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Radiation effect on pn-SiC diode as a detector

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Abstract

We studied radiation tolerance of pn junction 6H-SiC (silicon carbide) diodes on electrical properties and detector performance for alpha particles. Three pn-SiC diodes were irradiated with gamma-rays at doses (^{60}Co source) up to 2.5 MGy and two diodes were irradiated with beta-rays (2 MeV) at fluences up to 1×10^{15} electrons/cm^2. The ideality factors η, which are estimated from current–voltage (I–V) characteristics of diodes, were around 2.0 for all diodes, and no significant change in η was observed after both gamma and beta irradiations. The leakage currents increase with gamma doses up to range of 0.4–1.5 MGy and decrease with gamma doses above 1.5 MGy. For beta-rays, a little increase in leakage current was observed due to irradiation. The depletion layer width W was estimated from capacitance–voltage (C–V) characteristics of diodes. The W at several reverse bias voltage increases with increasing both gamma doses and beta fluences. The detector performance was examined by using alpha particles of two different energies, 4.3 and 1.8 MeV.For 1.8 MeV alpha particles, a charge collection efficiency, CCE, of 100% were demonstrated at reverse biases above 20 V, even after the irradiation at gamma doses up to 2.5 MGy.

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Keywords: Radiation hardness; Silicon carbide; Semiconductor detector; pn junction; CCE

1. Introduction

Silicon carbide (SiC) has been regarded as a useful material for usage in harsh environment (under high radiation condition, etc.), because SiC has many excellent physical properties such as wide bandgap, high saturation velocity of

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electrons, high break-down field and high thermal conductivity. Since SiC has been reported to be high radiation tolerance [1,2], it is expected that the radiation hardness of particle detectors, which is limited by the performance of Si detectors at present, can be much improved by using SiC detectors. In recent years, many researchers have studied the detector characteristics [3] of Schottky barrier [4–6] and p–n junction SiC diodes [7,8] in harsh environments, and promising results for SiC detectors with high radiation resistance were reported with improving crystal quality and device fabrication process. The interest of SiC in nuclear physics is the potential of high radiation hardness and the possibility of their operation at high temperature. In particular, radiation hardness is very important for detector systems in experiments of high-energy physics.

In this paper, we report the electrical characteristics of the pn-SiC diodes and the radiation response by exposing the pn-SiC diodes to alpha particles with 1.8 and 4.3 MeV before and after irradiations of gamma- and beta-rays.

2. Sample preparation and experiment method

The pn-SiC diodes with 300 μm diameter measured in this study were fabricated on a p-type 6H-SiC epitaxial layer grown on a p-type 6H-SiC substrate (CREE inc.). The mean acceptor concentration in the epitaxial film is $4.2\times10^{15}/\mathrm{cm}^3$. Fig. 1(a) and (b) show the schematic structure of cross-section and top view of the pn-SiC diode, respectively. The n^+-type region with a mean phosphorus (P) concentration of $5\times10^{19}/\mathrm{cm}^3$ was fabricated in 6H-SiC p-type epitaxial layer by 3-fold P-implantation (140, 60, 90 keV) at 800 °C and subsequent annealing at 1650 °C for 3 min in Ar ambient. The electrodes on n^+-type region were formed by Al evaporation at 20 nm (lift-off technique). As for the contacts on p-type substrates, electrodes were formed by Al evaporation at 70 nm and subsequent sintering at 850 °C for 5 min in Ar ambient [8].

The *I–V* and *C–V* characteristics of the pn-SiC diodes were measured using a KEITHLEY 2400 high voltage source meter and a Hewlett Packard

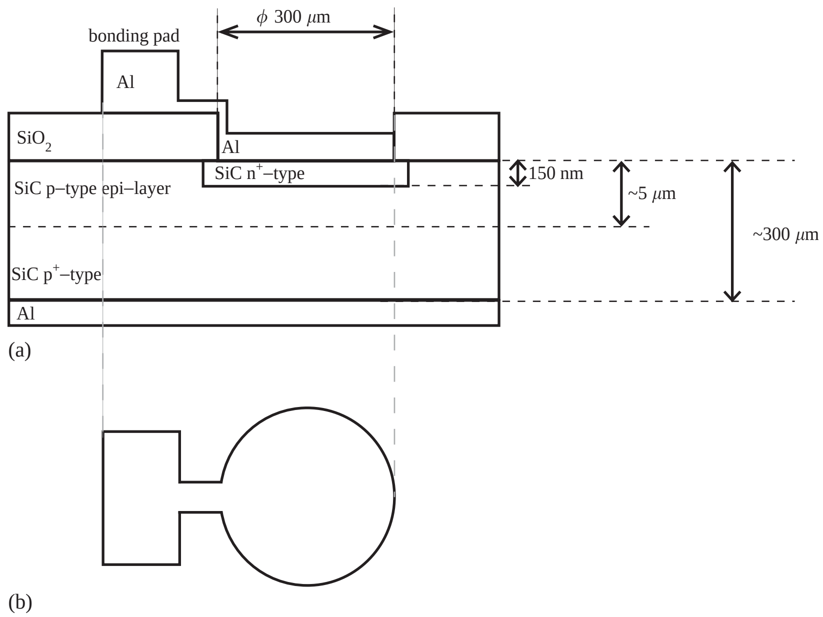


Fig. 1. (a) The cross-section of pn-SiC diode. (b) The top view of aluminum part.

4277A 1 MHz LCZ meter controlled by a personal computer (PC) through the GPIB interface, respectively. During *I–V* and *C–V* measurement, a pn-SiC diode was in a shielded fixture to minimize external spurious noise. The *I–V* and *C–V* measurements of the pn-SiC diodes were performed at room temperature (RT). The net capacitances at several reverse bias voltages were obtained by subtracting stray capacitance from total capacitance of the pn-SiC diode at each voltages.

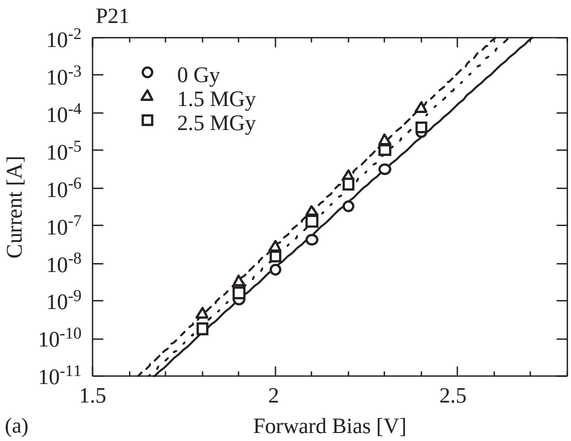
The charge collection efficiency (CCE) was measured by exposing the pn-SiC diodes to alpha particles from the ^{241}Am sealed source. The mean energy, 4.3 MeV, of alpha particles emitted from the ^{241}Am sealed source was estimated by a standard measurement using a PiN Si diode S3071 (HAMAMATSU Photonics KK). For the conversion from charge collected by the Si PIN diode to the energy of incident alpha particles, the value of 3.6 eV was used as the energy of the generation of an electron–hole pair in Si [9,10]. The pulse-height measurements of pn-SiC detectors were carried out in vacuum chamber (~1 kPa) at RT by using a pulse processing system consisting of a pre-amplifier (ORTEC 142AH Preamplifier), a main amplifier (ORTEC 672 Spectroscopy Amplifier), an Analog-to-Digital Converter (HOSHIN CAMAC PH-ADC C008), and a PC through the CAMAC interface. The charge collection by pn-SiC diodes were measured in a shielded aluminum box. Alpha particles were introduced into the electrode of the pn-SiC diode through a guide pipe with diameter of 300 μm which is needed for focusing alpha particles to the electrodes of pn-SiC diode, to minimize unnecessary charge collected from the inversion layer under the interconnection. A thin Mica film was used for the reduction of energy of alpha particles from 4.3 to 1.8 MeV.

The gamma- and beta-ray irradiation to pn-SiC diodes were carried out under no bias condition. Three pn-SiC diodes were irradiated with gamma-rays at doses (^{60}Co source) up to 2.5 MGy at RT. Two diodes were irradiated with beta-rays (2 MeV) at fluences up to 1×10^{15} electrons/cm^2 on the radiator.

3. Experimental results

3.1. I–V and C–V characteristics

Forward *I–V* characteristics of a pn-SiC diodes irradiated with gamma-rays at doses up to 2.5 MGy and beta-rays at fluences up to 1×10^{15} electrons/cm^2 are shown in Fig. 2(a) and (b), respectively. For both gamma- and beta-irradiations, a good linearity of log(I) as a function of *V* is observed before and after irradiation (Fig. 2). The values of ideality factor (η) are obtained from the *I–V* curves (See Tables 1 and 2). The value of η for pn-SiC(P22) diode cannot be



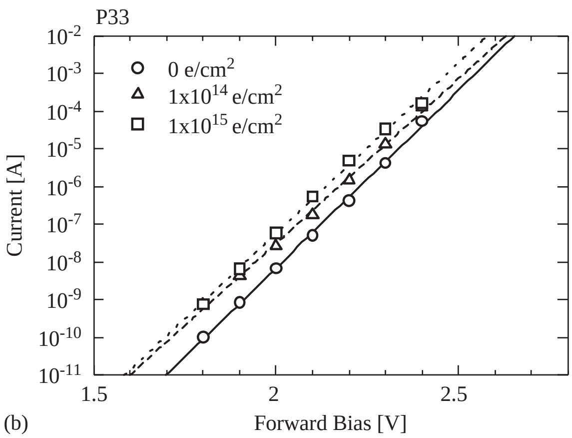


Fig. 2. Current versus forward bias voltage for the pn 6H-SiC diode irradiated with (a) gamma-rays (^{60}Co source) at doses up to 2.5 MGy and (b) beta-rays (2 MeV) at fluences up to 1×10^{15} electrons/cm^2.

Table 1
Ideality factors η of the pn-SiC diodes irradiated with gamma-rays

	P11	P21	P22
0 Gy	2.20	1.98	1.92
1.5 MGy	2.10	2.07	2.01
2.5 MGy	2.04	1.87	—

Table 2
Ideality factors η of the pn-SiC diodes irradiated with beta-rays

	P33	P4
0	1.98	1.97
1×10^{15} electrons/cm^2	1.95	1.94

determined after 2.5 MGy because of a large increase in the series resistance of the electrodes due to irradiation. However, the value of η for all diodes except P22 irradiated with 2.5 MGy are estimated to be around 2.0. The value of η obtained in this study indicates that the recombination current dominates [11,12].

On the other hand, a change in leakage current by irradiation is observed. Fig. 3 (a) and (b) show the current versus the reverse bias voltage for pn-SiC diodes irradiated with gamma- and beta-rays, respectively. For comparison, the results obtained before irradiation are also plotted in the figures. In Fig. 3(a), the leakage current of a pn-SiC diode irradiated with gamma ray increase after 1.5 MGy and subsequently decrease after 2.5 MGy. Another two diodes irradiated with gamma-rays show this behavior that the leakage current increase with gamma dose up to range of 0.4∼1.5 MGy and subsequently decrease. Fig. 4 shows gamma doses versus leakage current at −200 V for three diodes. The reason why the leakage current decrease after 2.5 MGy irradiation as compared to 0.4∼1.5 MGy irradiation is no yet clarified. Since in addition to SiC materials itself, all parts of diodes such as metal electrodes, field oxide, bonding pad and wire are damaged by gamma-ray irradiation, further investigations are necessary to understand this decrease in leakage current in high dose regions [13]. On the other hand, the leakage current increases with beta doses in Fig. 3(b).

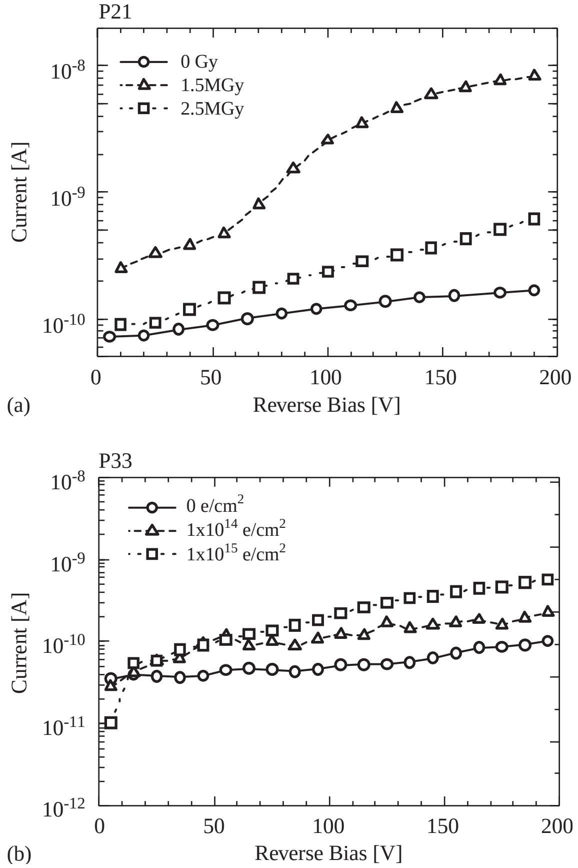


Fig. 3. Current versus reverse bias voltage for the pn 6H-SiC diode irradiated with (a) gamma-rays (^{60}Co source) at doses up to 2.5 MGy and (b) beta-rays (2 MeV) at fluences up to 1×10^{15} electrons/cm^2.

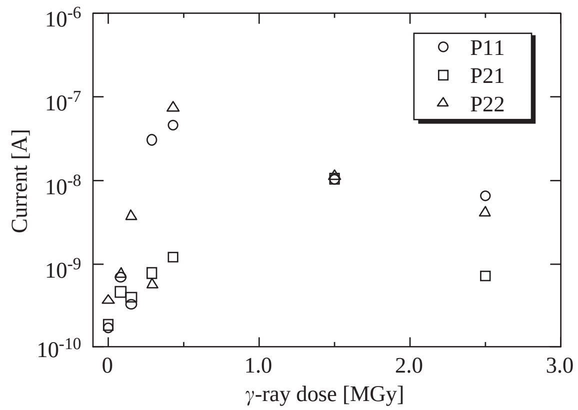


Fig. 4. Gamma doses versus leakage current at −200 V for three pn 6H-SiC diodes.

Fig. 5(a) and (b) show the $1/C_0^2$ as a function of the applied reverse bias for diodes after gamma and beta irradiation, respectively, where C_0 is the capacitance per unit area. The linearity for the slope of $1/C_0^2$–V plots in Fig. 5 show the uniform distribution of effective doping concentrations. The depletion layer width, which is calculated from ε/C_0, at several reverse bias voltages increase with both gamma and beta irradiation doses, where ε is the permittivity.

3.2. Evaluation of CCE

Figs. 6 and 7 show the CCE as a function of the applied reverse bias in the range of 0–200 V for alpha particles with 1.8 and 4.3 MeV, respectively. CCE is the ratio of the loss energy in a pn-SiC diode of incident particle to the charge collected from that diode, where the conversion between collected charge and loss energy is calculated by using e–h pair producing energy 8.4 eV for SiC [10].

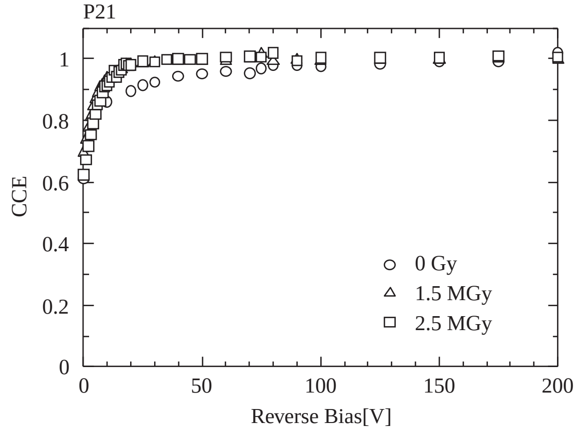


Fig. 6. CCE versus reverse bias voltage obtained by alpha particles measurement with 1.8 MeV for the pn 6H-SiC diode irradiated with gamma-rays (^{60}Co source) at doses up to 2.5 MGy.

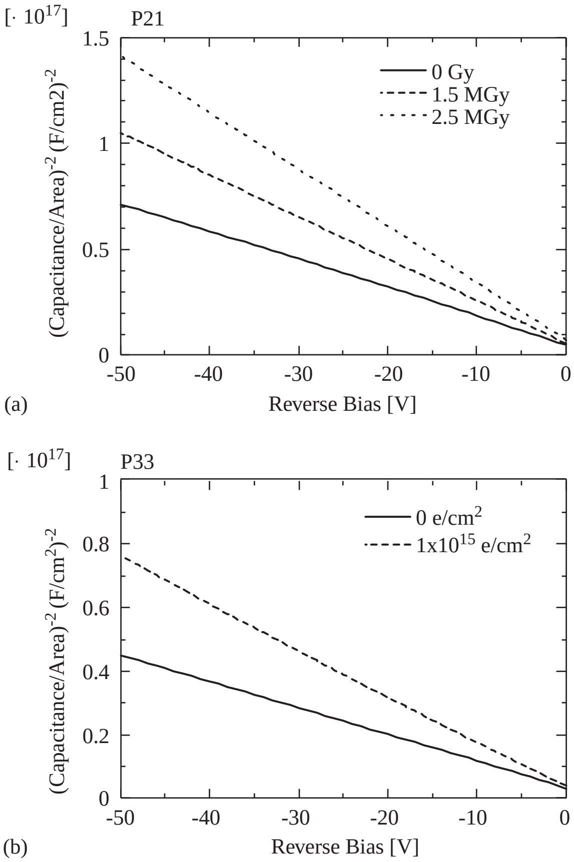
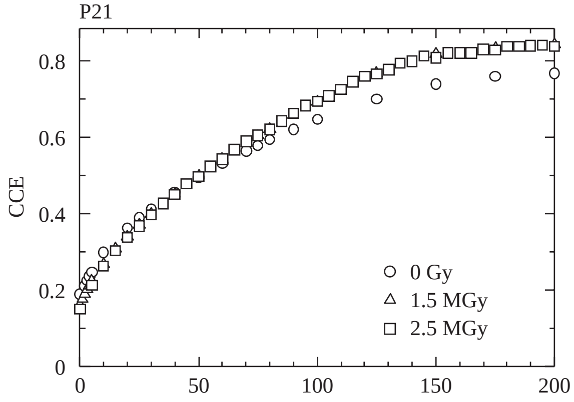
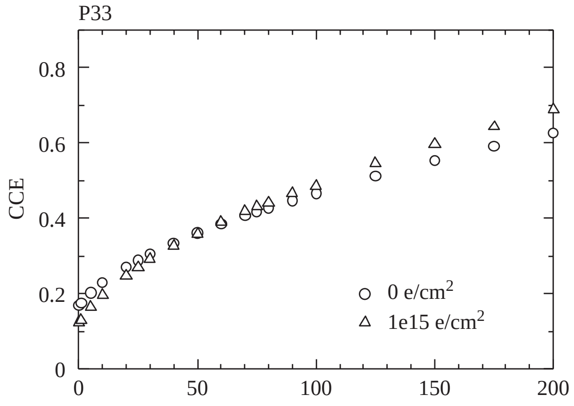


Fig. 5. $1/C_0^2$ versus reverse bias voltage for the pn 6H-SiC diode irradiated with (a) gamma-rays (^{60}Co source) at doses up to 2.5 MGy and (b) beta-rays (2 MeV) at fluences up to 1×10^{15} electrons/cm^2.

No significant difference in CCE is observed between before and after gamma-ray irradiation as shown in Figs. 6 and 7(a). As for beta-ray irradiation, the value of CCE is not affected by irradiation (Fig. 7(b)). In Figs. 6 and 7, CCE after irradiation is slightly higher than that before irradiation at high reverse bias voltages, since the thickness of the depletion layer for irradiated pn-SiC is wide as compared with that for non-irradiated pn-SiC described above. In Fig. 7(a) and (b), no saturation is observed in the CCE plots since the depletion region of a pn-SiC diode does not extend beyond the range of 4.3 MeV alpha particles, which is about 13 μm shown in Fig. 8. In Fig. 7(a), the width of depletion layer for the pn-SiC(P21) diode after 0, 1.5 and 2.5 MGy at the reverse bias voltage of 200 V were 4.4, 5.6 and 5.5 μm, respectively. For 1.8 MeV measurements, the CCE is saturated to be 1.0 at the high bias voltages more than 20 V since alpha particle with 1.8 MeV penetrate into the depth of 4.3 μm for SiC (Fig. 8). In Fig. 6, the width of depletion layer for



(a)



(b)

Fig. 7. CCE versus reverse bias voltage obtained by alpha particles measurement with 4.3 MeV for the pn 6H-SiC diode irradiated with (a) gamma-rays (^{60}Co source) at doses up to 2.5 MGy and (b) beta-rays (2 MeV) at fluences up to 1×10^{15} electrons/cm^2.

the pn-SiC(P21) diode after 0, 1.5 and 2.5 MGy at the reverse bias voltage of 20 V were 1.6, 2.0 and 2.2 μm, respectively. The reason why CCE saturated at the depletion width less than penetration depth of alpha particle with 1.8 MeV can be interpreted in terms of the diffusion of generated electrons. The Bragg ionization curves for incident alpha particle with 1.8 and 4.3 MeV in Fig. 8 were obtained from SRIM2000 simulation [14].

A least-squares fit of the experimental curve for 1.8 MeV measurement was performed by considering L, electron diffusion length, as a free parameter using following Eq. [4–6,15,16].

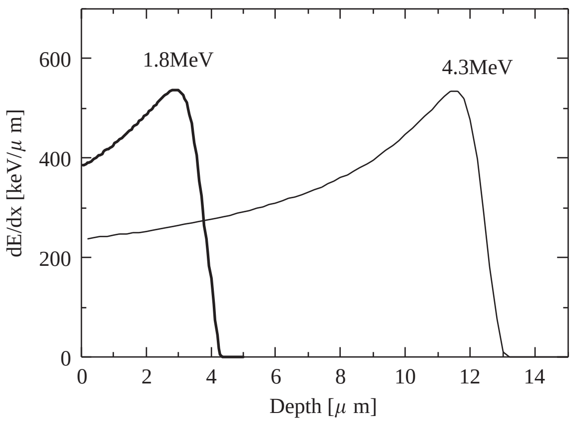


Fig. 8. Bragg ionization curve of (1) 1.8 MeV and (2) 4.3 MeV alpha particles for SiC.

$$\mathrm{CCE} = \frac{1}{E_\mathrm{p}} \int_0^W \frac{\mathrm{d}E}{\mathrm{d}x}\,\mathrm{d}x + \frac{1}{E_\mathrm{p}} \int_W^d \frac{\mathrm{d}E}{\mathrm{d}x} \exp\left(-\frac{(x-W)}{L}\right)\mathrm{d}x, \qquad (1)$$

where E_p [MeV] is the total energy of incident alpha particles with 1.8 MeV, $\mathrm{d}E/\mathrm{d}x$ [keV/μm] is the ionization energy loss for incident alpha particle per unit path length, L [μm] is the electron diffusion length and d[μm] is the penetration depth of alpha particle with E_p. In this estimation, we assumed that all carriers generated within depletion layer are collected. The first term is corresponding to the carriers collected in depletion layer and the second term is the contribution of diffusion carrier. L is defined by equations, $L = (D\tau)^{1/2}$ and $D = (kT/q)\mu$. Where D [cm^2/s] is the diffusion coefficient, μ[cm^2/V s] is the electron mobility and τ (s) is the lifetime of electrons.

The least-squares fit between the experimental data and Eq. (1) was performed for L as a free parameter in the range of 0–15 μm by the step of 0.1 μm. The best-fit result for a pn-SiC diode is shown by the solid line in Fig. 9. The closed circles in Fig. 9 are the experimental CCE. The open squares and triangles indicate theoretical CCE calculated from the first term and second term of Eq. (1), respectively. We obtained an electron diffusion length of $L = 4.6$ μm for a 2.5 MGy irradiated pn-SiC (P21). Table 3 shows the electron diffusion length and life time for three

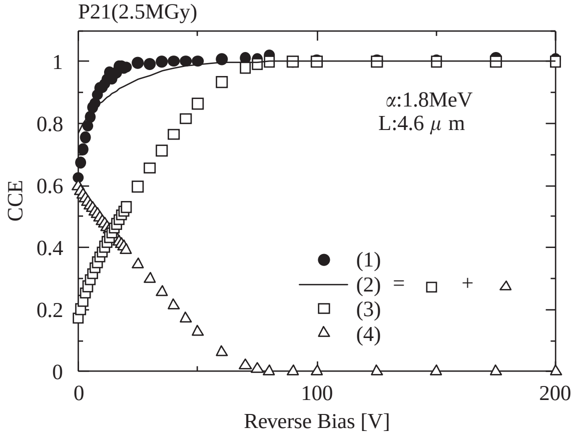


Fig. 9. The experimental CCE for the pn-SiC versus reverse bias voltage and relevant theoretical evaluations of the CCE: (1) experimental CCE; (2) theoretical CCE equal to (3) plus (4); (3) theoretical CCE from depletion region; (4) theoretical CCE from neutral region.

Table 3
Electron diffusion length (life time) obtained by 1.8 MeV alpha particle measurement for SiC diode irradiated with gamma-rays

	P11	P21	P22
0 Gy	7.9 μm (63 ns)	4.9 μm (24 ns)	4.8 μm (23 ns)
1.5 MGy	7.1 μm (51 ns)	6.4 μm (41 ns)	—
2.5 MGy	3.4 μm (12 ns)	4.6 μm (21 ns)	6.1 μm (37 ns)

samples non-irradiated and irradiated with gamma-rays at 1.5 and 2.5 MGy doses. For the pn-SiC(P22) diode after 1.5 MGy irradiation, the diffusion length of electrons (life time) was not possible to estimate due to a measurement problem (high noise). The relevant electron lifetimes are several tens of ns using $400\,\mathrm{cm^2/V\,s}$ electron mobility for 6H-SiC. For the value of lifetime τ, no significant difference between before and after gamma irradiations is observed, though τ decreasing with gamma dose in Schottky barrier diodes for 4H-SiC is reported [6,7]. It is difficult to compare the result of τ for pn-diode in this study to for Schottky barrier diode, because life time τ is influenced from many factor such as crystal condition, defect type formed by irradiations, fabrication process of diode or difference of defect formation between politypes.

In this study, the no significant change in CCE for high irradiated pn-SiC diodes indicate that SiC has the radiation hardness and the possibility as particle detector in high radiation environment.

4. Summary

The pn junction 6H-SiC (silicon carbide) diodes were evaluated in respect to radiation tolerance on electrical properties and detector performance for alpha particle. Three pn-SiC diodes were irradiated with gamma-rays (^{60}Co source) at doses up to 2.5 MGy in air at RT. Two diodes were irradiated with beta-rays (2 MeV) at fluences up to 1×10^{15} electrons/cm^2 in air on a water cooling radiator.

The properties of the pn-SiC diodes were measured by the ideality factor η and leakage current by *I–V* technique, and depletion layer width by *C–V* technique before and after irradiations. The ideality factors η were not significantly different before and after both gamma and beta irradiation. The leakage currents were increasing with beta doses. On the other hand, the leakage current of pn-SiC diode irradiated with gamma ray increase after 0.4–1.5 MGy and subsequently decrease after 2.5 MGy.

The detector performance of charge collection has been tested by alpha particles of two different energies, 4.3 and 1.8 MeV.CCE is not significantly different between non-irradiated and irradiated pn-SiC diodes for both gamma and beta doses. For 1.8 MeV alpha particles, CCE of 100% was demonstrated at reverse biases above 20 V before and after irradiations. The electrons lifetime with several tens of ns for 6H-SiC was obtained from CCE measurement and Eq. (1) before and after gamma irradiations.

The excellent radiation hardness shown in this study indicates that SiC is suitable for particle detectors used in severe radiation environments.

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