PHOTONUCLEAR TRANSMUTATION DOPING OF THE n-TYPE DETECTOR SILICON

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New experimental quantitative data on the efficiency of photonuclear transmutation doping of n-type detector silicon were obtained. The express technique for measurement of the efficiency of producing the acceptor minority (Al) in high resistant detector silicon was developed. The transmutation doping is studied for increase of the detector silicon resistivity from about 1 to 5 kOhm×cm and for correction of the resistivity distribution over the silicon bulk. The studies of photonuclear doping were performed applying the beams of gamma-bremsstrahlung with $E_\gamma^{max} \approx 25$ MeV. Using the doping efficiency data, the cost of detector silicon doping was calculated for case of the bremsstrahlung of 25 MeV energy electrons.

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INTRODUCTION

The doping is carried out to produce an n-type high-resistivity semiconductor of detector quality. The urgency of the problem is due to the fact that in the manufacture of n-type high-resistance silicon (for fabrication of nuclear detectors) by the crucible-free zone melting method, the yield of silicon with a resistivity higher than 8 kOhm×cm is not above 10% [1].

Transmutation doping of crystal silicon is used mainly for low-resistivity silicon processing in microelectronics technology using reactor neutrons. Transmutation doping applications for detector silicon production connected with the difficulties. The concentration of the doping minority in the detector silicon with the resistivity above 1 kOhm×cm is of the order of 10^{12} atom/cm^3. The control of such a doping minority by neutron transmutation doping is very difficult and, therefore, the main part of the detector silicon by the neutron doping is done with resistivity in range of 0.5-1 kOhm×cm [1]. For increase the resistivity of the rest silicon, it is necessary to introduce an exactly controllable amount of the acceptor impurity.

The technique of photonuclear transmutation doping was proposed [2,3] to use for production of the p-type low-resistivity silicon. In works [4,5] was presented first trying to increase of a resistivity of n-type silicon. In this work, the resistivity of the doped silicon was studied as a function of the dopant concentration and of the initial resistivity of the primary silicon (0.8-4 kOhm ×cm). It is shown that a strict dosage, of aluminium dopant allows permit of production of n- and p-type silicon with controllable resistivity. The technique for precise measurement of transmutation doping concentration is described.

1. TRANSMUTATION DOPING TECHNIQUE

The production of aluminum by photonuclear transmutation doping of silicon is accomplished as a result of the following nuclear reactions [1]

$$^{28}Si(\gamma,n)^{27}Si \xrightarrow[4.3\,s]{\beta^+} {}^{27}Al \qquad (1)$$

$$^{28}Si(\gamma,p)^{27}Al\,. \qquad (2)$$

To determine the concentration of the aluminum produced may be used the measurement of the γ-radiation appearing in the process of photonuclear doping because of the reaction

$$^{30}Si(\gamma,p)^{29}Al \xrightarrow[6.6\,min]{\beta^+} {}^{29}Si\,,\ E_\gamma=1273\ \text{keV}. \qquad (3)$$

The ^{29}Al decay is accompanied by the gamma-quantum radiation with the 1237 keV energy. The use of this reaction is the most convenient for measurements taking into account the radiating time and the gamma-radiation energy being recorded.

When carrying out the work under this stage of this technique test, the silicon samples were manufactured having a normalized mass and resistivity known to a high accuracy. The accuracy of determining the efficiency of Al production, using the technique offered, was checked by comparison of the transmutation doping results for the specimens with the different initial resistivity. The bremsstrahlung beam with the energy of E_γ^{max} = 25 MeV was used for these experiments (Fig. 1).

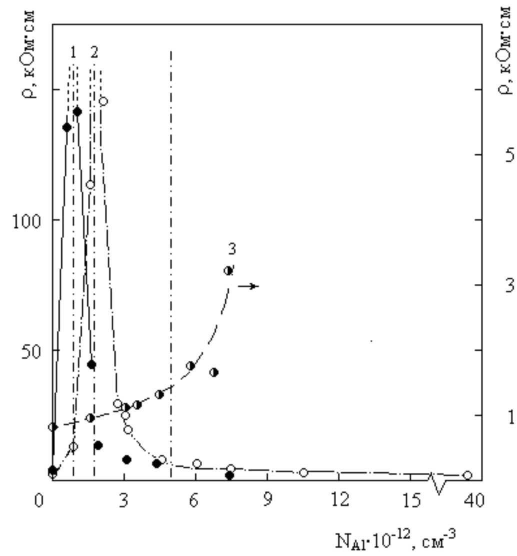

Fig. 1. The silicon resistivity after transmutation doping. 1.2,3 – initial resistivity of the silicon specimens 4: 2.5 and 0.9 kOhm×cm, accordingl

Fig. 1 represents the detector silicon resistivity after the photonuclear doping as a function of the transmutation aluminum concentration in silicon [2]. The experimental results gave support to the accuracy of the proposed technique sufficient for providing the photonuclear doping of the detector silicon having the low initial concentration of the doping. The Al concentration was measured with the use of the proposed technique for measurement of the induced γ-activity in specimens-witnesses. To obtain a resistivity value after irradiation of the specimens, the special annealing and contact deposition were done.

It is evident, that the full compensation of detector silicon (maximum resistivity) is well coinciding with the concentration value of noncompensated phosphor for silicon with the initial resistivity 4 and 2.5 kOhm× cm. The concentration value of noncompensated phosphor in Fig. 1 indicated by vertical dotted lines.

The full compensation of 0.9 kOhm×cm silicon may be realized using transmutation doping concentration slightly more, than initial concentration value of noncompensated phosphor. Obviously, it may be explained that the low-resistivity silicon (0.9 kOhm× cm) has an impurity, which is the sink for Al atoms.

2. DOPING THE DETECTOR SILICON INGOTS

The measurement of the resistivity ρ of the grown detector silicon ingots evidences that the distribution of this resistivity across the ingot has the form "W". Therefore, the injection of doping aluminium should be nonuniform. The gamma-quanta radiation should be directed to the end of the ingot and have the maximum formed by a proper way. This maximum can be selected by locating the ingot at a certain distance from the electrons-bremsstrahlung converter. To obtain a suitable doping for 100-mm ingots diameter was measured the distributions of nuclear-active gamma-quanta at different distances from the converter (Fig. 2).

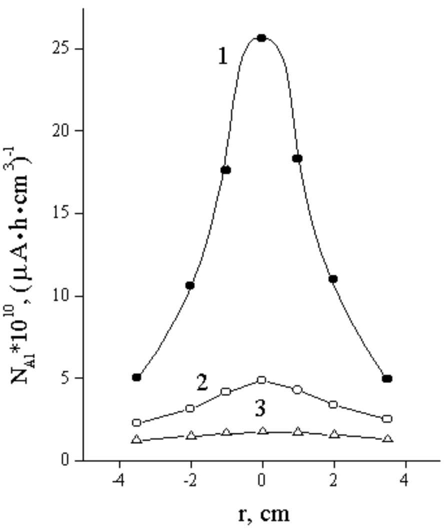

Fig. 2. The Al atom production in silicon at distances 180 (•), 500 (○) and 840 (Δ) mm from the converte

In Fig. 2 shown are the results of measuring the number of produced Al atoms at distances 180, 500 and 840 mm from the converter (curves 1, 2 and 3, respectively). The most suitable for ingot doping is the gamma-quanta distribution at a distance 840 mm.

However, because of such irradiation distance, the significant part of gamma-radiation is lost and the radiation time should be significantly prolonged. Therefore, it may be proposed to use the narrower gamma-distribution at a small distance, which is directed to the end of the rotating ingot with the beam centre displacement relatively to the rotation centre (Δr).

The possibility to apply this proposal was checked on the ingot-simulator that was an aluminium cylinder of a 100 mm diameter and 135 mm length. The silicon specimens-witnesses were located both at the front and back ends of the cylinder. The most suitable distribution was obtained for irradiation distance 180 mm and beam-ingot centres displacement Δr = 25 mm. In Fig. 3 shown is the Al product distribution at the front end (2), back end (3) and the total value (1).

The calculations have shown that such a doping is 3.9 fold more economic as compared with the irradiation to the ingot centre at an 840 mm distance. To obtain the uniform irradiation over the whole bulk the ingot should be placed so that during first half-hour the irradiation was passing through one end of the ingot, and during second half-hour through another end.

So, for the ingot irradiation with concrete distribution of R_0 one can select the radiation field configuration with a best efficiency and maximum economic effect.

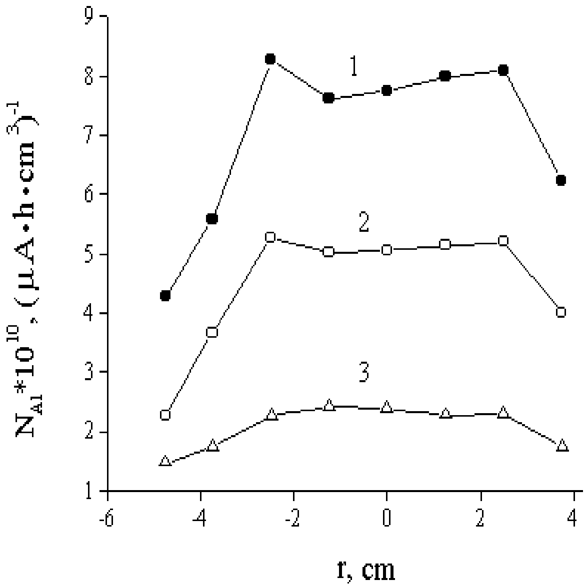

Fig. 3. Distribution of Al production on the simulator: at the front end (2); at the back end (3); total value (1)

The simple device for ingot rotation under irradiation is shown at Fig. 4.

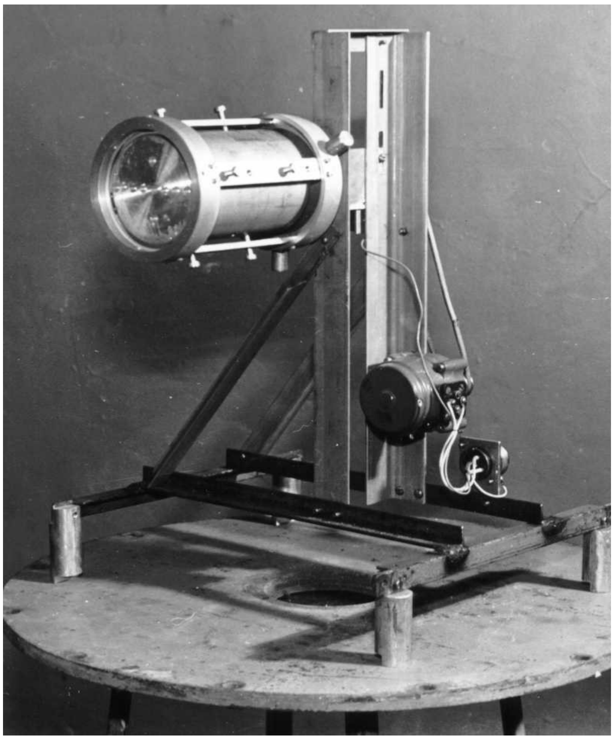

Fig. 4. *The device for ingot rotation under irradiation*

3. ECONOMIC POINT OF THE DETECTOR SILICON DOPING

To evaluate the cost of detector silicon doping it is necessary to measure the transmutation Al concentration required for increase of the silicon resistivity to 5 kOhm ×cm for silicon with different initial resistivity. The measurements were done (Fig. 5) for silicon with the initial resistivity in the range of 0.8–4 kOhm×cm.

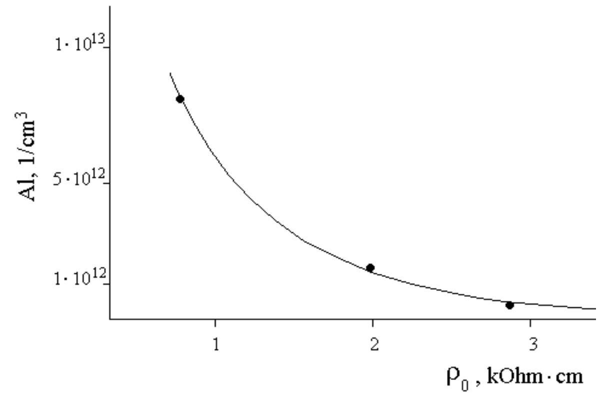

Fig. 5. *The transmutation Al concentration required for increase of the silicon resistance to 5 kOhm×cm*

The cost of doping is determined with taking into account the measured dependence and the expected cost of the beam time of 25 MeV electron energy and ≤500 μA average current (linear electron accelerator "EPOS"). The cost of silicon doping of an initial resistivity ≤1 kOhm×cm (for production of the detector silicon of a resistivity ≥ 5 kOhm×cm) is \$100 per one kg. It is seen from Fig. 5 that the Al concentration required for silicon subdoping decreases with the initial resistivity increasing. However, the time expenses for crystals arrangement under the beam and for measurement carrying out decrease the gain of cost for silicon with higher initial resistivity. Therefore, the cost of increasing the resistance of silicon with the ~2 kOhm× cm initial resistivity is ~\$80 per one kg. The high cost of silicon with the resistivity above 3 kOhm×cm (~ \$1000 per one kg) indicates on the expediency of the technique of increasing the detector silicon resistance being developed.

CONCLUSIONS

The transmutation doping was carried out to produce an n-type high-resistivity semiconductor of detector quality. The express technique for measurement of the concentration of transmutation producing the acceptor minority (Al) in high resistant detector silicon was developed. Using this technique, the efficiency of photonuclear transmutation doping was investigated and the new experimental quantitative data on efficiency of the detector silicon doping with the gamma-ray bremsstrahlung was obtained.

The cost of doping ~\$100 is determined with taking into account the measured dependence on the doping efficiency and the expected cost of ≥25 MeV electron beam by the ≤500 μA average current (linear electron accelerator "EPOS"). The cost of silicon doping of an initial resistivity ≥1 kOhm×cm (for production of the detector silicon of a resistivity ≥5 kOhm×cm) is ≤\$100 per one kg. The high cost of silicon with the resistivity above 3 kOhm×cm (~\$1000 per one kg) indicates on the expediency of the technique of increasing the detector silicon resistance being developed.

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