Applied Radiation and Isotopes 70 (2012) 133–138

Contents lists available at SciVerse ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Effects of silicon cross section and neutron spectrum on the radial uniformity in neutron transmutation doping

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A R T I C L E   I N F O

Article history:
Received 9 February 2011
Received in revised form
8 July 2011
Accepted 5 August 2011
Available online 26 August 2011

Keywords:
Neutron transmutation doping (NTD)
Radial uniformity
Reaction rate distribution
Single crystal cross section
Neutron scattering
Neutron spectrum

A B S T R A C T

The effects of silicon cross section and neutron spectrum on the radial uniformity of a Si-ingot are examined experimentally with various neutron spectrum conditions. For the cross section effect, the numerical results using silicon single crystal cross section reveal good agreements with experiments within relative difference of 6%, whereas the discrepancy is approximately 20% in free-gas cross section. For the neutron spectrum effect, the radial uniformity in hard neutron spectrum is found to be more flattening than that in soft spectrum.

1. Introduction

Neutron transmutation doping silicon (NTD-Si) for n-type semiconductors is produced by the conversion of ^{30}Si isotope (abundance; 3.12%) into phosphorus atom by the neutron absorption reaction as follows:

$$^{30}\mathrm{Si}(n,\gamma)^{31}\mathrm{Si} \rightarrow {}^{31}\mathrm{P} + \beta\text{-}(T_{1/2} = 1.26\,\mathrm{h}).$$

whereas the resistivity of a semiconductor is inversely proportional to the ^{31}P atom concentration. Using this method, silicon semiconductors with uniform resistivity distribution can be produced (Larrabee, 1982). The uniform resistivity distribution was the main advantage of NTD in comparison to the conventional chemical doping methods. This uniform resistivity distribution is generally required for high power semiconductor device to prevent device break down (Schmidt and Vedde, 1998). Then, a prime target of NTD was to achieve the uniform neutron irradiation throughout an entire Si-ingot, since the resistivity distribution mainly depends on the neutron reaction distribution by irradiation.

The neutron irradiation for a large diameter Si-ingot of more than 8″ was requested to satisfy the increasing demand for NTD-Si. The larger the Si-ingot diameter, the worse the radial uniformity, which is the ratio of reaction rate between surface and center of Si-ingot, since neutron attenuation effect was increased. The neutron attenuation effect made the non-uniform resistivity distribution inside Si-ingot, and a limit of the feasible diameter of Si-ingot (larger than 8″) was caused by the non-uniform resistivity distribution (Kim et al., 2008). Accordingly, additional efforts were concentrated on the radial uniformity flattening by reducing the neutron attenuation effect inside Si-ingot. Concerning this, the normalized reaction rate gradient (NRG) and the surface normalized reaction rate gradient (SNRG) were newly proposed to improve the conventional radial uniformity evaluation, as the Si-ingot diameter is getting large (Kim et al., 2010a).

Meanwhile, numerical evaluation of radial uniformity in NTD-Si is largely affected by the accuracy of silicon cross section. A pure silicon-ingot for NTD was produced by the Floating Zone (FZ) or the Czochraski (CZ) methods with cylindrical shape (Janus and Malmros, 1976). In the process of Si-ingot growth, silicon elements had a form of single crystal, and neutron thermal-elastic scattering inside silicon crystal (a diamond-like lattice structure) showed different behavior in comparison to non-crystal described in a free-gas model. In neutron energy less than 0.5 eV (Fig. 1), total cross section of single crystal silicon is smaller than that of non-crystal silicon, which means free-gas, because of its small neutron scattering cross section (Freund, 1983). And the neutron attenuation by small neutron scattering reactions made the Si-ingot more transparent to neutrons. When the radial uniformities of Si ingots were estimated numerically in the actual irradiation

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doi:10.1016/j.apradiso.2011.08.006

condition, such as the reflector of HANARO (H.S. Kim et al., 2006), the radial uniformities of Si ingots using single crystal cross section were smaller than those of free-gas one (Kim et al., 2010b). The discrepancies between single crystal and free-gas cross sections were significantly emphasized according to the increasing diameter of Si ingots.

In this study, the main purpose is the verification of silicon cross section of single crystal model through the comparison between neutron irradiation experiments and numerical analysis of Si-ingot by changing neutron spectrum. Additionally, for the investigation of the effect of neutron spectrum on the radial uniformity, the radial neutron flux distributions inside Si-ingot by different neutron spectrum are evaluated using the NRG and SNRG.

2. Experimental settings

2.1. Vertical setting experiment

For the experimental verification of silicon cross section, experimental settings of neutron irradiation were prepared as shown in Fig. 2. Total 200 pieces of Si-wafers with 6″ diameter and 0.625 mm thickness were formed in a shape of cylindrical Si-ingot with 125 mm axial height by piling up. The Si-wafers were fully surrounded by polyethylene (PE) or graphite (GR) blocks for the moderation of fast neutrons generated by ^{252}Cf neutron source. The verification of silicon cross section was conducted by measuring neutron flux distribution inside Si-ingot instead of direct measurement of silicon reaction rate due to its low absorption cross section. For measuring neutron flux distribution inside Si-ingot, five pieces of Au-foils with 10 mm diameter and 0.05 mm thickness were sandwiched between the Si-wafers (M.S. Kim et al., 2006). In these experiments, the piled-up Si-wafers were irradiated vertically: the top surface of a Si-wafer was faced to the neutron source to attain two-dimensional (r–z) neutron irradiation, and the position of

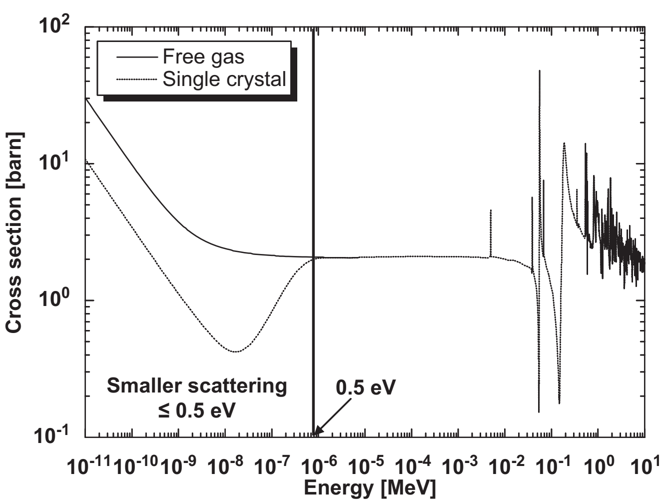

Fig. 1. Comparison between neutron total cross sections of single crystal and non-crystal silicon.

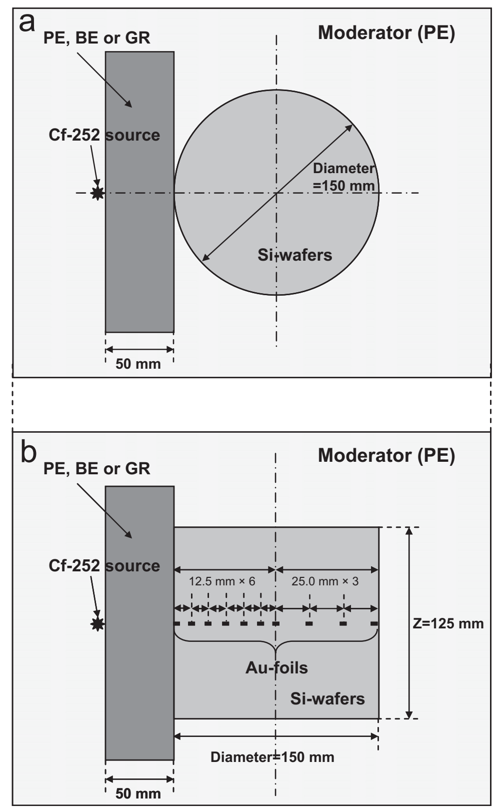

Fig. 3. Horizontal setting of neutron irradiation system: (a) top view and (b) side view.

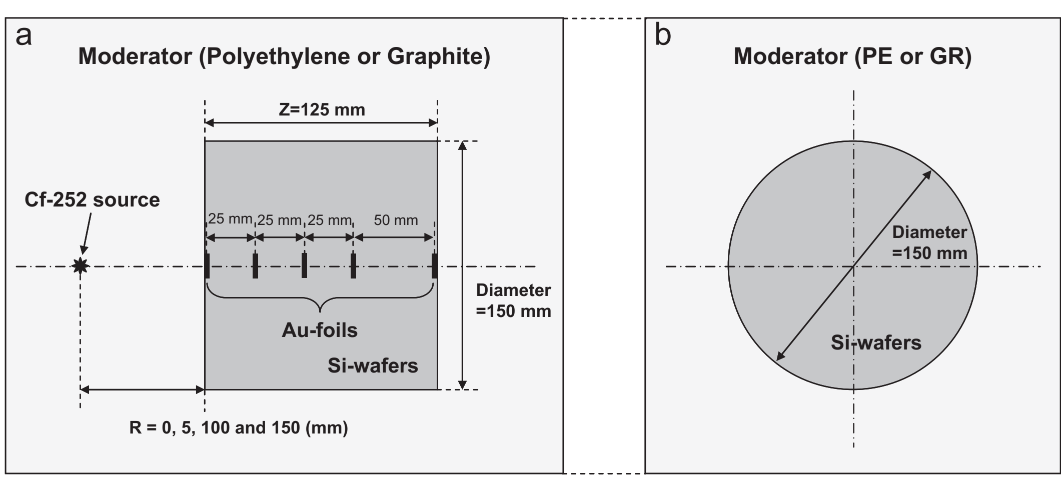

Fig. 2. Vertical setting of neutron irradiation system: (a) side view and (b) front view.