching speed are required [1]. This makes them ideal as rectifiers in photovoltaic systems and high-efficiency power supplies [2]. SBDs also have important uses in optoelectronics, high frequency and bipolar integrated circuits applications [3,4]. The reliability of SBDs is influenced significantly by the quality of the M-S junction [5]. The performance of the devices can be quantified experimentally in terms of their ideality factor, Schottky barrier height (SBH), saturation current, series resistance and free carrier concentration. Among these properties of the M-S interface, SBH plays a major role in the successful operation of many devices in transporting electrons across the M-S junction [6].

Silicon carbide (SiC) is a promising semiconductor with a wide bandgap of 3.26 eV [7], which has drawn the interest of many researchers due to its excellent properties such as high thermal conductivity, high breakdown field and high saturated drift velocity [8]. These characteristics make SiC a very good semiconductor capable of outperforming silicon in electronic devices for high-power, high-frequency and high-temperature applications [9], and is a key material for the next-generation photonics [10]. SiC is also good candidate for electronic devices used in harsh radiation environments such as in space, accelerator facilities and nuclear power plants [11–13].

In this study, we report the behavior of 4H-SiC SBD prior to and after alpha-particle irradiation at different fluences. In order to use SiC in radiation hard devices, there is need to know the radiation response of SiC. Also, the fluence SiC can withstand before the characteristics of devices fabricated on it degrade and they start to malfunction, needs to be determined. Current–voltage (*I–V*), capacitance–voltage (*C–V*) and deep level transient spectroscopy (DLTS) have been carried out on SBDs to study the change in characteristics of the devices at different fluences.

2. Experimental procedure

The samples used for this work were cut from a nitrogen-doped *n*-type 4H-SiC wafer, double polished with the Si face epi layer. The substrate was doped by $1\times10^{18}\,cm^{-3}$, while the epi layer had a resistivity of 0.02 Ω-cm and a doping density of $1.9\times10^{16}\,cm^{-3}$. The wafers were supplied by CREE Res. Inc.

The samples were cut into smaller pieces (area of 8 mm^2) and degreased by boiling for 5 min each in trichloroethylene, acetone, methanol and followed by 1 min rinse in de-ionized water. They

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were etched in 40% hydrogen fluoride for 30 seconds in order to remove the native oxide layer on the samples, then rinsed in de-ionized water, followed by blowing dry with nitrogen gas prior to thermally evaporation of nickel ohmic contacts onto the back surfaces (1.0×10^{18} cm^{-3} doped side) of the samples.

Nickel was used for both ohmic and Schottky contacts. Resistive evaporation was employed in both cases as it does not introduce measurable defects. The ohmic contact with a thickness of 2500 Å was deposited at a rate of 0.9 Å s^{-1}. The samples were annealed in a tube furnace under flowing argon gas at 950 °C for 10 min to form nickel silicides [14] in order to minimize contact resistance. The samples were also cleaned in ultrasonic water bath for 3 min each in trichloroethylene, acetone and methanol followed by 1 min rinsed in de-ionized H_2O after the annealing of the ohmic contact. Nickel Schottky contacts were resistively evaporated through a metal contact mask and had an area of 2.4×10^{-3} cm^2. The contacts of thickness 1000 Å were deposited at a rate of 0.5 Å s^{-1} under a vacuum of 3.0×10^{-5} mbar.

Samples were irradiated at room temperature and a fluence rate of 7.1×10^6 cm^{-2} s^{-1} with alpha-particles of energy of 5.4 MeV from a 241-Am radionuclide source. The radioactive foils were placed on top of the SBDs in such a way that the emitted alpha-particles were directed on diodes. The alpha-particle fluence ranged from 2.6×10^{10} to 9.2×10^{11} cm^{-2} (i.e from 1 to 36 h). The same SBD was used throughout the study and the radiation fluence quoted is the cumulative fluence over all radiations. A second SBD was irradiated and measured separately to check for repeatability.

Before in between irradiations, the samples were characterised at room temperature with *I-V* and *C-V* measurements, performed by an HP 4140 B pA meter/DC voltage source and an HP 4192A LF Impedance Analyzer, respectively. Hereafter, the sample was placed in a closed cycle helium cryostat and characterised by conventional DLTS.

3. Results and discussion

3.1. I–V and C–V characteristics

The devices were tested from *I–V* and *C–V* measurement systems to determine the quality of diodes before in between irradiations. Fig. 1 shows the forward semi-logarithmic *I–V* characteristics of the SBD measured at 300 K for un-irradiated to the radiation fluence of 7.9×10^{11} cm^{-2}. For biases below

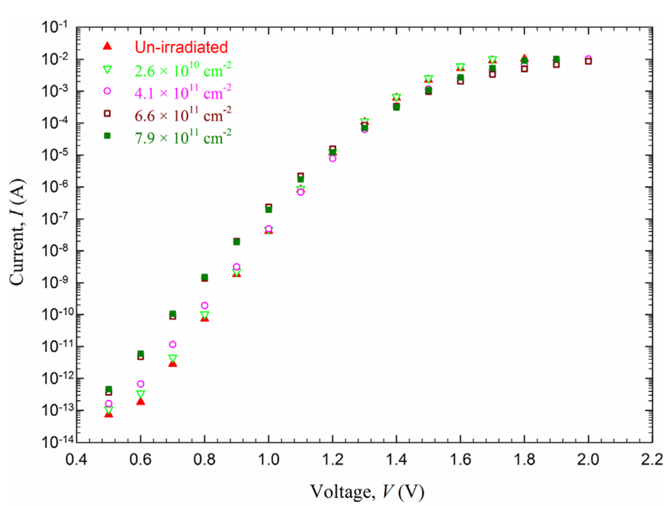

Fig. 1. Forward *I–V* characteristics of 4H-SiC SBD before and after 5.4 MeV alpha-particle irradiation up to fluence 7.9×10^{11} cm^{-2} measured at 300 K.

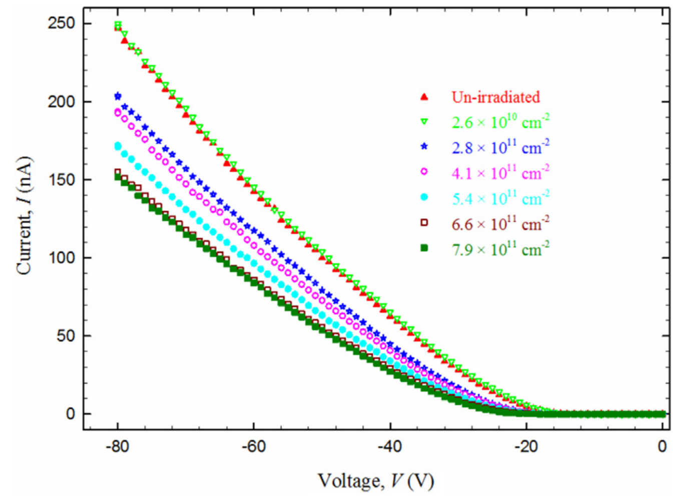

Fig. 2. Semi-logarithmic curves of the reverse leakage current measured up to −80 V as a function reverse voltage measured at fluence ranges from 2.6×10^{10} cm^{-2} to 7.9×10^{11} cm^{-2}.

approximately 1 V, where thermionic emission dominates, a slight increase in forward current was observed as a result of increase in radiation fluence. The ideality factor was 1.20 for the as-deposited sample and increased to 1.85 after 9.2×10^{11} cm^{-2} bombardment. This confirms that the current transport mechanism at low fluence was dominated by thermionic emission. The increase in ideality factor at higher fluences indicates that, in addition to thermionic emission, other transport mechanisms might also contribute. Barrier height inhomogeneiety might also play a role. The Schottky barrier height ($\Phi_{b,\ I-V}$) decreased with increasing irradiation fluence (1.47–1.34) eV and saturation current also increased with fluence from 2.3×10^{-21} to 5.2×10^{-19} A. The fluence dependency of the n, $\Phi_{b,\ I-V}$ and I_s may also connected with the movement (shift) of Fermi level pinning at the surface of SiC, since irradiation-induced defects can creates interface states. The electrical parameters were determined as reported earlier by Omotoso et al. [15,16]. From these characteristics, it shows that 4H-SiC with doping density 1.9×10^{16} cm^{-3} is radiation hard compare to Si [17].

In Fig. 2, the leakage current is less than 1.8×10^{-10} A at reverse voltage (V_r) below 15.0 V for all the *I–V* measurements, starting from as deposited to the fluence of 7.9×10^{11} alpha-particles-cm^{-2}. From Table 1, as the reverse bias increased, an increase in leakage current was observed before and after irradiation. But, contrary to the case in other semiconductors, the leakage current decreased with increase in radiation fluence. This occurs despite a decrease observed in the forward barrier height. A possible explanation would be that the decrease in leakage current is related to the decrease in free carrier density caused by the introduction of compensating defects. This would, in turn, decrease the electric field in the depletion region. Three possible reverse conduction mechanisms were considered: Thermionic emission (with image force barrier lowering), thermionic-field emission

Table 1
Comparison of leakage current and reverse voltage in a Ni/4H-SiC SBD before and after irradiation with alpha-particles.

Reverse voltage (V)	Leakage current (nA)	
	Un-irradiated	At fluence of 7.9×10^{11} cm^{-2}
40	64	27
60	143	85
80	247	153