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Physica B 219&220 (1996) 741–743

PHYSICA B

Particle detection and non-equilibrium phonons: Experience with large germanium crystals and NTD Ge thermistors

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Abstract

We have studied particle detectors consisting of neutron transmutation doped (NTD) Ge phonon sensors attached with a eutectic bonding process to large mass germanium crystals. These thermistors remain one of the most performant temperature sensors at temperatures as low as 20 mK. We summarize the experimental evidence for the significant role of non-equilibrium phonons in their observed behavior. However, the difficulties of forming a high transparency interface and the lack of inelastic channels appear to limit their effectiveness as non-equilibrium phonon sensors.

1. Particle detection and non-equilibrium phonons

We are developing low temperature particle detectors for a search for dark matter particles [1]. In a first generation of detectors, we are using ultrapure (n_a, $n_d \approx 10^{11}$ cm^{-3}) germanium crystals of 60 g (soon to become 160 g) operated in vacuum, typically at 20 mK. We sense the phonons created by a particle interaction with neutron transmutation doped (NTD) germanium thermistors [2] of a few mm^3, which are eutectically bonded to the main crystal [3]. A simultaneous measurement of the ionization [4] allows a discrimination between nuclear and electronic recoils, a crucial tool to reach the necessary sensitivity.

Phonons produced by particle interactions at this low temperature take a long time to thermalize [5] and it may be advantageous to attempt to detect them while they are still out of equilibrium and carry information about the interaction: e.g., position, nature of the recoil, and potentially its direction [6]. Cabrera describes in an accompanying paper sensors designed specifically for this purpose. In this article we summarize our experience with NTD germanium sensors. Although designed primarily to measure the temperature rise of the crystal, they appear to be sensitive to high energy phonons.

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SSDI 0921-4526(95)00871-3

2. Evidence for non-equilibrium phonon sensitivity of NTD Ge

At the low temperatures at which we operate, thermal phonons tend to decouple from charge carriers in the thermistors [7] as the effective electron–phonon conductance displays a rapid temperature dependence ($\approx T^5$). On the contrary, phonons of energy greater than about 1 K seem to readily couple and out-of-equilibrium phonons play an important role in the detection process. This is suggested by a number of experimental facts:

(a) We observe very fast rise times for particles impinging directly on one of the sensors and the decay time of a few milliseconds can be readily explained by the heat capacity of the thermistor and the effective electron–phonon conductance at the operating temperature. It can be shown that the ionization produced by the particle interaction in the NTD is a negligible component of the observed pulse height.

(b) For events occurring in the main crystal, typically of 60 g mass, we observe rise times of a few hundred microseconds. If the coupling to the sensor was purely thermal, we would expect a rise time similar to the relaxation time observed in the previous case.

(c) Moreover, this rise time is dependent on the interface [8]. We observe two time constants when we use thin gold–germanium eutectic interfaces [3] (primarily to minimize the thermistor stress), while thin glue interfaces ($\approx 25\,\mu$m of silver epoxy) display a single slower rise time. We interpret this fact as evidence for higher phonon transparency in the eutectic case.

(d) We consistently observe two decay time constants, one of a few milliseconds, which is strongly bias dependent, and a second one of a few tens of milliseconds, which is compatible with the thermal time constant of the crystal. We estimate the latter from the Debye heat capacity of the crystal, the observed heat capacity of the thermistors and the measured conductance to the thermal heat sink. The first decay time constant could be interpreted either as thermistor relaxation from its heating by the non-equilibrium phonon component or as a thermal effect (due to additional heat capacities weakly coupled to the crystal, e.g., metal films or adsorbed gas on the crystal surface).

(e) Finally, for small crystals we observe significant position dependence of our signals.

It is possible to model [8] this behavior in terms of a direct coupling of a small fraction (a few percent per bounce) of the impinging phonons with the thermistor charge carriers. Unfortunately our current set of data is not complete enough to fully identify the origin of the four time constants and in particular to unambiguously determine the reverberation time of high energy phonons in the crystal.

3. Limitations of NTD Ge as non-equilibrium sensors

We have attempted to further enhance the sensitivity of our NTD thermistor to non-equilibrium phonons, as this would clearly be beneficial for our particle detection goals. We have not been successful in significantly enhancing the non-equilibrium component, which typically represents half the pulse height for detectors with thin eutectic interfaces.

It does not seem that this problem arises from a short phonon lifetime in our devices. Our crystals have very small dislocation densities. We have minimized the metallized area on the surface of our crystals. They represent only a fraction of a percent of the total area. We attempt to minimize contamination of the surface by organic material and we have no evidence that gas is significantly adsorbed on the crystal surface. Because we collect ionization, the crystal surface is implanted with boron (4000 Å deep, $10^{14}\,\mathrm{cm}^{-2}$) which forms a low density metallic contact. If we trust at least as an order of magnitude the Pippard formula for electron–phonon interaction in a metal, this should not be a problem. If our interpretation is correct, the phonon lifetime is at least equal to the first rise time of our pulses, typically half a millisecond.

The interface between the main germanium crystal and the NTD Ge thermistor is likely to be a significant barrier for phonons of a few 100 Å wavelength. However, improvements in our eutectic bonding do not seem to have a major impact. We are now able to work with gold layers as thin as 300 Å deposited on each of the two chemomechanically polished germanium surfaces to be bonded ($\approx 10\,\mathrm{mm}^2$ area). The two pieces are pressed together and brought to the eutectic temperature (370°C) in an inert atmosphere, and then cooled slowly over a period of several hours. High resolution transmission electron microscopy shows that the gold precipitates in small crystals separated by a few microns and that the germanium regrows epitaxially with minimal distortion of the lattice [3]. Moreover, the transmission of ballistic phonons of comparable wavelength has been investigated in collaboration with Wolfe and gives a typical transmission between 25% and 65% [9]. Although we cannot guarantee that the interfaces are as good on our particle sensing devices, we do not observe any significant improvement for gold thicknesses below 1000 Å per side.

This may indicate that a third mechanism is also at play. In order to effectively act as a non-equilibrium sensor, our thermistors should have a high absorptivity for high energy phonons. We suspect that this is not the case and that phonon interactions in the NTD medium are mostly elastic, dominated for instance by the resonant scattering on the two-level systems formed by neighboring impurity centers [10] which may share one electron. This would lead to a strong diffusive behavior and could explain why NTD Ge appears to be quite sensitive to high energy phonons when directly hit by a particle and less sensitive when phonons impinge from the outside. Not enough inelastic channels are present (at least compared to a metal) and the large diffusion leads to a reflection of most of the phonons.

In conclusion, the NTD Ge thermistors remain one of the most performant temperature sensors at temperatures as low as 20 mK, and non-equilibrium phonons play a significant role in their observed behavior. However, the difficulties of forming a high transparency interface and the lack of inelastic channels appear to limit their effectiveness as non-equilibrium phonon sensors.

Acknowledgements

This work was supported by the Center for Particle Astrophysics, a National Science Foundation Science and Technology Center operated by the University of California under Cooperative Agreement No. AST-912005 and by the Department of Energy under the contract DE-AC03-76SF00098.

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