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Electrical characterization of deep levels created by bombarding nitrogen-doped 4H-SiC with alpha-particle irradiation

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ABSTRACT

Deep-level transient spectroscopy (DLTS) and Laplace-DLTS were used to investigate the effect of alpha-particle irradiation on the electrical properties of nitrogen-doped 4H-SiC. The samples were bombarded with alpha-particles at room temperature (300 K) using an americium-241 (^{241}Am) radionuclide source. DLTS revealed the presence of four deep levels in the as-grown samples, $E_{0.09}$, $E_{0.11}$, $E_{0.16}$ and $E_{0.65}$. After irradiation with a fluence of 4.1×10^{10} alpha-particles-cm^{-2}, DLTS measurements indicated the presence of two new deep levels, $E_{0.39}$ and $E_{0.62}$ with energy levels, E_C – 0.39 eV and E_C – 0.62 eV, with an apparent capture cross sections of 2×10^{-16} and 2×10^{-14} cm^2, respectively. Furthermore, irradiation with fluence of 8.9×10^{10} alpha-particles-cm^{-2} resulted in the disappearance of shallow defects due to a lowering of the Fermi level. These defects re-appeared after annealing at 300 °C for 20 min. Defects, $E_{0.39}$ and $E_{0.42}$ with close emission rates were attributed to silicon or carbon vacancy and could only be separated by using high resolution Laplace-DLTS. The DLTS peaks at E_C – (0.55–0.70) eV (known as Z_1/Z_2) were attributed to an isolated carbon vacancy (V_C).

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1. Introduction

The importance of deep level defects that act as charge carrier traps in semiconductor industry and applications of semiconductor devices cannot be over-emphasized [1,2]. The deep level defects (both hole and electron traps) are formed during the growth of the semiconductor, processing during fabrication of the electronic device (e.g. electron beam and sputtering deposition) and operation in radiation harsh environments. Deep levels can be introduced intentionally into electronic devices and can be beneficiary or detrimental. For detrimental defects, it is important to find methods to remove these defects. Some of the defects anneal out at room or elevated temperatures while some emanate at certain annealing temperature. The signatures of a deep level (i.e. its activation energy in the band gap and apparent capture cross section) can be determined from temperature depended deep level transient spectroscopy (DLTS) and Laplace DLTS measurements on Schottky barrier diodes (SBDs). Effects of radiation and annealing temperature on semiconductors are technologically important for radiation sensing applications as well as manufacturing processes and high temperature and high power applications [3].

SiC is a promising semiconductor with a wide bandgap of 3.26 eV [4]. Because of its wide bandgap, SiC is a suitable substrate for developing devices that are capable of operating at high temperature as well as in harsh radiation fields [5,6], such as space, accelerator facilities and nuclear power plants [7–9]. The electrical and thermal properties of SiC also make it suitable for electronic devices operating at high power, high temperature and high frequency [10]. Furthermore, SiC is a key material for the next generation of photonics [11]. Because of the aforementioned features, SiC is superior to Si in a number of applications.

In this work, the effect of alpha-particle irradiation at high fluences and annealing of 4H-SiC has been investigated by means of current–voltage (*I*–*V*), capacitance–voltage (*C*–*V*), DLTS and Laplace DLTS measurements. The major aim was to determine the effect of irradiating *n*-type 4H-SiC at high fluence and investigate the annealing of these defects.

2. Experimental procedure

The samples used for this work were cut from a nitrogen-doped *n*-type 4H-SiC wafer. The samples were grown on the Si-face of a SiC substrate with a net doping density of 10^{18} cm^{-3} and a resistiv-

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ity of 0.02 Ω-cm. The epilayer had a doping density of 7.1×10^{15} cm^{-2}. The wafers were supplied by CREE Res. Inc.

The samples were cut into smaller pieces and prepared according to the procedure reported by Omotoso et al. [12]. Resistive evaporation was employed for the deposition of ohmic and Schottky contacts since it does not introduce defect(s) in measurable quantity. Nickel was used for both contacts. The ohmic contact with a thickness of 3000 Å was deposited at a rate of 0.9 Å s^{-1} onto the highly doped (10^{18} cm^{-3}) back surface of the samples. The samples were annealed in a tube furnace under flowing argon at 950 °C for 10 min to form nickel silicides [13] in order to obtain low resistivity ohmic contacts. Before deposition of the Schottky contacts, the samples were degreased as previously reported [12]. Directly after cleaning, the samples were inserted into a vacuum chamber where NiAu (20% Au) Schottky contacts were resistively evaporated through a metal contact mask on the Si-face. The diameter and the thickness of the Ni/Au Schottky barrier diodes (SBDs) were 0.57 mm and 1000 Å respectively, and they were deposited at a rate of 0.5 Å s^{-1} under a vacuum of approximately 3×10^{-5} mbar on Si-face.

The samples were irradiated at room temperature with alpha particles of average energy 5.4 MeV by placing the samples on a ^{241}Am radio-nuclide foil. The samples were irradiated for 16 h, measured, and then irradiated for a further 19 h. The fluence rate from this foil was 7.1×10^6 alpha-particles cm^{-2} s^{-1}. The total fluence received by the SBD after 19 h was 8.9×10^{11} alpha-particles cm^{-2}. The quality of the Schottky barrier diodes was tested by carrying out current–voltage (*I–V*) and capacitance–voltage (*C–V*) measurements in the dark at room temperature. The *I–V* and *C–V* measurements were carried out by an HP 4140 B pA meter/DC voltage source and an HP 4192A LF Impedance Analyzer, respectively. Conventional DLTS as well as Laplace DLTS were used to characterize the defects present in the as-grown and alpha-particle irradiated material, as well as after annealing in argon ambient at 300 °C for 20 min.

3. Results and discussion

3.1. I–V and C–V characteristics at room temperature

I–V and *C–V* measurements were performed to test the suitability of the devices for the study. Fig. 1 shows the semi-logarithmic *I–V* characteristics of the Schottky barrier diodes (SBDs) as grown (i), after bombardment with a fluence of 4.1×10^{11} (ii) and 8.9×10^{11} cm^{-2} (iii), and after annealing at 300 °C for 20 min in flowing argon (iv). The effect of irradiation and annealing on the SBDs can be quantified in terms of the ideality factor (n), Schottky barrier height (ϕ_b), saturation current (I_s) and series resistance (R_s), as obtained from the plots in Fig. 1. The ideality factor obtained in (i) was 1.12 suggesting that thermionic emission is the dominant current transport mechanism. In (ii) and (iii), the ideality factor increased to 1.20 and 1.77, respectively. The increase in ideality factor was attributed to deviation from thermionic emission. This suggests that other current transport mechanisms such as generation recombination could be dominant as well especially at lower voltages. Above 0.7 V, series resistance is dominant in (iii). After the annealing at 300 °C, the dominance of series resistance reduced as shown in the plot represented by (iv). Table 1 compares the properties of the diode at aforementioned conditions. The ϕ_b of the contacts were determined from the *I–V* characteristics analyzed using the thermionic emission model [14,15]. The I_s was derived from the straight line intercept of log*I–V* plot at $V = 0$. The fluence and annealing dependency of n, $\phi_{b,I-V}$ and I_s may connected to the movement (or shift) of Fermi level pinning at the surface of SiC, since irradiation-induced defects can create interface states. Fig. 2 shows the plot of C^{-2} (pF^{-2}) as a function of voltage, V (V) for (i)–(iv) processes as defined earlier, all were measured at a frequency of 1 MHz with the sample at room temperature. The capacitance increased with decrease in reverse voltage for all conditions, but the capacitance of (iii) was the lowest and very distinct from others because of the position of the Fermi level with respect to the conduction band. A decrease in the capacitance after irradiation was attributed to the reduction of net donor concentration at 4H-SiC interface due to the effect of radiation induced defects. The *C–V* characteristics for the different conditions are also tabulated in Table 1.

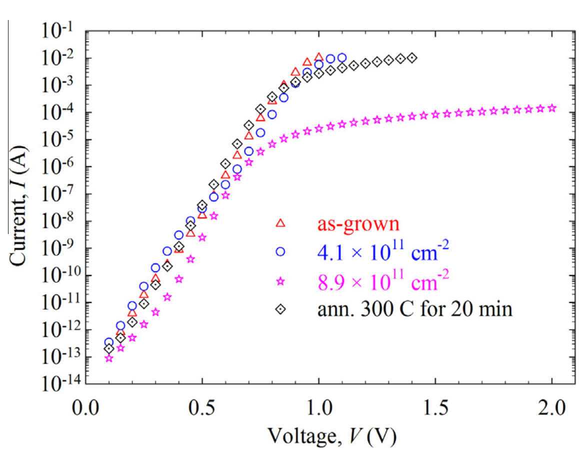

Fig. 1. Forward *I–V* characteristics of 4H-SiC SBD in as-grown (i), irradiated with 5.4 MeV alpha-particles at fluence 4.1×10^{11} (ii), 8.9×10^{11} cm^{-2} (iii), and after annealing at 300 °C for 20 min in flowing argon (iv), measured at 300 K.

3.2. Conventional DLTS analysis

Fig. 3 shows the DLTS spectra for SBD under different conditions. The measurements were obtained over a temperature range 30–380 K, at a quiescent reverse bias of −5.0 V, filling pulse amplitude of 6.0 V, filling pulse width of 1.0 ms and at different rate windows (2.5–1000 s^{-1}). The *signatures* of the defects in terms of activation energy, E_n and apparent capture cross section, σ_n were determined from the Arrhenius plot in Fig. 4. The activation energy of each defect was determined from the slope, and the corresponding apparent capture cross section was calculated from the intercept of the Arrhenius plot of log (T^2/e_n) versus $1/T$ as reported by Auret et al. [16]. The attributes of all the electron traps in (i)–(iv) are tabulated in Table 2.

Curve (i) is the spectrum of the as-grown sample and indicates the presence of four electron traps ($E_{0.09}$, $E_{0.11}$, $E_{0.16}$ and $E_{0.65}$) with energies 0.09, 0.11, 0.16 and 0.65 eV below the conduction band. These defects were associated with the growth of 4H-SiC. The Arrhenius plots of the defects present in as-grown 4H-SiC as well as their attributes have been reported by Omotoso et al. [12,17].

Table 1
Comparison of some electrical parameters of 4H-SiC in as-grown (i), irradiated with 5.4 MeV alpha-particles at fluence 4.1×10^{11} (ii) 8.9×10^{11} cm^{-2} (iii), and after annealing at 300 °C for 20 min in flowing argon (iv). The parameters estimated from *I–V* and *C–V* characteristics measured at 300 K.

Process	n	I_s (A)	R_s (Ω)	V_{bi}	N_D (cm^{-3})	$\phi_{b,I-V}$ (eV)	$\phi_{b,C-V}$ (eV)
(i)	1.12	2.1×10^{-14}	12	0.93	7.0×10^{15}	1.06	1.21
(ii)	1.20	1.1×10^{-14}	15	2.38	4.6×10^{15}	1.08	2.68
(iii)	1.77	6.9×10^{-15}	13,000	18.3	2.9×10^{15}	1.09	18.6
(iv)	1.15	1.9×10^{-15}	48	2.96	4.4×10^{15}	1.13	3.25

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