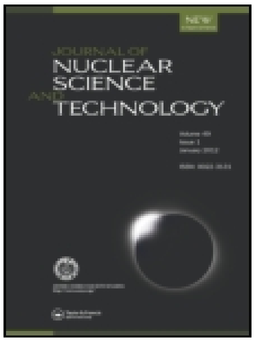

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6H-SiC Solid State Detector Development for a Neutron Measurement

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A new solid state detector based on 6H-SiC is one of the promising devices in the nuclear industry for high-level radiation applications in a harsh high-temperature environment. SiC is a semi-conductor with a 3.03-eV band gap energy, and known as a radiation-resistance material. SiC detectors were fabricated by using a 6H-SiC wafer. The properties of the 6H-SiC wafer were over a 10^6 ohm-cm resistivity, a 380 μm thickness, and a (0001)-oriented type. The 6H-SiC detector was prepared by the processes of a dicing, etching, removal of an oxidation layer and a mounting on an alumina substrate. SiC detector was 10×10 mm^2 with a 19.6mm^2 active area. The circular metal contacts consisted of a Si-face/Ni/Au and a C-face/Ni/Au structure. Thin LiF and B film was coated onto the SiC detector surface for a neutron converter. The electrical current-voltage performances of the detectors were measured by using the Keithley 4200-SCS parameter analyzer with self voltage sources. Neutron responses were measured by using a ^{252}Cf source.

KEYWORDS: solid state detector, semiconductor, silicon carbide, neutron measurement, surface barrier detector

I. Introduction

Solid state radiation detectors have been investigated for many applications within various environments. The harsh radiation environments such as a nuclear reactor core, high energy physics experiments, or outer space can cause radiation damage to detectors1). A radiation damage which deteriorates the performance of the devices is a serious and important problem for semiconductor radiation detectors 2).

The SiC semiconductor has recently emerged as an attractive material for an ionization radiation detection3). A SiC is known as a useful material for the harsh environments needed for a radiation-resistance4), a high-temperature operation and a high-critical breakdown voltage, and a high thermal conductivity. Radiation detectors based on semiconductors like SiC, AlN, and BN with a large band energy gap are the most promising for an ionizing detector. For the purposes of a fabrication of a radiation hard detector, a large band gap and a low leakage current are important parameters. SiC has over 170 polytypes. The commercially available single crystals are the hexagonal 4H and 6H. Large diameter single crystals are grown by a physical vapor transport (PVT) process which is based on a modification of the original SiC sublimation method5). In the metal/semiconductor Schottky device the current is induced by the major carrier. Therefore the switching time is faster than that of the p-n junction device6). However, the characteristics of the Schottky device are sensitive to the interface property on the semiconductor's surface. The surface treatments with an oxidation/HF etching and a boiling water immersion during the fabrication of the metal/6H-SiC Schottky device decreased the Schottky barrier heights by about 0.3 to 0.5 eV with respect to that of a 5% HF etching7). It means that a surface treatment is a major parameter for the electrical property of the Schottky device.

Present study is focused on the fabrication and performance of a radiation hard SiC neutron detector which is applicable in air and at a high temperature. Detection principle is shown in **Fig. 1**. The incident neutron was converted into charged particles by a nuclear reaction and the energetic charged particles were absorbed in the SiC sensor. The absorbed mechanism generated electron-hole pairs proportional to the incident charged particle energy.

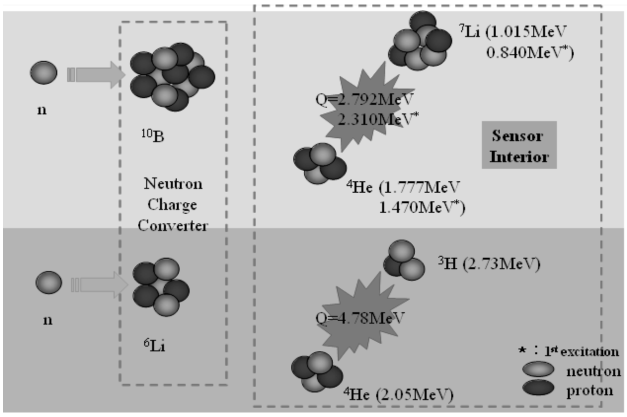

Fig. 1 Neutron detection mechanism in semiconductor detector with neutron conversion film

II. Detector Fabrication Process

We used a 6H-SiC wafer of 2 inch diameter supplied by the Dow Corning Co. The properties of the 6H-SiC wafer are an upper 10^6 ohm-cm resistivity, 380 μm thickness, and a (0001)-oriented type. We prepared 10×10 mm^2 samples by using a semiconductor diamond saw. Generally, a cutting process uses a wax to fix the wafer onto the working table of

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the diamond saw devise. After the cutting process, the wax is removed by an organic solvent or acetone from the wafer's surface. The surface of a SiC wafer was generally etched by using the standard process with H_2SO_4 and H_2O_2 solutions and rinsed with de-ionized (DI) water, and the removal of an oxidation layer by a HCl solution was performed for the metal/semiconductor contacts on the surface which were fabricated by using a thermal evaporator in a vacuum condition. The metallization process was performed under the following conditions; 1.2×10^{-5} Torr, 80 ℃ heating, and a 180°/min rotation speed of the SiC samples holder. The metal contact of the Si-face was Ni(300 Å) and Au(2000 Å), and C-face was Ti(300 Å) and Au(2000 Å). The metal contact shape was a circle with a diameter of 5 mm. To convert the neutron into a charged particle a ^{6}LiF conversion film was evaporated onto an Au metal contact. The thickness was about 10 μm. The LiF(B) film did not have a good contact with the Au layer, so the LiF(B) layer was positioned between another thick Au layer just like a sandwich type.

As a result of process we obtained metal/semiconductor Schottky barrier detectors for neutron detection with a neutron conversion layer.

III. Detector Performance and Results

1. I-V Characteristics Measurement

A major electric detector property is obtained by leakage current measurement with respect to a baised voltage. The SiC detectors were mounted by a conducting epoxy onto the PCB substrate and connected by a wire for the electrical signal readout. The wire terminal was connected to a signal readout and a biased voltage, and the electrical contact pad on PCB substrate was grounded. The current-voltage characteristics of the 6H-SiC radiation detector were measured by using the Keithley 4200-SCS semiconductor characteristics system with a self voltage supply by adjusting the internal biased voltage within -100 V to 100 V. Electric characteristics measurements were carried out at room temperature in a box shielded from the light. The measured I-V characteristics were determined that the detector was a type of metal/semiconductor surface barrier device.

High breakdown voltage is concerned with the maximum operating electric field inside a detector and a charge collection efficiency. We observed that the breakdown voltage was over 100 V.

2. High Dose γ -ray Irradiation test

High neutron field always contains a high γ-ray dose. One of the important characteristics is a γ-ray resistance. SiC samples with 10x10 mm were irradiated by Co-60 γ-ray up to 120 kGy. The irradiation was performed at a γ-ray irradiation facility at the Korea Atom Energy Research Institute (KAERI) with a dose rate of 5 kGy/hour and 15 kGy/hour for 8 hours. A dose rate of 15 kGy/hour is the maximum capacity of the Co-60 γ-ray source at KAERI. The total doses were 40 kGy and 120 kGy, respectively.

We measured the band gap property by using a photon absorption spectroscopy. The difference of the band gap result before and after an irradiation was 0.01eV which was placed in the error ranges of the measurement and the determination.

The radiation-induced damage can be classified into two categories of bulk and surface effects. The most fundamental type of a bulk radiation damage is the Frenkel defect, produced by the displacement of an atom of the semiconductor material from its normal lattice site. The vacancy left behind, together with the original atom now at an interstitial position, constitutes a trapping site for normal charged carriers. These are called as point defects to distinguish them from the more complex "clusters" of a crystalline damage. The γ–rays can create only point defects. When these defects have been formed enough, a carrier lifetime is reduced. The leakage currents of the non-irradiated sample and two 40 kGy, 120 kGy-irradiated samples with the Si-face/Ni/Au interface were measured in the range from 0 to 100 V. We did not find any remarkable differences between before and after an irradiation at 40 kGy and the leakage current was increased at 120 kGy as shown in **Fig. 2**.

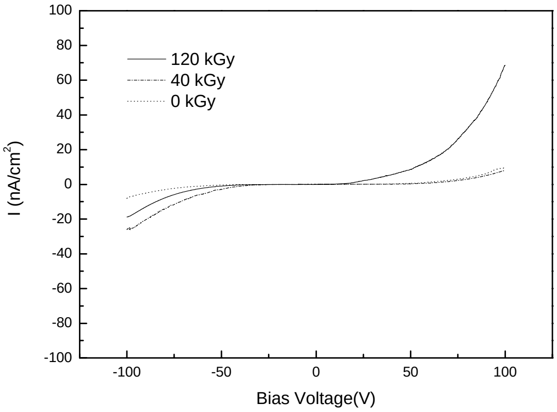

Fig. 2 Typical I-V curve before and after γ-ray irradiation

3. Schottky Barrier Height Determination

The fabricated detector type is one of the Schottky barrier ones. The current transport in the metal-semiconductor Schottky contacts is mainly due to majority carriers, in contrast to p-n junctions, where the minority carriers are responsible. For high-mobility semiconductors the transport can be adequately described by the thermionic emission theory 8).

According to the thermionic emission theory, the flow is limited by the rate at which carriers try to cross the barrier and the Schottky barrier height (SBH) was determined by using the forward current-voltage characteristics of the metal/semiconductor Schottky contacts. The total current density over a potential barrier is analyzed within the framework of the thermionic emission model originally described by Bethe 9) :

$$J_n = J_{ST}\,[\exp(qV/kT) - 1]$$

$$J_{ST} = A^*T^2\exp[-(q\Phi_{Bn}/kT)],$$

where J_{ST} is the saturation current density, k is the Boltzman constant, q is the carrier charge, T is the temperature and A* is the effective Richardson constant $A^* = 194\ A/cm^2K^2$ for a thermionic emission, by neglecting the effects of a optical phonon scattering and quantum mechanical reflection[10].

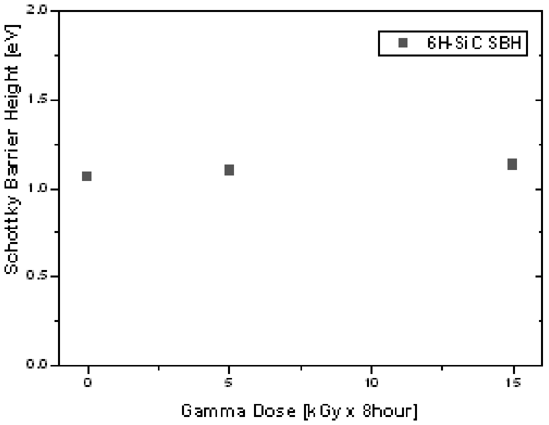

Fig. 3 Schottky bairrier heights with respect to γ -ray dose

The 6H-SiC semiconductor showed similar Schottky barrier heights independent of the different dose rates of the irradiation with Co-60 γ–rays as shown in **Fig. 3**. The SBHs of the C-side of the non-irradiation, 40 kGy and 120 kGy samples are 1.06 eV, 1.11 eV and 1.13 eV, respectively. The SBHs for the 6H-SiC with an orientation (0001) were known to be placed between approximately 0.8 and 1.25eV for the Si-terminated face and between 1.0 and 1.6 eV for the C-terminated face.

3. α-ray Response Measurement

Our detector adapted a neutron to charged particle conversion film. Detector performance was highly dependent on the charge particle detection efficiency. The α–ray responses were measured by a Pu-238 plate-type source with 5.5-MeV at room temperature in a 1-atm air pressure[11]. The α–ray particle was confirmed by using a thin Al plate which is sufficient enough to stop the α–rays. The Al absorber thickness was determined by a charged particle range simulation code (TRIM) which is sufficient enough to stop the α–rays. The energy moderation effect of the 5.5 MeV The α–rays in air was measured by adjusting the distance between the Pu-238 source and the SiC detector. The energy moderation and the simulated deposition energy were used to calculate the energy calibration to determine the energy resolution of the detector operating in room temperature and a 1-atm normal air pressure. Pulse height spectra were obtained by ORTEC and eV-products preamplifiers, as well as a shaping amplifier, and a multi-channel analyzer. **Fig. 4** is the α-ray spectra with different biased voltages. As bias voltage increases, the 5.5 MeV α-ray peak centroid increases because the charge collection efficiency increases.

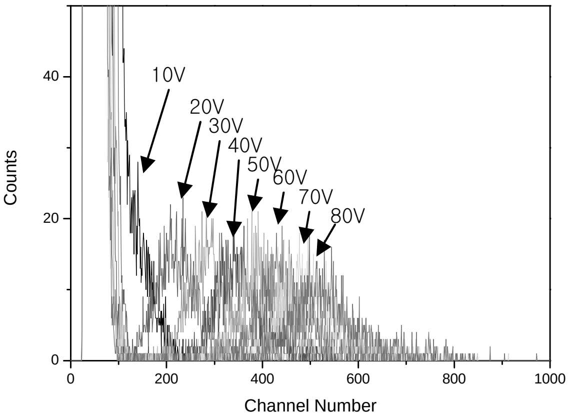

Fig. 4 α-ray responses at 5.5 MeV with respect to different biased voltages

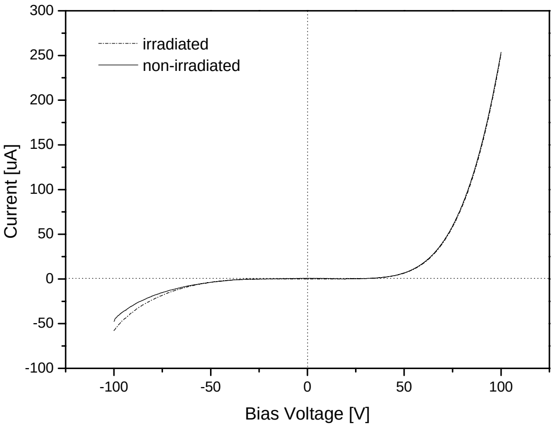

Fig. 5 Typical I-V curve before and after neutron irradiation

In order to investigate the origin of the low energy contribution which is the lowest energy region less than channel no 100 in **Fig. 4**, we compared our results with a silicon surface barrier (SSB) detector purchased from EG&G ORTEC, which can be used at a 1-atm air pressure. From this investigation, the low energy contribution seems to consist of mainly electrical noises originating from the connector and ground loop, and partially from a γ-ray and light leakage contribution.

4. Neutron Response Measurement

Neutron Detection response was performed by using a ^{252}Cf neutron source in air. Neutron damage evaluation was performed by an irradiation of the neutron source up to the $10^8\ n/cm^2$. **Fig. 5** is the I-V characteristics before and after the neutron irradiation. I-V curves showed almost similar tendencies. As a result SiC detectors were resistant to the neutron damage up to the $10^8\ n/cm^2$.

One of the effective neutron conversion materials are ^{10}B and ^{6}Li. We fabricated two types of conversion films with a 10 micron thickness. The energy losses of the neutron conversion film and metal contact structure were simulated by TRIM code. The energy losses were 149, 155, 162 keV for secondary α-rays with energies of 2050, 1777 and 1470 keV, respectively, from (n, α) reaction, and 289 keV for 2730 keV from (n, t) reaction. **Fig. 6** and **7** are the neutron spectra of the ^{10}B and ^{6}Li conversion films. The neutron detection efficiency was expected to be 2.8% as a result of the MCNP and TRIM codes calculation, and measured as 2.5% efficiency.

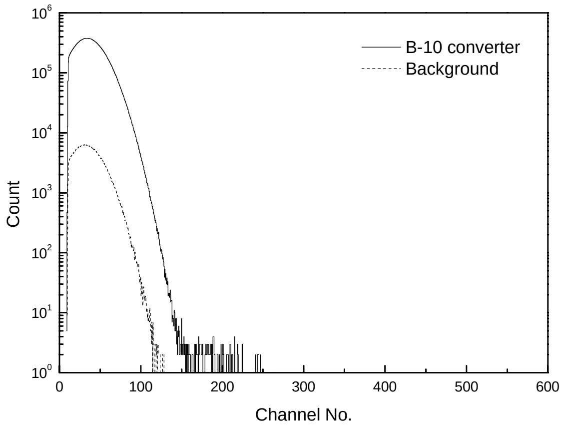

Fig. 6 Neutron detection spectrum measured using by B-10 convert film detector

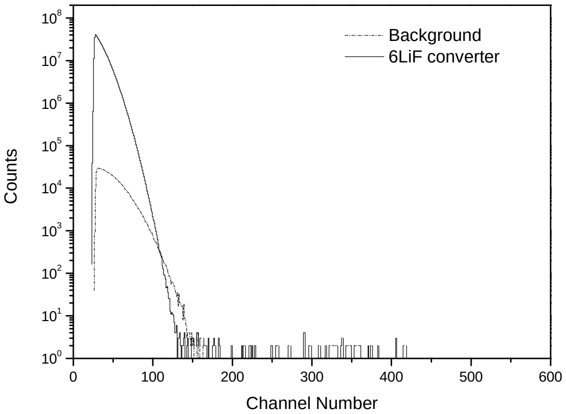

Fig. 7 Neutron detection spectrum measured using by ^{6}LiF convert film detector

The ^{6}LiF converter was 10 micron thickness and the incident Neutron produced from ^{252}Cf was moderated by using high density polyethylene slabs with 30mm thickness. **Fig. 6 and 7** showed neutron spectra. ^{6}Li was known that produced more energetic charge particles compared to ^{10}B converter. It means ^{6}Li gives better neutron discrimination than ^{10}B by energy threshold level from noise and background.

IV. Conclusions

Neutron SiC detectors were fabricated and measured its performances. I-V measurement revealed that this detector was a Schottky barrier type. High dose of γ-rays were irradiated up to 120 kGy and could not find any changes of its electrical properties. Neutron damage was tested by a ^{252}Cf source up to a 10^{8} n/cm^{2}. Neutron responses were measured with two different types of neutron to charge particle converters based on ^{6}Li and ^{10}B materials. The neutron detection efficiency was in good agreement with the calculated result. As a result, the SiC detectors showed a good performance for neutron detection.

Acknowledgement

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