Annealing Effects on Charge Collection Efficiency of an Electron-Irradiated 4H-SiC Particle Detector

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Abstract

Thermal annealing effects on the charge collection efficiency (CCE) of an electron-irradiated4H silicon carbide Schottky barrier diode (SBD) particle detector have been studied.The CCE of the SBD detector is degraded by 1 MeV electrons with a fluence of 1×10^{15} cm^{-2}. The degraded CCE recovers with low temperature annealing up to 300 °C. However, CCE starts to decrease again by annealing at 350 °C. Conventional electrical characterization such as current and capacitance vs voltage measurements, deep level transient spectroscopy used to understand the CCE variation on annealing is discussed.

1. Introduction

Silicon carbide (SiC) is a promising material for high-energy charged particle detectors. Because of wide bandgap energies (3.2 eV for 4H-SiC, 3.0 eV for 6H-SiC) and small intrinsic carrier densities (<10^{-6} cm^{-3} at room temperature), leakage currents of SiC diodes arevery small even above room temperature and under visible light. Therefore, SiC diode particle detectors can ideally be operated with a sufficient signal to noise ratio under such conditions where silicon diode particle detectors cannot [1]. Over the last decade, many researchers demonstrated that SiC detectors show excellent charge collection characteristics for high-energy particles[1-3]. The radiation resistance of SiC detectors for high-energy particles and gamma-rays has also been studied [4-6]. These data are very important to predict the detectors' lifetime. In addition, it is also important to study post-irradiation annealing effects on the detectors. Provided that a detector performance is recovered by annealing at a practical temperature, the detector's lifetime can be prolonged. However, only a few studies of post-irradiation annealing effects on SiC detectors have been carried out so far [7].

In this study we investigate thermal annealing effects on the charge collection efficiency (CCE) of an electron-irradiated SiC detector. We also attempt to explain the variation of CCE after electron irradiation and during annealing by comparing the data obtained by conventional electrical measurements.

2. Experiment

Schottky barrier diode (SBD) particle detectors were fabricated on an n-type 4H-SiC epitaxial wafer. The epilayer was grown on a low-resistivity n-type 4H-SiC substrate (Si-face, 8^{o}off) by a hot-wall chemical vapor deposition technique [8]. The thickness of the grown epilayer was 140 μm. Nickel (Ni) was deposited on the bottom side of the wafer and subsequently sintered at 1100°C for 3 minutes to form an Ohmic contact. For a Schottky contact on the top side, Ni with an area of 1 mm × 1 mm was deposited and no thermal treatments were carried out. The ideality factor and the Schottky barrier height of the SBD detector determined from the current-voltage (I-V) characteristics were 1.06 and 1.68 eV, respectively. The carrier density of the epilayer estimated from the capacitance-voltage (C-V) characteristics was 4×10^{13} cm^{-3}.We note that the C-V characteristics did not depend on the measurement frequencies between 1 MHz and 1 kHz.

In order to form defects in the SiC crystal, the SBD detector was irradiated with 1 MeV electrons to the fluence of 1×10^{15} cm^{-2}. The projected range of these electrons is approximately 1 mm, well beyond the active device region, with a relatively constant defect density generated throughout the sample. The SBD detector was mounted on a water-cooled plate to avoid an increase of the temperature during the irradiation. The electron-irradiated SBD detector was subsequently annealed between 100 °C and 400 °C for 30 minutes in an Ar atmosphere.

The CCE of the SBD detector was characterized at room temperature by using 5.5 MeV alpha particles and a standard pulse height analysis system which consists of an Ortec 142A charge sensitive preamplifier, an Ortec 571 spectroscopic amplifier with a shaping time of 0.5 μs, and a Canberra Multiport II multi-channel analyzer. I-V and C-V characteristics of the SBD detector were also measured at room temperature using an Agilent 4156B semiconductor analyzer and an Agilent E4980A LCR meter.

Deep level transient spectroscopy (DLTS) was also performed to characterize the defects in the SiC crystal. Since the SBD detector has a large series resistance making DLTS measurements difficult, a SBD made on a low-resistivity (highly-doped) epilayer was used. The highly-doped SBD was also irradiated with 1 MeV electrons to a fluence of 1×10^{15} cm^{-2}, and subsequently annealed at 300 and 400 °C for 30 minutes. For the capacitance transient measurements, the highly-doped SBD was reverse-biased to8 V, and a carrier filling pulse of0 V for 50 ms was applied. The capacitance transients were measured at temperatures between 150K (-123 °C) and 350 K (77 °C) by using a Boonton 7200 capacitance meter, and were analyzed by the rate window method [9].

3. Results and Discussion

3.1 Charge Collection Efficiency, Capacitance, Leakage Current

Figure 1 shows the reverse bias voltage-dependent CCE of the SBD detector before and after the electron irradiation characterized by using 5.5 MeV alpha particles with the pulse height analysis system. We note that the fluence of alpha particles used for each bias voltage is as low as 7×10^{4} cm^{-2}, and they did not affect the CCE and electrical measurements. Before the electron irradiation, pulse heights of the SBD detector increase with increasing reverse bias voltage and become constant at 15 V and higher. Since a good saturation of the pulse heights is observed above 15 V, we define the CCE of the SBD particle detector is 100% at these bias voltages. The depletion region width at 15 V is estimated to be 20 μm from the C-V characteristics, and is comparable to the projected range of a 5.5 MeV alpha particle in 4H-SiC.Therefore,all carriers induced by the alpha particle strike are efficiently collected by the drift effect within the depletion region. Degradation of the CCE is seen after the electron irradiation, and is more pronounced at lower bias voltages. Since the electric field formed in the depletion region is weaker and the carrier drift velocity is smaller at lower bias voltages, more carriers are captured by and/or recombine via defect levels formed by the 1 MeV electrons.

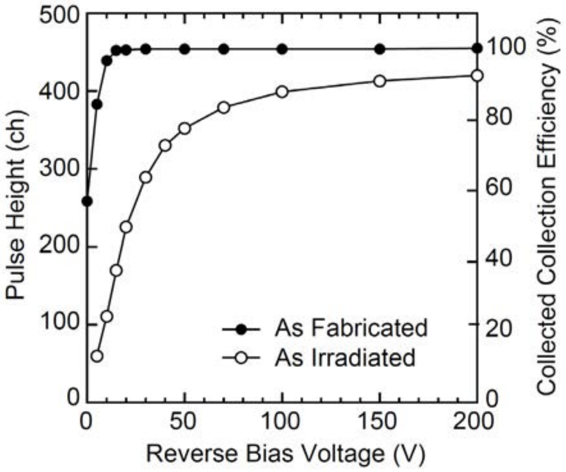

Fig.1 Reverse bias voltage dependence of CCE of a 4H-SiC SBD diode before and after the electron irradiation. The CCEs were characterized by using 5.5 MeV alpha particles at room temperature.

Figure 2 (a), (b) and (c) show CCEs, capacitances and leakage currents of the SBD detector, respectively, before and after the electron irradiation, and as a function of annealing temperature. As the CCEs decrease after the electron irradiation, capacitances of the SBD detector also decrease and become independent of the reverse bias voltage as shown in Fig. 2 (b). This implies that defects formed by the 1 MeV electrons compensate electrons supplied from donors, and decrease the effective carrier density in the epilayer. Since a wider depletion region is formed in an epilayer with a lower carrier density, the electric field and the carrier drift velocity in the depletion region decrease. This also reduces the CCE.

The degraded CCE recovers as the annealing temperature increases up to 300 °C as shown in Fig. 2 (a). At a reverse bias voltage of 50 V, the CCE, which had decreased to 78% by the electron irradiation, recovers to 93% after annealing at 300 °C. Namely, the 300 °C-annealing significantly suppresses the electron irradiation-induced degradation of CCE. On the other hand, the decreased capacitances of the SBD detector do not change up to 400 °C as shown in Fig. 2 (b). From these results it is speculated that various types of defects are formed by the 1 MeV electrons. Some defects act as traps and/or recombination centers for alpha particle-induced carriers and are removed by annealing up to 300 °C.Other defects reduce the

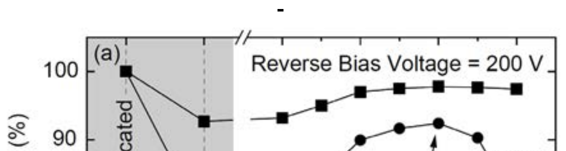

Fig. 2 (a) CCEs, (b) capacitances and (c) leakage currents of 4H-SiC SBD particle detector before and after the electron irradiation, and as a function of annealing temperature.

effective carrier density in the epilayer and persist up to 400 °C.

Recovered CCE starts to degrade again by annealing at 350 °C as shown in Fig. 2 (a). Re-degradation of CCE seems to be correlated with a drastic increase of the leakage current seen at same annealing temperatures (350-400 °C) as shown in Fig. 2 (c). The leakage current after annealing at 400 °C are three orders of magnitude larger than those after annealing at 300 °C. We have also measured temperature-dependent leakage currents of the SBD detectors at a reverse bias voltage of 50 V (not shown in the figure), and determined their activation energy (E_A) according to the Arrhenius equation,

$$I_{\mathrm{Leak}}(T) \propto \exp\left(-\frac{E_A}{kT}\right), \quad (1)$$

where $I_{\mathrm{Leak}}(T)$ is temperature-dependent leakage current, k is Boltzmann's constant and T is temperature. The E_A of the leakage current after annealing at 300 °C is estimated to be 1.16 eV around room temperature while the E_A after annealing at 400 °C is 0.70 eV. The change of the E_A indicates the change of electron-hole pair generation process in the depletion region. Namely, some defect levels which act as efficient electron-hole pair generation/recombination centers newly emerge in the bandgap of 4H-SiC after annealing at 350-400 °C. These defect levels may also act as efficient recombination centers for alpha particle-induced carriers.

3.2 Deep Level Transient Spectroscopy

Figure 3 shows the DLTS spectra of a highly-doped SBD before and after the electron irradiation, and after annealing at 300 and 400 °C. The spectra were obtained from the capacitance transients analyzed by the rate window method with an emission rate of 8.89 sec^{-1} [9]. We note that all peaks shown in Fig. 3 correlate to majority carrier (electron) traps. No peaks are found in the spectrum before the electron irradiation. On the other hand, three distinct peaks, labeled as EH_1, $Z_{1/2}$ and EH_3, emerge after the electron irradiation. These results are consistent with data often reported in the literature [10-12]. The energy levels of EH_1, $Z_{1/2}$ and EH_3 are known as E_C– 0.45, E_C– 0.68, E_C– 0.72 eV, respectively, where E_C is the bottom of the conduction band [12].Defect densities of these levels are reduced by annealing at 300 °C. EH_1 and EH_3 are completely removed by annealing at 400 °C while $Z_{1/2}$ still remains. Reductions of these defect densities may contribute to the recovery of CCE found in the annealing temperature range up to 300 °C. However, new defect levels, which correlate to the drastic increase of leakage current as shown in Fig. 2 (c), are not obvious in the DLTS spectrum after annealing at 400 °C. Such defect levels may be convoluted with other defect peaks oremerge at scan temperature outside of the range employed here. Danno *et al.* indeed reported that some defect levels emerge in the lower half of bandgap after post-electron irradiation annealing [13]. However, since the conditions of electron irradiation and annealing in their study are quite different from ours, it may be difficult to compare these results directly.

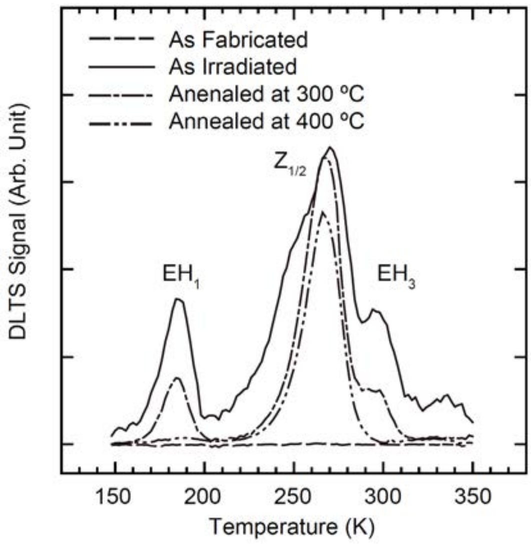

Fig.3DLTS spectra of a highly-doped 4H-SiC SBD obtained before and after the electron irradiation, and after annealing at 300 and 400 °C with a emission rate of 8.89 sec^{-1}. All peaks correlate to electron traps in n-type 4H-SiC epilayer.

4. Summary

Thermal annealing effects on CCE of an electron-irradiated4H-SiC SBD detector have been studied. It was found that the 300 °C-annealing significantly suppresses the electron irradiation-induced degradation of CCE. Since most materials such as metals and ceramics, which are conventionally used to assemble a commercial particle detector, withstand a temperature as high as 300 °C, it is possible to practically recover the SiC detectors' performance. It was also found that the annealing temperature should not exceed 300 °C, otherwise re-degradation of CCE occurs. Some hints to understand the CCE variation during annealing were found in the data of conventional electrical measurements. However, further systematic defect studies are needed for a comprehensive explanation.

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