Calculated and experimental studies at critical facility in view of development of a technology for neutron transmutation doping of a large size silicon specimen in WWR-K reactor

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Abstract. The Institute of Nuclear Physics using WWR-K research reactor were carried out studies to develop the technology of neutron-transmutation doping of silicon ingot with a diameter of 150 mm and a height of 200 mm. As a result, was obtained silicon ingot with an uneven electrical resistivity at the level of ~6%. In 2017, together with the Chiyoda Technol Corporation, (Japan) were started the activities to develop a technology of neutron-transmutation doping of large sized silicon with a diameter of more than 150 mm and a height of up to 500 mm for the WWR-K reactor. The main goal is to achieve an irregularity electrical resistivity in terms of the volume of the silicon ingot at the level of 3-4 %. At the first stage, were performed the works on the formation of the thermal neutron field in irradiation device. The object of investigation is a silicon ingot with a diameter of 150 mm and a height of 500 mm. For reduction of the height irregularity are used neutron absorbers arranged along the height of the ingot. The development of irradiation device with a neutron absorber and the corresponding neutron measurements were performed at the critical facility. The silicon ingot is modeled by a block of the aluminium. At the second stage it is planned to perform the works on the WWR-K reactor to test the developed technology with the further irradiation of a silicon ingot.

1. Introduction

Neutron transmutation doping (NTD) of semiconductors, such as silicon, is one of the actual and perspective radiation technologies, which gives a chance to receive a silicon ingot with the doping uniformity at the level 4-5% against 15-20 % provided by metallurgical technologies The advantages of semiconductor neutron doping are, first of all, that a doping agent is distributed uniformly over a volume of the ingot and, secondly, that the doping level, being proportional to the accumulated neutron fluency, can be controlled rather accurately. Silicon monocystals, which are used in neutron transmutation doping, should be produced with a high extent of purity, being dependent of a way of crystal growth. 90% of silicon in the world is produced by the Czochralski method. Silicon ingots of a 6-inch diameter are in demand throughout the world, however, due to the growing popularity of “Green energy” technologies, the demand is shifted towards large diameter ingots [1]. Demand for doped silicon ingots with a diameter of 8 inches and higher increases. The requirements to the quality of semiconductor materials obtained by neutron transmutation are tightened. As a result, neutron sources with the well-studied neutron and physical characteristics are required.
Research reactor facilities are powerful sources of neutrons, thus being used for NTD silicon doping. However, the reactor neutron flux is non-uniform. Uniformity of the distribution of the doping agent depends on a size of the irradiated ingot and the irradiation technology. Adequacy of the doping target resistance to the customer’s demand in the market of the semiconductor industry is the main qualitative criterion of the doping process in the reactor.

The uniformity of doping is determined by the radial and axial changes in the final resistance after irradiation.

The Institute of Nuclear Physics (INP) under the Kazakhstan Ministry of Energy operates the WWR-K tank type water-water 6 MW thermal research reactor [2], where an opportunity is available to solve tasks of neutron transmutation doping in the of large diameter channels, namely: in vertical channels of a diameter of 200 mm, located in the core water reflector, in the tangent horizontal channel of a diameter of 192 mm and in the heat column recess of a diameter of 1000 mm.

In a period from 2011 to 2015, two 150 mm silicon ingots were irradiated in the reactor 200-mm diameter vertical irradiation channel in framework of cooperation between INP and JAEA (Japan) [3]. As a result, silicon ingots were obtained with a doping inhomogeneity 5.6 % and 12 % [4].

In 2017, the joint study (in cooperation with the Japan Chiyoda Technol Corporation) on the development of a technology of the large size silicon ingot neutron transmutation doping in the WWR-K reactor was started. The main purpose of the study is to obtain the non-uniformity of the specific electrical resistivity over the silicon ingot height not larger than 2-4%. The first stage of the study is a development of a special irradiation device of a diameter of 152 mm and a height of 500 mm. The article presents results of relevant calculations and experiments.

2. Experimental study

Experimental study of a device for irradiation of a silicon ingot with a diameter of 150 mm and a height of 500 mm was carried out at the INP critical facility. The critical test facility the low power reactor on thermal neutrons with a light water moderator and a reflector, made of water or beryllium, was put into operation in 1972. The facility makes it possible to reproduce the water-water reactor cores of various configurations [5].

Since a silicon ingot of a diameter of 150 mm is expected to be irradiated in the WWR-K reactor vertical channel, similar irradiation condition are to be modeled in the critical facility, namely: a distance of a channel from the core center, positions of the control rods and configuration of the core. The WWR-K reactor core with burnt fuel is surrounded by a beryllium reflector [6]. However, it is impossible to reproduce it at the critical facility, because fuel burn up and core poisoning effects are absent due to low power of the facility; so only a segment of the beryllium reflector is reproduces (see figure 1).

In view of testing the influence of the control rods on the axial distribution of the neutron flux density in the experimental channel, the reactor core was at first converted to a critical state by shifting the fuel assemble (FA) from the cell 11-8 to the cell 11-11; then the neutron field was studied. In the configuration under study, control rods, practically, don’t affect the neutron axial distribution because almost all control rods are withdrawn from the core. The map of the core, composed of 24 FAs and 10 beryllium blocks, is shown in figure 1.

Later the shift of the FA from the core peripheral cell (11-11) to the central one (11-8) will lead to an increase in the excess reactivity and, respectively, to insertion of all the reactivity compensation rods to a certain depth. A new position of the reactivity compensation rods will be adequate to that of the reactor rods at the time of irradiation of the silicon ingot. Therefore, all further studies were conducted for this configuration of the core.

The experiments carried out the core configuration under study make it possible to study the axial distribution of the neutron flux taking into account the influence of the control rods.

The silicon ingot was imitated by an aluminum block of the outer diameter of 152.4 mm and the height of 500 mm. The unit, having 5 through holes for placing neutron radiation detectors inside, was placed in a basket holder, which is an aluminum pipe with a welded bottom. The basket holder was
placed in an aluminum experimental channel of the outer diameter of 200 mm. The channel was filled with water.

![Core map of the operating load of the active core (24 FA+10 Be).](image)

Peripheral holes in the aluminum block have a diameter of 12 mm, whereas the diameter of the central hole is 16 mm. It is possible to install activation detectors in all holes. The central hole can be used for allocation of neutron counter. The aluminum block in the basket was moved to the irradiation position of the experimental channel so that the center of the block coincides with the center of the core.

To reduce the coefficient of axial unevenness of the distribution of the thermal neutron flux density, a neutron absorber from cadmium was used. Cadmium has a large thermal neutron absorption cross section (2400 barn) and low melting point (321°C); its mass density is 8.65 g/cm³. Due to these properties, Cadmium is used as a good thermal neutron absorber. Cadmium rings with a thickness of 0.5 mm and a height of 3-5 mm were installed on the basket. The device exterior with cadmium rings is shown in figure 2.

![Irradiation device with cadmium rings.](image)

The spatial distribution of thermal neutrons in the aluminum block was investigated using a corona neutron counter and activation detectors. In the small sized corona neutron counter with a boron radiator
the following reaction takes place: \( ^{10}\text{B}(n,\alpha)^{7}\text{Li} \). Dysprosium detectors were used as activation ones, where the following nuclear reaction is used: \( ^{164}\text{Dy}(n,\gamma)^{165}\text{Dy} \). The activity of irradiated activation foils was determined using a beta meter. The measurement uncertainty of the neutron counter did not exceed 2%. The measurement inaccuracy of measurements with activation detectors did not exceed 6%.

3. Calculation studies
The calculation support of the experiments was carried by means of the computational code MCU-REA [7], which is used for calculation of neutron physical characteristics of nuclear reactors of various types. The neutron transport equation is solved by the Monte Carlo method on the basis of the estimated nuclear data for systems with random three-dimensional geometry. The constant support for the code is a bank of nuclear and physical data DLC/MCUDAT [8]. The fuel assembly is described as a homogeneous aggregate of Uranium, Aluminium and water. Neutron-physical calculations were performed in the registration zone of a height of 50 mm and a radius of 25 mm. High statistics was provided by 180 million of neutron histories. Statistical inaccuracy of calculations did not exceed 3%.

4. Results
For the reactor core shown in figure 1, the axial distribution of the thermal neutron flux density in the experimental channel is studied in the case when the control rods are withdrawn from the core. The distribution of the thermal neutron flux density is performed by the corona neutron counter. The theoretical curve is also \( \cos \pi z/H \). The theoretical function of the axial distribution of the neutron flux density for a cylindrical reactor with the effective height of the core \( H \) and the effective radius \( R \) in the direction of the radius \( r \) and the axis \( z \) with the origin in the center of the reactor core is determined by the following formula 1:

\[
F(r, z) = F_0 J_0 \left( \frac{2.405r}{R} \right) \cos \left( \frac{\pi z}{H} \right),
\]

where \( F_0 \) – is the peak density of the neutron flux in the center of the reactor core [9].

The non-uniformity of the neutron field distribution is determined by the irregularity factor, formula 2:

\[
K = \frac{F_{\text{max}}}{\overline{F}},
\]

where \( F_{\text{max}} \) – is the peak neutron flux, \( \overline{F} \) – is the neutron flux average.

The irregularity factor for the theoretical curve (1) was found to be equal to \( K_h \sim 1.11 \) whereas for the experimentally (2) obtained data it \( K_h \) was equal to 1.12 (see figure 3).

![Figure 3. Axial distribution of neutron flux density in the experimental channel in the critical core.](image-url)
Further experiments on formation of a uniform distribution of the thermal neutron axial flux (\(K_h = 1.02 - 1.04\)) were carried out for the configuration of the core shown in figure 1. Figure 4 shows the results of studies of the thermal neutron field in the aluminum block without cadmium rings, revealing good agreement between calculation (1), experiment (2) and (3).

![Axial distribution of neutron flux density in the aluminum block without cadmium rings.](image1)

**Figure 4.** Axial distribution of neutron flux density in the aluminum block without cadmium rings.

The irregularity factor of the axial distribution of thermal neutrons in the aluminum block:
- 14% for measurements with a neutron counter (see figure 4, curve 2),
- 18% for measurements with activation detectors (see figure 4, curve 3),
- 16% the calculated value (see figure 4, curve 1).

The installation of cadmium rings allowed us to align significantly the axial distribution of the thermal neutron flux density in the aluminum block.

![Axial distribution of neutron flux density in the aluminum block with cadmium rings.](image2)

**Figure 5.** Axial distribution of neutron flux density in the aluminum block with cadmium rings.

The experimental value of the axial irregularity factor 3%.

The optimum positions of cadmium rings have being chosen.

**5. Conclusion**

The developed device provides the irregularity factor of the axial distribution of the thermal neutron flux density for silicon ingots with a diameter of 150 mm and a height of 500 mm at the level of not greater than 3%.
The expected next stage of the work is the trial of the device in the WWR-K reactor, prior to irradiation of silicon ingots.

The results of the studies show that the WWR-K reactor can provide irradiation of silicon with the doping homogeneity at the level not greater than 2-4%.

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