

LOW TEMPERATURE PROPERTIES OF NTD GE: BEST CHOICE FOR CUORE EXPERIMENT

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A new series of NTD Ge thermistors has been produced by the Lawrence Berkeley National Laboratory in the framework of the CUORE (Cryogenic Underground Observatory for Rare Events) experiment. The electrical characteristics of the new materials have been measured at the Department of Physics of the University of Florence. The goal of this study was the choice of the best type of thermistor to use in the CUORE experiment. We report also the electrical resistivity, electron specific heat and electron-phonon decoupling of the NTD31 Ge material selected for CUORICINO (single CUORE module, which has become operative at the end of 2002).

1. Introduction

The main goal of CUORE (Cryogenic Underground Observatory for Rare Events) is the detection of a neutrinoless double β decay¹. The CUORE detector will consist of an array of 1000 closely packed low temperature TeO_2 bolometers. The array will consist of 25 towers containing 10 cells of 4 bolometers each.

The investigated decay is $^{130}\text{Te} \rightarrow ^{130}\text{Xe} + 2 e^-$ (transition energy 2528 keV). The decay should take place in the TeO_2 absorbers. The isotopical abundance of ^{130}Te is 34% of total Te atoms².

Each bolometer consists of a TeO_2 absorber of $5 \times 5 \times 5 \text{ cm}^3$ dimensions and a thermal sensor (a chip of Neutron Transmutation Doped Germanium of low specific heat³ and high sensitivity).

The CUORICINO experiment, consisting of a single CUORE tower with

44 5x5x5 cm³ and 18 3x3x6 cm³ absorbers and NTD31 Germanium thermistor as thermal sensor, is presently running in the Laboratori Nazionali del Gran Sasso.

In this paper we report on the production of 9 new types of NTD Ge for the CUORE project (numbered in ascending order from 33 to 38, and 33B, 34B, 35B; the latter three being series 33–35 that have received a second neutron irradiation); we investigated the properties of these new NTD Ge sensors, as well as those of NTD 31, aiming to select the best one for CUORE. Furthermore, for NTD 31 we report electronic specific heat and electron-phonon decoupling.

2. NTD Germanium

NTD Germanium is produced by irradiating an ultrapure Ge crystal by means of a flux of thermal neutrons. Ge nuclei capture the neutrons and form various radioactive Ge isotopes, which subsequently decay into As, Se and Ga⁴. Due to the isotopical composition of Ge and to the neutron cross section, the resulting doping is of p-type. The neutron capture cross section for Ge nuclei is sufficiently low that the neutron flux can be considered constant through all the Ge crystal, resulting in a very uniform distribution of dopants in the crystal.

Such a doped semiconductor, at low temperatures, has a resistivity dominated by Variable Range Hopping effect⁵:

$$\rho(T) = \rho_0 \exp\left(\frac{T_0}{T}\right)^\alpha \quad (1)$$

where ρ_0 , T_0 and α are constants. α depends on the shape of the density of states of the charge carriers at the Fermi surface. For NTD Ge it is believed that the density of states goes to zero at the Fermi surface as a parabola, resulting in a $\alpha = 0.5$ ⁵. T_0 is related to the doping level of the thermistor, and it increases as doping decreases; ρ_0 depends on the intrinsic properties of the Ge lattice and on stresses applied to the sample, and it does not depend on the doping level⁴.

At very low temperature, the phenomenon of electron-phonon decoupling, which is well known in metals⁶, is present in NTD Ge. Electron-phonon decoupling is due to the fact that electrons, do not have enough states available to excite a phonon, or viceversa. An empirical model (Hot Electron Model^{4,7}) describes the electron and the phonon systems as com-

municating via a thermal conductance G_{e-p} , which represents the decoupling between the two systems.

Considering a degenerate electron gas, the number of states available at the Fermi surface increases as $N^{\frac{1}{3}}$, N being the total number of electrons in the gas. In this rough approximation one would expect the G_{e-p} in NTD Ge to increase with the increase of doping (i.e. decrease of T_0).

Electron-phonon decoupling tends to worsen the detector performance in the low temperature range, since together with the electron heat capacity it changes the pulse shape and rise time.

3. Experiments and Results

3.1. Sample Production

Each pure Ge sample was irradiated by a flux of thermal neutrons and then annealed at about 400°C for six hours in order to "repair" damage in the crystal structure. Electrical contacts were made by heavily doping two sides of the sample with B^+ ions ($3 \cdot 10^{14} \text{ cm}^{-2}$) to a depth of about 200 nm. A layer of Pd (about 20 nm) and one of Au (about 400 nm) are sputtered onto the two surfaces. The sample is then annealed at 250°C for one hour.

3.2. Electrical resistivity

Low temperature resistivity of the new NTD samples was measured in a dilution refrigerator, in the temperature range 26 – 200 mK.

Each sample (chip of about $3 \times 3 \times 1 \text{ mm}^3$) was glued on a copper holder in thermal contact with the mixing chamber. Electrical insulation and good thermal contact between holder and sample was obtained by interposing a thin foil of mylar ($4 \mu\text{m}$). The electrical contacts were made with two thin gold wires ($50 \mu\text{m}$ in diameter, about 2 cm long) ball-bonded to each Au surface. 2 manganine wires were soldered to each gold wire. An LR-700 AC resistance bridge was used to measure the resistance of the sample. A calibrated RuO_2 thermometer and an AVS-47 AC bridge were used to measure the temperature of the samples. Each electrical lead to the experiment was RF filtered on the top of the cryostat.

In Table 1 we report the results of the measurements carried out on the NTD samples.

Table 1. Data of the 9 NTD series produced for CUORE, and of NTD 31; doping is the compensate doping: #Ga-#As-2#Se.

NTD family	Dimensions [mm ³]	T_0 [K]	R_0 [Ω]	Doping [cm ⁻³]
33	2.9x1.6x6	12.44 ± 0.08	0.328 ± 0.001	5.0E16
34	2.9x1.6x6	10.88 ± 0.05	0.278 ± 0.001	5.3E16
35	2.9x1.6x6	9.27 ± 0.08	0.342 ± 0.001	5.6E16
36	2.9x1.6x6	7.07 ± 0.05	0.208 ± 0.001	5.9E16
37	2.9x1.6x6	5.41 ± 0.07	0.281 ± 0.001	6.0E16
38	2.9x1.6x6	4.66 ± 0.06	0.283 ± 0.001	6.0E16
31, ⁸	2.9x1.6x6	4.1	0.164	6.6E16
33B	3x3x1	4.25 ± 0.04	0.830 ± 0.001	6.2E16
34B	3x3x1	4.23 ± 0.04	0.835 ± 0.001	6.4E16
35B	3x3x1	3.07 ± 0.03	0.949 ± 0.001	6.8E16

3.3. Specific heat and Electron-Phonon decoupling of NTD31

The Debye temperature of Ge is 370 K⁹. Hence, at very low temperature, its specific heat³ is due to the charge carriers: $c(T) = \gamma T$ with $\gamma = 1.05 \cdot 10^{-6}$ J K⁻² cm⁻³. The total heat capacity of a NTD 31 thermal sensor (the dimensions of the thermal sensor are 3x3x1 mm³) at 10 mK is about 4% of that of the absorber¹⁰.

We have measured the electron-phonon decoupling in NTD 31 Ge⁸; this effect becomes important below a temperature of $T_d \approx 30$ mK. We expect this temperature T_d to decrease with increase of doping, but further measurements on different types of NTD Ge are necessary.

4. Conclusions

In the frame of the CUORE experiment, 9 new NTD Ge materials have been produced. On the basis of the electrical characteristics ($T_0 \approx 3$ K) the NTD 35B seems to be the best choice for CUORE.

Further measurements on charge carriers specific heat and electron-phonon decoupling will be necessary before the final choice.

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