＜炉物理部会賞受賞記念寄稿＞

Design study on small and simple nuclear reactors intended for large-diameter Si crystal doping using PWR fuel assemblies

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Introduction

Nowadays, the use of electric vehicles such as hybrid cars and electric trains is increasing rapidly. Each such vehicle requires a considerable amount of semiconductor devices, suggesting an ever-growing demand for such devices in the near future. Thus, the mass production of the semiconductor material is becoming a very important issue for many manufacturers. There are several methods for mass production, but Neutron Transmutation Doping of Silicon (NTD-Si) is the most promising method for the production of silicon based semiconductor. Natural silicon has three stable isotopes: Si-28 (92.3%), Si-29 (4.7%) and Si-30 (3.1%), and these stable isotopes are homogenously mixed in natural silicon crystal. The principle of NTD-Si is that conversion of a small amount of natural stable isotope Si-30 into the stable isotope P-30 by nuclear reaction; uniformly doped silicon crystal can therefore be expected after irradiation[1].

The production of doped Si is usually carried out in research reactors because the suitable irradiation condition exists in these types of reactors. In other words, the research reactors can easily be modified for this purpose; therefore, all the silicon irradiation facilities in the world have been built around these research reactors. The current NTD market is dominated by 5 and 6 inch ingots, and the share of 4 inch ingots has been decreased drastically. Recently the demand for irradiation of 8 inch ingots has grown, and its market share could expand in the future. Since the typical diameter of silicon ingots has become much larger, a large amount of silicon can be irradiated at an irradiation site. The CZ-Si market has jumped from 8 to 12 inches. Therefore, the next wave of NTD ingots would be 12 inches rather than in between 8 and 12 inches such as a 10 inch ingot. It seems that the industry is now developing technology for 18 inch CZ-Si production but NTD for 18 inch ingots may be difficult to satisfy not only in terms of irradiation uniformity but also accommodation at reactors[2].

The doped Si is widely used in various fields such as high quality semiconductor devices, sensors and other standard devices, but mainly used for high power devices such thyristor and several types of insulated gate bipolar transistors (IGBT). These high power devices are mostly adopted in hybrid electric vehicles, carrying both conventional and electric propulsion systems, for controlling the traction. The performance of such vehicles such as motor power is important, and it depends on the performance of the key component like IGBT. It is known that the doped Si is suitable base material for high performance IGBTs because of its higher uniformity compared to others doped by conventional methods. Rapid increase in demand of hybrid cars is expected due to the high cost of fuel and environmental concerns. A recent survey made by Korean Atomic Energy Research Institute (KAERI) indicated that 50 million hybrid electric vehicles would be produced, and almost 1000 tons of NTD-Si would be needed in 2030[3-4].

At present, the worldwide capacity of the NTD-Si facilities is estimated to be 150~180 tons per annum. This capacity cannot be increased drastically because most research reactors with NTD facilities were constructed many years ago and they have little potential for expansion; in addition, number of research reactors to be constructed in the future is few. Another important issue is that the present research reactors are not NTD-dedicated facilities, and thus a stable and adequate supply is not expected. If the hybrid electric vehicles increase according to the current forecast, the existing research reactors cannot supply future demand. As such, a new doping facility with a large irradiation capacity for NTD-Si may need to be constructed to ensure an adequate supply of doped silicon.

Purpose of study

The purpose of the study was to design small and simple nuclear reactors for large-diameter (12 inches) NTD-Si using PWR fuel assemblies. By using conventional fuel assembly, which is commercially available fuel, the reactor concept can be easily realized, and the supply of the fuel can also be assured. The proposed reactor concepts are for industry, not for research, and they need to be economically profitable; therefore, the stable operation and reliable fuel supply are major requirements. There are several facilities fabricating PWR fuel assemblies in the world, and it can be said that PWR fuel supply is more reliable than supply of plate type fuel which is mainly used in the research reactors. Another important advantage of using conventional fuel assembly is the spent fuel from reactor, and the spent fuel can be sent and accepted at existing fuel reprocessing facilities.

Design concepts

Two design concepts were proposed. The neutronic and thermal hydraulic analyses were performed to obtain the optimum core composition, operating period, necessary condition for uniform doping and the reactor production rate. Criticality and burn-up analyses were performed using the continuous energy Monte Carlo code MVP/GMVP II[5] with the JENDL-4.0[6] data library. The core burn-up calculation was carried out by auxiliary code MVP-BURN[7]. The single-channel steady-state thermal hydraulic analysis was performed using COMSOL Multiphysics[8] which is a finite-element analysis, solver, and simulation software. A neutron transport calculation was performed in the reflector region by the continuous energy Monte Carlo code MVP/GMVP II with the JENDL-4.0 data library to determine the necessary condition for uniform irradiation.

First one was a design concept of a small and simple nuclear reactor for large-diameter NTD-Si using full-length conventional PWR fuel assemblies[9-10]. The idea was to use commercially available conventional PWR fuel (fabricated for power reactors) directly without any modification. A conventional 17×17 PWR fuel assembly was used. The reactor power was 15 MWth, and operating pressure was 1 atm. The excess reactivity was managed by a combination of the burnable poison Gd_2O_3 and control rod. The criticality and burn-up calculation results showed that the operating period of the reactor concept was over 18 years without refueling. The thermal hydraulic analysis showed that the heat removal from core under 1 atm operating pressure was possible, and no need to pressurize the reactor systems. The necessary condition for uniform doping was determined. Si ingots, 12 inches in diameter, up to 20 cm in height could be doped with sufficient uniformity. The reactor semiconductor production rate was estimated assuming the reactor would be in 24–hour operation for 8 months per year, and the estimated production rate varied between 111 tons/year and 140 tons/year for 50 Ω·cm target resistivity depending on the control rod positions. The disadvantage was the height of the core.

Second one was a design concept of a small and simple nuclear reactor for large-diameter NTD-Si using short PWR fuel assemblies[11]. The core height was reduced by using shorter assemblies. But the irradiation capacity was reduced drastically. Thus, the reactor design was modified and optimized for maximum capacity as possible. The criticality and burn-up calculation results showed that the operating period of reactor concept was over 3 years without refueling. The thermal hydraulic analyses showed that the heat removal from core under 1 atm operating pressure was possible. Large Si ingots with 12 inches in diameter were able to be doped with sufficient uniformity. The estimation of reactor production for 50 Ω·cm target resistivity showed that the rate varied between 48 tons/year and 70 tons/year depending on the position of the control rod. The study showed that short PWR fuel assemblies could be used for this concept, and the reactor production rate was a good rate, as compared to the present worldwide capacity.

Conclusions

The reactor concept using full-length conventional PWR fuel assemblies had a very good performance, for instance, a long operating period and a large production rate, but the size of the core could become big which could lead a large construction cost (initial investment). On the other hand, the reactor concept using short PWR fuel assemblies might require a less construction cost due to the smaller core, and the production rate was not that bad, but the operating period was much shorter than first concept. It should be mentioned here that only the fuel assemblies may need to be replaced every 3 years. This concept with short assemblies may be attractive for industry if the shorter PWR assemblies can be fabricated without major difficulties in existing fuel manufacturers, needless to say that they are technically capable to produce such assemblies.

These concepts were intended for industry, not for research. The PWR fuel assemblies were used as a fuel in both concepts to ensure the stable and reliable supply of the fuel. The study showed that it could be possible to design small and simple reactors for large-diameter NTD-Si using such PWR fuel assemblies. If these concepts were realized for semiconductor industry, it could make a great contribution in the worldwide supply of doped Si.

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