<Technical Notes>

DESIGN OF A NEUTRON SCREEN FOR 6-INCH NEUTRON TRANSMUTATION DOPING IN HANARO

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The neutron transmutation doping of silicon (NTD), as a method to produce a high quality semiconductor, utilizes the transmutation of a silicon element into phosphorus by neutron absorption in a silicon single crystal. In this paper, we present the design of a neutron screen for a 6″ Si ingot irradiation in the NTD2 hole of HANARO. The goal of the design is to achieve an even flat axial distribution of the resistivity, or $Si^{30}(n,\gamma)Si^{31}$ reaction rate, in the irradiated Si ingot. We used the MCNP4C code to simulate the neutron screen and to calculate the reaction rate distribution in the Si ingot. The fluctuations in the axial distribution were estimated to be within ±2.0% from the average for the final neutron screen design; thus, they satisfy the customers' requirement for uniform irradiation. On the other hand, we determined the optimal insertion depths of the Si ingots by varying the critical control rod position, which greatly affects the axial flux distribution.

KEYWORDS : Neutron Transmutation Doping, Silicon, Neutron Screen, Uniform Irradiation, HANARO

1. INTRODUCTION

HANARO is an open-tank-in-pool type research reactor of 30 MW. The thermal neutron flux reaches $\sim 3 \times 10^{14}$ n/cm$^2\cdot$s in the reflector region, which is comparable with the flux levels of the most powerful research reactors in the world. Since the HANARO reached its first criticality in 1995, its performance has been improved continuously, and the fields of utilization have been expanded. Fig. 1 shows the plane view of the HANARO core and reflector regions.

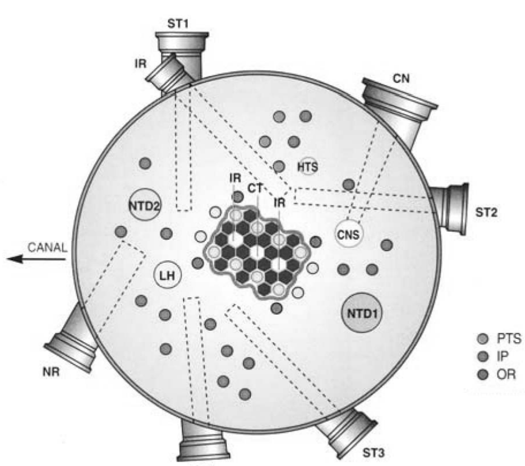

Fig. 1. Vertical Irradiation Holes and the Horizontal Beam Tubes in HANARO

The reactor core is separated from the reflector by the inner shell of the reflector tank. The core, resembling a honeycomb inside the inner shell, is cooled and moderated by light water. In the reflector tank, a total of 33 vertical holes with various sizes and seven horizontal beam tubes are arranged for various purposes. Two holes among the vertical holes, NTD1 and NTD2, are provided in the reflector region for the Neutron Transmutation Doping (NTD) service. Table 1 describes the characteristics of each irradiation hole.

The irradiation of silicon for NTD is an important industrial application item of a research reactor. The NTD method utilizes the transmutation of a silicon element into phosphorus by neutron absorption in a Si single crystal. The reaction for this process is as follows:

$$Si^{30}(n,\gamma)\,Si^{31} \longrightarrow P^{31} + \beta\,.$$

P^{31} is a stable isotope which plays the role of a dopant.

The semiconductor silicon produced by this method is known as the NTD silicon. The uniformity of a dopant of

Table 1. Characteristics of the NTD Holes in HANARO

	Hole Size, Inner Dia. (mm)	Thermal Neutron Flux ($n/cm^2\cdot s$) (at 30 MW)	Acceptable Ingot Size		Typical Irradiation Time
			Diameter (in)	Total length (mm)	
NTD 1	220	3.7×10^{13}	6, 8	600	About 4 hours to produce resistivity of 50 ohm-cm
NTD 2	180	3.7×10^{13}	5, 6	600	

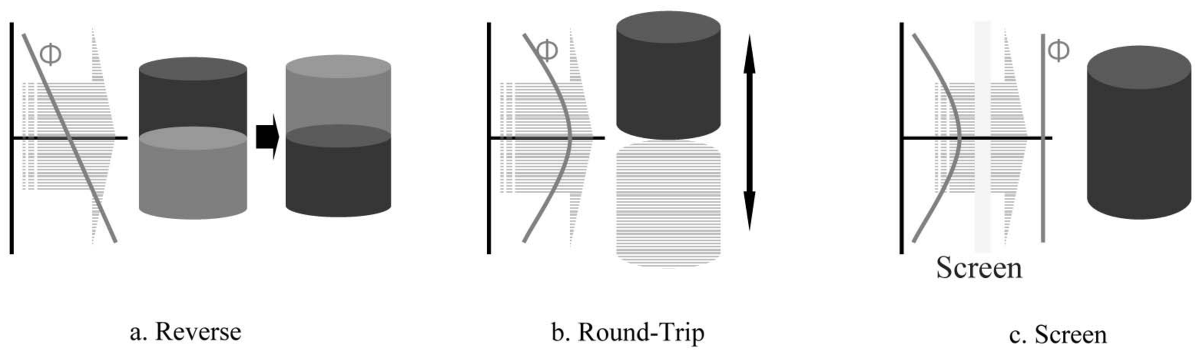

Fig. 2. Methods to Achieve an Axial Uniformity of the Resistivity

the NTD silicon is known to be superior to that produced by other methods. The Korea Atomic Energy Research Institute (KAERI) has been providing a commercial NTD service for a 5″ silicon ingot in NTD2 hole since the end of 2002, and developing the facility for a 6″ ingot irradiation in the NTD2 hole as well as a facility for 6″ and 8″ ingots in NTD1. This paper presents the design of the neutron irradiation device for the 6″ silicon ingot in the NTD2 hole from the viewpoint of nuclear design.

2. DESIGN OF THE NEUTRON SCREEN

2.1 Methods to Achieve an Axial Uniformity of the Resistivity

A Si ingot for NTD, which is usually grown by the floating zone method, is in the shape of a cylinder of whose length is normally 20 to 30 cm. Ingots of 4″, 5″ or 6″ in diameter are available in the market, and an 8″ ingot is under development. A NTD-Si should have highly uniform resistivity in both the radial and axial directions to meet the specification given by each customer. The relative difference between the maximum and minimum resistivity in the axial or radial distribution should be within a few % of each other. While a radial uniformity is usually achieved by rotating the ingot during an irradiation, three different methods are used to achieve an axial uniformity, as shown in Fig. 2.

The reverse method achieves uniformity by turning the Si ingot upside down at half the irradiation time at the symmetrical point of a neutron flux distribution. The round-trip method achieves the goal by moving the Si ingot up and down cyclically during an irradiation. Meanwhile, a neutron screen is used to make the axial flux distribution as flat as possible by adjusting the amount of neutron absorption in the screen along the axial positions. We adopted the neutron screen method for HANARO because not enough space is available above and under the reflector tank where the ingots travel for the round-trip method. The neutron screen is, in fact, the wall part of the ingot container, which is used to load and withdraw the ingot(s) from the NTD hole. The role of the screen is to make the axial neutron flux distribution in the Si ingot as flat as possible. Note that the resistivity is inverse-proportional to the total number of $Si^{30}(n,\gamma)\ Si^{31}$ reactions, which is almost proportional to the thermal neutron fluence. Thus, we are using either the thermal neutron flux or reaction rate distribution to represent the distribution of the resistivity.

2.2 Neutron Screen Design

In this design work, we used the MCNP4C code to simulate the details of the neutron screen. As the diameter

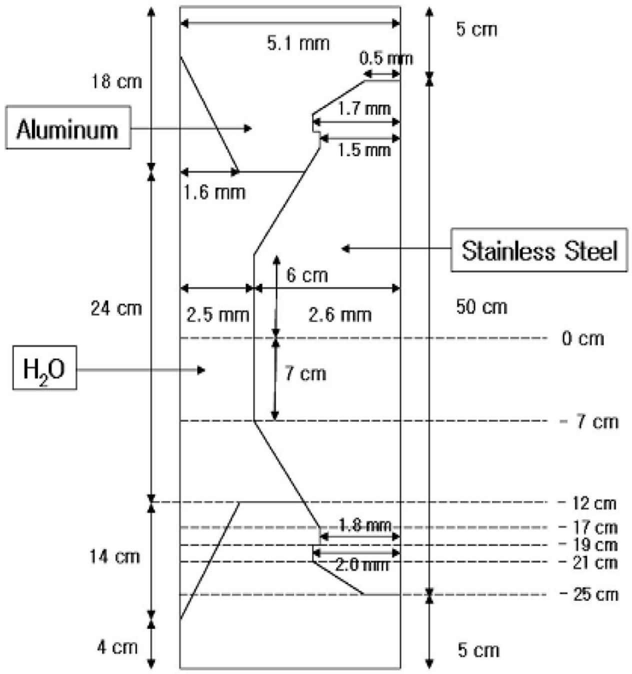

Fig. 3. Neutron Screen for the 6˝ Ingot Irradiation in NTD2

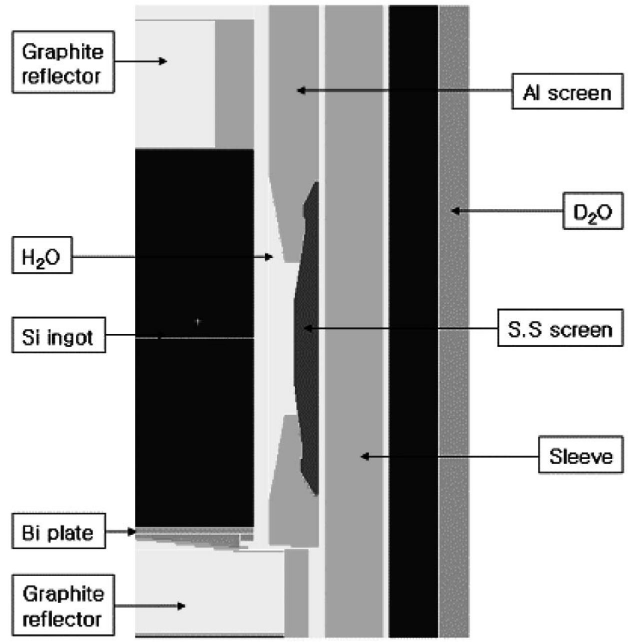

Fig. 4. MCNP Model of the Si Ingots and the Neutron Screen Inside the NTD2 Hole

of the Si ingot increases from 5˝ to 6˝, the gap available between the inner surface of the NTD2 hole (diameter of 18 cm) and the outer surface of the ingot is reduced significantly: only about 5 mm is available to set up the neutron screen in the gap. Thus, aluminum, which is the screen material for the current 5˝ ingot irradiation device, is no longer suitable due to its small neutron capture cross section.

From the preliminary analyses based on the thermal diffusion length of several kinds of structural materials, we chose stainless steel as the material for the screen. Then, we optimized the neutron screen design for a uniform irradiation in the NTD2. Fig. 3 shows the shape and dimensions of the neutron screen, and Fig. 4 shows its MCNP model containing two Si ingots stacked vertically inside the NTD2 hole.

In profiling the axial reaction rate distribution, a 60 cm long Si ingot was axially divided into 30 of 2 cm-thick disks. An MCNP run made use of a total of 30 million histories, with which the fractional standard deviation (fsd) of the thermal flux was less than 0.5%.

3. AXIAL UNIFORMITY

3.1 Calculation Results

Fig. 5 shows the plate-average, relative $Si^{30}(n,\gamma)$ Si^{31} reaction rate distribution in the Si ingot by using this neutron screen design under the control rod position of a 500 mm condition.

As shown in Fig. 5, we achieved an axial uniformity of about ±1% from the average, which is well within a usual customers' requirement, a 5% fluctuation.

Meanwhile, the neutron screen method has a problem in that the axial flux distribution varies with the core conditions, particularly with the critical control rod position. However, it could be overcome by controlling the insertion depth of the Si ingot. As a result of an investigation on the axial flux distribution by varying the control rod position, Fig. 6 shows the optimum insertion depth of the Si ingot depending on the control rod position. From the curve, we can decide the best axial location of the ingots at any core burn-up condition.

Fig. 7 shows the axial profiles of the $Si^{30}(n,\gamma)$ Si^{31} reaction rate corresponding to different control rod positions. It is expected that the fluctuation in the resistivity does not exceed 2.5% throughout the whole reactor operation cycle.

3.2 Measured Axial Uniformity

For implementing this neutron screen design, KAERI was requested to manufacture the irradiation facility for the NTD2 6˝ irradiation and to test it before a commercial service. Some zirconium foils, as the flux monitor, were attached at the surfaces of the Si ingots to obtain the distri-

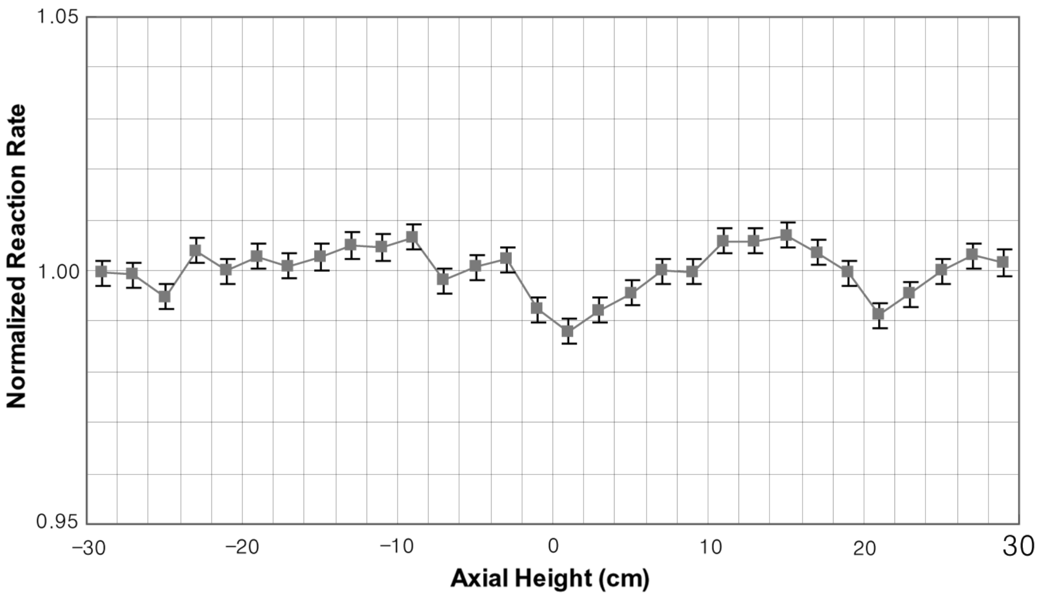

Fig. 5. Axial $Si^{30}(n,\gamma)Si^{31}$ Reaction Rate Distribution

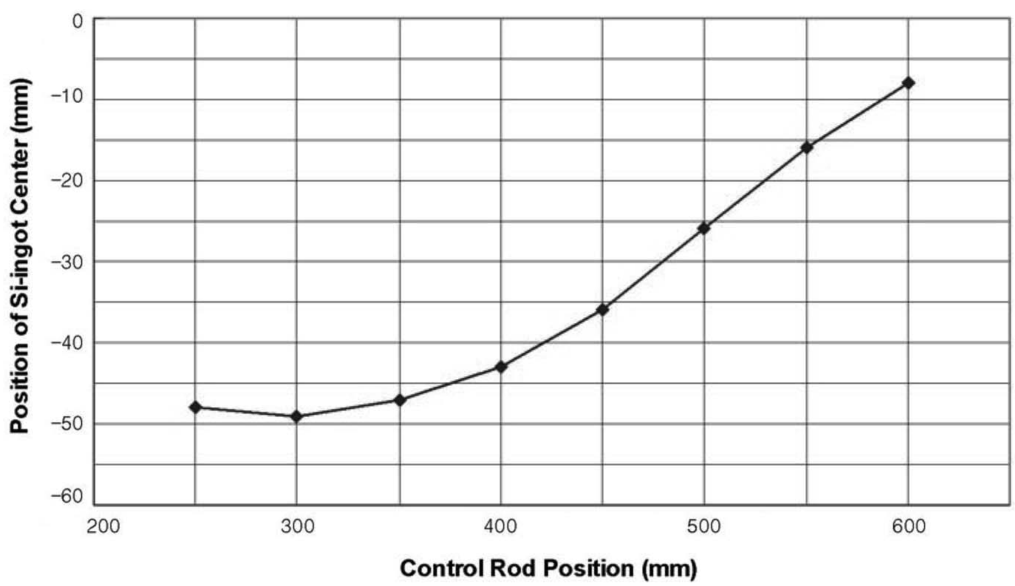

Fig. 6. Optimum Position of the Si Ingot Center by Varying the Control Rod Position

bution of the thermal neutron flux. For the flux mapping, we irradiated four 6˝ diameter Si ingots, 188, 95, 111 and 187 mm-long each, stacked in the container. The locations of the zirconium foils are on the top surface of the upper Si ingot, between every two Si ingots, and on the bottom surface of the lower the Si ingot. Fig. 8 gives the relative values of the measured thermal fluxes along with the calculated values. As shown in the figure, the measured and calculated values show a good agreement with each other within 2%.

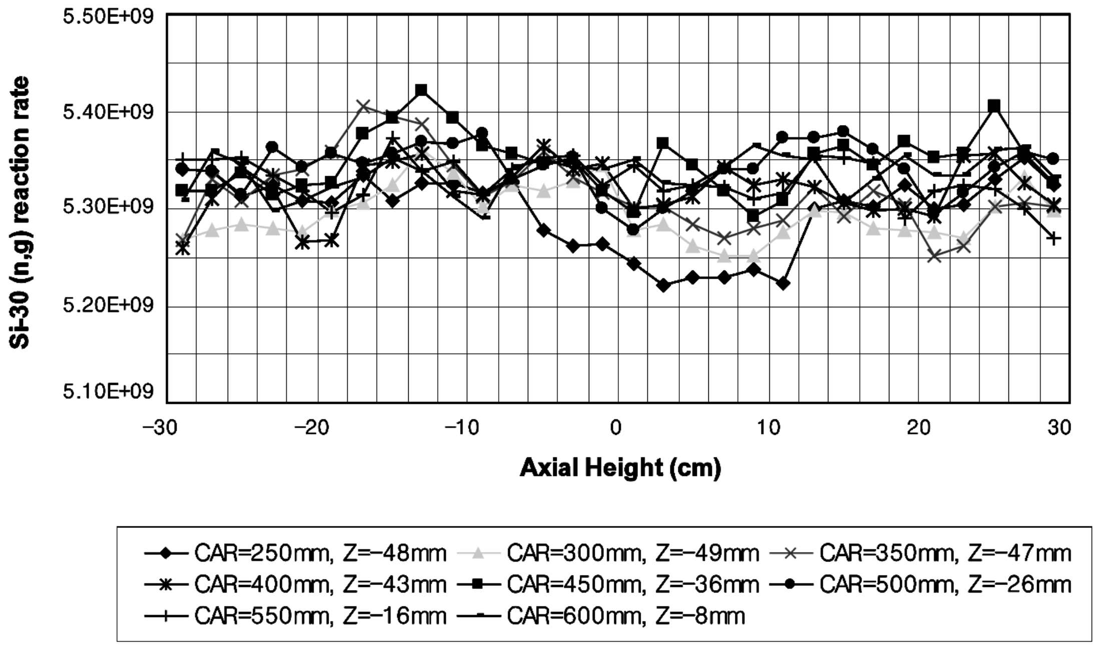

Fig. 7. Axial Distributions of the $Si^{30}(n,\gamma)Si^{31}$ Reaction Rate by Varying the Control Rod Position (CAR: control rod position, Z: center position of Si ingot)

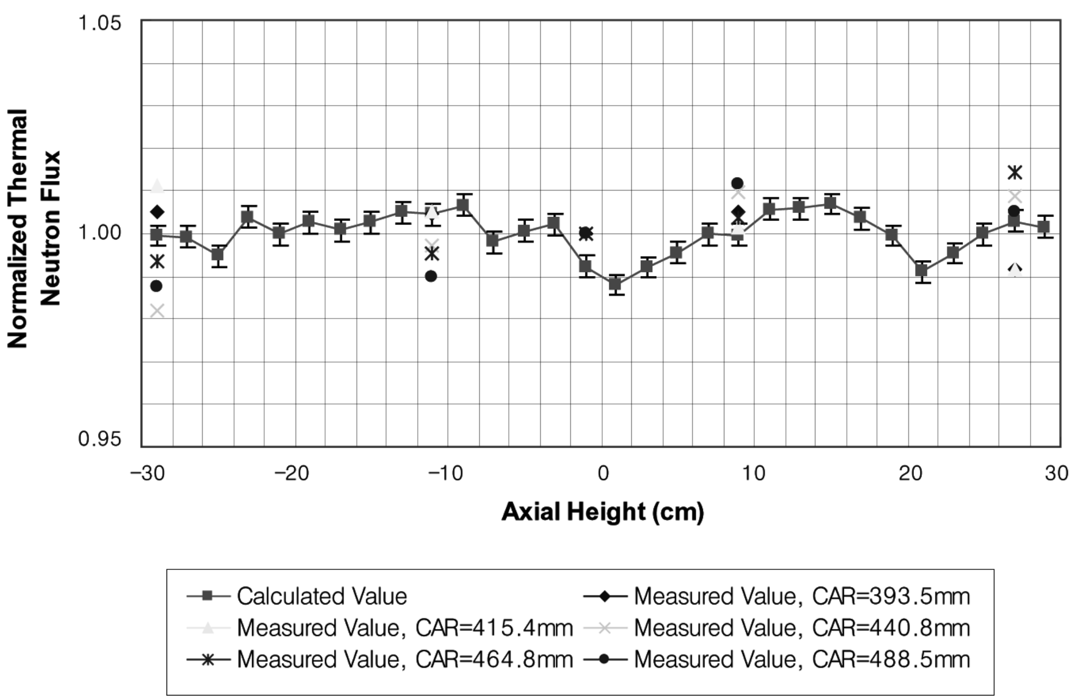

Fig. 8. Relative Values of the Measured and Calculated Thermal Fluxes

4. CONCLUSIONS

The rapidly increasing need for NTD silicon has made it necessary to design and construct new and better facilities. The objective of this work is to design a new neutron screen for a 6″ Si irradiation in the NTD2 hole of the HANARO. The design is nearly optimum for achieving a flat axial distribution of the resistivity in the irradiated Si ingot. The fluctuations in the axial distribution were estimated to be within ±2.0% from the average. In addition, the optimum insertion depth of the Si ingot was analyzed over various control rod positions. As a result, we obtained an axial uniformity of less than ±2.5% from the average during the whole reactor operation period. By using this design, we expect the commercial 6″ NTD service will be able to satisfy a customers' requirement for a uniform irradiation.

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