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Design and burn-up analyses of new type holder for silicon neutron transmutation doping

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HIGHLIGHTS

- We developed and fabricated a new silicon irradiation holder with a neutron filter at the JRR-3.
- Design analyses of the irradiation holder were investigated by using the Monte Carlo code (MVP code).
- We investigated the influence of ^{10}B reduction in the filter on doping distribution under long-term use by the MVP code.

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ABSTRACT

We have developed a new silicon irradiation holder with a neutron filter to increase the irradiation efficiency. The neutron filter is made of an alloy of aluminum and B_4C particles. We fabricated a new holder based on the results of design analyses. This filter has limited use in applications requiring prolonged use due to a decrease in the amount of ^{10}B in B_4C particles. We investigated the influence of ^{10}B reduction on doping distribution in a silicon ingot by using the Monte Carlo Code MVP.

1. Introduction

Natural silicon comprises 3.1% of an isotope of ^{30}Si. ^{30}Si captures thermal neutrons and forms an unstable isotope ^{31}Si. ^{31}Si changes to phosphorus-31 by beta decay. These phosphorus atoms then act as n-type dopants. This method of doping by irradiating neutrons is known as neutron transmutation doping (NTD) method (Lark-Horovitz, 1951; Tanenbaum and Mills, 1961), and the resulting doped silicon is known as NTD silicon. NTD is prepared in research reactors because the process involved requires a high neutron flux and easy access to the irradiated area. The NTD method has higher uniformity than other doping methods. Therefore, NTD silicon is used mainly in high-voltage devices such as insulate gate bipolar transistors (IGBT). IGBTs constitute a type of power device and are used to control the voltage of various instruments. High-voltage IGBTs are used in public infrastructure modules such as electric substation equipment and trains, and the demand for them is increasing.

We performed NTD at the Japan research reactor number 3 (JRR-3) in the Japan Atomic Energy Agency (JAEA) complex. A silicon ingot measuring approximately 60 cm in height and 15 cm in diameter was used. The length of the fuel meat was 75 cm. The neutron flux distribution in the vertical direction followed the cosine curve along fuels. Therefore, nonuniform doping is not avoidable simply by inserting a silicon ingot in an irradiation hole. Overall, there are two methods to achieve uniform doping in the vertical direction. One is the so-called reverse method, and the other is the filter or screening method (IAEA, 2012). JRR-3 applies the reverse method. In this method, a silicon ingot is irradiated in the upper half of the

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vertical neutron flux distribution that has a cosine shape. After the first pass of irradiation, the silicon ingot is reversed and irradiated again. Uniform doping is accomplished by two passes of irradiation. Although this reverse method is simple in execution, the resulting irradiation efficiency is low because of the following two reasons.

Long cooling time is required between the first and second passes of irradiation, approximately two days in the case of JRR-3.

This method does not use the lower half of neutron distribution in the vertical direction.

Conversely, in the case of the filter method, silicon ingots are irradiated by neutrons generated by a thermal neutron filter and having a flat shape distribution. This method does not have the abovementioned limitations. The filter method has already been applied in a few research reactors, for example, FRM II (Li, et al., 2009) in Germany and HANARO (Kim, et al., 2006) in Korea. However, in these studies, a filter material was applied on the irradiation tubes. We have attempted to apply the filter material onto a silicon holder because application of the material onto the irradiation tubes would require considerable modifications to JRR-3. No research reactor has been used to apply the filter method to an irradiation holder. Various investigations are necessary for applying the filter method to a silicon holder because the filter material can be attached to a limited holder area and the irradiation tubes lack extra space. A study for applying the filter method to a silicon holder has already concluded that such application is possible in the case of the JRR-3 (Komeda, et al., 2013). The purpose of the current study is to perform design analyses and fabrication of the actual silicon holder with neutron filter. Here we call the silicon holder with neutron filter as a new type holder. We employ an aluminum alloy containing B_4C particles as the filter material. Clearly, the filtering ability decreases with a reduction in the amount of ^{10}B in B_4C particles after long periods of irradiation. To the best of our knowledge, no study investigating the decreased filtering ability of new type holders has been conducted. Another purpose of this study is to investigate the influence of reduction in the amount of ^{10}B after long-term irradiation using the Monte Carlo calculation code.

2. Design analyses and fabrication of new type holder

The JRR-3 diagram in the X–Z direction is shown in Fig. 1. There is an irradiation tube for silicon ingots in a heavy water tank, and the distance between the reactor core and the tube is approximately 30 cm. The silicon ingots are irradiated with thermal neutrons moderated by heavy water. Neutrons emitted from the core have a similar shape to cosine curve, actually the peak position of the curve is a little lower than the fuel center part because there are control rods on the upper area of the core. The neutron shape is reshaped by the neutron filter to a flat shape. We selected the parameters shown in Fig. 2 for design analyses under the condition that B_4C density was fixed to 0.27 wt% and the length of the holder was fixed to 74 cm. The middle part of the filter is flat, and its upper and lower parts are tapered. The lengths of the lower, middle, and upper parts are defined as fh1, fh2, and fh3, respectively. The filter parts are welded with aluminum parts, with the thickness of the upper welding part defined as ft1 and the thickness of the lower part as ft3. The thickness of the middle part of the filter is defined as ft2. The length of the lower aluminum part under the filter is defined as ah1. We searched for appropriate values of the aforementioned seven parameters by analyses using the MVP Monte Carlo code developed in JAEA (Nagaya et al., 2005). The results of parameter selection and a photo of the fabricated new type holder are shown in Fig. 3. The new type holder comprises aluminum parts and a filter part comprising aluminum alloy and B_4C particles. Electron beam welding is employed for joining aluminum parts and the filter part. After fabricating the new type holder, we examined the tensile strength of its welding point. It was found that the breaking load of the welding point between the aluminum part and the filter part was 5897 kg, considerably higher than the 30-kg breaking load of silicon ingots. The mechanical strength of the filter part does not decrease under irradiation by alpha rays for total

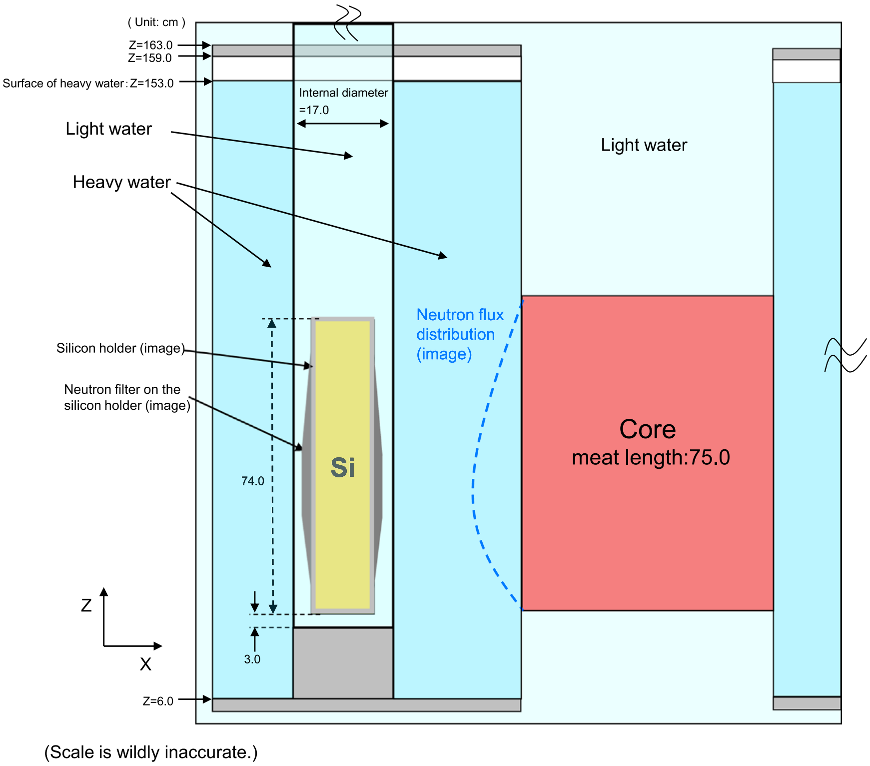

Fig. 1. The JRR-3 diagram in the X-Z direction.