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Optimization of Si-Implanted Thermistors for High Resolution Calorimeters to be used in a Neutrino Mass Experiment

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A procedure of optimization of Si-implanted thermistors was started, with the final aim to develop bolometers with a resolution of a few eV in the keV range. The initial approach was to assume that a thermal decoupling between phonons and hopping electrons establishes inside the thermistors, with consequent reduction of the sensitivity and incomplete transfer of the particle generated phonons to the conduction electrons. This assumption however failed in explaining the collected experimental data, which can be described much more satisfactorily introducing an electric field dependance of the thermistor resistance. This alternative interpretation modifies the parameter choice for an optimum device

1. INTRODUCTION

The Wisconsin-Nasa collaboration[1] has shown that low mass bolometers, if carefully optimized as far as both absorber and sensor are concerned, can reach impressive FWHM resolution (below 10 eV) for energy depositions of the order of a few keV. These bolometers are designed for the investigation of the sub-keV portion of the astronomical X-ray spectra. As particle physicists and as experimetalists, we regard these high resolution bolometric devices as very interesting detectors for a measurement of the neutrino mass through the calorimetric determination of the shape of a beta spectrum with a low end-point energy. In order to perform such an experiment, we have started a collaboration with the Istituto di Ricerche Scientifiche e Tecnologiche (IRST), Trento, Italy, which prepares the implanted thermistors, with the aim, in a first phase, to study and optimize thermistor thermal properties; secondly to develop a detector with performances comparable to those obtained by the Wisconsin-Nasa collaboration and never reproduced by other teams; and finally to realize the detector for the neutrino mass experiment.

2. ELECTRIC FIELD EFFECT OR PHONON-ELECTRON DECOUPLING?

There are several experimental evidences[2-4] of an intrinsic non-ohmic behaviour of doped semiconductor thermistors operated in the Variable Range Hopping (VRH) regime. The typical manifestation of this phenomenon consists of a decrease of the thermistor resistance on increasing the measuring voltage, even though another temperature sensor in intimate thermal contact with the lattice thermistor itself does not reveal any temperature change.

Two alternative (or maybe complementary) explanations of the phenomenon have been proposed: either the hopping electrons become "hot" when conducting electrical current, thermally decoupling from the phonon bath[4], or the electron temperature does not change at all, but the thermistor resistance exhibits an applied voltage dependance due to the fact that the electrons acquire energy from the electric field during the hopping process[5]. Both effects have a direct or indirect theoretical founding: an electron-lattice decoupling is predicted and observed in metals at low temperatures[6], while an electric field dependance of the resistance is expected in the hopping model[7].

Of course, a contemporary presence of both effects should not be excluded. But if one of them is dominant for a particular thermistor type in a particular temperature range, its determination is not only a subtle low temperature solid state physics question: the details of thermistor optimization depend on which effect prevails. The two basic equations which represent the two effects are the following:

$$P = g\,(T_e^{\beta} - T_l^{\beta}) \qquad (1)$$

$$\sigma(E) = \sigma_0 \exp\,[e\,(E - E_c)\,L/kT] \qquad (2)$$

where in (1) P stands for the power flowing form electrons to lattice, T_e for the electron temperature and T_l for the lattice temperature; g defines the magnitude and the temperature scale of the phenomenon, and β should be close to 6[4]. In (2) L is a characteristic length which rules the dependance of the conductivity σ on the field E; σ_0 is the 0-field conductivity and E_c the field value below which there is still an ohmic behaviour.

The two phenomena exhibit some common characteristics which make sometimes hard to distinguish which is the dominant effect:

1) in both cases, the effect gets more evident as the temperature decreases;

2) in both cases, the effect is stronger if thermistor sensitivity increases, as this determines a decreasing of g and an increasing of L;

3) in both cases, the geometry of the thermistor is crucial, because in one case g scales as thermistor volume, while in the other the electric field is obviously fixed by contact configuration;

4) in both cases, the effect has a negative influence on bolometric performances, since thermistor ability to feel lattice temperature changes is deteriorated.

Therefore, thermistor optimization is not trivial: an optimum temperature T and an optimum sensitivity A (defined as -dloR/dlogT) exist; the conductance to bath G must in any case be minimized: if phonon/electron decouplng prevails, to avoid phonon escape to bath; if field effect is dominant, to have an optimum operation point (optimum signal to noise ratio does not depend in principle on the heat conductance[8]) corresponding to a low bias level. Although the qualititative features of the optimization are the same in the two cases, it is clear that the actual optimum thermistor configuration depends on the dominant one of the two effects and on its parametrization, which must be carefully established through *ad hoc* measurements.

3. MEASUREMENTS OF THERMISTOR NON LINEARITY

IRST provided us with Si:P thermistors doped at 9 different levels; 3 samples are B compensated. In table I we report the doping levels for the various samples. The construction and technological characterization details are reported in another poster presentation held at this conferences, to which we refer for any supplementary information on the devices.

The R(T) behaviour of the samples was previously determined between 4.2 K and 1.8 K, in order to select those devices suitable to be employed at low temperatures. Samples of type 3, 8, 9 and 10 were characterized down to 20 mK: the agreement between the high and the low temperature measurements is remarkable.

PROVENIENCE	DOPANT CONCENTR.	B COMPENSATION
Wafer 1	3.6×10^{-18} cm^{-3}	0 %
Wafer 2	3.5×10^{-18} cm^{-3}	0 %
Wafer 3	3.4×10^{-18} cm^{-3}	0 %
Wafer 4	3.2×10^{-18} cm^{-3}	0 %
Wafer 5	3.0×10^{-18} cm^{-3}	0 %
Wafer 6	2.7×10^{-18} cm^{-3}	0 %
Wafer 7	2.4×10^{-18} cm^{-3}	0 %
Wafer 8	3.5×10^{-18} cm^{-3}	10 %
Wafer 9	3.5×10^{-18} cm^{-3}	30 %
Wafer 10	3.5×10^{-18} cm^{-3}	50 %

Table I

Assuming the usual law $R = R_0 \exp [(T_0/T)^{1/2}]$, the measured values of T_0 are 6.1, 4.4, 14.0 and 50.7 K respectively for wafers 3, 8, 9 and 10.

A first phenomenological way to represent thermistor non linearity, neglecting for the moment any interpretation of its source, is, following D. McCammon et al., to plot the power density necessary to decrease by 1/3 thermistor resistance, starting from 0 field value, as a function of thermistor sensitivity, for various heat sink temperatures. Fig. 1 shows the results that we have obtained for samples from wafers 3,8,9 and 10 superimposed to similar measurements performed by McCammon et al.[9]. The consistance of the measurements show that we are observing the same phenomenon and not some instrumental effect.

As a second step we have decided to interpret our data in terms of phonon/electron decoupling. We have used special samples in which there were a thermistor and a heating resistance integrated in the same silicon substrate.

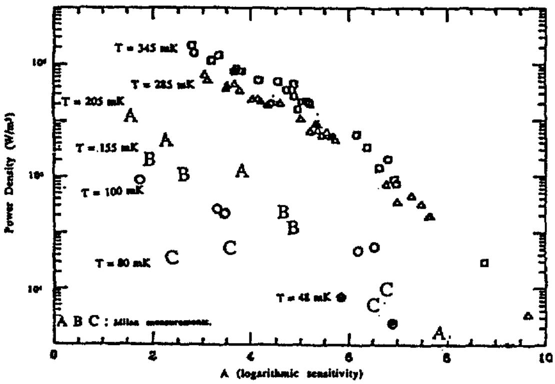

Fig. 1 Power which reduces by 1/3 0 field resistance measured by Wisconsin-Nasa (symbols) and Milan (letters)

The heating resistance was used to inject a known power into the sample, measuring in the meantime the temperature with the thermistor in the 0 field limit. From these measurements it is possible to derive the conductance G of the sample lattice to the heat sink. Then we have constructed a P-T curve injecting this time the power directly in the thermistor electrons. This latter measurement should give the total thermal conductance G_{tot} between hopping electrons and thermal bath.

The thermal conductance between electrons and phonons G_{ph} should then be deduced by $G_{ph} = G\, G_{tot} / (G-G_{tot})$, as expected by a conductance series.

Fortunately, the data have been taken for samples from the same wafer but with different conductances to the bath. In one case the sample was glued with GE varnish to the heat sink, while in another case it was just suspended by 4 gold wires 4 mm long and with a diameter of 25 µm. As expected, G is about 2 orders of magnitudes higher if obtained with the glue rather than with the gold wires; G_{tot} is always lower than G, as though a further decoupling stage were really interposed between the lattice and the hopping electrons.

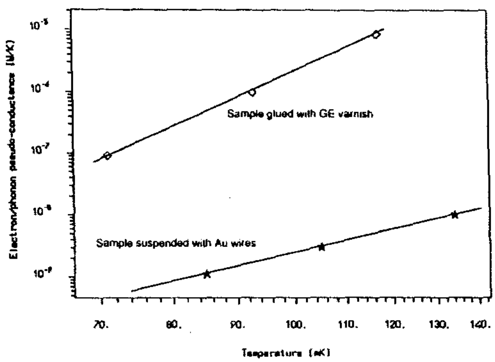

Fig. 2 Phonon/electron conductance seems to depend on heat sinkings

But a main point is absolutely inconsistent with the phonon/electron decoupling model: the computed values of G_{ph} depend strongly on G: no physical meaning can be assigned to this behaviour in the two series conductance model.

G_{tot} remains always lower than but close to G, while we should have expected G_{tot} to be largely dominated by G_{ph} for high values of G.

If we had performed a measurement with a unique type of coupling to the bath, we would have deduced an apparently consistent set of values for G_{ph} as a function of the temperature. The inconsistancy is shown by fig. 2, where the pseudo-conductance between electrons and phonons is shown as a function of the temperature for a wafer 8 sample: the two incompatable sets of points correspond to the two different heat-sinkings.

At a first glance, one can immediately realize that on the contrary a field effect interpretation can account for the obtained results. In this case indeed the electron temperature follows the lattice temperature (and this explains why G_{tot} is always close to G), but the resistance of the thermistor, as the measuring bias increases, is lower than expected at that temperature, erroneously leading to consider a higher electron temperature. Systematic measurements on a compensated sample from wafer 8, was at this point performed to characterize quantitatively the field effect as a function of T.

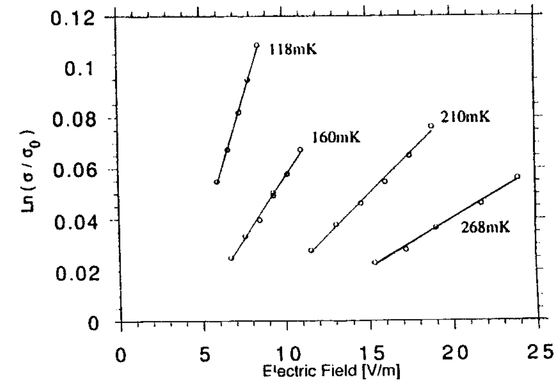

Fig. 3 Field dependance of conductivity measured at various temperatures

Further measurements on wafers 9 and 10 are foreseen in order to determine also T_0 dependance.

The measurements were performed at 4 different temperatures between 100 and 300 mK. A measurement taken at 57 mK has given ambiguous results and has not been included in this analysis. For any I-V curve, we have chosen a voltage range for which, on the high voltage side, the temperature of the thermistor lattice did not vary appreciably (we knew from the previous measurements the thermal conductance of the lattice toward the thermal bath) and, on the low voltage side, the electrical conductivity of the device started to increase with respect to the 0 voltage value.

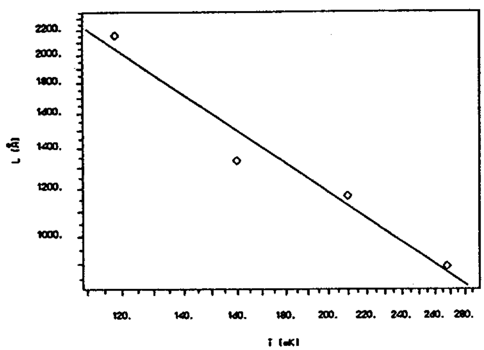

Fig. 4 Temperature dependance of the lencth parameter L: the straight line corresponds to -1.02 slope

In this range, ln(σ) depends linearly on the applied voltage, as predicted by (2). The set of curves obtained are shown in fig. 3. L values range between 2156 and 893 Å, from which, according to the Shklovskii thoery[7], hopping lengths ranging from 185 Å to 119 Å can be derived using the relation $L=R^2/a$, where a is 16 Å, Bohr radius of isolated P donors in Si. These values are to be compared with 75 Å, which is the average separation between impurity sites, and to which the hopping lengths must tend as the temperature increases and the conduction takes mainly place through nearest-neighbor hopping. L scales with temperature as $T^{-1.02}$ (fig. 4), again in agreement with Shklovskii model, which predicts a 1/T behaviour. A contrast with the Shklovskii theory can be found in the values of the critical fields E_c below which the ohmic regime should hold. From measured values of L, we obtain, following Shklovskii, E_c values which are more than an order of magnitude higher than those we have measured. As found out by other experimentalists[10], the dependance of σ on E begins at fields much weaker than predicted by VRH theory.

4. CONCLUSIONS

Non linear behaviour of a Si:P(B) implanted thermistor can be satisfactorily explained assuming a dependance of the conductivity on the electric field, in the frame of a VRH model of the conduction. Systematic measurements of this phenomenon are planned in the future, for various doping levels, in view of a final optimization of a microbolometer to be operated in the keV range.

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