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# NTD-Ge Production in the LUMINEU Experiment Using Cryogenic Detectors for Rare Event Searches and Other Applications

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## Abstract

To cope with the future large demand on neutron-transmutation-doped germanium of (NTD) sensors, our groups in LUMINEU started a new production line for NTD-Ge. This paper contains details on the NTD-Ge production, resistance measurement and a comparison of the performance in terms of noise and signal-to-noise ratio with an existing sensor contacts. This demonstrates our ability to produce NTD sensors for the desired range of working temperature.

## Keywords

Thermal sensor, Cryogenic, Dark matter, Double beta decay

## 1 Introduction

Neutron-transmutation-doped germanium thermistors (NTDs) are still the baseline solution of heat channel measurements for a certain number of experiments searching for Neutrinoless Double Beta Decay (0νDBD) or Dark Matter (DM) such as LUMINEU, CUPID-Mo and EDELWEISS-3 projects for example [1,2,3]. This choice is motivated by their robustness, reliability, ease of use over a large range of temperature and large dynamic range in energy.

In the past, Haller and Beeman [4] from Lawrence Berkeley National Laboratory (LBNL) were producing NTDs. Their NTDs have outstanding performances in terms of sensitivity and reproducibility, satisfying the needs of present large-scale experiments such as EDELWEISS, CUORE and CUPID-Se [5, 6]. But to our knowledge, this team completely stopped their production of NTDs.

Our NTD development is motivated by the requirements of perennial and reproducible large-scale production. Following the development plans described in a previous paper [4], we pursue the processing of such sensors to get the optimal doping, keeping in mind the need for improvements in energy resolution and threshold (for DM detection in particular). We present in the following the irradiation parameters of wafers, the  $R(T)$  dependences of some of them

and the relative sensitivity between some of our NTDs and a reference NTD produced at LBNL for CUORE.

## 2 Production Steps of New Series of NTD-Ge for LUMINEU

The irradiation of thin wafers of germanium by thermal neutrons leads to a very uniform p-type doping by the transmutation of the nucleus in these wafers [4]. Our production is based on two phases of irradiation to get optimal dose. In the first exposure, the high-purity Ge single-crystal (HPGe) wafers were intentionally under-irradiated. The fine adjustment was realized in a complementary irradiation controlling the total neutron exposure.

Characterizations at room temperature, 77, 4 K and down to very low temperature from 200 to 20 mK, of NTD samples extracted from wafers after the first neutron irradiation, were reported in [7]. They show high homogeneity of the doping, high quality of the Ohmic contacts and a range of temperature of use between 120 and 60 mK for this first batch of NTDs according to the neutron dose. The complementary irradiation was realized to work in the range of 15–30 mK [8].

The first irradiation demonstrates that discrepancy between desired and real doses could rise up to 25%. So AlCo wires joined the wafers during the irradiation.

Table 1 presents for each wafer the total neutron fluence extracted from the AlCo activities measured after the first and the second irradiations. The uncertainty on the dosimeters' activity measurement is in the range of 0.4%.

Wafer	Total neutron fluence in $10^{18} \text{ n cm}^{-2}$	$R_0$ in $\Omega$	$T_0$ in K	$R$ @ 20 mK in $M\Omega$
658	3.44	3.48	4.43	10
825	3.44	7.42	2.41	4.34
606	3.48	3.45	4.23	7.1
807	3.48	5.70	3.28	2.08
622	3.51	5.44	2.34	2.76
809	3.51	4.25	3.11	1.1
660	3.53	3.52	4.31	8.3
628	3.54	3.35	3.62	2.3
641	3.55	3.52	3.56	2.2
806	3.56	3.99	2.98	0.79

Table 1 Total neutron exposure for the two irradiations relatively to the wafers

$R_0$  and  $T_0$  are parameters for the Efrös and Shklovskii law fitting the resistance curves for NTD sensors of a geometry given in Fig. 1. Last column is the value of  $R$  at 20 mK

The metallization of our second irradiated NTDs became closer to the “standard” procedure described by Haller et al. [4, 8]. Indeed, a first annealing (600 °C during 2 h) was realized on the doped material before boron implantation to reconstruct the crystalline structure. Boron implantation took place at CSNSM in Orsay, with three energies, 5, 15 and 25 keV, for a flat impurity profile [9] and at 7° from the crystallographic axis of the  $\langle 100 \rangle$  oriented wafers to avoid channeling which would induce a higher  $1/f$  noise.

Pd and Au layers of 6 and 500 nm thickness, respectively, were evaporated under high vacuum at the technical platform Minerve of IEF in Orsay. A second annealing (at 250 °C for 6 h) activated the implanted ions.

### 3 Resistivity Measurements

In order to characterize the temperature dependence of the resistivity of the different wafers, NTD chips have been cut and measured in dilution refrigerators. The dimensions of the chips are  $3.5 \times 3 \times 0.5 \text{ mm}^3$ . Electrodes of  $3 \times 0.2 \text{ mm}^2$  area are produced along the two opposite edges of one of the  $3.5 \times 3$  surfaces at 3 mm from each other (see Fig. 1) as described in Sect. 2. Figure 2 (left) presents the  $R(T)$  curves for NTD sensors of different wafers. Figure 2 (right) presents the same curves in  $\ln(R)$  versus  $1/\sqrt{T}$  format. The straight lines in the latter demonstrate that these NTDs follow perfectly the Efrös and Shklovskii law [10]:

$$R = R_0 \cdot \exp\left(\sqrt{T_0/T}\right)$$

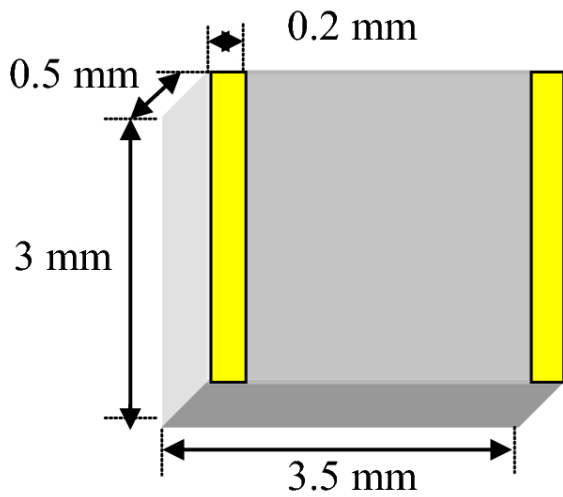


Fig.1 : NTD chip geometry

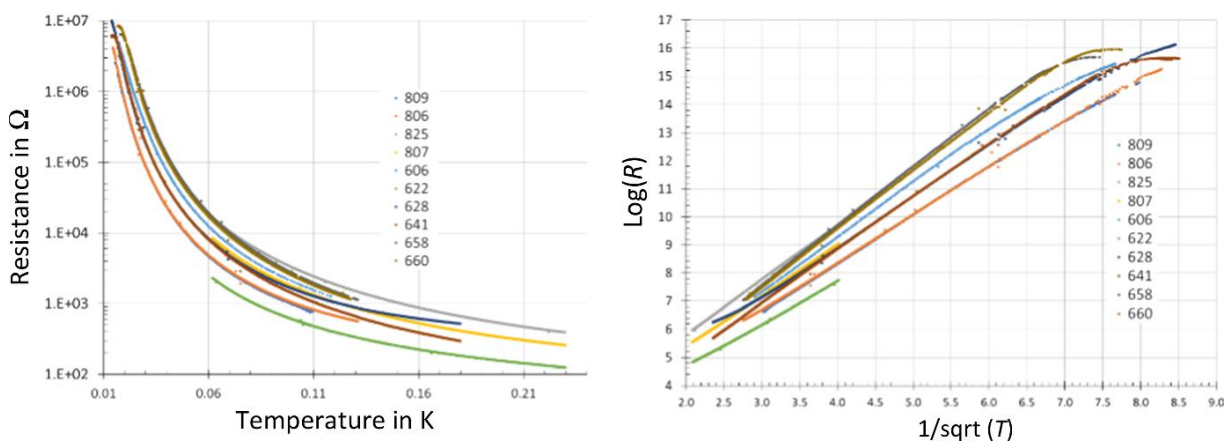


Fig. 2 : Left: resistance versus temperature for NTDs extracted from different wafers. Legend corresponds to wafer numbers. Errors on the resistivity measured with a Wheatstone bridge TRMC2 (Air Liquide) are lower than 1%.

Right:  $\log(R)$  versus  $1/\sqrt{T}$  plot for the same measurement

A saturation is observable for high resistance values ( $\geq 3 \text{ M}\Omega$ ) in Fig. 2. This is due to a limitation of the measurement range of the resistance bridge. As seen in Fig. 2 (left), the resistivity increases steeply upon cooling below 30 mK. The desired impedance depends on the temperature of the front end electronics: 1–10 M $\Omega$  for a FET at 110 K. Owing to the complementary irradiation, present sensors are useable in the temperature range 15–30 mK. More accurate measurement could be taken with the use of a bias amplification, but this requires more dedicated channel; nevertheless, the present measurement allows a reliable extrapolation in the range of interest.

#### 4 Heat Signal and Comparison with a Reference NTD

To compare the performances, two NTD thermal sensors produced in the framework of LUMINEU, extracted from two different wafers, have been glued, together with a NTD34B produced at LBNL as a reference, on a single 400 g  $\text{Li}_2\text{MoO}_4$  absorber (see Fig. 3) constituting a 3-NTD calorimeter. So it is possible to compare the pulse height, the time constant and the resolution of such sensors. Figure 3 (right) shows the pulses obtained with these three sensors for a current event. This amplitude ratio stays the same for any event; no position dependence has been observed. Figure 4 presents a background spectrum obtained in an aboveground laboratory with this detector.

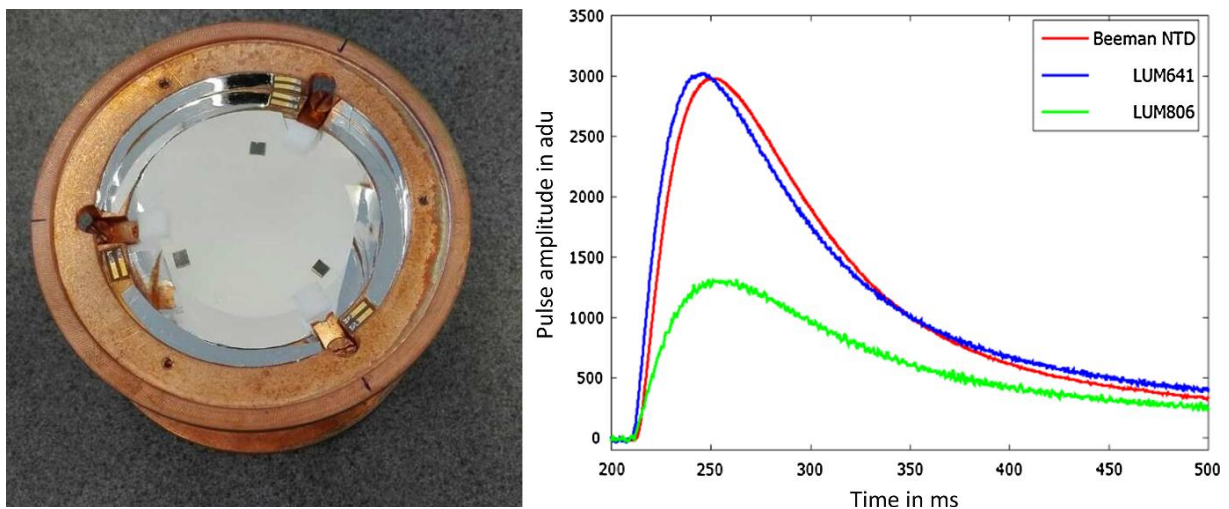


Fig. 3 : Left: 3 different NTDs glued on a single 400 g LMO crystal in its copper holder. Right: pulses of these 3 NTDs for a current event. Small difference in rise time (22, 20 and 26 ms resp.) is due to a not perfectly reproducible gluing

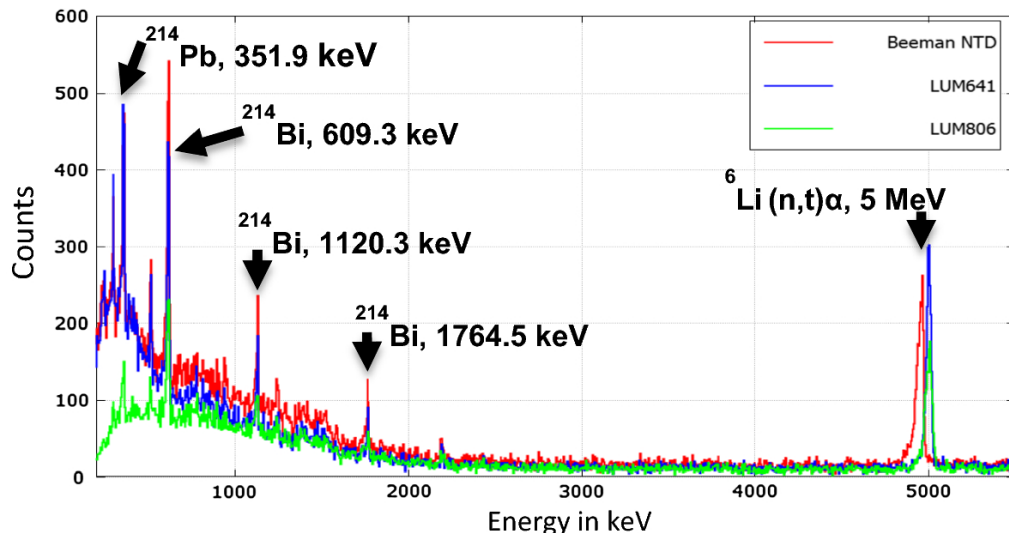


Fig. 4 : Background spectra obtained in an aboveground lab with 3 NTDs glued on the same LMO crystal (40 h). The sensitivity being lower for LUM806, the pulse-shape-cut induces a reduction of the event rate for this sensor. The energy calibration is done with gamma rays. The energy scale for alpha particles is different due to the different thermal quenching. The Li-peak position is slightly different for the three NTDs because of the nonlinearity due to different working points and different thermal couplings

Table 2 shows sensitivities and resolution that were obtained with the different NTDs. These results demonstrate that NTD 641 has the same sensitivity and resolution as LBNL NTD.

NTD	Total neutron fluence in $10^{18} \text{ n cm}^{-2}$	Sensitivity in nV/K	Baseline FWHM in keV	$^{214}\text{Bi}$ , 609.3 keV peak FWHM	$^{214}\text{Bi}$ , 1764.5 keV peak FWHM
34B	3.6	68.8	6.4	10.6 (7)	12 (1)
641	3.55	68.8	6.0	10.1 (7)	10 (1)
806	3.56	30.2	12.2	12 (2)	13 (3)

Table 2 Comparison of sensitivity and resolution for NTD 641 and 806 (our prod.) and NTD 34 B (LBNL prod.) glued on the same 400 g LMO crystal tested aboveground

## 5 Conclusion

Some wafers have been submitted to a complementary neutron irradiation for a fine tuning of the doping level.  $R(T)$  curves indicate the doping is optimized for standard working temperature of rare event search experiments in the range of 20 mK and the good quality of the electrical contacts. Comparison data taking with a NTD produced at LBNL shows similar performance in terms of sensitivity and resolution.

The results presented here demonstrate our ability to produce NTD thermistors. We are presently able to provide NTD sensors to experiments working between 10 and 30 mK.

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