A feasibility study on irradiation facilities of TRR for Neutron Transmutation Doping (NTD)

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Abstract

Different irradiation facilities of research reactors can be used for Neutron Transformation Doping (NTD) application. For this purpose, irradiation facilities of Tehran Research Reactor (TRR) were simulated and evaluated by MCNP-4C code and a special irradiation rig inside the reactor core was designed. The most important criteria evaluating is neutron flux profile and doping homogeneity. The use of irradiation facilities for NTD will require special changes and design. The evaluation results show that the thermal column, through tube and the designed irradiation rig can meet the IAEA criteria for NTD.

Keywords: TRR, Neutron Transformation Doping (NTD), MCNP-4C code.

Introduction

Nuclear Transmutation Doping (NTD) means the change of a nucleus to another or multiple other nuclides through a nuclear reaction such as interaction with neutrons, photons or high energy charged particles. NTD is defined as the process by which neutron irradiation creates the impurity in an intrinsic or extrinsic semiconductor to increase its value for various uses.[1]

The most prominent target or candidate materials for NTD are Si, Ge, GaAs, GaN, GaP, InP, InSe and HgCdTe. Silicon is a widely used semiconductor in industry and devices production. The natural silicon consists various stable isotopes such as ^{28}Si, ^{29}Si and ^{30}Si with abundance 92.2%, 4.7% and 3.1% respectively. NTD of silicon for n-type semiconductor is produced by the conversion silicon into a phosphorus atom using neutron absorption reaction as follows[2]:

$$^{28}\mathrm{Si}(n,\gamma)^{29}\mathrm{Si}\rightarrow{}^{29}\mathrm{Si}(n,\gamma)^{30}\mathrm{Si}\rightarrow{}^{30}\mathrm{Si}(n,\gamma)^{31}\mathrm{Si}\rightarrow{}^{31}\mathrm{P}+\beta^{-}(T_{1/2}=2.62\mathrm{h})$$

This reaction is obtained by irradiating the single-crystal silicon with neutrons from the reactor core. However, a silicon ingot is not easily irradiated uniformly, because the distribution of neutron flux has a comparatively large gradient in silicon ingot at rest.[3]

Generally, two aspects should be considered in NTD

- Uniformity and doping accuracy
- Cooling of the ingot

For the radial uniformity the only way is rotating the ingots when irradiated. A low power reactor (e.g., 250 kW) with a neutron flux of 2×10^{12} n.cm^{-2}.s^{-1} can be used to produce useful quantities of doped silicon. However, for the production of commercial quantities of doped silicon, the flux should be greater than 10^{13} n.cm^{-2}.s^{-1} but not more than about 2×10^{14} n.cm^{-2}.s^{-1}.[4]

For light water pool-type reactor, the ratio of thermal to fast neutron flux is considered to be greater than 10. The fast neutron spectrum is above 1MeV. [5]

Experimental

TRR irradiation facilities simulation

Tehran Research Reactor (TRR) is a 5MW MTR pool-type research reactor. TRR irradiation facilities include various beam tubes, thermal column, and in-core irradiation boxes. Figure 1 shows TRR equilibrium core configuration and structure of irradiation facilities.

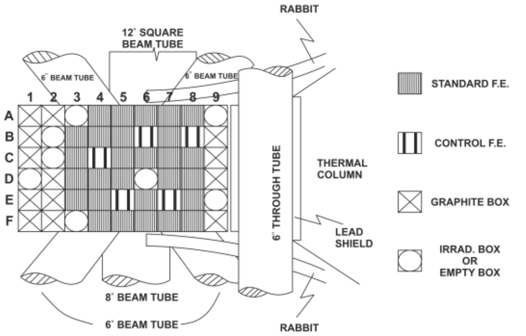

Figure 1. schematic TRR equilibrium core configuration and structure of irradiation facilities

In this study the TRR core configuration and irradiation facilities simulated by Monte Carlo MCNP-4C code[6]. Also, a conceptual design of a special NTD irradiation rig considered and designed inside the reactor core. In order to compare the ratio of thermal to fast neutron flux, three-groups energy (thermal: below 0.625eV, epithermal: between 0.625eV and 1MeV, fast: above 1MeV) simulations of neutron flux has been performed. In order to use beam tubes, thermal column, through tube and in-core irradiation facilities for NTD, some equipments must be considered and designed. For this purpose, irradiation facilities of Tehran Research Reactor (TRR) such as thermal column, beam tubes, irradiation boxes and designed irradiation rig and reactor core were simulated and evaluated by MCNP-4C code. Figure 2 shows the schematic of TRR in-core irradiation facilities and beam lines by MCNP-4C code.

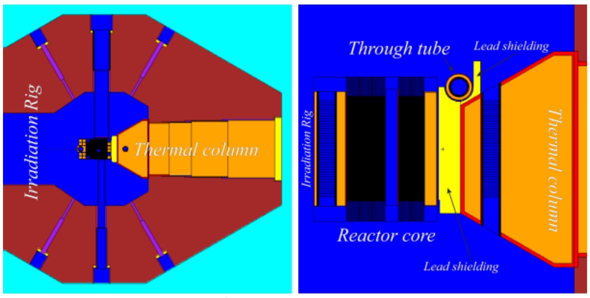

Figure 2. TRR irradiation facilities simulated by MCNP-4C code.

Results and discussion

The ingots are placed inside the radial beam tubes in the axial direction. The value thermal neutron flux decreases exponentially along the sample axis so the radial beam tubes are **not** suitable for NTD.

Thermal to fast ratio of neutron flux increases in the depth of the **thermal column**. Figure 3 shows trend of values of thermal and fast neutron flux and Figure 4 shows trend of thermal/fast ratio of neutron flux in depth of the thermal column. Neutron flux value in the thermal column, which is an important parameter in evaluation and determination of irradiation rig position, should not be less than 2×10^{12} $n.cm^{-2}.s^{-1}$. Considering positions of the through tube and its lead reflector on the top of the thermal column, the axial center of the rig is located in the depth of 17cm of the graphite reflector of the thermal column. In order to create radial uniformity in the target, the ingots must be rotated and to create axial uniformity ingots position should be changed.

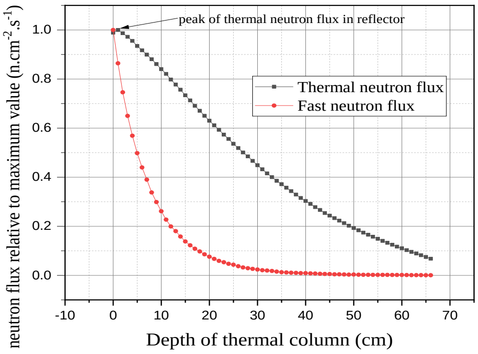

Figure 3. Thermal and fast neutron flux trend normalized to maximum flux value in depth of thermal column by MCNP-4C code.

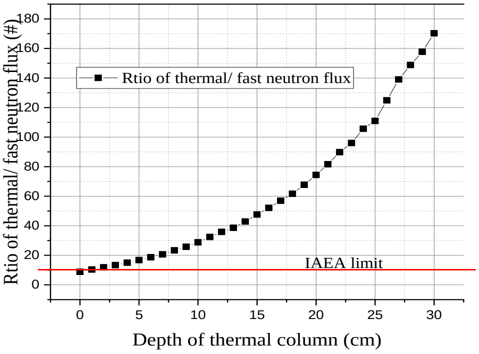

Figure 4. Ratio of thermal to fast neutron in depth of thermal column by MCNP-4C code.

The evaluation results which is presented in Table 1 shows that the thermal column, through tube and the designed irradiation rig can meet the criteria for use in NTD. In the following, thermal column, through tube and irradiation boxes and rig are evaluated and compared.

Table 1. recommended limits by IAEA, and MCNP-4C code results

	$\varphi_{th}[n.cm^{-2}.s^{-1}]$*	$\varphi_{th}/\varphi_{fast}$
IAEA limit	$2\times10^{12}<\varphi_{th}<2\times10^{14}$	>10
Thermal column	3.63×10^{12}	80.64
Through tune	2.71×10^{12}	31.65
Irradiation box D1	1.89×10^{13}	11.90
Irradiation rig	2.19×10^{13}	13.91

*The average thermal neutron flux in sample/ingot diameter 101.6mm(4”), length 600mm

Thermal neutron flux in the center of the 6” diameter **through tube** meets the IAEA criteria for NTD applications. Ingots can be fed to through tube and extracted from the other side continuously. In addition to a sample rotating system, the through tube also needs an appropriate cooling system for under-radiation sample.

The **irradiation box** D1 (8.1cm×7.71cm) and the designed **irradiation rig** offers an appropriate neutron flux in rank of 10^{13}, which is applicable for NTD. Reactor core coolant system can also be used for cooling of the ingots in the process of irradiation.

Conclusions

At greater depths of the thermal column, the ratio of thermal neutrons to fast neutrons is larger, but the value of thermal neutron flux decreases. The through tube provides a suitable ratio of thermal to fast neutron flux (Table 1) and according to its diameter can be used for ingots up to 6 inches diameter.

The irradiation box D1 has a small dimension so an irradiation rig was designed for providing bigger irradiation space for ingot with more than 2 inches up to 4 inches diameter. The designed irradiation rig provides more value of thermal neutron flux in comparison to other present irradiation facilities in TRR so it leads to higher efficiencies and throughputs.

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