CHARACTERISTICS OF FABRICATED SiC RADIATION DETECTORS FOR FAST NEUTRON DETECTION

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Silicon carbide (SiC) is a promising material for neutron detection at harsh environments because of its capability to withstand strong radiation fields and high temperatures. Two PIN-type SiC semiconductor neutron detectors, which can be used for nuclear power plant (NPP) applications, such as in-core reactor neutron flux monitoring and measurement, were designed and fabricated. As a preliminary test, MCNPX simulations were performed to estimate reaction probabilities with respect to neutron energies. In the experiment, I-V curves were measured to confirm the diode characteristic of the detectors, and pulse height spectra were measured for neutron responses by using a ^{252}Cf neutron source at KRISS (Korea Research Institute of Standards and Science), and a Tandem accelerator at KIGAM (Korea Institute of Geoscience and Mineral Resources). The neutron counts of the detector were linearly increased as the incident neutron flux got larger.

Keywords: MCNPX, Silicon carbide (SiC), Neutron detector, Fast neutron, Response spectrum, Linearity

1. INTRODUCTION

To detect neutrons in a nuclear power plant (NPP), a self-powered neutron detector (SPND) is widely used because it is inert with respect to the detection of gamma rays. However, the SPND cannot detect neutrons in real time due to the delay time of beta emissions (>48 sec), and it is difficult to apply to Generation IV reactors, such as the sodium-cooled fast reactor or the molten-salt reactor, because of its large size. That means a neutron detector for a GEN IV reactor must be fabricated with a compact size if it is to be applied in such a reactor [1]. In recent years, there have been studies on wide band-gap semiconductors, such as SiC, AlN, and GaN, to detect neutrons in fields such as nuclear reactor fuel development, detection of concealed fissionable materials, nuclear weapons, drug inspection and even astronomy. Wide band-gap semiconductors can be made in a compact size for application in GEN IV reactors and have the advantages of a lower operating voltage and faster charge-collection times.[2-5]

Silicon carbide (SiC) semiconductor material is suitable for high-temperature applications in harsh environments because SiC has a wide band-gap energy (3.25 eV) compared with conventional semiconductors, such as silicon (1.12 eV), a relatively high radiation resistance and the capability of high-temperature operation (~ 600℃).[4] For fast neutron detection, the primary nuclear reactions between neutrons and the SiC material are the $^{12}\mathrm{C}(n,n')^{12}\mathrm{C}$ and the $^{28}\mathrm{Si}(n,n')^{28}\mathrm{Si}$ elastic and inelastic scatterings. For thermal neutron detection, [3] if a converter such as ^{6}LiF is mounted on the SiC material, it can emit a charged particle from the $^{6}\mathrm{Li}(n,\alpha)^{3}\mathrm{H}$ nuclear reaction. In this study, two PIN-type SiC semiconductor detectors were designed and fabricated to detect fast neutrons for application in next-generation NPP reactors. In experiments, the I-V measurements were performed to confirm the diode characteristic of the detectors, and neutron responses were obtained by using a ^{252}Cf neutron source (KRISS) and a Tandem accelerator (KIGAM).

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2. MATERIALS AND METHODS

A N-type SiC wafer with 3-inch diameter was obtained from Cree Corporation. The wafer was cut into 5×5 mm^2 pieces by using a laser precision saw [6]. HNO_3, DI water and acetone were used to clean the processed wafer [4]. As a buffer layer to enhance adhesion, gold and nickel were evaporated onto the SiC substrate by using a thermal evaporator. The gold thickness was 0.2 μm, and the nickel thickness was 0.03 μm. Next, the ^{6}LiF converter was deposited with a 9 μm thickness onto one of the SiC detectors, and then another gold layer (4 μm) was deposited to prevent the oxidization of the ^{6}LiF converter. This converter produces alpha particles and tritium by nuclear reactions with thermal neutrons. The processed PIN-type neutron detectors were mounted on a ceramic substrate. Fig. 1 shows the thickness and doping profiles of a schematic PIN- type SiC detector.

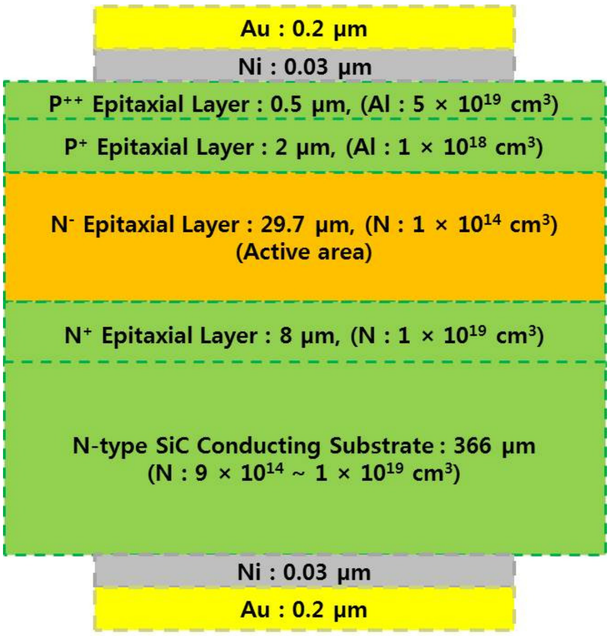

Fig.1. A schematic of a PIN-type SiC neutron detector. The active area is 4 mm in diameter.

As a preliminary test, the neutron detection efficiencies were calculated by using an MCNPX code with respect to neutron energies [7]. The neutron reactions used in the calculation are $^{6}Li(n,\alpha)^{3}H$ for thermal neutron detection and $^{12}C(n,n')^{12}C$ and $^{28}Si(n,n')^{28}Si$ scattering for fast neutron detection, respectively. Neutrons were generated over a range of 0.01 eV-10 MeV at the point, which was 5 mm from the detector surface. 9 μm ^{6}LiF layer with a diameter of 2 mm was used as the neutron convertor material. An active area of the detector in the simulation was a circle with a diameter of 4 mm. Fast neutron counts in two types of detectors also were calculated with respect to the distance (14 cm, 29 cm, and 58 cm) between the source and the detector surface.

In experiments, the I-V curve of the detector was measured by using a 4200 Keithley semiconductor characterization system. Neutrons were also measured with the detectors. Signals from the detector were processed with charge sensitive preamplifier (SP technology SP-100), shaping amplifier (SP-200), and Multi Channel Analyzer (MCA, ORTEC 919). Neutrons energy spectrum from ^{252}Cf source with neutron emission rate of 10^{6} s^{-1} were measured at KRISS. In addition, a neutron spectrum was obtained using Tandem accelerator at KIGAM. The range of neutron energies was 730 keV to 1030 keV and the neutron emission rate was 10^{7} s^{-1}. The shaping time of the detection system amplifier and the gain were set at 3 μs and 7, respectively. Additionally, the neutron detectors were zero-biased throughout the measurements.

3. RESULTS AND DISCUSSION

Fig. 2 shows the neutron detection efficiencies of the two types of SiC detectors. The fast neutron detector detects only neutrons from scattering reactions. However, the thermal neutron detector (SiC semiconductor detector with the ^{6}LiF converter) detects not only charged particles generated from the $^{6}Li(n,\alpha)^{3}H$ reaction at low neutron energies but also neutrons from scattering reactions. As a result of the calculation, it was found that the $^{6}Li(n,\alpha)^{3}H$ nuclear reaction occurred within the energy range of 0.01 eV-1 eV. Above 1 eV, both neutron detectors showed the same detection efficiencies.

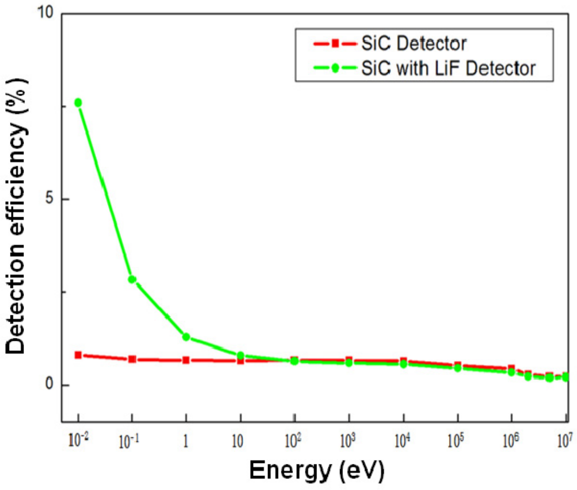

Fig.2. Neutron reaction probabilities with respect to neutron energy.

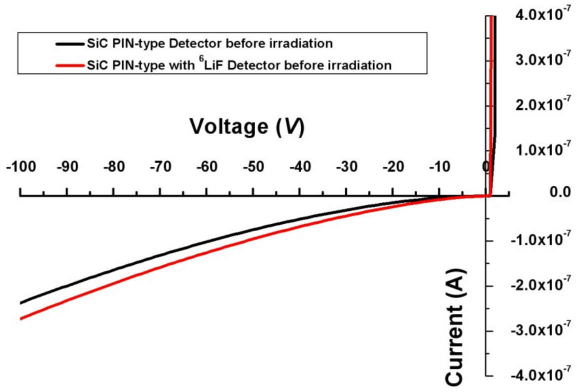

Fig. 3. I-V characteristics of PIN-type SiC neutron detectors.

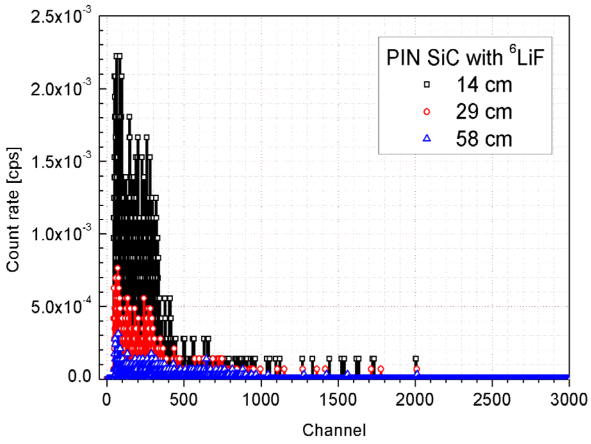

Fig. 4. Pulse height spectrum using a thermal neutron detector with use of a ^{252}Cf source.

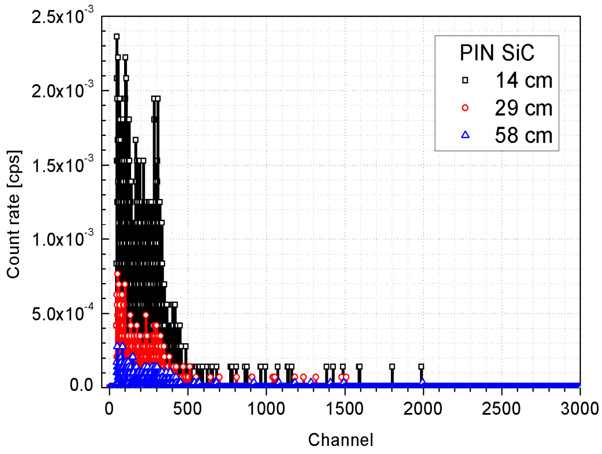

Fig. 5. Pulse height spectrum using a fast neutron detector with use of a ^{252}Cf source.

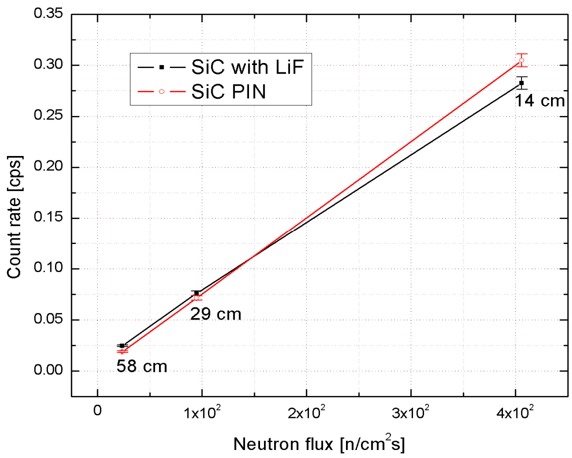

Fig. 6. Count rate of SiC neutron detectors by using a ^{252}Cf source.

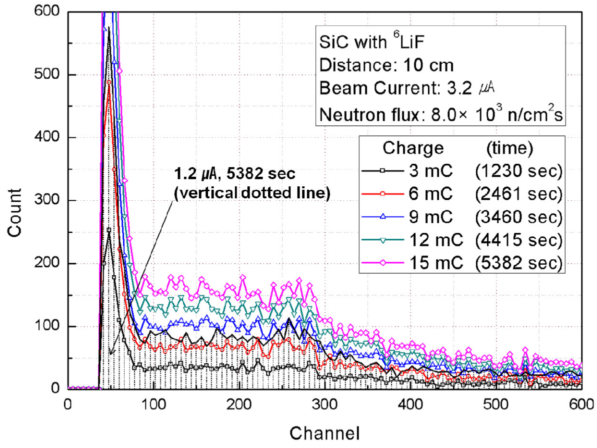

Fig. 7. Pulse height spectrum of a thermal neutron detector with the use of a Tandem accelerator (Beam current: 3.2 µA, total 4095 channels, bin size: 6 channels).

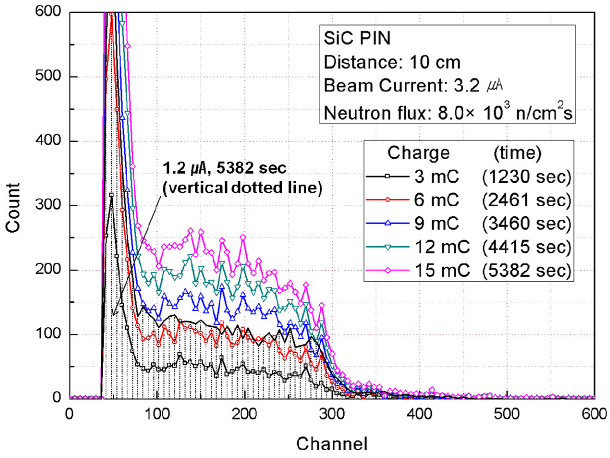

Fig. 8. Pulse height spectrum of a fast neutron detector with the use of a Tandem accelerator (Beam current: 3.2 µA, total 4095 channels, bin size: 6 channels).

Fig.3 shows the I-V curves, which measured with two PIN-type SiC neutron detectors. The SiC neutron detector with the ^{6}LiF converter showed a slightly higher leakage current than the fast neutron detector. This would be related to the ^{6}LiF layer, but is not fully understood yet. The leakage current of the two SiC neutron detectors were measured below 0.3 µA at up to -100 V.

Fig. 4 and 5 show the count rates of two types of SiC neutron detectors with respect to the distance between the source and the detector. The measurement was carried out with ^{252}Cf neutron source (emission rate of 10^6 s^{-1}) at KRISS. In measured pulse height spectra, the detector count at each distance was difficult to be distinguished from each other because the number of nuclear reactions was low due to the low activity of the neutron source. To confirm those differences, the count rate of each experiment was calculated with respect to measuring time. Fig. 6 shows the count rates calculated from measured values. As a result of the calculation, the count rate was determined to be 0.02 s^{-1}-0.3 s^{-1}, and it decreased approximately by a factor of 4 when the distance between the source and the detector was doubled. These results were confirmed to correspond with the simulation results. The pulse height spectra measurements show that the PIN-type SiC radiation detectors are suitable for fast neutron detection.

Fig. 7 and 8 show the pulse height spectra of the SiC neutron detectors when used in a Tandem accelerator at KIGAM. When protons (3.2 μA) generated in the accelerator strike a target, 10^7 s^{-1} emission rate of neutrons in an energy range from 730 keV to 1030 keV were produced and irradiated the SiC neutron detector. The distance between the accelerator and the detector was 10 cm, and the beam currents used in the experiment were 1.6 μA and 3.2 μA. Because the charge of the beam increased when the spectra measurement time increased, the neutron spectra were measured with respect to the charge increase. The pulse height spectra indicate a continuous neutron energy distribution from ^{12}C(n,n`)$^{12}$C and $^{28}$Si(n,n`)^{28}Si nuclear scattering reactions.

Because neutron radiation fields are strongly dependent on charge increases, the total counts were calculated, and the root-mean-square value of linearity was obtained to evaluate the radiation hardness of the SiC neutron detectors with respect to charge build-up. The linearity of the SiC neutron detectors against the total accumulated charge was evaluated. Fig. 9 shows the linearity curves. For each beam current (1.6 μA and 3.2 μA), the evaluated linearity was 99.9% for fast neutron measurement. This indicates that the fabricated PIN-type SiC neutron detectors can be applied to detect fast neutrons in strong neutron radiation fields.

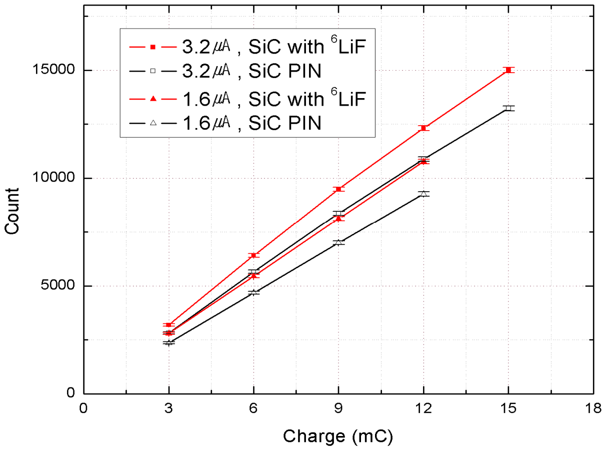

Fig. 9. Linearity of twoPIN-type SiC neutron detectorswith respect to the charge change.

4. CONCLUSION

SiC, with its wide band-gap energy, is a promising material for neutron detection in harsh environments due to its capability to withstand strong radiation fields and high temperatures. SiC semiconductor detectors can currently be considered a very interesting alternative to conventional neutron detectors because they can be operated at temperatures up to 600℃ by virtue of their physical and chemical stability. Therefore, they can be used in Generation IV reactors and commercial NPPs. In this study, two types of PIN-type SiC semiconductor radiation detectors were designed and fabricated to measure thermal/fast neutrons in the harsh environment of a nuclear reactor. As a preliminary test, the neutron reaction probability of the SiC detector was calculated by using an MCNPX code to confirm nuclear reactions between neutrons and the SiC detectors. Neutron responses were measured by using a ^{252}Cf neutron source at KRISS and a Tandem accelerator at KIGAM. As a result of the experiment, linearity was confirmed for the SiC neutron detectors. In conclusion, the fabricated SiC radiation detectors can be applied to measure fast neutrons. In future work, the SiC radiation detectors will be irradiated by neutrons with varying energies and dose rates, and the results will also be discussed with regard to GEN IV reactor applications.

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