Neutron Transmutation Doping of Silicon Crystal in HANARO

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1. Introduction

Two vertical irradiation holes are provided in the heavy water reflector region of the HANARO for the neutron transmutation doping (NTD). The smaller hole (NTD-2) has been used for the commercial NTD service for 5 inch silicon crystals from the early 2003 and for 6 inch crystals from the end of 2005. Up to present time, 5 and 6 inch crystals are leading the NTD-Si market in the world and it is expected that 8 inch NDT-Si will share a large portion of the market in near future. Providing for the fast increase of the NTD-Si market as well as the advent of 8 inch NTD-Si demands, we completed the development and test irradiation of the irradiation equipments for 6 and 8 inch silicon crystals using the other larger hole (NTD-1) in 2008. Now HANARO can produce more than 50 tons of NTD-Si per year including 8 inch crystal.

This paper presents the prominent features and actual results of NTD-Si production accomplished in the HANARO.

2. NTD System in HANARO

At the design stage of the HANARO, there were no intense studies about the future use of two vertical holes for NTD. And HANARO had been operated long time before the first study for NTD was commenced in 2001. In this situation we confirmed that the most effective and productive way is to adopt a neutron screen for the axial uniformity of the silicon crystal and to integrate the neutron screen with the irradiation can for the precise optimization of the irradiation position [1-3].

2.1 Irradiation Can and Neutron Screen

The irradiation system for the NTD in HANARO has some special features that a neutron screen for the axial flatness of the neutron flux and an irradiation can (silicon container made of aluminum or aluminum/stainless steel) are integrated in a body [4-5]. The wall thickness of the can varies along its height and this gives an axially flat thermal neutron distribution to the crystal inside by changing the neutron absorption probability using the different water gap size between the can and the crystal. As the material of the irradiation can is only aluminum or aluminum adopting a small amount of stainless steel, it can minimize the thermal neutron flux depression by the screen material. As well, the screen integrated irradiation can makes it easy to optimize very precisely the axial irradiation position of the crystal when the neutron distribution inside the irradiation hole is changed during the reactor cycle.

In addition, to make the axial range having a flat neutron distribution as long as possible, two graphite blocks are used at the top and bottom of the crystal. The top graphite is placed above the crystal in the irradiation can. The bottom graphite is put on the floater, which is installed permanently in the irradiation hole.

The average thermal neutron flux inside the crystal is around 3.5×10^{13} n/cm^{2}sec for all cases over 60 cm of the crystal length.

Table 1. Characteristics of irradiation cans

Hole Name		NTD-2		NTD-1	
Inner Dia. (mm)		180		220	
Crystal size		5 inch	6 inch	6 inch	8 inch
Thickness (mm) (min/max)		5.0/17.9	2.2/5.1	19.5/29.4	2.5/4.0
Material		Al, Air	Al, STS	Al, Air	Al, STS
Thermal flux (10^{13}/cm^{2}s)	empty	5.2		5.2	
	with Si	3.8	3.5	3.6	3.4

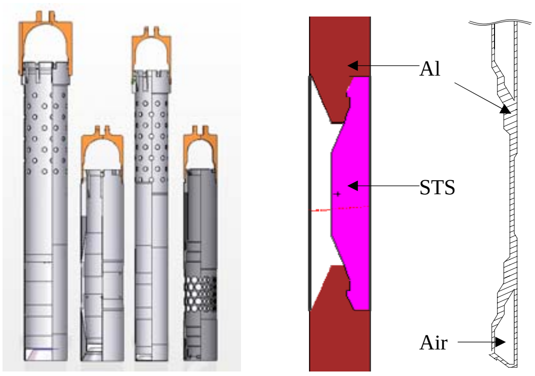

Fig. 1. Irradiation cans for 5, 6 and 8 inch crystals and enlarged neutron screens.

2.2 Floater

The insertion and withdrawal of the irradiation can during reactor operation changes the neutron flux at the nearby irradiation holes or neutron detectors. To minimize this effect, a floater, an empty aluminum can, was installed at the bottom of the irradiation hole. A bottom graphite block is placed on the top of the floater. When the irradiation can is being inserted, the bottom of the can is close to the top of the graphite block and all parts including can, floater and graphite rotate together during the irradiation.

The floater also has a number of helical grooves on the surface. They pump water up along the narrow gap between the irradiation can and the crystal to remove the heat released from the crystal and to prevent the boiling at the crystal surface [6].

2.3 Fluence Monitoring

The HANARO NTD system has two kinds of neutron fluence monitors. One is the zirconium foils to measure the absolute neutron fluence after irradiation. Normally two or three crystals form an irradiation batch and three Zr foils are fixed on the top, bottom and middle side of the batch. The measured results from the Zr foils are used as a measure of forecasting the final resistivity and its axial deviation of the crystal batch.

Beside the Zr foils, two rhodium SPNDs are installed at the upper part of the sleeve, which is a kind of guide tube for the irradiation can. The SPNDs measure the real time neutron fluence to make a decision when the irradiation is finished. The target fluence is calculated from the target resistivity and corrected by the relationship between the absolute fluence from Zr foils and the relative fluence from SPNDs.

3. Irradiation Capacity

The high purity silicon crystals grown by FZ-method or MCZ-method are normally used for NTD application and the required target resistivity is in the range of 20 ~ 1,000 Ohm-cm. In HANARO, the average neutron flux in the crystal is around 3.5×10^{13} n/cm^{2}sec and it takes from 0.1 hours to 10 hours to achieve the corresponding target resistivity. Considering the operating days of HANARO and market preferences in the target resistivity, the maximum capacity of the NTD-2 hole only is around 20 tons for 5 inch crystal and 30 tons for 6 inch crystal respectively. As a new irradiation hole is ready to start the commercial service for 6 and 8 inch crystals, it is expected that HANARO can produce more than 60 tons of NTD-Si per year from 2009 and occupy around 30 % of the market demands in the word.

4. Irradiation Results

The irradiation accuracy and axial and radial uniformity are the basic requirements for the NTD-Si. The accuracy is the deviation of the final resistivity from the target value and is within ±5% normally. The axial and radial uniformity are the deviations of the finally measured resistivity in axial and radial direction and their requirements are less than 5~8 % normally.

We have produced the world best quality NTD-Si since we started the commercial NTD service in 2001. The average hitting ratio to the targets is more than 99% and average accuracy is within ±2% for all the cases we have produced. The average axial deviation is also less than 4% except some special cases that the crystals suppliers recognize the results as their own problems.

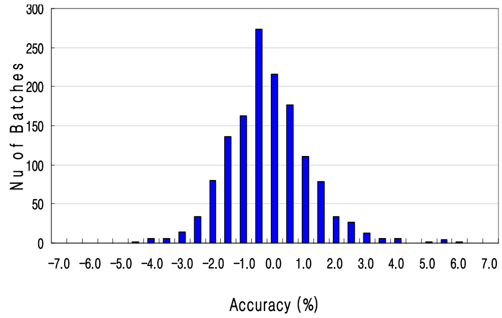

Fig 2. The irradiation accuracy (2007)

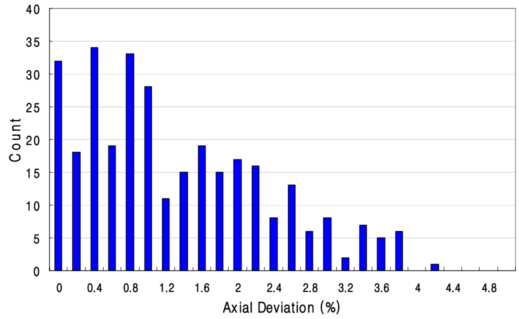

Fig. 3. The axial deviation (2007)

5. Conclusion

We have provided the world with the best quality 5 and 6 inch NTD-Si since 2003 and have completed the development of a remaining NTD hole in HANARO, which can irradiate the 8 inch crystal. Through the test irradiation at the new system, we confirmed that 8 inch NTD-Si can be produced with the same quality as the smaller ones.

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