MPI-PHE-92-24C

Phonon-Mediated Detection of Particles

F. Pröbst for the Munich Cryogenic Detector Collaboration

Max-Planck-Institut für Physik, Föhringer Ring 6
D-8000 München 40, Germany

Dec 1992

Munich, Max Planck Inst.

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1 Introduction

At the Max-Planck-Institut für Physik and the Technische Universität München we are developing massive cryogenic detectors for scattering events with small deposited energy (< 1 keV). The type of detector I report on here consists of a dielectric absorber crystal, a strip of superconducting material evaporated onto it serving as thermometer, and a weak thermal coupling connecting the thermometer to a constant temperature bath. The detector is operated within the superconducting-to-normal transition of the thermometer, where a small temperature rise of the strip leads to relatively large rise of its resistance. The resistance of the strip (~0.1 Ω) is measured by passing a constant current through a circuit in which the strip is in parallel with a 0.05 Ω resistor and the pickup coil of a SQUID. A particle-induced rise in the strip resistance is measured via the current rise through the SQUID.

Here I report on tests of a detector with a 19 g Si crystal and an Ir/Au proximity-effect thermometer with a very wide transition (15 to 115 mK) of nearly constant slope, which enables systematic studies of the detector response in this temperature range. The energy resolution improves with decreasing operating temperatures. At 17 mK, single 60 keV photons have been detected with an energy resolution of 1 keV (FWHM).

The pulses have two exponential components: a fast nonthermal one with a decay time of ~1.5 ms at all temperatures, and a slow thermal one with a temperature-dependent decay time of 40 to 60 ms. At the higher operating temperatures the amplitude of the slow component is approximately as expected from the heat capacity of the absorber and the deposited energy. However, at lower temperatures it becomes smaller than expected from the heat capacity, with a factor of ~ 100 missing at 17 mK.

In the following section I present a thermal model of the detector which explains the time structure of the pulses and the suppression of the thermal component at low temperatures.

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Invited talk at the 7th Int. Conf. on Phonon Scattering in condensed Matter, Ithaca, NY, USA, Aug. 3–7, 1992.

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2 The Model

The electrons and phonons of the metallic film are considered as subsystems weakly coupled by the electron-phonon coupling G_{e-p}. The phonon systems of the film and the absorber are coupled by the Kapitza coupling G_K across the interface, while the electrons are coupled to the thermal bath via G_{e-b}. The particle interaction creates high frequency phonons which do not thermalize in the absorber. These high frequency phonons are efficiently absorbed by the electrons in the metal film. Due to the strong interaction among the electrons, the energy transferred to a single electron is thermalized within the electronic subsystem. The absorption of high frequency phonons is thus a time-dependent power input P(t) into the electronic subsystem of the film, and is responsible for the fast signal component. Thermal phonons emitted from the electrons can either escape into the absorber or into the heat sink via G_{e-b}. The thermal signal is reduced by two mechanisms:

- Some of the phonons thermalized by the conduction electrons escape into the heat sink and do not heat the absorber.
- The thermometer does not "see" the full temperature rise of the absorber, because at low temperatures $G_{e-b} \gg G_{e-p}$.

2.1 Calculation of the thermometer response

The electrons are coupled to the heat bath at temperature T_b on the left side (x=0) of the strip by a Au-bonding wire of thermal conductance G_{Au}. Electrical connection is made by superconducting Al-bonding wires of negligible thermal conductance. A homogeneous heat input P(t) leads to a rise of the electron temperature $T_e(x,t)$. The resistance rise and hence the signal is assumed proportional to the average rise of electron temperature $\Delta\bar{T}_e = \bar{T}_e - T_b$. T_e and the absorber temperature T_a are calculated from:

$$C_e \frac{\partial T_e}{\partial t} - \kappa V_e \frac{\partial^2 T_e}{\partial x^2} + (T_e - T_a)\, G_{e-a} = P(t) \tag{1}$$

$$C_a \frac{dT_a}{dt} = (\bar{T}_e - T_a) G_{e-a} \tag{2}$$

where C_e, κ and V_e are the heat capacity, thermal conductivity and the volume of the electron system, C_a is the heat capacity of the absorber, and G_{e-a} the effective coupling of the electron system of the film to the phonon system of the absorber ($1/G_{e-a} = 1/G_{e-p} + 1/G_K$). Apart from a short period after "switching" on P(t) (the signal rise time), $C_e \partial T_e/\partial t$ in eq. 1 is negligible, and is therefore omitted.

With the boundary conditions $T_e = T_b + (P - C_a dT_a/dt)/G_{Au}$ at x=0 and $dT_e/dx = 0$ at x=L (L=length of the strip) equations 1 and 2 are solved by:

$$\Delta\bar{T}_e(t) = \frac{(1-\gamma)}{G_{e-a}}P(t) + (1-\gamma)\Delta T_a(t) \tag{3}$$

$$\Delta T_a(t) = \left(\frac{E}{C_a}\right)\left(\frac{1-\gamma}{1-\frac{\tau}{\tau_{eff}}}\right)\left(\exp\left(\frac{-t}{\tau_{eff}}\right) - \exp\left(\frac{-t}{\tau}\right)\right)\Theta(t) \tag{4}$$

with E the energy deposited in the crystal, $\Delta T_a(t) = T_a(t) - T_b$, and γ, λ, and τ_{eff} given by:

$$\gamma = \left(\frac{G_{e-a}}{G_{Au}} + \frac{\lambda L}{\tanh(\lambda L)}\right)^{-1}; \quad \lambda = \sqrt{\frac{G_{e-a}}{\kappa V_e}}; \quad \tau_{eff} = \frac{1}{\gamma}\frac{C_a}{G_{e-a}} \tag{5}$$

$\Delta\bar{T}_e(t)$ has two components, a fast and a slow one with the time structure of P(t) and $\Delta T_a(t)$, respectively. The thermometer "sees" $\Delta T_a(t)$ reduced with a factor $(1-\gamma)$. The absorber temperature rises with the decay time constant τ of $P(t)$ and decays with τ_{eff}; its amplitude is suppressed essentially by another factor of $(1-\gamma)$ compared to E/C_a .

$P(t)$ is calculated from:

$$P(t) = P_0 \exp\left(\frac{-t}{\tau}\right)\Theta(t) \tag{6}$$

with P_0 and τ given by:

$$P_0 = \frac{1}{2}\frac{E}{V_a}A < v_{g\perp}\alpha >; \qquad \tau = \frac{E}{P_0} \tag{7}$$

where A is the area of the absorber-thermometer interface, V_a the volume of the absorber, $v_{g\perp}$ the normal component of the phonon group velocity , α the transmission probability and $< .. >$ denotes an average over modes and angles of incidence of phonons impinging on the interface. Equation 7 assumes a homogeneous distribution of the high frequency phonons in the absorber, the absorption of all phonons transmitted into the thermometer, and exclusive thermalization in the thermometer.

3 Comparison with experiment

In this section the model is applied to the detector with the Ir/Au thermometer. The thermal conductivity κ of the Ir/Au film is estimated by inserting its normal conducting resistance of R_{nc}=0.4 Ω into Wiedeman-Franz law. This would yield a good approximation for κ within a narrow transition. With the wide transition of the Ir/Au thermometer (15 to 115mK), κ may be overestimated up to a factor of four at the lowest operating temperatures, where the resistance is 1/4 of R_{nc}.

A thermal conductance of $G_{Au} = 9.2\times10^{-7}\times T$ W K^{-2} of the Au-bonding wires, as calculated from Wiedemann-Franz law, and a Kapitza conductance

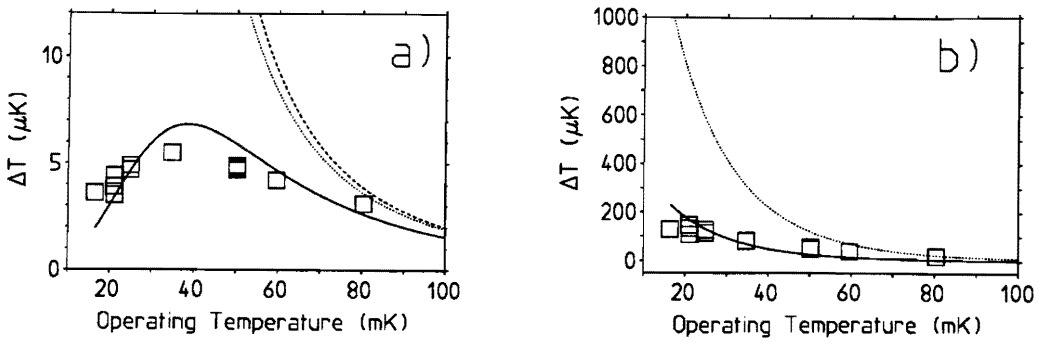

Figure 1: *Amplitudes of 60 keV pulses.*
a) Slow (thermal) component: The fully drawn curve is the best fit of β, the dotted curve is $\beta \rightarrow \infty$, and the dashed curve is $\Delta T = E/C_a$.
b)Fast component: The fully drawn curve assumes absorption of all high frequency phonons transmitted into the thermometer, the broken curve assumes that only those transmitted as longitudinal phonons are absorbed.

of the thermometer-absorber interface of $G_K = 1.44 \times 10^{-3} \times T^3$ W K^{-4}, as calculated from acoustic mismatch, are used throughout the analysis.

The electron-phonon coupling is parameterized as $G_{e-p} = \beta T_e^4$. The only free parameter of the model is β, which is determined by fitting the amplitude of the slow component, shown as the fully drawn curve in fig. 1a. This value of $\beta = 2.4 \times 10^{-3}$ W K^{-5} is then used to calculate the amplitude of the fast component and the signal rise time, shown in figures 1b and 2. With the volume $V_e = 2 \times 10^{-7}$ cm^3 of our Ir/Au film, this β translates into an electron phonon resistance of $R_{e-p}\, V\, T^4 = 0.83 \times 10^{-4}$ K^5 cm^3/W, which is close to $R_{e-p}\, V\, T^4 = 1.5 \times 10^{-4}$ K^5 cm^3/W measured for Rh:Fe [1] .

The calculated amplitude of the fast component, shown as the broken curve in fig. 1b, is considerably larger than the experimental values. Consequently, the thermometer does not absorb all high frequency phonons as assumed in eq. 7.

In the following I estimate the mean free path l for inelastic scattering of high frequency phonons in the thermometer from the value of β. The assumed temperature dependence of $G_{e-p} = \beta T^4$ corresponds to a frequency dependence of $l = \eta\nu^{-1}$ in the range of thermal phonon frequencies [2]. Anharmonic decay in Si [3] degrades the phonons to an average frequency of $\nu \sim 0.3$ THz within the ms time scale of P(t). Using η calculated from β by assuming the same scattering rate for all phonon modes, a naive extrapolation with $l = \eta\nu^{-1}$ to ν=0.3 THz yields l=700 nm. (l is an average of the mean free path in the Ir and Au films). With our film thickness of 100 nm this large l would lead to an incomplete absorption of high frequency phonons and thus to a reduction of P_0 compared to eq. 7.

At high frequencies $\nu > 10^{10}$ s^{-1} it is dominantly the longitudinal phonons which scatter with $l \propto \nu^{-1}$. At lower frequency transverse phonons also con-

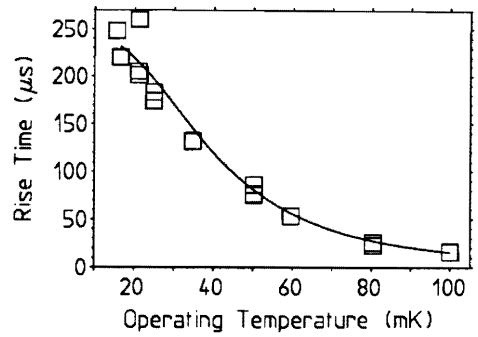

Figure 2: *Dependence of the signal rise time on the operating temperature.*

tribute, leading to a more complex frequency dependence of l [4]. Neglecting this contribution of transverse phonons and extrapolating to ν=0.3THz yields l=70 nm for longitudinal phonons. This value of l would lead to a complete absorption of all longitudinal phonons. Averaged over the Si-Au and Si-Ir interface areas 22% of all phonons in Si are transmitted into the film as longitudinal phonons. This reduces P_0 accordingly and brings the prediction, shown as the full curve in fig. 1b, closer to the data.

For the absorption of all high frequency phonons eq. 7 yields τ=3.4 ms. A reduction of P_0, which results from a smaller absorption probability, would increase τ accordingly, as long as all phonons are thermalized in the thermometer. This would lead to τ=15 ms in the case of exclusive absorption of longitudinal phonons. From the much shorter experimental value of τ=1.5 ms one has to conclude, that only ~10% of the phonons are thermalized in the thermometer.

During the rise of the pulse $\Delta Ta(t)$ can be neglected, so we obtain from eq. 3 a total thermal coupling of the electron system of $G = G_{e-a}/(1-\gamma)$. This gives a signal rise time of $\tau = C_e/G$ shown in fig. 2, which agrees nicely with the data.

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