Test of neutron transmutation doping of SiC by implantation of phosphorous

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1. Introduction

Silicon carbide (SiC) as a wide band-gap semiconductor material, is suitable for high power and high frequency electronic devices because of its excellent thermal and electrical properties compared with silicon (Si) [1]. Until now the commonly used dopants in SiC have been nitrogen as a donor and aluminum as an acceptor. However, in situ doping during crystal growth or epitaxy is difficult to control the homogeneity of dopants. Up to now Si is still the best semiconductor material for high power devices. For this purpose it is homogenously doped by neutron transmutation doping (NTD) using phosphorous to get a n-type material [2]. Phosphorous is also a donor in SiC. Therefore, studies using NTD for uniform doping of SiC have been conducted by some researchers [3-5]. However, most of these studies irradiated SiC by neutrons on a laboratory scale and the main purpose was to analyze the defects that occur by radiation.

HANARO has been providing the commercial NTD service for 5”, 6” and 8” Si ingots since the end of 2002. For the SiC, the implementation of doping process was a breakthrough in the development of SiC power devices. In this study, a neutron irradiation device was designed to realize NTD for a large amount of SiC single crystal in HANARO, and the results of the neutron doping test were presented.

2. Methods and Results

The NTD for producing n-type SiC is based on the conversion of the ^{30}Si isotope into phosphorus (P) atoms by neutron absorption as follows:

$$^{30}Si(\mathrm{n},\gamma)^{31}Si \rightarrow {}^{31}P + \beta^{-}\ (T_{1/2} = 2.62\ h) \quad (1)$$

A prime target of NTD is to achieve uniform neutron irradiation throughout an entire SiC since the resistivity distribution mainly depends on the neutron irradiation. The research reactor HANARO has two vertical irradiation holes for NTD, NTD1 and NTD2. We developed an irradiation devices for the SiC in the NTD2 hole from the viewpoint of the nuclear design. The fabrication performance indexes of the SiC-NTD device are as follows.

1) Accuracy of neutron doping: resistivity of the SiC single crystal is within 10% of the target resistivity
2) Axial uniformity of neutron doping: reaction rate of ^{30}Si(n,γ)^{31}Si in the axial direction of SiC is within ±5%
3) Radial uniformity of neutron doping: radial ^{30}Si(n,γ)^{31}Si reaction rate distribution of SiC is within ±7%

Using MCNP 6.2 code, HANARO core model was developed, and a neutron irradiation device was designed considering the neutron properties of the vertical irradiation hole. Aluminum alloy, water and graphite were considered as screen and reflector materials of the neutron irradiation device for 4” SiC based evaluation of the doping uniformity. The design of the irradiation device was optimized to achieve a flat axial and radial distribution of the ^{30}Si(n,γ)^{31}Si reaction rate.

Figure 1 shows the screen of the SiC-NTD basket and the axial reaction rate for the SiC. Water is thick at the axial center of the SiC and gradually decreases in thickness as it goes to both ends. At both ends of the SiC, the Al body is 2.4 cm thick. The axial uniformity of the NTD is defined as the difference between the maximum and minimum relative ^{30}Si(n,γ)^{31}Si reaction rate. We achieved the axial uniformity of less than 1.0%, and the radial uniformity of 4.8% which are well within a usual requirement. The final 3-D model of the SiC-NTD basket is shown in Figure 2.

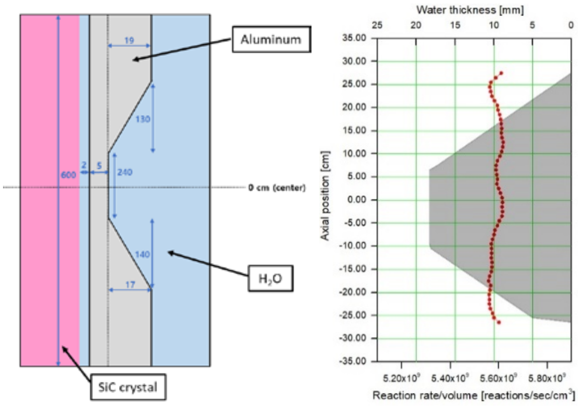

Fig. 1. Sectional view of the screen of the SiC-NTD irradiation basket and the axial reaction rate distribution

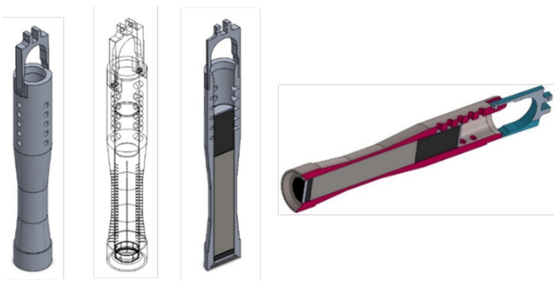

Fig. 2. Final 3-dimensional model of the SiC-NTD irradiation basket

Prior to commercial NTD service for SiC semiconductors, a neutron irradiation test was performed on a 4” high purity semi-insulating 4H-SiC wafers. We used commercially available high purity semi-insulating wafers (Synlight Crystal Inc.) of 500 μm thick and 1E7 Ω-cm resistivity. The wafers were irradiated for 16 hours in the NTD2 vertical irradiation hole at HANARO. Reactor power during the irradiation was 25 MW and the average position of the control rod assemblies was 457 mm. The neutron flux at the SiC wafer was monitored using the Zirconium foils which were attached near the SiC wafer. Measured thermal neutron flux was estimated to be 2.6E13 n/cm^{2}s. After irradiation, the integrity of the SiC wafer was confirmed, and the resistivity and P-31 doping density of the irradiated SiC were estimated.

Resistivity of semiconductor material with thickness of *t* and area of *A* is given

$$\rho = AV/It \quad (2)$$

where, *V* is the voltage, and *I* is the current. *I* is the sum of the electron current and hole current as follows

$$I = I_e + I_h = An_i\varepsilon(v_e + v_h) \quad (3)$$

where, n_i is the intrinsic carrier density, ε is the electronic charge(1.602E-19 C), and v is the drift velocity of the charge carrier. Applying the mobility of the charge carrier(μ), the resistivity can be written as

$$\rho = \frac{AV}{An_i\varepsilon\frac{V}{t}(\mu_e+\mu_h)t} = \frac{1}{n_i\varepsilon(\mu_e+\mu_h)} \quad (4)$$

For the NTD, the resistivity of the SiC can be derived using the doping density of N_D instead of the intrinsic carrier density as follows

$$\rho = \frac{1}{N_D\varepsilon\mu_e} \quad (5)$$

In addition, the target resistivity of the SiC is

$$\rho_t = \frac{K}{\phi t} \quad (6)$$

Where, Φ is the neutron flux (n/cm^{2}s), *t* is the irradiation time (s), and *K* is the constant which is resistivity times fluence (Ω/cm). The K-value was evaluated in consideration of the neutron energy spectrum at HANARO core and the effective cross-section for ^{30}Si of the 4H-SiC by using the MCNP simulation. The calculated K-value is 3.91E19 Ω/cm. The resistivity of the 4H-SiC semiconductor as a function of the neutron irradiation time is shown in Figure 3.

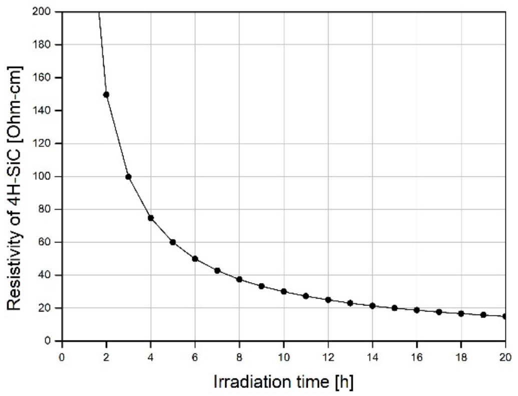

Fig. 3. Resistivity of the 4H-SiC semiconductor as a function of the neutron irradiation time

Pictures of the experiment of the NTD for SiC wafer and the unirradiated and irradiated SiC wafers are shown in Figure 4. As shown in the figure, it can be observed that the color of the SiC wafers has been changed from transparent to amber. Because of the wide bandgaps of SiC, some, or perhaps even all, visible light is not absorbed by SiC. The wavelength of absorbed light is determined by the bandgap, the major impurity levels, and the intra-band excitation levels. The carrier absorption in the conduction band is well known for most SiC polytypes, and occurs at about 460 nm (blue light) for n-type 4H-SiC. High-purity 4H-SiC, which possess very wide bandgaps, are colorless and transparent, like glass. However, n-type doping causes carrier absorption in the visible region. Its individual light absorption and transmission characteristics give each SiC crystal a unique color. Additionally, radiation damage can create defects in the SiC, and the defects can distort the band structure. Defects of the SiC make energy state between conduction band and valance band, and it affects the transmission of the visible light. The resistivity and the P-31 doping density of the irradiated SiC were estimated to be about 14.9 Ω-cm and 4.2E14 cm^{-3}, respectively.

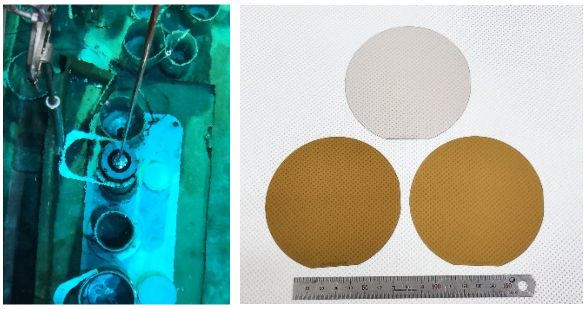

Fig. 4. Pictures of the NTD experiment at HANARO, and the 4 inch SiC wafers before and after neutron irradiation

3. Conclusions

The neutron irradiation basket was designed for SiC single crystal irradiation in the NTD2 hole of HANARO, which is optimum in achieving a flat axial and radial distribution of resistivity in the irradiated SiC. ^{30}Si(n,γ)^{31}Si reaction rate distributions of 4 inch 4H-SiC were estimated to be 1.0% and 4.8% for axial and radial directions, respectively, which are well within a usual requirement. Commercial available HPSI 4H-SiC wafers were doped by neutrons for 16 hours. From the color change after neutron irradiation, it was found that the P-31 dopants created by neutrons was uniformly distributed throughout the wafer. It is expected that high-quiality with high voltage devices will be able to be developed by using the NTD-SiC material instead of the conventional epi-wafer for the n-drift layer of the power semiconductor.

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