Development of NTD-Ge Sensors in Low-temperature bolometers

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1. Introduction

Various studies to understand the origin of the universe or Dark Matter have been developing new detection methods and sensors to observe very rare phenomena. The results of these studies are expected to provide important clues not only to test hypotheses beyond the standard model, but also to shed light on the origin of the universe. However, these interactions are rare phenomena that occur at very small frequencies. In particular, experiments to observe the very rare phenomenon of double beta decay have been interested in developing bolometer. It can resolve the very small energy(temperature) changes in isotopic crystals that can undergo double beta decay in cryogenic environments. Currently, Korea Atomic Energy Research Institute (KAERI) start to develop Neutron Transmutation Doping (NTD) germanium (Ge) sensors using 30 MW HANARO research reactor.

Ge semiconductors exhibit the best energy resolution of any other material, as shown in Fig. 1. In addition, while chemical methods are commonly used to dope semiconductors, NTD methods yield much better results when it comes to uniformity of doping concentration as shown in Fig. 2.

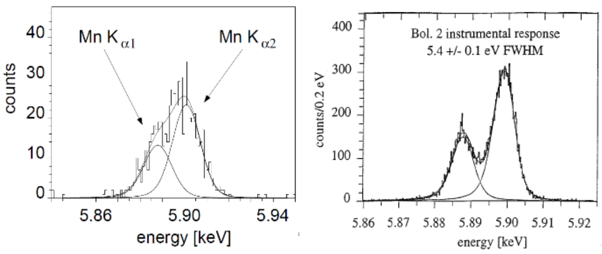

Fig. 1. Si resolution (~14eV) vs. Ge resolution (~5eV) [1,2]

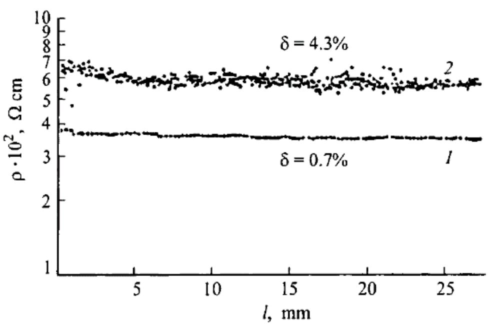

Fig. 2. Comparison of doping concentration between chemical method and NTD method. [4]

2. International Research Status [4]

Republic of Korea, Belgium, Australia, Germany, and South Africa have a reactor-based Si semiconductor doping industry, while United States, India, and China have experience with NTD-Ge for research purposes. In the United States, University of California at Berkeley has been conducting research on conventional Ge semiconductor materials since the 1980s, and has a lot of research experience in fabricating NTD-Ge materials and characterizing devices. Berkeley's results are currently being utilized in experiments to measure neutrino-free double beta decay (0νββ-decay) (CUORE, CUPID (Italy), CROSS (Spain)) and the search for dark matter (CUORE (Italy), EDELWEISS (France)). Recently, NTD-Ge studies have also been started and are underway in India (TIN.TIN experiment) and China (CPSD experiment).

In Republic of Korea, Underground Experiments Division at Institute of Basic Science (IBS) conducted the AMoRE experiment to search for rare interactions between particles in the cryostat using scintillating bolometers. The AMoRe project is using temperature-dependent magnetization of paramagnetic materials (metallic magnetic calorimeter, MMC). KAERI has used HANARO research reactor to produce NTD-Si for power semiconductors. NTD-Si and supplying it to foreign companies (with NTD irradiation technology).

3. Development of NTD-Ge sensor

2.1 NTD-Ge characterization

The isotopic composition of high-purity germanium and the reaction rate of each isotope are shown in Table 1. The doping process can be predicted as followings:

$$^{70}_{32}\mathrm{Ge}\,(n,\gamma) \rightarrow {}^{71}_{32}\mathrm{Ge} \xrightarrow{\mathrm{EC}(11.2\mathrm{d})} {}^{71}_{31}\mathrm{Ga}$$

$$^{72}_{32}\mathrm{Ge}\,(n,\gamma) \rightarrow {}^{73}_{32}\mathrm{Ge(stable)}$$

$$^{73}_{32}\mathrm{Ge}\,(n,\gamma) \rightarrow {}^{74}_{32}\mathrm{Ge}\,\mathrm{(stable)}$$

$$^{74}_{32}\mathrm{Ge}\,(n,\gamma) \rightarrow {}^{75}_{32}\mathrm{Ge} \xrightarrow{\beta^-(82.8\mathrm{m})} {}^{75}_{33}\mathrm{As}$$

$$^{76}_{32}\mathrm{Ge}\,(n,\gamma) \rightarrow {}^{77}_{32}\mathrm{Ge} \xrightarrow{\beta^-(11.3\mathrm{h})} {}^{77}_{33}\mathrm{As} \xrightarrow{\beta^-(38.8\mathrm{h})} {}^{77}_{34}\mathrm{Se}$$

Table I: Ge description

Isotopes	Abundance (%)	Neutron capture cross section (b)
^{70}Ge	20.57	3.05
^{72}Ge	27.45	0.89
^{73}Ge	7.75	14.7
^{74}Ge	36.50	0.36
^{76}Ge	7.73	0.055

Depending on the neutron irradiation conditions, the concentration of radioactive elements produced can be changed and determines the doping level of NTD-Ge as following equation:

$$N_A - N_D = \left[N_{^{71}Ga} - \left(N_{^{75}As} + 2 \times N_{^{77}Se} \right) \right] \quad (1)$$

For example, the CUORE, a bolometric experiment at Gran Sasso for search of neutrinoless double beta decay, characterized the NTD Ge sensor with the carrier concentration in the range (5.0 - 6.8) $\times 10^{16}/\text{cm}^3$ and found 6.8 $\times 10^{16}/\text{cm}^3$ to be the best choice for their detector [5].

2.2 Evaluation of NTD-Ge doping level

The carrier concentration produced by doping can be estimated from the production rate (Table.1) and the neutron fluence computed from the reactor data. The results can be verified experimentally by Hall effect measurement. The experimental set-up of Hall effect measurements are shown in Fig. 3. Carrier concentrations in NTD-Ge samples can be estimated from the Hall effect measurement carried out using Van der Pauw method on a symmetrical sample [6]. The Hall voltage (V_H) is used to estimate the carrier concentration (n) by the following expression.

$$n = \sqrt{\frac{B \cdot I}{e \cdot V_H \cdot t}} \quad (2)$$

where e is the electric charge, I is the supplied current and t is the thickness of the sample.

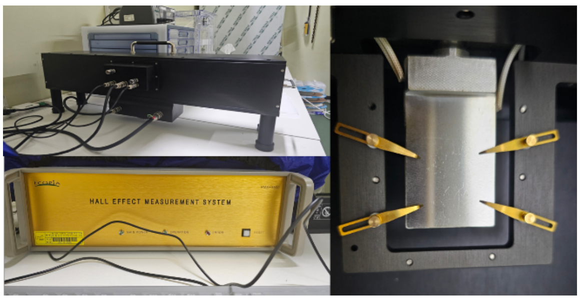

Fig. 3. Hall Effect Measurement system at KAERI

2.3 Analysis of NTD-Ge defect

Germanium suffers damage to its semiconductor structure from neutrons of various energies during neutron irradiation. The defects in the semiconductor will affect its performance as a cryogenic calorimeter sensor and must be annealed by temperature treatment. The defects in the NTD-Ge can be evaluated by the positron annihilation spectroscopy method. Figure 3 shows the positron annihilation spectroscopy system (CDBS, PALS) owned by KAERI.


Fig. 4. Positron Annihilation Spectroscopy system at KAERI.

3. Summay and Plan

The purpose of this study is to develop an NTD-Ge sensor using the NTD facility at KAERI's research reactor. As a first step, after neutron irradiation of high-purity germanium wafers, the radioactive impurity of the wafer will be addressed and the neutron irradiation conditions will be optimized for uniform doping levels. We will also work on minimizing the effect of NTD-Ge defects for use as a sensitive sensor at cryogenic temperatures.

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