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PARTICLE DETECTION WITH SEMICONDUCTOR THERMISTORS AT LOW TEMPERATURES.

N.Wang[†],J.Beeman,A.N.Cleland[†],A.Cummings[†],E.E.Haller[*],
A.Lange[†],R.Ross[†],B.Sadoulet[†],H.Steiner[†],
T.Shutt[†],F.C.Wellstood[†]

Lawrence Berkeley Laboratory
and
Department of Physics[†]

Department of Material Science and Mineral Engineering[*]
University of California, Berkeley CA 94720

Abstract

We have studied the use of neutron transmutation doped (NTD) Ge thermistors as phonon sensors at dilution refrigerator temperatures. In addition to measuring their thermal and electrical properties, we have observed pulses generated by X-rays incident on a thermistor thermally well-clamped to a heat sink. We find that during these pulses the lattice temperature of the thermistor apparently does not change. This surprising result is interpreted as evidence of a strong coupling between the high energy phonons generated by the interaction and the charge carriers in the thermistor. Additionally, these phonons appear to be absorbed within a fraction of a millimeter. We conclude that these thermistors have several desirable properties for a good high energy phonon sensor. It remains to be seen, however, if a composite detector consisting of a large crystal and attached phonon sensors can be developed.

1 Introduction.

When a particle interacts in a semiconductor crystal such as Ge, the immediate result can be both ionization in the form of electron-hole pairs, and phonons generated by the recoil of the nucleus. At low temperatures, detection of the phonons may provide a method of measuring the interaction[1] which has the following advantages:

- Most of the deposited energy (at least 2/3 before recombination of electrons and holes for the case of a particle interacting with a nucleus in the crystal) appears in phonons. In particular, the measurement of phonons may allow the efficient detection of a nucleus recoiling with energies (of a few keV or less) for which there is very little ionization. This could make possible many fundamental physics measurements, such as the search for dark matter particles[2] or the detection of coherent neutrino scattering[3].
- By working at low enough temperatures, the thermal fluctuations should be small enough to allow high energy resolution. McCammon, Moseley and Mather have demonstrated[4] this for the case of X-rays interactions, and many important improvements in X-ray and nuclear spectroscopy, X-ray astronomy and particle physics (e.g. neutrinoless double beta decay[5]) should be obtainable.
- Finally, phonon detection may result in dramatically lower backgrounds for the detection of rare processes such as dark matter interactions, for several reasons. The ballistic[6] nature of these phonons (see discussion below) may allow the determination of the position of an interaction. Also, the simultaneous measurement of both the phonon and ionization components of the total energy deposition[7] may provide a method for differentiating between an interaction that has occurred on a nucleus, and one that has occurred on an electron - which is the case for most radioactive background processes. Finally, there is even the remote possibility of measuring the direction of the initial recoil[8].

The most immediate method for detecting phonons is to let them thermalize and to measure an increase of the temperature of the sample. While this calorimetric method would likely retain its intrinsic sensitivity and accuracy as the temperature is decreased, the response of the thermistors becomes very slow. This method is also intrinsically incapable of detecting the ballistic properties of the phonons, something which may be essential to have fast, position-sensitive and perhaps direction-sensitive detectors.

However, as first emphasized by H.Maris[9], the phonons created in the initial "fire ball" around the interaction will down-convert to lower energy phonons with a lifetime inversely proportional to the fifth power of their energy. This means that for practical purposes they will stop down-converting at an energy of the order of 1 meV, which is many orders of magnitude greater than the thermal energy of the crystal. Their mean free path then becomes of the order of a centimeter and they propagate "ballistically". The ballistic nature of the phonons produced in particle interactions has been recently unambiguously demonstrated by the Von Feilitzsch group[10]. If, as was first advocated by Cabrera[6], suitable sensors on the surface of a crystal could detect and absorb these phonons before they bounce around too much and thermalize, it may be possible to build larger detectors and have access to much more information to reject the background[8] than is possible with purely calorimetric detectors.

Two basic methods have been proposed for detecting these 1 meV phonons. One method involves either superconducting films or tunnel junctions, both of which respond when phonons have enough energy to break Cooper pairs. An alternative method uses "ordinary" semiconductor thermistors, which can be sensitive to high energy phonons.

We report here recent results obtained around 20 mK which show that NTD Ge thermistors[11] are indeed sensitive to the high energy phonons produced by X-rays. The coupling between these phonons and the charge carriers in the thermistor is strong, while we have shown in a previous work[12] (summarized in section 2) that thermal phonons at these temperatures couple very poorly and that, as a consequence, the signal rise-time of a temperature change is extremely slow (several milliseconds). Section 3 describes our experimental setup. Section 4 describes results obtained when X-rays interact directly in a thermistor and compares that response with the thermistor's response to electrical pulses. Section 5 shows what happens when phonons are created in a region of the crystal lattice outside the thermistor. These data allow us to make a rough estimate of the mean free path of the phonons which couple to the charge carriers in our NTD Ge material. In section 6, we give an interpretation of our results and conclude in section 7 with the implications it has for the design of composite ballistic-phonon detectors.

2. Electrical and Thermal Properties of Neutron Transmutation Doped Ge at 20 mK.

After our initial results presented at the 1987 IEEE Symposium on Nuclear Sciences[13], we have continued to study in detail the electrical and thermal properties of neutron transmutation doped Ge. This doping method consists of exposing an ultra-pure single crystal of Ge to thermal neutrons. The neutron rich Ge isotopes formed by neutron capture decay to dopant impurities (Ga, As and Se), which should have excellent spatial uniformity. This fact is important since the dopant concentration has to be very close to the metallic transition. The net dopant concentration (i.e. the difference n_A-n_D between acceptors and donors) is 6.64 10^{22} m^{-3} for the material that we are using (NTD#12)[11]. Thermistors made out of this material have the following properties:

1) Their resistance at zero bias power is strongly dependent on the temperature, varying by more than 4 orders of magnitude between 20 mK and 70 mK (cf ref [13]).

2) Unfortunately, in order to measure a resistance, some bias current has to be used. Biasing powers as low as 10^{-14}W in a sample of 0.2mm^3 decrease the resistance, and therefore the sensitivity, appreciably. Such an effect has been seen at higher temperatures but not with such a magnitude[4].

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3) We have been able to show[12] that the extreme nonlinearity of the I-V curve results from the very weak coupling between the charge carriers in the thermistors and the thermal phonons. We can describe this effect by an effective thermal conductance per unit volume which we measure to be given by

$$g \approx 2.4\ 10^{8}\ T^{5}\ \mathrm{W\ K^{-1} m^{-3}}$$

with T measured in Kelvin. At 20 mK, for our 1x1x0.2 $\mathrm{mm^3}$ thermistor, this gives a thermal conductance $G \approx 1.5\ 10^{-10}\ \mathrm{W\ K^{-1}}$.

Not only does such a mechanism satisfactorily describe the static nonlinearity of the I-V curves measured at base temperatures between 18mK and 40mK, but it also accounts for the dynamic behavior of the system observed when a small electrical pulse is applied to the thermistors.

We have also shown that the thermal conductivity within the lattice itself due to ~20mK thermal phonons is excellent ($G > 10^{-9}\ (T/20\mathrm{mK})^3\ \mathrm{W\ K^{-1}}$). The long mean free path implied by this observation is in good agreement with the poor coupling between the phonons and the charge carriers.

4) Preliminary results show that the effective heat capacity of the charge carriers varies rapidly with temperature. The two thermistors also appear to have different heat capacities, C. At a carrier temperature of 27 mK, thermistor a has $C=3\ 10^{-13}\ \mathrm{J\ K^{-1}}$ while thermistor b has $C=3\ 10^{-12}\mathrm{J\ K^{-1}}$. We do not as yet understand this discrepancy.

The fundamental reason for the observed decoupling is presumably that the phase space available to an electron after an interaction with a very low energy phonon ($\approx 2\mu$eV at 20mK) is extremely small. Therefore any transition probability is very small, even if the matrix element does not vary strongly with phonon energy. If this interpretation is correct, this would be a general effect roughly independent of the type of semiconductor thermistor used.

The main practical consequences of our observation are that extrapolating down to low temperature does not increase the sensitivity of semiconductor thermistors as much as could have been hoped, and that calorimetry or more generally the measurement of a temperature rise at low temperature is very slow.

On the other hand, if the phase space argument given above is correct, the detection of high energy phonons by these thermistors will not be significantly impeded and will be fast. The purpose of the experiments described in the present article was to test that proposition.

3. Description of the setup.

Since we intend eventually to use these sensors to detect particles, we have chosen to generate these high energy phonons[9] with 60 keV X-rays from an Americium 241 source, incident directly on the NTD material. The alpha particles from the source are stopped by 1mm of aluminium, which also attenuates the 18 and 14keV X-ray lines so that they do not dominate the count rate. Note that ionization is also produced in the sample and this may complicate the analysis. However, as shown below in section 6, the effect of electrons and holes is expected to be small.

Since our goal is to test whether high energy phonons couple directly to the charge carriers in the thermistors, we use two thermistors sharing the same lattice. One thermistor acts as the high energy phonon sensor while the other monitors the temperature of the lattice. For this particular experiment, we have chosen to thermally clamp the lattice as well as possible to the heat sink. In that way, the thermalized phonons will mostly escape to the sink before having a chance to couple to the charge carriers. Thus our test is insensitive to the low temperature phonon component.

The sample arrangement is shown in Fig. 1. The NTD Ge chip has the dimensions 1x3x.2 $\mathrm{mm^3}$, and is cut out of uniformly doped material. Two sets of contacts on the chip form two thermistors. Both thermistors have an area of $1\mathrm{mm^2}$ and are separated by 1mm so as to minimize the electrical cross talk. The contacts are made by implantation of boron ($3\ 10^{14}\ \mathrm{cm^{-2}}$) about 2000 Å deep from both sides, which provides uniform metallic contacts to the Ge. A layer of Pd approximately 200 Å is sputtered onto the p^+ boron layer and serves to bond the semiconductor to 4000 Å of Au sputtered, in turn, on top of the Pd. Electrical contact is then made to the Au (as described below.) The sample is thermally clamped by a $1\mathrm{mm^2}$ patch of silver epoxy. The measured conductance between the lattice and the sink is $10^{-9}\ \mathrm{W\ K^{-1}}$ at 20 mK. This clamp is below thermistor a. The conductive epoxy is isolated electrically from (but thermally connected to) a Cu sample holder by a copper-Kapton-copper sandwich (the Kapton thickness is 200 µm and the Cu area is about $1\mathrm{cm^2}$) which is indium soldered to the sample holder. The holder is then screwed onto the mixing chamber (which is the coldest point) of a dilution refrigerator. In order to eliminate any extra heat loads to the sample, aluminum wires 17.5µm in diameter are bonded ultrasonically to the three Au patches that are not heat sunk; Al is superconducting at the operating temperatures and therefore allows little heat to flow through the wires to the sample; the thermal conductance of such a wire 1 cm long at 20 mK is only about $2\ 10^{-12}$ W/K. A Cu wire 25 µm in diameter is soldered with Sn-Pb alloy to the heat sunk patch. The sample is enclosed in a Cu box which is also heat sunk to the mixing chamber, and acts as an electromagnetic shield. Figure 2 shows the configuration used to irradiate thermistor b.

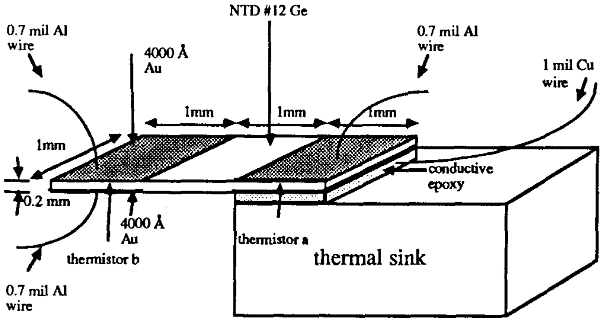

Figure 1. *Schematic diagram showing the configuration of the thermally clamped double thermistor. The entire Ge chip is uniformly doped by neutron transmutation.*

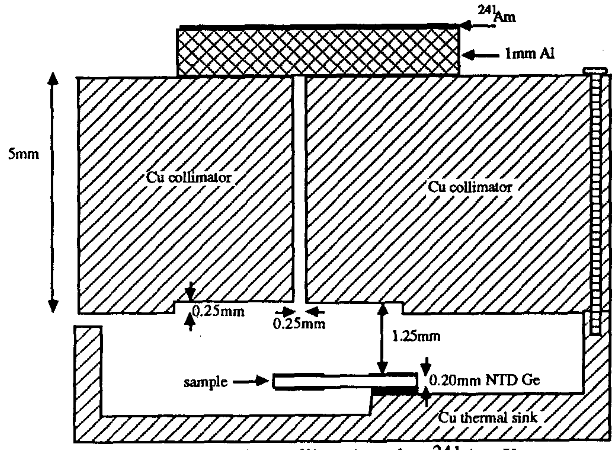

Figure 2. *Arrangement for collimating the* ^{241}Am *X-rays onto thermistor a.*

Figure 3 shows the equivalent electrical circuit for a thermistor in one of our measurements. The thermistors are biased through a large load resistort R_{bias} ($=10^7\Omega$) which approximates a constant current bias. Since our thermistors are sensitive to powers of order 10^{-14} W, the refrigerator and all the amplifiers and the bias circuit are placed inside a screen room and powered by batteries. RF filters (with about 1MHz cutoff frequency) are used on all the leads to the sample. In the simple arrangement used, the amplifiers are located outside of the refrigerator and each signal wire is affected by a significant stray capacitance to ground ($C_s \approx 660$pf and 900pf for a and b respectively), limiting the rise time of our signals to approximately 150µs. The capacitance between the 2 signal wires is also of the same order of magnitude and leads to an effective cross talk of 15% for pulses faster than 150µs.

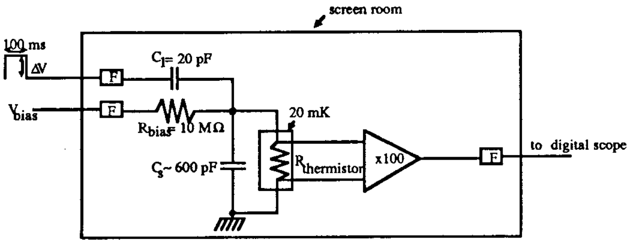

Figure 3. *Equivalent electrical circuit for a thermistor in our experiment*

By injecting an electric pulse through a small capacitor (C_I), it is possible to calibrate the response of the thermistor to the deposition of a given energy in the charge carriers. In section 4 we describe how this allows us to estimate the efficiency of the coupling of the phonons to the charge carriers.

4. Deposition of energy in the thermistor volume.

In this section we consider the measurements made when thermistor b was irradiated directly by the X-ray source, as shown in Fig. 2. In this case the phonons produced in the X-ray interaction can themselves interact directly with charge carriers. These charge carriers can then be electrically collected.

Figure 4 shows an example of pulses obtained in this configuration. The temperature of the thermal sink was 18 mK and the bias current was 2 nA.

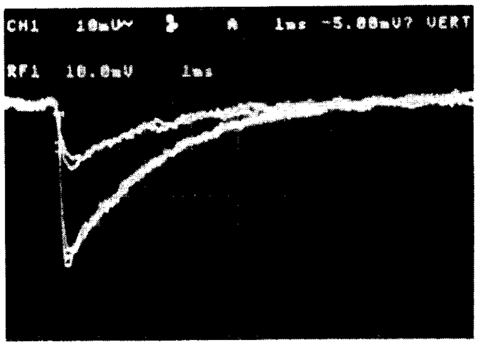

Figure 4. *Pulses from X-rays of ^{241}Am incident on thermistor b at 18 mK. We chose typical pulses corresponding to the two peaks shown in Figure 5. The vertical scale is 100 μV/div, and the horizontal scale is 1 ms/div.*

The rise time of the pulses is limited by stray capacitances and indicates a very fast coupling of at least some of the phonons to the charge carriers (the coupling time, τ, is shorter than 200μs.) Making use of our previous charge carrier heat capacity estimate of $C \approx 3\ 10^{-12} J\ K^{-1}$, we deduce an effective conductance between charge carriers and high energy phonons $G \approx C/\tau > 1.5\ 10^{-8} W\ K^{-1}$. This is more than an order of magnitude greater than the effective conductance we measured between the charge carriers and thermal phonons.

In figure 5 we show the observed spectrum of pulse heights. The peak at 320 μV corresponds to 60 keV X-rays, and the peak at 120 μV comes from the unresolved 14 and 18 keV X-rays. The width of the peaks is larger than the electronic noise. The shape of the peaks is also asymmetric, with a tail extending toward lower pulse heights. This tail is an indication that there is an energy escape mechanism. Note that this spectrum does not give an indication of the intrinsic resolution of our thermistors. For a proper measurement of the total energy deposition, the thermistor should not be thermally clamped. Moreover, we did not use ultra-low noise amplifiers, and our setup was subject to strong microphonics.

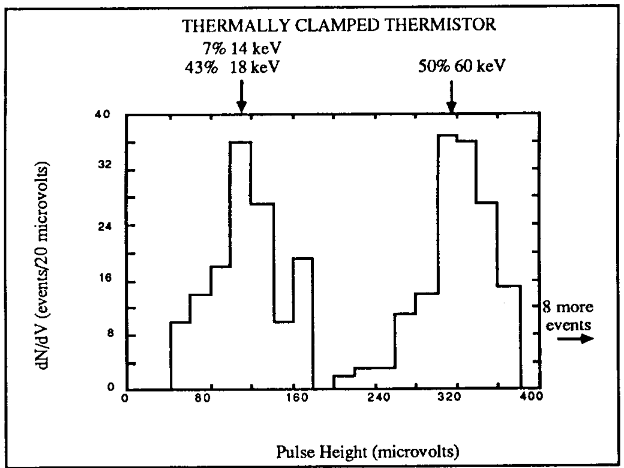

Figure 5. *Pulse height spectrum for a thermally clamped thermistor. ^{241}Am X-rays are incident directly on thermistor b. The NTD Ge chip is thermally clamped to the heat sink at 18 mK. The percentages are deduced from the attenuation in 1 mm of Al and the absorption in the Ge.*

Note finally, as shown in Figure 6, that no significant pulse is observed on the other thermistor, showing that the lattice temperature does not change appreciably on the time scale shown.

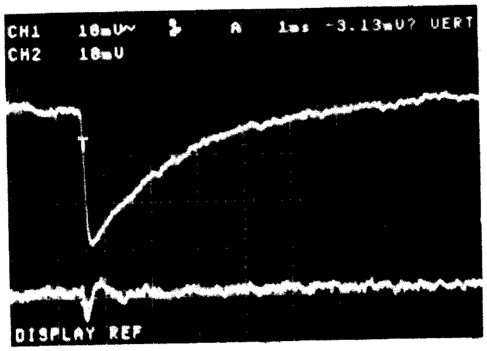

Figure 6. *Simultaneous pulses on thermistor a (lower trace) and thermistor b (upper trace) with X-rays incident on b. The small signal in a is entirely due to electrical cross talk.*

It is possible to compare the pulse height obtained with 60keV X-rays to the pulse heights obtained with electrical pulsing using a capacitor at the same temperature and bias current. The energy deposition is calculated from the energy stored in the capacitor using the thermal model described in detail in ref.[12]. This calculation takes into account the correction due to thermal feed-back effects[14], and also considers the leakage of energy to the heat sink during the pulse rise-time. The results are shown in figure 7. At 18 and 60 keV, we expected 260μV and 650μV respectively, and observed 120μV and 320μV. Therefore the fast component represents about 50% of the total energy deposition.

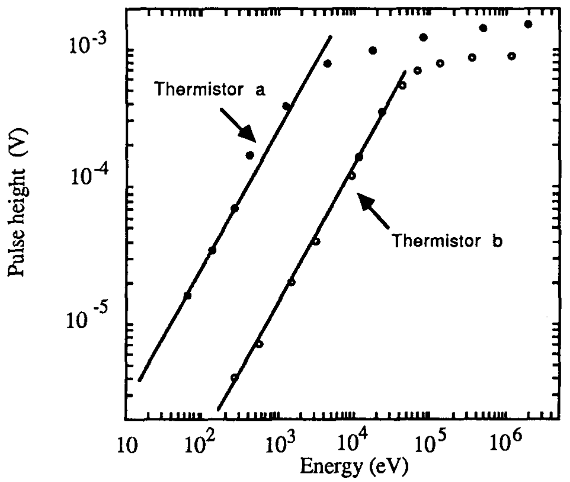

Figure 7. *Calibration of thermistors a and b at 18mK. Pulse height is plotted as a function of deposited energy. The energy is deposited by discharging a capacitor through the thermistor.*

Note that our sensors are quite sensitive. With a good amplifier having voltage noise less than 1nV/√Hz, such as the one we have developed[15], the rms electronic noise at the adequate bandwidth of 1kHz is 30 nV. The energy deposition which would give a pulse height of 30 nV in thermistor a is 0.2 eV! Note, however, that the thermal fluctuations of the charge carriers would be of the order of 1 eV.

5. Deposition of the X-ray energy between the 2 thermistors.

We have also investigated the case where the X-rays irradiate the region between the two thermistors . In this case, the phonons have to travel through heavily doped material (remember that the whole lattice is uniformly doped) before reaching the thermistor, and are likely to be thermalized before they can be detected. Figure 8 shows typical pulses obtained in that configuration. Several remarks may be made:

- Again the rise time is fast, especially for the largest pulses, which is another indication of good coupling.
- The spectral lines are completely washed out. The spectrum is peaked at low pulse height, with no structure. We consider this fact to be evidence for a strong attenuation of the high energy phonons in the intervening Ge. In that case, the pulse height should be strongly dependent on the position of the interaction.
- Usually a pulse is observed only on one thermistor, with practically no pulse seen on the other. Figure 9 gives examples of pulses observed simultaneously on the two thermistors. Note that the smaller pulses have slow rise times (the same effect is noticeable in figure 8.)

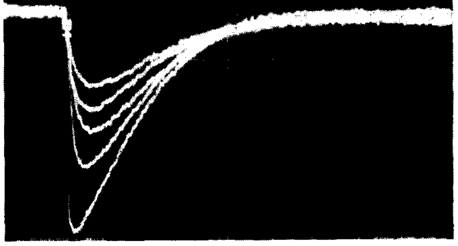

Figure 8. *Pulses, observed on thermistor a, from X-rays of ^{241}Am incident on the region between the two thermistors. Note the spread in heights compared to Figure 4.*

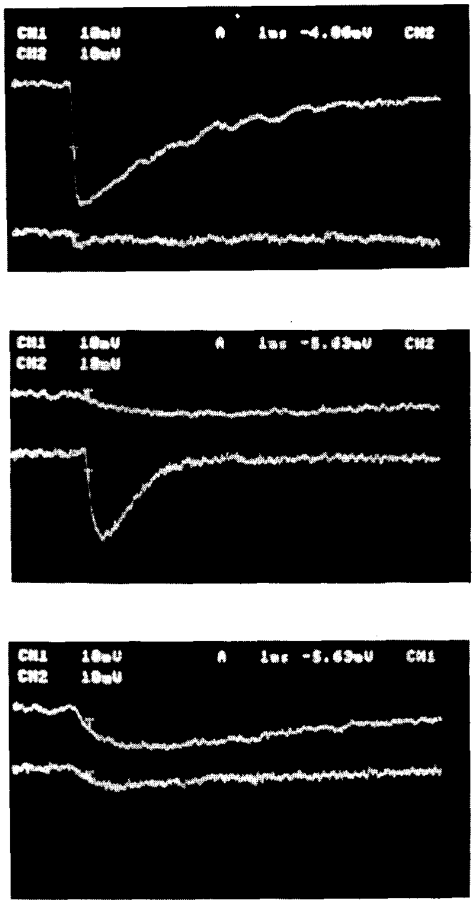

Figure 9. *Simultaneous pulses from thermistors a and b. The upper trace in each photograph is from thermistor b, and the lower trace is from thermistor a. The X-rays were incident on the region between the two thermistors. The pulse height appears to be dependent on the interaction distance from the thermistor.*

6. Interpretation.

The above results are most easily interpreted, within the framework of the model outlined in section 2, as evidence for excellent coupling between the phonons created in the X-ray interactions and the charge carriers in the NTD Ge. These phonons presumably interact with the carriers when they are still at high energy. In that case the phase space suppression which occurs at very low temperature is not operative. The evidence for this strong coupling is the following three facts: the fast rise time, the short absorption length in the material and the degradation of the rise time with small pulses. The short absorption length has to be contrasted with the long mean free path inferred for thermal phonons from excellent thermal conductance that was measured between the two thermistor areas. The slower rise-time observed after the phonons have traveled more than a few hundred microns is consistent either with a diffusion phenomenon or a lower effective energy of the phonons, and both effects are expected in the above picture.

Our experiment remains incomplete for the time being. Four issues require further study.

First, as emphasized earlier, we produce ionization in our sample ($N \approx 20{,}000$ electron-hole pairs),and that may play a role in the pulses. However, the effect is expected to be small. If the carrier drift velocity is v, the thickness of the sample $d=200\mu m$, and the charge of the electron q, their contribution to the current will be Nqv/d for a time d/v. Since we are approximately in a constant current configuration, the decrease of voltage will be $RNqv/d$ with R being the thermistor resistance ($R \approx 1M\Omega$). The drift velocity v is unknown, but even if it is as slow as 20cm/s (i.e. a mobility of 400 $cm^2\ V^{-1}\ s^{-1}$ since our bias voltage is typically 1mV) so as to contribute for a time $d/v \approx 10^{-3}$s, the voltage difference would be approximately 3 μV. This is less than 1% of our signal. If the drift velocity is much larger (as expected at our low temperature), the ionization signal is too fast to be seen. Note also that the heat Q generated by the drift of these charges is small,

$$Q \approx 10^{-3} x 20{,}000 = 20 eV.$$

A second point is that we should recover the undetected energy as a temperature rise of the sample. This measurement is not possible in our present experiment since the sample is well thermally clamped to the heat sink. We are currently planning a second experiment to measure this component.

Third, the difference in sensitivity and heat capacity between our two thermistors has to be understood.

Finally, we cannot estimate the energy of the active phonons. It is not clear from our experiment, for example, whether or not the phonons are captured before they down-convert to an energy similar to that of a ballistic phonon propagating in pure Ge. In order to test our interpretation, it is necessary to use a composite structure where the X-rays interact, for instance, in a pure crystal of Ge, properly coupled to a NTD Ge thermistor. This is clearly the next step of our experimental program along the lines explained in the next section.

Since we have not studied other doping levels, or other materials at the same temperature, we cannot comment on the generality of the effects we observe. However, if the picture of the phase space suppression is correct, we expect these effects to be quite general in semiconductor thermistors.

7. Conclusion: implications for particle detection.

Pending the results of more complete experiments, the following picture emerges.

Purely calorimetric measurements with semiconductor thermistors attached to large crystals could be very sensitive at temperatures as low as 20 mK. The thermistors we have studied also have the advantage, in this scheme, of having a very low heat capacity. However this method would be intrinsically slow because of the time necessary for complete phonon thermalization, and because of the poor coupling between thermal phonons and the charge carriers in the thermistor. This last effect is clearly present in our NTD Ge thermistors.

In contrast to this, the detection of ballistic phonons could in principle be much faster and carry much more information about the interaction. Our results show that NTD Ge thermistors could be very effective sensors. They are clearly sensitive to phonons of high energy which appear to couple well with charge carriers in the sensor. Further they absorb these phonons in a fraction of a millimeter, and therefore act as efficient high energy phonon sinks. At the level of the present experiment they are fast, but it remains to be seen if they are fast enough to allow precise position measurement by timing. Finally, the usefulness of these devices as high energy phonon sensors is completely dependent on the demonstration that we can manufacture an interface with a pure crystal which does not thermalize these phonons. We have started an active development along those lines.

Acknowledgements

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