Specification of Irradiation Conditions in the DONA 5 Rotational Channel of the LVR-15 Reactor

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Abstract—This article summarizes ways to verify neutron fluence for neutron transmutation doping of silicon with phosphorus on the LVR-15 reactor. Neutron fluence is determined using activation detectors placed along the crystal in a strip or encapsulated in a rod holder. Holders are placed at the centre of a water-filled capsule or in an aluminum or silicon ingot that simulates a real single crystal. If the diameter of the crystal is significantly less than the capsule diameter and water from the primary circuit enters the free space in the capsule, neutron interaction in the water changes neutron fluence, affecting axial irradiation homogeneity. The effect of moving the capsule vertically in the channel relative to maximum neutron fluence in the reactor core was also measured. Even a small shift of the capsule's centre causes great irradiation inhomogeneity. This effect was measured using activation detectors, and was also confirmed by MCNP calculation.

Keywords—Irradiation homogeneity, neutron fluence, neutron transmutation doping, rotational channel.

I. INTRODUCTION

THE DONA 5 rotational channel on the LVR-15 research reactor is used for irradiation of silicon single crystals for purposes of transmutation doping of silicon with phosphorus (NTD-Neutron Transmutation Doping). When pure silicon is irradiated with a beam of thermal and epithermal neutrons, the required ^{31}P phosphorus dopant is created from [31]Si silicon via an (n,γ) reaction (and subsequent β decay). The ^{31}P nuclide is stable. The result of the process is the n type impurity doping in silicon materials and the amount of dopant added to a silicon determines the level of conductivity.

The NTD method has been widely used in industries, especially for high quality semiconductor power devices. Nowadays, NTD faces another new situation. The demand for high power semiconductors is growing constantly given the rapid increase of green energy technologies such as solar cells as well as electric vehicles.

In semiconductor manufacture, great emphasis is placed on the quality of the doped silicon, especially the average concentration of phosphorus and its homogeneity throughout the entire volume of the crystal. The article [1] provides an overall summary of NTD, crystal lattice defects, and single crystal irradiation methods. The decisive quality parameter is the specific resistance of the crystal after irradiation and annealing. The incremental value of conductivity (the inverse of resistivity) is proportional to the total concentration of the produced dopants, which is created during irradiation and is thus proportional to the irradiated thermal neutron fluence, which is a product of the neutron rate, time of irradiation and the reaction cross-section [2]. As the neutron cross-section varies by neutron energy, it is influenced from the neutron spectrum. We determine neutron spectrum in the LVR-15 reactor during silicon irradiation using the method of activation detectors.

Exposure to fast neutrons and gamma rays is not suitable for the NTD method. Fast neutrons are a major source of the permanent displacement of silicon atoms from their normal lattice positions, and gamma rays are a major source of heat generation in crystals. The low fast neutron fluence is needed to avoid the permanent lattice defect in a silicon crystal caused by fast neutrons [3].

Phosphorus distribution in the single crystal must be homogenous both in the radial and axial direction. The effects of the radial non-homogeneity of the neutron fluence are compensated by rotating the crystal during irradiation. Although silicon is rather transparent to neutrons, some attenuation of the neutron inside the crystal will occur. The neutron fluence at the centre of the crystal becomes lower than at the surface.

Axial resistivity variation (ARV) is defined according to recognized methodology [4] based on measuring specific resistance as follows:

$$ARV = \frac{\rho_{\max} - \rho_{\min}}{\rho_{\min}} \times 100 \tag{1}$$

where $\rho_{\min}$ and $\rho_{\max}$ are minimum and maximum measured specific resistance.

It is recommended to design the irradiation channel to minimize the axial variation of the neutron fluence as much as possible. Aside from resistivity measurement and other methods [5], axial irradiation homogeneity can also be

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measured using activation detectors located along the crystal. Detectors are either in a strip or rod holder, and depending on the situation a continuous wire can also be used. The wire is then cut up into smaller segments, thus measuring neutron fluence in smaller increments along the crystal. Results show that the most important thing is to find the proper channel position relative to maximum neutron fluence in the vertical direction. Fig. 1 shows the reactor core cartogram with the DONA 5 rotational channel in position C, D 9, 10.
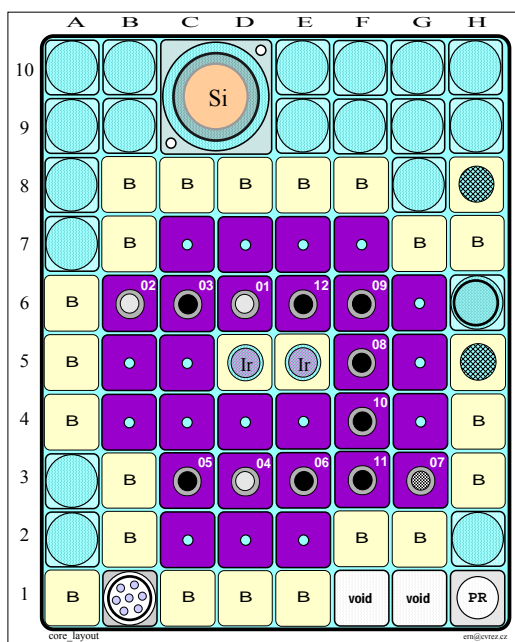
Fig. 1 The reactor core cartogram with the DONA 5 rotational channel in position C, D 9, 10

The evaluation of neutron fluence is based on a method using activation detectors. The detectors are cut from certified material provided by CEC JRC Institute for Reference Materials and Measurements, Geel, Belgium. The mass of detectors and concentration of isotopes is known, detectors activity is measured after irradiation with gamma spectrometric assembly (Canberra) with the HPGe detector. The calibration of the detector and the method of the measurement are in accordance with ASTM standard [6].

II. ASSESSING NEUTRON FLUENCE USING A DOSIMETRIC STRIP

Silicon single crystals are irradiated in a special correction filter designed to ensure thermal neutron fluence along the crystal is as homogenous as possible. The filter design (variable filter wall thickness) was based on MCNP calculations [7]. Shielding design was contingent on the maximum difference between fluence values along the entire capsule being less than 3% for crystals 3" in diameter. To check neutron fluence, strips with activation detectors are irradiated along with selected single crystals. Strips can be used for crystals with a diameter of less than 3", because

otherwise the strip will not fit in the capsule along with the crystal. A strip with seven sets of activation detectors (Fe, Ni, Co) is placed along the single crystal. Fig. 2 plots the relative reaction rate (RR) for the following reactions: $^{59}Co(n,\gamma)^{60}Co$, $^{58}Fe(n,\gamma)^{59}Fe$, $^{58}Ni(n,p)^{58}Co$. The shape of the curve for RR for thermal neutrons (n,γ) reaction is flatter than for fast neutrons, corresponding to an (n,p) reaction. The crystal length was 28 cm.
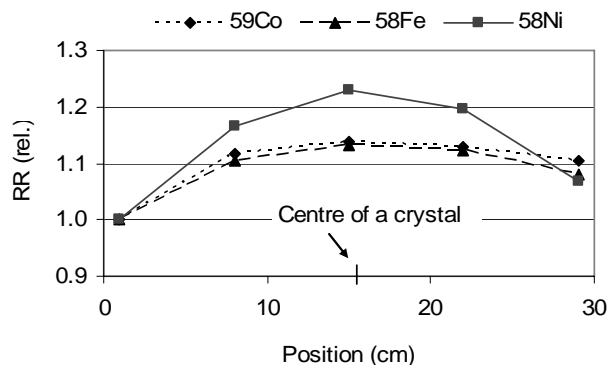

Fig. 2 Relative reaction rate for a strip along a Si single crystal

III. ASSESSMENT NEUTRON FLUENCE USING A ROD HOLDERS

Rod holders placed in an empty capsule were used to verify irradiation conditions. Rod holders with an 8 mm diameter were populated with sets of activation detectors (Fe, Ni, Zn, Zr) 5 cm apart over a distance of 30 cm, i.e. seven positions. During irradiation, the drilled-out capsule was filled with primary circuit water. The holder could be removed from the capsule only after four days, when the activity of the entire assembly had decreased sufficiently. To verify irradiation conditions, it was sufficient to assess only reaction rate; results showed that the water in the capsule had large moderation and absorption effects, and the RR for thermal neutron reactions were much distorted compared to measurements using a strip on the crystal, where the crystal displaces water in the capsule. Fig. 3 plots relative RR $(^{58}Fe(n,\gamma)^{59}Fe$, $^{58}Ni(n,p)^{58}Co$, $^{64}Zn(n,\gamma)^{65}Zn$, $^{94}Zr(n,\gamma)^{95}Zr)$ for measurements with a rod holder in a capsule that is filled with water during irradiation. The RR along the axis is similar for both thermal and fast neutrons. While the configuration as proposed does not correspond to actual irradiation, the RR profile along the vertical axis can be used to find the proper position for the centre of the capsule (crystal).

Measurements using holders showed that water in the capsule has a great effect on neutron moderation and absorption. For 3" crystals, a shielded capsule was designed, while for narrower crystals irradiation homogeneity is reduced due to the effect of water, and a displacement will need to be designed to ensure that ARV is as low as possible for all crystal diameters.
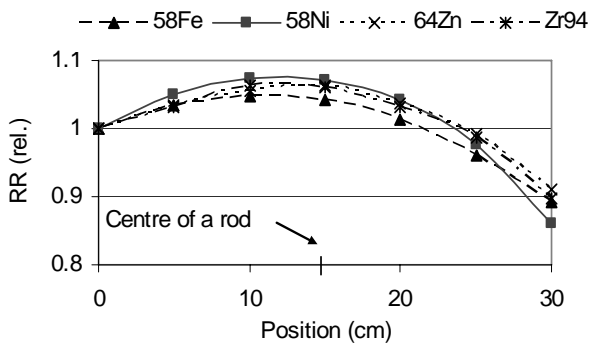
Fig. 3 Relative reaction rate for a rod holder placed in the centre of capsule

Fig. 5 The aluminum phantom and the rod holder with activation detectors

IV. Neutron Fluence Assessment Using an Aluminum Phantom

After experiences with rod holders that are affected by water as a moderator and absorber, irradiation with an aluminum ingot was proposed, which would simulate the silicon crystal and displace the water from the capsule. Aluminum has similar properties to silicon in the radiation field. A longitudinal slot was routed into the aluminum ingot, into which a rod holder with activation detectors (Fe, Ni, Zn) can be inserted. The entire phantom was designed so that the holder could be removed in hot cells immediately after irradiation, ensuring that irradiation results are available as soon as possible. Fig. 4 contains a sample of measured relative RR ($^{58}Fe(n,\gamma)^{59}Fe$, $^{58}Ni(n,p)^{58}Co$, $^{64}Zn(n,\gamma)^{65}Zn$, $^{68}Zn(n,\gamma)^{69m}Zn$) from the rod holder for the aluminum phantom. From the graph it is evident that for (n,γ) reactions, RR are uniform, and that the position of the centre of shielding is very close to the neutron fluence maximum along the vertical axis. The photo of the aluminum phantom with the rod holder is shown in Fig. 5.
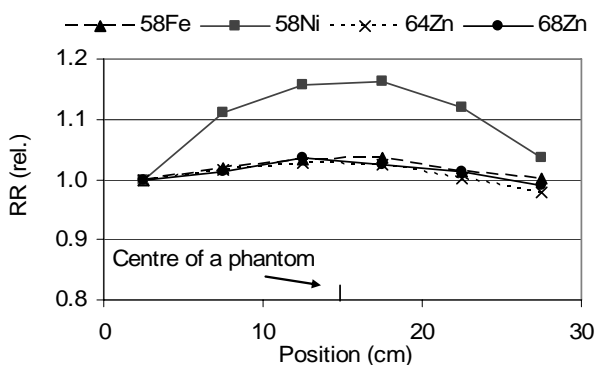
V. Assessment of Neutron Fluence Using a Silicon Phantom

In the future, the aluminum phantom will be replaced by a silicon phantom so that we can determine neutron fluence under actual irradiation conditions. During the first phase, when we are trying to find the correct silicon irradiation parameters, we are counting on using the phantom often, and that we will be checking crystal position, neutron fluence, axial homogeneity, etc. Once we are sure that irradiation is taking place under stable conditions, we will use the phantom less often, and only to confirm that irradiation conditions have not changed.

VI. The Effect of Position on Homogeneity

Table I and Fig. 6 show the effect of correct vertical positioning of the silicon crystal. Calculations were performed for the crystal in its optimum position (0 cm) corresponding to the vertical centre of the reactor core, and for positions shifted by 1 cm and 2 cm in both directions. The calculation corresponds to observations – crystal homogeneity exhibits a high degree of sensitivity to correct positioning.

TABLE I
AXIAL CRYSTAL HOMOGENEITY DEPENDENT ON VERTICAL POSITION

Shift (cm)	ARV (%)
-2	10.3
-1	5.2
0	3.1
+1	4.2
+2	9.4

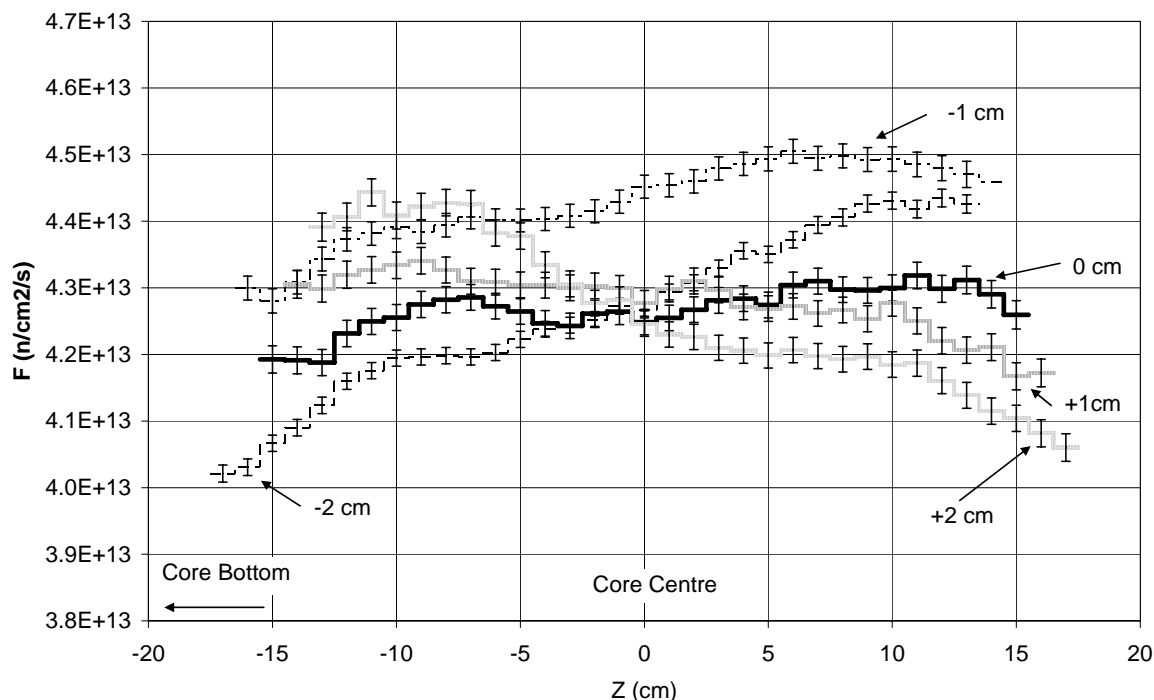Fig. 4 Relative reaction rates for a holder placed in the centre of an ingot

Fig. 6 The effect of DONA 5 channel position on the homogeneity of the irradiated Si crystal

VII. CONCLUSION

The advantage of NDT compared to other doping method is the high uniformity of the final resistance after irradiation a whole single crystal, which entitles NTD to the claim of the best quality Si for high power semiconductors. The neutron rate in every reactor is not uniform. The quality of doping depends on the ingot size and irradiation conditions.

Irradiation homogeneity is very sensitive to the position of the capsule in the DONA 5 channel. A small shift (one or several centimetres) of the channel centre relative to the thermal neutron fluence maximum in the reactor core is enough to increase ARV greatly and thus also to reduce the homogeneity of phosphorus distribution in the crystal.

Neutron fluence measurements showed that with a filter designed for 3" crystals irradiation homogeneity is reduced for narrower crystals due to the effects of water as a moderator. Because phosphorus distribution in the crystal is an important parameter for NTD, a displacement must be designed, so that optimum homogeneity is achieved.

ACKNOWLEDGMENT

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