Neutron Transmutation Doping of Initially p-type Silicon for Production of Uniformly Doped n-type Silicon

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1. Introduction

Neutron transmutation doping(NTD) for producing n-type silicon semiconductor is based on the conversion of the Si-30 isotope into phosphorus atom by neutron absorption reaction. By using this method, silicon semiconductors with extremely uniform n-type dopant distributions can be produced, and this is the dominant advantage of NTD compared with the conventional chemical doping[1,2]. HANARO has two vertical holes for NTD, and the commercial NTD service for 5 and 6 inch silicon ingots has been going on at the NTD2 hole. Generally, NTD method is applied to the initially n-type silicon material. But, an initially p-type silicon material can also be used for the production of uniformly doped n-type silicon by using NTD method. Therefore, in this work, we investigated the relationship between the irradiation neutron fluence and the final resistivity of the initially p-type silicon material. Thereafter, we established the methodology for the neutron transmutation doping of initially p-type silicon ingot.

2. Methods

When impurity atoms are introduced into an intrinsic semiconductor material, densities of the charge carriers and impurities are represented by the charge neutrality[3],

$$n + N_A = p + N_D \tag{1}$$

where, n and p are the electron and hole densities, and N_A and N_D are the acceptor and donor densities, respectively. Since the np product is always independent of the added impurities,

$$n = \frac{(N_D - N_A) + \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2} \approx N_D - N_A \tag{2}$$

where, n_i is the intrinsic carrier density.

Final resistivity after doping is as follows,

$$\rho_f = \frac{1}{\varepsilon n \mu_e} = \frac{1}{(N_D - N_A)\varepsilon \mu_e} \tag{3}$$

where, ε is the electron charge, and μ is the drift mobility of the carrier in the crystal lattice.

Then, the concentration of the donor that should be formed in the doping procedure to reach the final resistivity is

$$N_D = \frac{K_P}{\rho_f} + \frac{K_B}{\rho_i} = K_P\left(\frac{1}{\rho_f} - \frac{A}{\rho_i}\right), \quad A = -\frac{K_B}{K_P} \approx -2.8, \tag{4}$$

where, ρ_i is the initial resistivity of the p-type silicon. Since the donor concentration is directly proportional to the neutron fluence, for initially p-type silicon, we can obtain the relationship,

$$\phi t = K\left(\frac{1}{\rho_f} - \frac{A}{\rho_i}\right), \tag{5}$$

where, K is the proportional constant that should be determined in the real irradiation experiments.

One of the most widely used materials for acceptor impurity in the p-type silicon is boron. The absorption cross-section of the B-10, which is one of the naturally existing isotopes of boron, is extremely large. So the burn-up effect of the boron impurities was analyzed. When the neutron irradiation fluence corresponds to the final resistivity of 22 Ω·cm, the burn-up of B-10 was calculated to be about 0.4%. Therefore, it is confirmed that the burn-up effect of the boron impurity is negligible.

3. Irradiation of the p-type Silicon Ingot

There were several neutron irradiations for initially p-type silicon ingots with a diameter of 5 and 6 inch. The target resistivities of the irradiated ingots were 20.5, 22, 24, 24.5, 39.5, 59, 60 and 67 Ω·cm. Most of them had initial resistivities of 1000~3000 Ω·cm, however, there were a few ingots with the initial resistivity under 600 or over 7000 Ω·cm. The silicon ingots were irradiated with the neutron flux monitors to confirm the target neutron fluence. Zirconium foils and cobalt wires were used as flux monitors, and the induced activities of the foils and wires were measured by using HPGe gamma-ray detection system[4].

After an irradiation, we compared the irradiated neutron fluence determined by the flux monitor with the resistivity measurements data presented by NTD customer. From this comparison, the proportional constant, K -value in eq. (5), had been determined. The results are summarized in Figure 1. In the figure, ρ_f is the final resistivity confirmed by the customer at the same position of the irradiated ingot as the position of the neutron flux monitor. The gradient of this fitting line corresponds to the K value, and for p-type silicon irradiation, it was determined to be 2.3473×10^{19} n·Ω/cm.

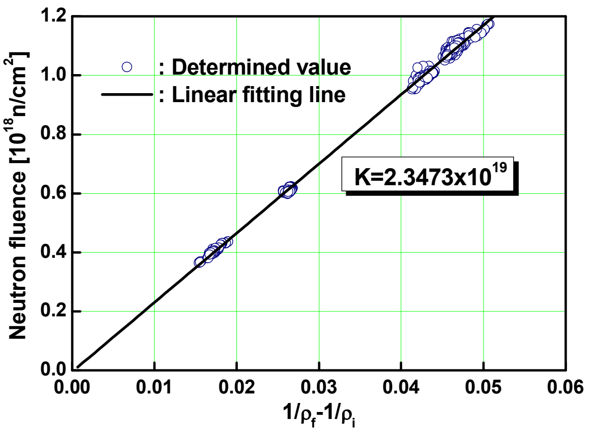

Figure 1. The relationship between the irradiated neutron fluence for p-type silicon and the measured resistivity at the same position as the neutron flux monitor.

Figure 2 shows the irradiation result for p-type silicon ingot at each reactor period. When the K -value given in the Figure 1 is applied, the deviation of the neutron fluence for the ingot from the fitting line is shown in the Figure 2. As shown in the figure, almost all of the irradiated neutron fluence is located at a range of ± 2.5%. Therefore, it is confirmed that the determined K -value is suitable for the irradiation of initially p-type silicon ingot.

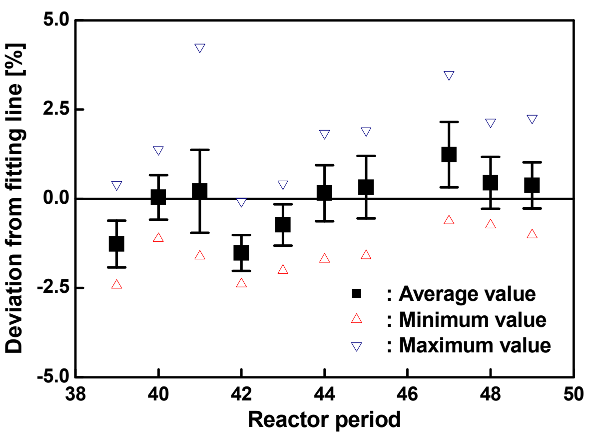

Figure 2. The irradiation result for p-type silicon ingot at each reactor period.

4. Conclusion

The relationship between the irradiation neutron fluence and the final resistivity of the initially p-type silicon material was set up. The proportional constant of the relationship for the p-type silicon was determined. Conclusively, the irradiation method for the p-type silicon ingot to produce uniformly doped n-type material was established

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