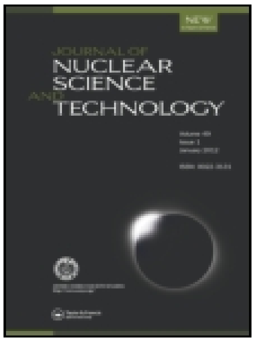

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ARTICLE

Effect of metal electrode on characteristics of gamma-irradiated silicon carbide detector

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Silicon carbide (SiC) is a highly promising semiconductor neutron-detector material for harsh environments such as nuclear reactor cores and spent-fuel storage pools. In the present study, three 4H–SiC p–i–n diode detectors were fabricated as variations of those metal-electrode structures. The *I*–*V* characteristics and alpha-particle responses of the detectors were measured before and after gamma-ray exposure. The detector with a Ti/Au electrode showed the lowest change of leakage current after irradiation; none of the detectors showed any change in the charge-collection efficiency when a sufficient electric field was applied after gamma irradiation of up to 8.1 MGy.

Keywords: silicon carbide; semiconductor detector; p–i–n diode detector; semiconductor neutron detector; radiation damage; gamma-ray irradiation; metal electrode

1. Introduction

The radiation hardness of bulk silicon carbide (SiC), an effect of its low lattice constant [1], is widely known to be outstanding compared with those of other semiconductor detectors. Due to the strong bonds between silicon (Si) and carbon (C), SiC has several remarkable physical properties, which include a wide bandgap energy (3.26 eV for 4H–SiC), a high thermal conductivity, electron mobility, and a high atomic displacement threshold energy [2–5]. SiC has been utilized as a radiation detector for harsh environments such as nuclear reactor cores, spent-fuel storage pools, and outer space [6].

Since high-quality SiC wafers (4H and 6H polytypes) became commercially available, various types of SiC diode detector have been fabricated and tested, mainly for nuclear power plant applications such as thermal/fast neutron fluence monitoring and material storage/research facility safeguarding purposes. Research has demonstrated that SiC radiation detector response is highly linear for neutron and gamma rays and highly feasible for harsh high-temperature and high-radiation environments [7–9]. Generally neutrons are measured with a semiconductor detector with neutron convertors such as ^{6}Li or ^{10}B. The neutron convertor, which is adjacent to the SiC wafer, emits charged particles after a neutron-capture reaction. These charged particles have specific energies and lose their energy by ionization while passing through the active volume of the SiC diode.

The radiation-damage effect on SiC detector has also been a key issue in the research because it is directly related to detector lifetime and also to determinations of optimal detection position. Radiation-damage effects on SiC detector have been studied in considerable breadth and depth [10–13]. Nava et al. [10] observed the change in properties of an SiC detector with various irradiations. They showed that charge-collection efficiency (CCE) can attain 100% when high reverse voltage is applied, even after irradiation with ^{60}Co gamma rays/electrons at doses of up to 40 Mrad. Ruddy et al. [13] observed the change in charged-particle response of SiC Schottky diode under intense gamma irradiation; they found that the energy spectrometry capability of an irradiated SiC detector was not decreased for gamma exposures up to 5.4 MGy with ^{137}Cs, though there is a slight change in resolution and peak centroid. These results are evidence that an SiC detector is highly resistant to radiation-induced damage. However, the issue of metal-electrode-dependent radiation tolerance has hardly been studied. In this study, the *I*–*V* curves

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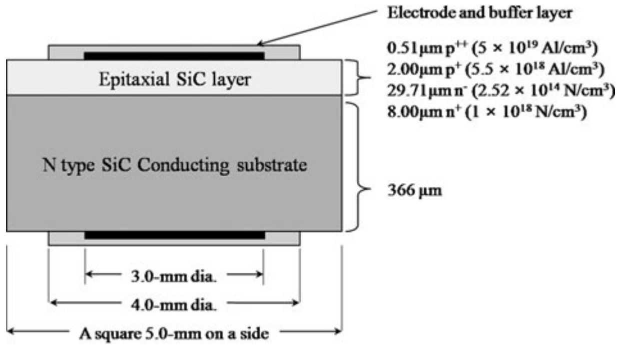

Figure 1. Schematic cross section of SiC *p-i-n* diode detector.

and alpha-particle responses of three different types of SiC diode detector were measured and compared as functions of gamma-ray exposure.

2. Detector fabrication

Figure 1 shows a schematic illustration of the SiC detector design. An n-type 4H–SiC substrate of 3 inch diameter and 366 μm thickness was obtained from Cree, Inc. [14]. Epitaxial layers were grown on the silicon side of the substrate to obtain the p–i–n diode. The orientation and resistivity of the wafer were 7.99° and 0.020 Ohm-cm, respectively. The wafer was cut to a size of 5 × 5 mm^2 using a Buehler wafering blade (model 11-4263). After cutting, three different circular metal electrodes were evaporated on each side of the wafer. The electrode structures were Cr/Au, Ni/Au, and Ti/Au. A Cr, Ni, or Ti of 30 nm thickness was deposited on both surfaces of wafer by a sputtering method in order to enhance the adhesion between the wafer and the metal electrode. An Au layer of 200 nm thickness was deposited on them using a thermal evaporator. The deposition speed was 4.0–5.0 Å/s and the pressure was a vacuum of 1.7 × 10^{-6} Torr. The buffer and electrode layer diameters were 3 and 4 mm, respectively.

To measure electrical characteristics and detection properties, the SiC diode sample was connected by a wire. The wires were not fixed by any chemical material but physically connected by inserting the SiC diode into two sheets of Ag-plated ceramic substrate, because the major aim of our study was to develop a robust detector suitable for use in harsh environment such as a reactor.

3. Gamma irradiation

The three detectors were exposed to gamma rays from ^{60}Co of the high-intensity irradiator at the Korea Atomic Energy Research Institute. The samples were mounted on an irradiation board with the metal electrode faces oriented towards the incident gamma radiation. The three irradiations were performed with a dose rate about 20 kGy per hour during 130 hours, and total exposure dose on the detectors was 2.7, 5.4, and 8.1 MGy, respectively.

4. Experiment

For a semiconductor radiation detector, the performance degradation caused by radiation damage generally appears in both forms of the decrease in CCE and increase in the leakage current. The decrease in CCE is caused by the defects created in the depletion region of a diode. Defects in crystalline lattice trap charge carriers and lead to incomplete charge collection (bulk effect). The energy resolution of the detector is also degraded due to fluctuations in the amount of charge lost. On the other hand, the increase in leakage current appears to be more directly related to surface effects and also contributes to a loss of detector resolution from the corresponding increase in leakage-current fluctuation [15]. In this study, two types of effects were considered because the metalization process was operated before an irradiation. To investigate the performance degradation, the measurements of *I–V* characteristics and response to alpha particles were carried out.

The charged-particle response of the SiC detector before and after irradiation was tested with a ^{238}Pu alpha-particle source under air condition. A charge-sensitive preamplifier (Cremat CR-110), a shaping amplifier (ORTEC 575A), and a multi-channel analyzer were used in the measurement. Reverse-bias voltage was applied up to 150 V to detector using an Aptec AHV-1. The detector and preamplifier were connected close to each other and covered with a metal shielding box for reduction of background noise. The source was fixed to the detector with a 3-mm diameter collimator. The detector-to-source distance was 5 mm, and the measurement-recording duration was 5 minutes. Alpha spectra were obtained by increasing the reverse bias.

The *I–V* characteristics were measured by the 4200 Keithley semiconductor characterization system. The measurements were taken for a biased voltage within +10 and −100 V range under room temperature and dark conditions.

5. Results

5.1. I–V *curve*

Figure 2 shows the leakage currents of the three non-irradiated SiC detectors. The leakage current is highly dependent on the metal electrode deposited on the SiC sensor. The detector with the Cr/Au electrode shows the lowest leakage current and that with the Ti/Au electrode the highest over the entire voltage range. The leakage current of Ni/Au electrode detector is 0.24 μA at −100 V, which is in good agreement with the data from our previous research [16].

Figure 3 shows the leakage currents of the three irradiated SiC detectors. In most cases, the current is increased with irradiation doses up to 5.4 MGy and then decreased after irradiation doses of 8.1 MGy. In the case of Ti/Au electrode, the current following the three irradiations are overlapped around −50 V, but the

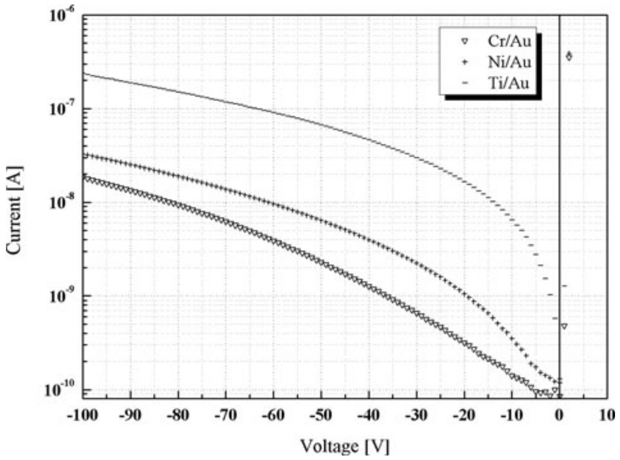

Figure 2. *I–V* curves of non-irradiated SiC samples.

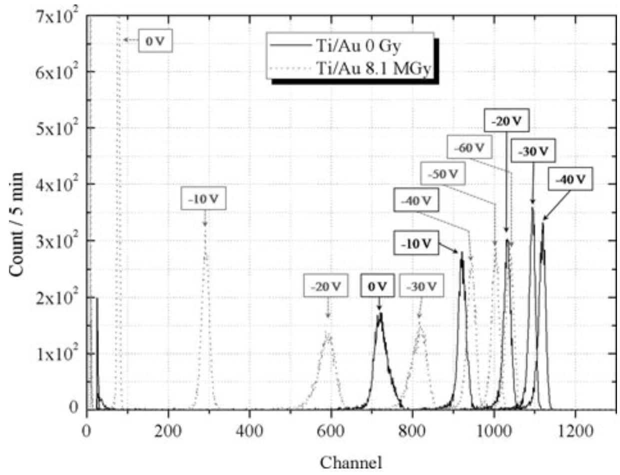

Figure 4. Typical response of SiC detector to alpha particle with respect to bias (non-irradiated: black solid line; 8.1 MGy irradiated: gray dotted line). The shaping time employed in the measurement was 0.5 μs.

difference is shown clearly at below −15 V. The detector with the Ni/Au electrode shows the highest increase of leakage current following 5.4 MGy of exposure; the current at −100 V is about 15 times higher than that of non-irradiated one. In contrast, the leakage current of the detector with the Ti/Au electrode shows the smallest fluctuation among the detectors. Its fluctuation is only from 0.18 to 0.31 μA at −100 V, and especially there is little difference between the current following 8.1 MGy of exposure and the non-irradiated one.

In our previous study [12], the *I–V* characteristics of SiC detectors irradiated by gamma ray were measured, and the result showed a decrease in the leakage current with increasing dose rate. Also, only the bulk effect was considered in previous result because the metal-contact process was operated after gamma-ray irradiation. In this study, on the other hand, the metal-contact process was operated before the irradiation, and the result shows the increase in leakage current with irradiation doses up to 5.4 MGy. This implies that the increasing leakage current comes from the radiation damage in an interface between the electrode and the SiC, because the level of the bulk effect in all detectors was same regardless of metal contact. It seems that the decreasing leakage currents from 5.4 to 8.1 MGy were caused by combinations of two effects.

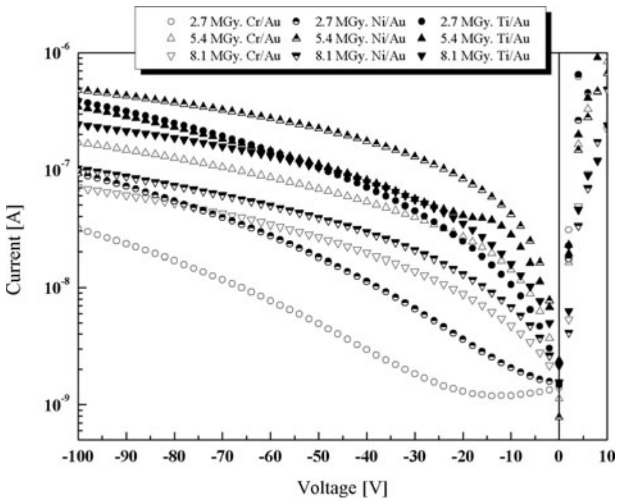

Figure 3. Change in leakage current for three detectors with ^{60}Co gamma-ray exposure.

5.2. *Alpha response*

Figure 4 shows the responses of the non-irradiated and post-irradiated SiC detectors to the ^{238}Pu alpha-particle source. Only the spectra of the Ti/Au electrode detector are shown because those of the other detectors were not significantly different. The result shows the effect of the gamma irradiation on the charged-particle response of the SiC detector. The channel of peak centroid is markedly shifted to the position corresponding low energy after gamma irradiation of 8.1 MGy. This implies that the active region, which the energy of incident particle is deposited along the particle track, was decreased due to damage.

The resolution also changed significantly. The peaks of the irradiated detector show an irregular pattern, where the peak width is broadened up to −20 V and then sharpened again with the bias, whereas the peak of non-irradiated one is sharpened with reverse bias.

Figure 5 shows the CCE as a function of bias with gamma-ray exposure. As shown in Figure 4 data, the CCE of the irradiated detector is much lower than that of the non-irradiated one. In no-bias case, the average CCE is decreased by about 80% after irradiation. The CCE of the Ni/Au electrode detector is slightly higher than other types of electrodes over all biases both before and after irradiation, but the difference is negligible. Moreover, when the sensor is fully depleted, the CCE is increased up to 100%, regardless of the type of electrode. The 8.1-MGy-irradiated detector is fully depleted at the

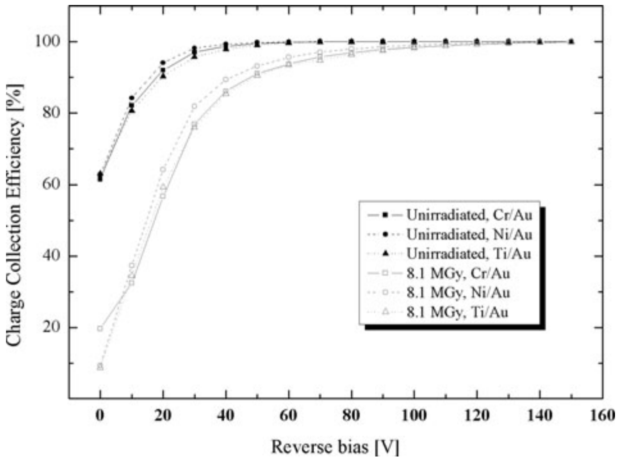

Figure 5. CCE of three SiC detectors as function of applied reverse-bias voltage before and after ^{60}Co gamma-ray irradiation of 8.1 MGy. The CCE was calculated from the ratio with the peak centroid at −150 V which the detector was fully depleted.

bias, which is about four times higher compared with the case of non-irradiated detectors.

Figure 6 shows the peak counts of the detectors with respect to bias voltage before and after gamma irradiation. The alpha energy spectrum was measured for 5 minutes. The separation between background noise and signal at no-bias is clear even after gamma irradiation of 8.1 MGy. As shown in the figure, the peak counts are distributed mainly in the range of 6750–7000. Although there are some fluctuations in the peak counts among detectors, it is believed that there were experimental errors such as detector-to-source distance as well as counting uncertainty. Consequently, all of the detectors show negligible changes in the charged-particle count rate after 8.1 MGy of gamma irradiation, regardless of electrode type.

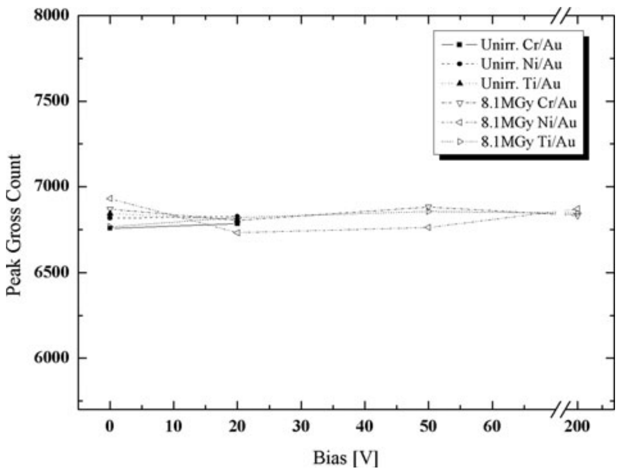

Figure 6. ^{238}Pu peak counts of three SiC detectors as function of applied reverse-bias voltage before and after ^{60}Co gamma-ray irradiation of 8.1 MGy.

6. Conclusion

SiC is highly attractive as a semiconductor material owing to its several outstanding wide-bandgap-derived physical characteristics: high thermal conductivity and electron mobility, and high atomic displacement threshold energy. An SiC radiation detector can be applied under various harsh conditions such as entail high temperatures and high radiation. Many experiments have been carried out to identify the detector's performance in potential applications. However, studies on the radiation tolerances of metal electrodes have been rare, although there were many experiments addressing the key issue of the radiation hardness of SiC.

In this study, the *I–V* curves and radiation responses of three different types of SiC diode detector were measured before and after ^{60}Co gamma irradiation, and the effect of the metal electrode on detector performance was investigated experimentally. The alpha-particle response to gamma irradiation of up to 8.1 MGy was almost identical among the detectors, regardless of electrode type. On the other hand, the detector with the Ti/Au electrode showed the lowest change in leakage current after irradiation. A study on radiation damage caused by fast and thermal neutron irradiation is in progress.

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