

Measurements and modeling of the thermal properties of a calorimeter having a sapphire absorber *

Y.H. Kim^a, H. Eguchi, C. Enss, Y.H. Huang, R.E. Lanou, H.J. Maris, A.N. Mocharnuk-Macchia, G.M. Seidel, B. Sethumadhavan and W. Yao

^aPhysics Department, Brown University, Providence, RI 02912, USA

The response of a magnetic calorimeter with a sapphire crystal serving as an x-ray absorber has been studied as a function of temperature. Several different Au films were used to connect thermally the magnetic sensor to the absorber. The amplitude and time dependence of the signal resulting from the absorption of an x-ray were fit using an idealized model for the calorimeter. The values of the various parameters resulting from a fit of the data are internally consistent and provide a physical understanding of the processes determining the performance of the calorimeter. The fraction of the energy of the x-ray that is captured by the film without having first been down-converted to thermal phonons in the sapphire is found to depend on both the area and thickness of the film. The rate at which energy is transferred between thermal phonons in the sapphire and electrons in the film is determined by the electron/phonon interaction in the gold. Also, an additional heat capacity was observed to be present in the sapphire, which, for want of a better means of characterization, is ascribed to tunneling systems. The magnitude of this additional heat capacity and its thermal coupling to the lattice has been studied.

1. Introduction

The performance of microcalorimeters for particle detection depends upon the thermodynamic properties of the constituents as well as the mechanisms for heat transfer between them. In many cases, calorimeters use materials whose properties have not been measured in the temperature range below 0.1 K where these devices are typically operated. Usually the extrapolation of measurements made at higher temperatures is satisfactory. However, such a procedure entails uncertainty, and we have endeavored to put our understanding of the important parameters of a calorimeter, consisting of a sapphire absorber and a metallic magnetic sensor, on a firmer basis.

2. Experiment

A sapphire crystal $2 \times 1 \times 0.5$ cm was used as the absorber. A 2 mm square Au film having a hole with 4 spokes ($30 \mu\text{m}$ wide and $115 \mu\text{m}$ long) at its center, see Fig. 1a, was deposited on its surface[1].

A $30 \mu\text{m}$ Au:Er magnetic sensor was bonded to the center of the spokes, the hole with spokes being required to visually align, by looking through the sapphire, the sensor within the pick-up loop of a SQUID. There was no thermal contact of the sensor with the loop or the chip on which the loop was deposited. Two additional much smaller Au films were deposited on the sapphire. One served as a heater (superconducting leads with negligible thermal conductance), and the other, with a Au wire bonded to it, provided thermal contact to the reservoir. The sample was irradiated by 60 keV gamma rays from a ^{241}Am source. Three different thicknesses of Au film were investigated in separate measurements as listed in Fig. 1b.

To assist in the analysis of the pulse shape, the thermal conductance between the sapphire and the bath, G_b in Fig. 1c, was determined by measuring the temperature rise resulting from the introduction of a constant Joule heat via the heater film. In addition, from the temperature response to a step heat input it was determined that there exists in the sapphire a system with a very large heat capacity, approximately 100 times larger than the lattice at 50 mK. This heat ca-

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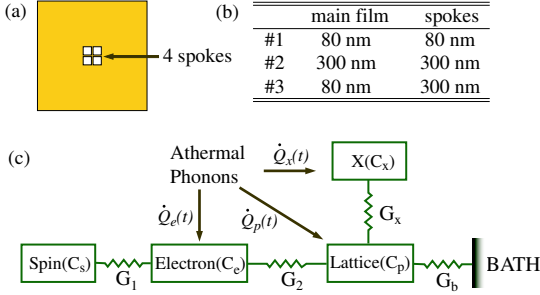


Figure 1. (a) Layout of Au film. (b) Film thickness. (c) Schematic diagram of heat transfer model.

capacity, ascribed to tunneling systems for want of a better understanding, is very weakly coupled to the lattice. The coupling cannot be described in terms of a single conductance.

3. Model

The model of the calorimeter, used to fit the pulse shapes, is illustrated in Fig. 1c. The thermal phonons of the sapphire lattice are assumed to be in internal equilibrium and connected thermally to the bath, to the electrons in the Au film and to the tunneling systems. The film, in turn, is connected to the magnetic sensor whose heat capacity is principally that of the paramagnetic spins in the applied field. Energy deposited in the sapphire very quickly is converted to athermal phonons with energies ranging up to perhaps 50 K, with mean free paths that are longer than the dimensions of the crystal, and having a reasonable probability of interacting with the electrons in the film. The fraction of the initial energy that is transferred directly by athermal phonons to the Au film is described by a time constant τ_e . The time constants τ_p and τ_x measure the fraction of athermal phonons that are converted to thermal phonons or heat the tunneling systems directly. Then the rate at which energy is deposited into the i th component, $i = e, p, x$, of the calorimeter is $\dot{Q}_i(t) = E/\tau_i \exp(-t/\tau)$, where

$1/\tau = 1/\tau_e + 1/\tau_p + 1/\tau_x$. Of the parameters appearing in Fig. 1c, C_e, C_p, C_s and G_b are known. There remain seven parameters, which are determined by fitting the measured pulse shape $T_s(t)$ using a least squares analysis to the solution of the set of differential equations for the model. Of these seven parameters, the quality of the fit to the shape of the pulse during the rise and the initial decay from the maximum is sensitive to only four, namely, G_1, G_2, τ_e , and τ_p . The other three, τ_x, C_x , and G_x are all related to the tunneling systems. It was found for all temperatures and for all 3 experiments with different Au films that $1/\tau_x$ was very small; less than 2% of the energy went directly into the tunneling systems rather than into thermal phonons or electrons. The two quantities, C_x and G_x , required to fit the measured pulse shape, are primarily determined by the non-exponential decay of the signal at long times and are not discussed further here.

4. Results

The temperature dependence of the parameters G_1 and G_2 are shown in Fig. 2 for the three experiments involving different Au films. Lines through the experimental points for G_1 in Fig. 2a are fits linear in T . The data for #2 and #3 agree within 15% with the thermal conductance calculated for the 300 nm thick spokes from the electrical resistivity and the Wiedemann-Franz law. The spin-electron time constant given by the Korringa con-

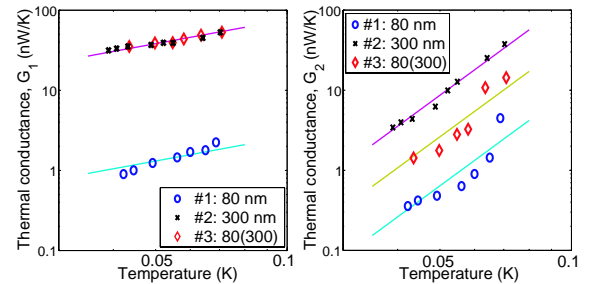


Figure 2. Thermal conductance, (a) G_1 (b) G_2 .

stant is much too short to be a factor[2] in determining G_1 . The electrical resistivity was not measured for a 80 nm thick film. The temperature dependence of the conductance G_2 is graphed in Fig. 2b. The lines through the points are a T^4 fit to the data. The T^4 dependence bespeaks of the electron-phonon coupling in the gold being the principal impedance for energy transfer. The calculated Kapitza resistance between sapphire and 4 mm² Au film is more than an order of magnitude smaller than the resistance obtained in these measurements. For #2 and #3 the measured value of G_2 is in reasonable agreement with other measurements of the electron-phonon coupling. The coupling constant Σ of the equation for the power transferred in a volume V between electrons and phonons, $P = \Sigma V(T_e^5 - T_p^5)$, can be calculated from $\Sigma = G_2/(5VT^4)$. For both #2 and #3, $\Sigma = 2.4 \times 10^8$ W/m³K⁵, which is well within the range of values, from 1 to 4×10^8 W/m³K⁵, typically found for other metals. The result for G_2 for #1 is about 4 times lower than expected when compared #2 and #3. The reason for this is thought to be related to the poor thermal coupling of the sensor to the electrons and through them to the rest of the calorimeter. The response of the sensor is not an accurate measure of what is happening regarding energy transfers in the calorimeter. With such a slow response the coupling of the lattice to the tunneling systems is difficult to separate from other processes.

The values for the time constants that determine the energy distribution of the athermal phonons among the various subsystems of the calorimeter are also found. There is little if any systematic temperature variation observed in any of the time constants. The values for τ_p for all three experiments cluster around $\tau_p = 0.2$ ms, whereas $\tau_e = 2$ ms for #1 and #3 having 80 nm thick films and $\tau_e = 0.7$ ms for #2 with the 300 nm film. This dependence of τ_e on film thickness indicates that between two and three times more energy is deposited directly by athermal phonons into the 300 nm film than into the 80 nm films.

The time constant for a phonon in the sapphire to hit the gold film depends upon geometry, $\tau_{geo} \approx 2V/A\langle v_{\perp} \rangle$, where A is the area of

the film, V is the volume of the sapphire and $\langle v_{\perp} \rangle$ is the average phonon velocity perpendicular to the surface. In these experiments with $A = 4$ mm², $V = 1$ cm³ and $\langle v_{\perp} \rangle \approx 3 \times 10^5$ cm/s, $\tau_{geo} \approx 0.2$ ms. This is much shorter than τ_e for either film thickness indicating that the probability that a phonon on hitting the film will be absorbed in the Au is considerably less than unity. High frequency phonons are known to have a transmission probability of close to unity across the Au/sapphire interface. However, for 20 K phonons the attenuation length of a longitudinal phonon is ≈ 2 μ m, and it increases with decreasing phonon energy. The interaction of transverse phonons with electrons is, in general, much weaker than that of longitudinal phonons. Thus, the Au films having thicknesses of 80 nm and 300 nm are much thinner than the attenuation lengths of the high frequency phonons. For the 300 nm film only $\tau_{geo}/\tau_e \approx 2/7 = 0.3$ of the phonons entering the Au film are absorbed rather than returned to the sapphire. For the 80 nm, film this ratio is $2/20 = 0.1$.

The usual explanation offered for the down conversion of high frequency phonons to the thermal regime is inelastic impurity and surface scattering. If the down conversion occurs principally by inelastic surface scattering, τ_p should be inversely proportional to the volume to surface ratio of the crystal. In this regard, the present result for $\tau_p/(V/A)$ of 1.5 ms/cm is comparable to that found by the CRESST group[3]. Since the inverse of ratio $\tau_p/(V/A)$ is between 2 and 3 orders of magnitude less than the phonon velocity, close to 1000 scatters are required to convert the energy of a high frequency phonon to thermal phonons.

REFERENCES

1. Some of the early data presented in a preliminary report of this work [Y.H. Kim *et al.*, Proc. LTD-9 p107] has been found to contain errors.
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