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Radiation damage of SiC Schottky diodes by electron irradiation

H. OHYAMA[1], K. TAKAKURA[1], T. WATANABE[1], K. NISHIYAMA[1], K. SHIGAKI[1], T. KUDOU[1], M. NAKABAYASHI[2], S. KUBOYAMA[3], S. MATSUDA[3], C. KAMEZAWA[3], E. SIMOEN[4], C. CLAEY[4,5]
[1]Kumamoto National College of Technology, 2659-2 Nishigoshi Kumamoto, 861-1102 Japan
E-mail: ohyama@ee.knct.ac.jp
[2]Renesas Technology Corp.4-1, Mizuhara, Itami, Hyogo, 664–0005, Japan
[3]JAXA, 2-1-1 Sengen Ibaraki, 305–8505, Japan
[4]IMEC, Kapeldreef 75, B-3001 Leuven, Belgium
[5]E.E. Dept., K. U. Leuven, B-3001 Leuven, Belgium

The impact of radiation damage on the device performance of 4H-SiC Schottky diodes, which are irradiated at room temperature with 2-MeV electrons is studied. After irradiation the reverse current increases, while the forward current and the capacitance decrease with barrier height and carrier density. The decrease of the barrier height is mainly responsible for the increase of the reverse current, while the decrease of the forward current for a high fluence is caused by the increase of the resistance in the bulk of the crystal. Although no electron capture levels are observed before irradiation, three electron capture levels (E_1, E_2, and E_3) are induced after irradiation. It is noted that the decrease in carrier density is partly caused by the contribution of non-observed electron capture level in the DLT spectrum, which compensates the free carriers.

1. Introduction

Silicon carbide (SiC) is regarded as a promising candidate for high-power and high-frequency devices because of its excellent thermal and electrical properties. The wide band gap (3.2 eV at room temperature) and high bond dissociation energy (435 KJ/mol) of 4H-SiC suggest it is available for sensors and high temperature electronics in the nuclear power industry and satellite-based systems [1]. For example, SiC rectifiers are attractive for many applications, including inverters in utility power flow control, traction motor control and combustion gas sensing [2]. Moreover as SiC has a good radiation hardness, it is also expected to be widely applied in electrical devices used in radiation environments such as in space [3]. In previous studies the properties of induced lattice defects in different crystal types, i.e. 4H or 6H, by electron or proton irradiation have been extensively investigated. The vacancy-related induced defects by electron and proton irradiation were investigated mainly with Electron Paramagnetic Resonance (EPR) and Deep Level Transient Spectroscopy (DLTS). The following defects induced by irradiation were reported; a Si Frenkel pair, a carbon monovacancy, a divacancy, and an antisite vacancy pair. There is, however, only limited information available on the correlation between degradation of device performance and irradiation-induced lattice defects. This paper reports on the impact of radiation damage on the device performance and induced lattice defect of 4H-SiC Schottky diodes, which are irradiated at room temperature with 2-MeV electrons. Also, the irradiation temperature dependence of device performance degradation is studied.

2. Experimental

In this study, SiC Schottky diodes (SDP06S60, Infineon) were used. Electron irradiation with 2-MeV was performed using the Dinamitron linear electron accelerator at Takasaki Japan Atomic Energy. The used electron fluence at room temperature ranged from 1×10^{15} to 1×10^{17} e/cm^2. To examine the effect of irradiation temperature on degradation of device performance, high temperature irradiation for 1×10^{16} e/cm^2 was carried out at 150 and 250 °C. Diodes were controlled by a panel heater mounted in a chamber with 50 μm thick Titanium window. Before and after irradiation, electrical performance of diodes was evaluated by recording the current/voltage (*I/V*) and capacitance/voltage (*C/V*) characteristics at 25 °C with applied voltage ranging from -20 to 1 V. The carrier density and width of depletion layer in SiC substrate are calculated from the result of *C/V* measurement, basing that the square of the capacitance is inversely proportional to the reverse voltage. In order to observe electron capture levels in the *n*-type 4H-SiC epitaxial layer, deep level transient spectroscopy (DLTS) in the temperature range between 77 and 300 K was carried out. The emission rate window used in this DLTS system is 1.18 to 26.51 msec. The applied filling pulse is ranging from −2.0 to 0 V. Moreover, the reverse voltage of −0.5, −1.0, −1.5 and −10 V are used to obtain the information on depth profile of the deep levels.

3. Results and discussion

Fig. 1 shows typical *I/V* characteristics for different electron fluence at room temperature irradiation. Form this figure, it is noted that after irradiation the reverse current increases, while the forward current decreases.

The barrier height (Φ_B) and ideality factor (n) were extracted from the relationship for forward current density (J_S)

$$J_S = A^{**}T^2 \exp\left(\frac{-e\Phi_B}{\kappa T}\right)\left[\exp\left(\frac{\text{eV}}{n\kappa T}\right) - 1\right] \quad (1)$$

where A^{**} is the Richardson's constant for SiC, κ is the Boltzman's constant, e is the electron charge V is the forward voltage, and T is the measurement temperature.

The barrier height before irradiation and for 1×10^{17} e/cm^2 is calculated to be 1.25 and 1.17 eV, respectively. The ideality factor for before irradiation and for 1×10^{17} e/cm^2 is estimated to be 1.02 and 1.27, respectively. The barrier height and ideality factor do not change by the fluence of 1×10^{16} e/cm^2. The decrease of the barrier height is mainly responsible for the increase of the reverse current, while the decrease of the forward current for a high fluence is caused by the increase of the resistance in the bulk of the crystal.

Fig. 2 shows the typical *C/V* characteristics for different electron fluences at room temperature irradiation. It is found from this figure that the capacitance decreases by irradiation, and that this decreases with increasing fluence. Above the fluence of 5×10^{16} e/cm^2, normal *C/V* characteristics could not observe due to the severe deactivation of dopant atom. Based on the results on *I/V* and *C/V* measurement, the degradation on device performance of the used diodes takes place over the fluence of 5×10^{16} e/cm^2.

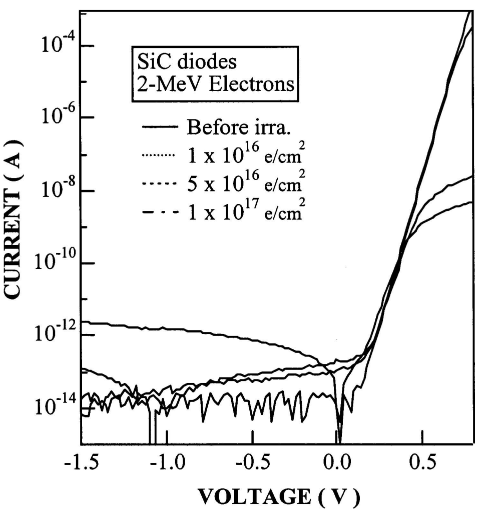


Figure 1 *I/V* characteristics for different electron fluence at room temperature.

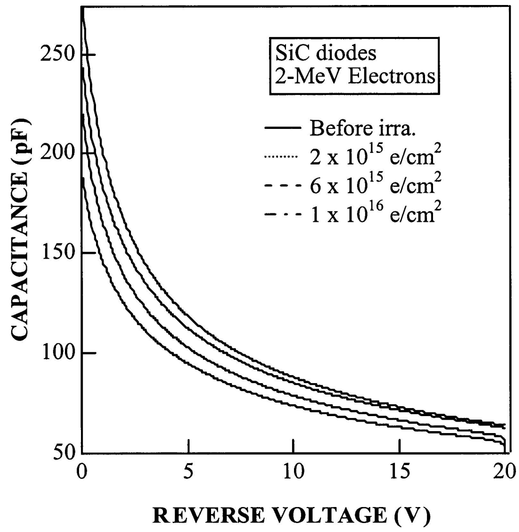


Figure 2 *C/V* characteristics for different electron fluence at room temperature.

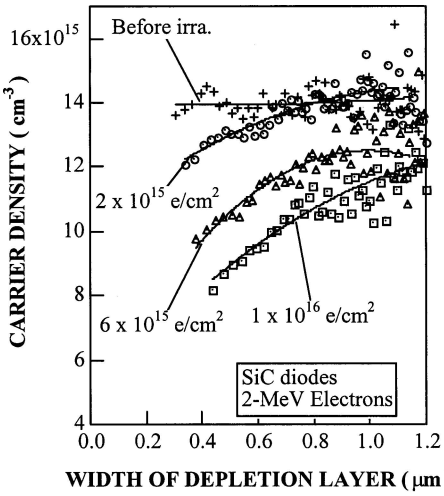


Figure 3 Carrier density profile for different fluence.

Fig. 3 shows the carrier density profile for different fluence as a function of width of depletion layer. The carrier density at 1.2 μm from the surface after a 1×10^{16} e/cm^2 irradiation is 1.16×10^{16} cm^{-3}, and is decreased by 81% compared to the value before irradiation. It is also fond that the decrease of carrier density is more remarkable near metal/SiC Schottky interface. The tendency consists with that defect density profile of induced lattice defects as mentioned below. The possible reasons of this reduction in carrier density are as follows: (1) a decrease in the donor density because substitutional donors are moved into the interstitial site or because the bonds between the substitutional donor and nearest neighbor atom are broken, or (2) the creation of electron capture levels or acceptor-like defects, which capture electrons emitted from the donors.

Fig. 4 shows typical DLTS spectra for the different fluences. Although no electron capture levels are observed before irradiation, three electron capture levels (E_1, E_2, and E_3) are induced after irradiation.

The defect density increases with increasing fluence, and reaches 1×10^{16} e/cm^2 about 5×10^{12} cm^{-3}. The energy level and the capture cross section of E_2 level are calculated to be E_C-0.41 eV and $\sigma = 9 \times 10^{-15}$ cm^{-2}, respectively. Those of E_3 level are E_C-0.68 eV and

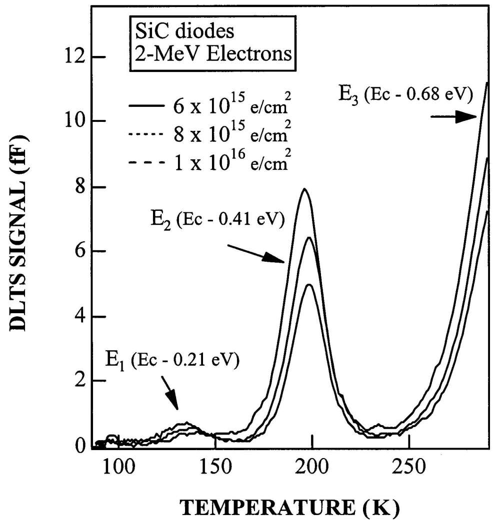
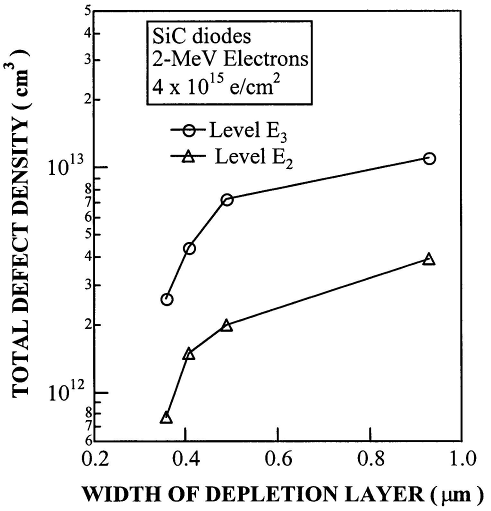
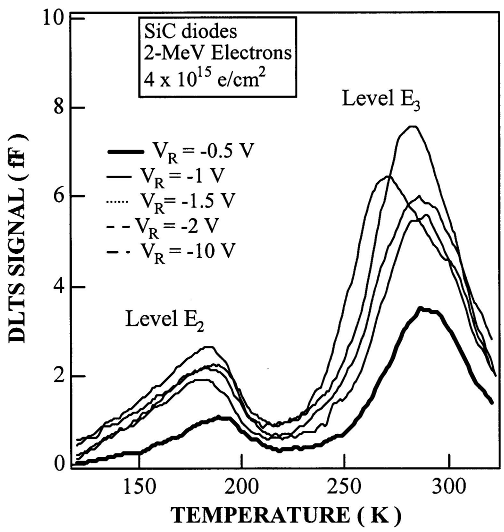


Figure 4 DLTS spectra for the different fluences.



(a)



(b)

Figure 5 DLTS spectra for diodes with different applied reverse bias (a) and defect density profile as a function of width of depletion layer for E2 and E3 levels (b).

$\sigma = 1 \times 10^{-15}$ cm^{-2}, respectively. Based on the previous results reported in the literature, the E_2 and E_3 levels are thought to be associated with silicon vacancy complexes [4, 5]. Origin of level E_1 (E_C-0.21 eV, $\sigma = 6\times10^{-15}$ cm^{-2}) is not sure at present. Fig. 5(a) and (b) show DLTS spectra for diodes with different applied reverse bias and defect density profile as a function of width of depletion layer for E_2 and E_3 levels, respectively. As shown in Fig. 5(b), there is tendency that total defects density over 0.5 μm saturates with increasing depletion width. This means that those electron capture levels are mainly present near metal/SiC Schottky interface as consisted with carrier density profile in Fig. 3. The decrease of the carrier density is, however, higher than the calculated generation of the electron capture levels (E_1, E_2, and E_3). Therefore, it is believed that the decrease in carrier density is partly caused by the contribution of non-observed electron capture level in the DLT spectrum, which compensates the free carriers.

Fig. 6 shows the typical *I/V* characteristics for different irradiation temperature for the fluence of 1×10^{16} e/cm^2. As shown in this figure, for a 250 °C irradiation, the increase of the reverse current is nearly same with starting value. This result suggests that the creation and recovery of the radiation damage proceeds simultaneously at high temperatures [6].

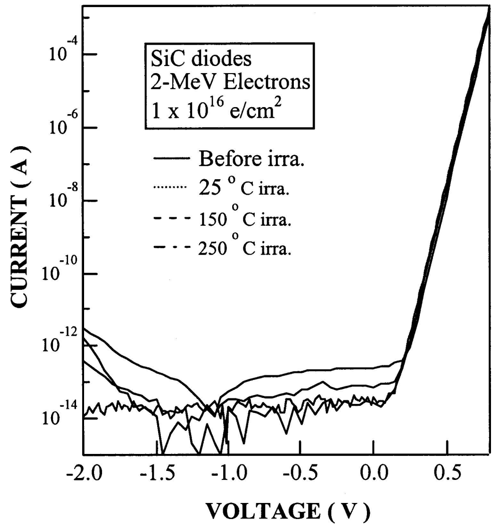


Figure 6 *I/V* characteristics for different irradiation temperature.

4. Conclusions

The following conclusions are obtained by this study,

(1) After irradiation the reverse current increases, while the forward current and capacitance decreases.

(2) The decrease of the barrier height is mainly responsible for the increase of the reverse current, while the decrease of the forward current for a high fluence is caused by the increase of the resistance in the bulk of the crystal.

(3) Electron capture levels are induced by irradiation, level E_2 and E_3 levels are thought to be associated with silicon vacancy complexes.

(4) For a high temperature irradiation, the increase of the reverse current is nearly same with starting value. This result suggests that the creation and recovery of the radiation damage proceeds simultaneously at high temperatures.

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