Neutron Transmutation Doping of ^{nat}Ge for thermal sensors

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Introduction

The NTD (Neutron Transmutation Doping) Ge thermistors have been widely used as low temperature sensors (in mK range) in dark matter searches and neutrino physics. The NTD technique has two main advantages over the conventional metallurgical methods of impurity incorporation. It is possible to achieve high precision doping due to the constancy of neutron flux as irradiation time can be controlled with a high accuracy and high homogeneity of impurity distribution due to the smallness of neutron capture cross section [1]. We have initiated the development of NTD Ge sensor for use in the feasibility study of $0\nu\beta\beta$ in ^{124}Sn cryogenic bolometer at the upcoming underground facility of INO.

Experimental Details and Analysis

To produce NTD germanium, semiconductor grade ^{nat}Ge ($10 \times 10 \times 0.4$ mm) was irradiated for $\sim$ 4 days with a thermal neutron flux of 0.5×10^{13}cm^{-2}s^{-1} at the Dhruva reactor, BARC. The sample was wrapped in an aluminium foil during the irradiation. The Ge nuclei capture neutrons and form various radioactive Ge isotopes, which subsequently decay into ^{71}Ga, ^{75}As and ^{77}Se. Due to the natural isotopical composition of Ge and the neutron capture cross section, the resulting doping is of p-type, as shown in Table I. The isotopic abundances in the Ge sample measured with SIMS were found to be in good agreement with the standard values.

TABLE I: Natural isotopes of Germanium and n-capture products [2], [3].

Isotope	Abun. (%)	σ_c (barn)	Product	$T_{1/2}$
^{70}Ge	20.4	3.43	^{71}Ga	11.43d
^{72}Ge	27.3	0.98	^{73}Ge	stable
^{73}Ge	7.8	15.0	^{74}Ge	stable
^{74}Ge	36.7	0.51	^{75}As	82.78m
^{76}Ge	7.8	0.16	^{77}Se	11.3,38.8h

The irradiated sample was counted in the low background facility at TIFR after a cooling period of about 40 days. The low background counting system consists of a special Ortec HPGe detector (70% efficiency, resolution of 2.3 keV at 1332 keV) with a 60 cm long cold finger shielded with 10 cm low activity lead ($<$ 0.3 Bq/kg) on all sides. Data was recorded in list mode using a CAMAC based acquisition system LAMPS [4]. Efficiency over 100-1500 keV energy range was obtained using calibrated sources like ^{152}Eu, ^{133}Ba and ^{241}Am (within $\pm$1%). The sample was counted in a close geometry for $\sim$ 1 day and at 10 cm from the face of the detector for $\sim$ 4 days. For comparison, a non-irradiated ^{nat}Ge sample of same dimensions was also counted in close geometry for $\sim$ 1 day.

Fig. 1 shows the spectra of the irradiated and non-irradiated Ge sample in a close geometry. Due to the relatively shorter half lives of the isotopes ^{71}Ga, ^{75}As and ^{77}Se (as compared to the cooling period of 40 days), their respective gamma rays are not observed in the spectra. However, ^{71}Ge dominantly decays by

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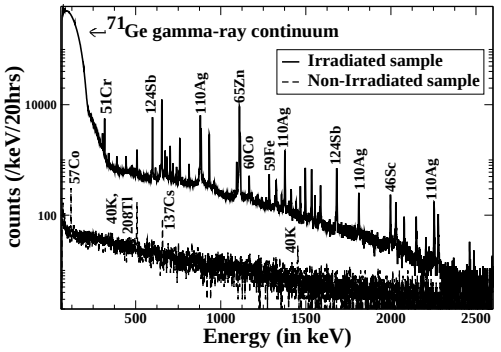

FIG. 1: Spectra of the irradiated and non-irradiated Ge sample in a close geometry.

electron capture to the ground state of ^{71}Ga, where a small fraction undergoes Radiative Electron Capture (REC) [5]. A continuous gamma spectrum of ^{71}Ge is observed with an end-point of 225 keV. The gamma lines identified in the spectra have been listed in Table II [2]. In close geometry coincidence summing lines from the multi-gamma emitting sources are also observed.

TABLE II: Gamma lines observed in the spectra

Impurity	Product	$T_{1/2}$	Energy (keV)
^{45}Sc	^{46}Sc	83.79d	889.3,1120.5
^{50}Cr	^{51}Cr	27.7d	320.1
^{58}Fe	^{59}Fe	44.5d	1099.3,1291.6
^{59}Co	^{60}Co	5.27y	1173.2,1332.5
^{64}Zn	^{65}Zn	243.66d	1115.5
^{109}Ag	^{110}Ag	249.76d	657.8,677.6,687.0 706.7,744.3,763.9 818.0,884.7,937.5 1384.3,1420.9,1475.8 1505.0,1562.3
^{123}Sb	^{124}Sb	60.2 d	602.7,645.9,722.8 1368.2,1691.0 2091.0,2294.0

The impurity level of the parent isotope is estimated by the formula given below:

$$N_{daughter} = N_{parent} \,.\, \sigma_c \,.\, \phi_{integrated} \qquad (1)$$

where σ_c is the thermal neutron capture cross-section (to the ground and/or excited state as the case may be) [3], and $\phi_{integrated}$ is the thermal neutron dose i.e., 1.9×10^{18}cm^{-2}. The $N_{daughter}$ is computed as given below :

$$N_{daughter} = \frac{\text{Activity} \,.\, T_{1/2}}{\ln 2} \qquad (2)$$

The activity for each parent impurity isotope has been calculated at 10 cm from the face of the detector to avoid summing effect.

TABLE III: Estimation of impurity levels of some isotopes in the ^{nat}Ge sample

Isotope	Gamma ray of Activation Prod. (keV)	Impurity (ppt)
^{45}Sc	889.3	2370(62)
^{50}Cr	320.1	783(60)
^{58}Fe	1099.3	1996(320)
^{59}Co	1173	1259(217)
^{64}Zn	1115.5	318289(7720)
^{109}Ag	657.8	33436(700)
^{123}Sb	602.7	2370(80)

Summary

The irradiated Ge sample was analysed in the low background set-up. All $\gamma-$rays were identified and impurity concentration estimated. The main concern is ^{64}Zn and ^{109}Ag due to their longer half-lives. However, ^{109}Ag may arise from the Ag impurity in the the aluminium foil and will be investigated further by using a different wrapping in the next irradiation. The process of making metal contacts on the irradiated sample is underway.

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