The Suitability of Sapphire for Large-Area Calorimeters: The Transfer of Energy to Gold Films

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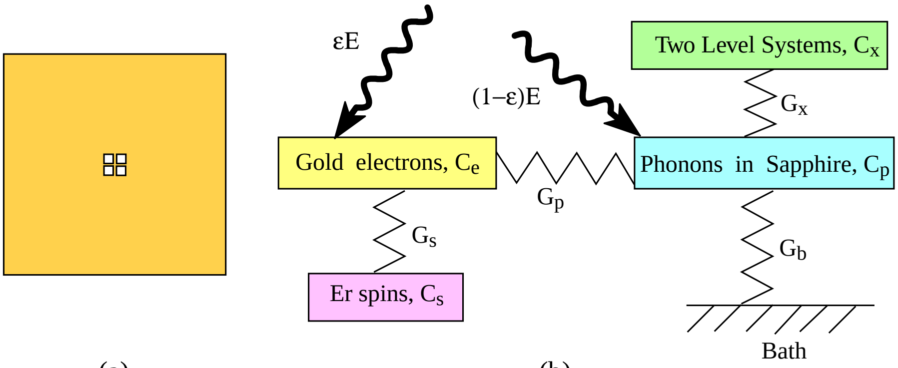
Abstract. The transmission of energy across the interface of a gold film with bulk sapphire has been studied using a metallic magnetic calorimeter. The transfer of energy by both high frequency and thermal phonons is found to be dependent upon the thickness of the gold film. For high frequency phonons the thickness dependence occurs when the size of the attenuation length in gold becomes comparable to the thickness. When the wavelength of the thermal phonons is larger than the thickness of the film, the density of modes of such phonons is altered from that of the bulk and the energy transmission is decreased.

In most high sensitivity calorimeters for particle detection that operate at low temperatures, the energy being measured is generated in an absorber, which is a distinct element from the temperature sensor. Both the time dependence and the magnitude of the response of the sensor are critically dependent on the coupling between the absorber and sensor as well as on the nature of the thermal excitations being transferred between the two elements. This problem of thermal coupling is especially important in the development of large-area wafers to be used in the proposed HERON detector of low-energy solar neutrinos[1]. This liquid helium-based detector of neutrinos requires for its successful implementation, the detection of single 16 eV photons produced by scintillation of the helium. Since the total area that must be covered by calorimeters is the order of 10 square meters, to keep the number of calorimeters reasonable (~ 1000) each must be approximately 100 cm^2 in size. We propose to make the absorbers from a dielectric with a high Debye temperature, such as sapphire or silicon. To study the transfer of energy from sapphire to a sensor we have investigated the coupling of a metallic magnetic sensor[2] to a 1 cm^3 piece of sapphire. One of the reasons for choosing to work with a magnetic sensor is the ability to study the temperature dependence of the coupling and thereby, hopefully, sort out several of the competing processes that influence the performance. This work is closely related to the research of the CRESST[3] group who have investigated the response of a transition-edge thermometer attached to large sapphire crystals.

The high-purity sapphire crystal, 5 mm$\times$10 mm$\times$20 mm, was kindly provided by the CRESST group. A gold film, 2 mm$\times$2 mm, with a 0.15 mm square hole in the center was evaporated on one surface, see Fig. 1a. In the central hole four spokes, 30 microns



(a) (b)

FIGURE 1. **(a)** Layout of gold film. **(b)** Schematic diagram of model used to describe the calorimeter.

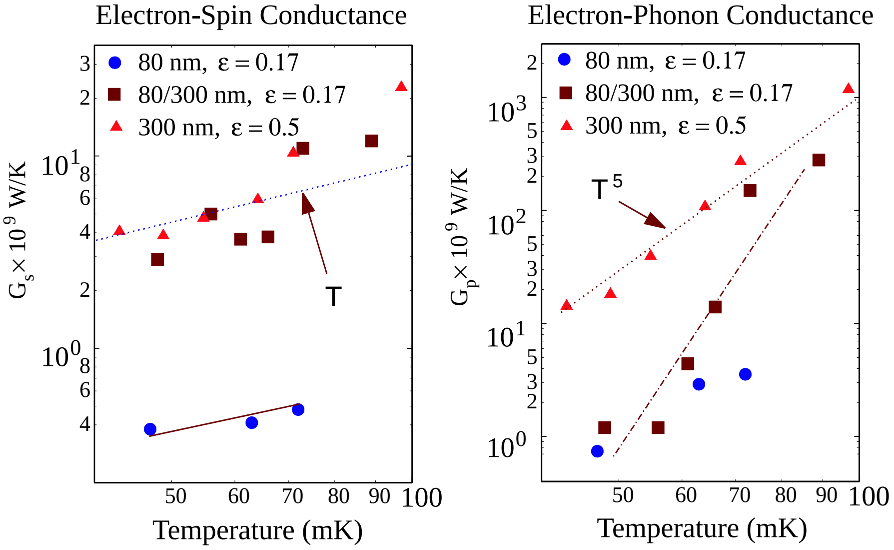
wide, of Au were deposited. This patterning was necessary in order to be able to see the position of the magnetic sensor, pressed at the hub of the spokes. The single-turn pickup loop of the SQUID used to measure the flux change of the paramagnetic ions in the sensor had to be positioned by hand around the sensor, a 35 micron diameter piece of gold doped with 900 ppm erbium. Measurements were made on the same piece of sapphire with three different thicknesses of Au films – (1) the 4 mm^2 area and spokes both 80 nm thick, (2) the large area and spokes 300 nm thick, and (3) the large area 80 nm thick but the spokes 300 nm thick. The sapphire was coupled to the thermal reservoir by an 0.1 mm^2 square, 200 nm thick, evaporated Au pad to which a 25 micron Au wire was wedge bonded.

Measurements were made between 40 mK to 100 mK using a 60 keV gamma-ray for the energy deposition. Pulses were recorded and averaged prior to analyzing shapes. When an x-ray is absorbed in sapphire, the recoil electron produces high energy phonons, which rapidly decay via anharmonic processes to lower energies[4, 5], the lifetime of a phonon varying as E^{-5}. At energies of approximately 1/20th the Debye energy, the mean free path becomes longer than a centimeter and such phonons have a reasonable probability of hitting the Au film and being absorbed in it rather than down converting further via inelastic surface scattering or other mechanisms.

We have used a simple model to characterize the thermal response of the magnetic sensor when an x-ray is absorbed in the sapphire, see Fig. 1b. A fraction εE of the initial energy is transferred to the gold film by non thermal phonons with a time constant $t = \frac{V_{sap}}{A_{Au}} \frac{1}{\langle v_\perp \rangle} = 0.07$ ms. The remainder of the energy, $(1-\varepsilon)E$, is assumed to thermalize in the sapphire. The coupling of the electrons in the Au film with the spins in the sensor is described by a conductance G_s while the interaction between electrons with the phonons in the sapphire is characterized by a conductance G_p. The phonons, in turn, are coupled to the bath with conductance G_b and to an additional thermal reservoir having heat capacity C_x with conductance G_x. This thermal reservoir, internal to the sapphire, is attributed to localized states. Such states, even in the highest quality materials, can make a significant contribution to the heat capacity of high Θ_D dielectrics at low temperature[6].

This model provides, at best, only a very rough description of the physical processes taking place within the calorimeter. We take as known the heat capacities of the Au film, C_e, the sensor, C_s, and the phonons in the sapphire, C_p. The rest of the parameters, ε, G_s, G_p, G_b, C_x and G_x, are adjusted to obtain this best fit to the temperature response of the sensor. The first three of these parameters, which are of the most interest and which we discuss here, determine the rise time of the pulse, its amplitude, and its initial decay. The latter three parameters primarily determine the long-time decay of the signal. The additional heat capacity, C_x has to be introduced to obtain even a rough fit to the decay, which deviates markedly from a simple exponential.

Several observations about the fitting procedure and the quality of fit are warranted. The measurements can be fit with a broad range of ε with the G_s, and G_p adjusted accordingly. Since G_s is determined by the conductivity of the spokes, we take its value to be the same for the measurements (2) and (3). As a result of this constraint the value of ε is much lower for (3) than for (2). With $\varepsilon = 0.5$ for the 300 nm film, then $\varepsilon \leq 0.2$ for the 80 nm film. With these values of ε the temperature dependence of the quantities G_p and G_s obtained by fitting the data are shown in Fig. 2.


Electron-Spin Conductance

Electron-Phonon Conductance

FIGURE 2. **(a)** The temperature dependence of the conductance between Au electrons and Er spins. **(b)** The temperature dependence of the conductance between Au electrons and sapphire phonons.

The magnitude and temperature dependence of G_s is roughly what one would expect for the thermal conductivity of the Au evaporated film comprising the spokes, namely, $K_{Au} = 5 \times 10^{-3}\ T\ \ \mathrm{W/(cm\ K)}$.

The coupling between electrons in the Au and the phonons in the sapphire, G_p, has a much stronger temperature dependence. For (2), the 300 nm film, $G_p = 1 \times 10^5\ V\ T^5$ W/K, where V is the volume in cm^3 of the Au. This is indicative of the fact that at these temperatures the principal impedance for the flow of thermal energy between the Au and sapphire is the electron-phonon interaction in Au. The value of the coefficient of 1×10^5 W/(cm^3 K^6) agrees very well with that found by the CRESST group[3]. The temperature dependence of G_p for (3) appears to be considerably higher than T^5

in the limited temperature region in which it has been measured. At low temperature, G_p for (3) is 25 times smaller than G_p for (2) whereas the ratio of the volume of the films is only 4. This suggests that another mechanism makes an increasing contribution to the impedance of the thinner film. Given that the wavelength of a 0.1 K phonon is 2.5×10^3 nm in Au, it may be that limitations on the phonon modes become important in the 80 nm film.

As noted above, not withstanding the fact that the amplitude of the signal is larger for (3) than for (2) at low temperatures, the value of ε for (2) is decidedly larger than for (3). The transmission probability of high-energy phonons through the Au-sapphire interface has been measured[7] to be close to unity. However, the attenuation length of a 50 K phonon in Au is 750 nm. Thus a high-energy phonon in a thin film has a significant probability of being reflected from the free surface and returning to the sapphire. This is more likely to occur in the 80 nm film than in the one 300 nm thick and accounts for the thickness dependence of ε.

Although less energy is transmitted by non thermal phonons to the sensor using a thin Au film, the retardation of the loss of energy by thermal phonons from sensor to sapphire results in a larger signal at low temperature with the thinner film. This is not the case at higher temperatures. The thickness of film that maximizes the response of the sensor depends, as well, on other factors such as the coupling of the electrons to the spins. In this set of measurements that coupling is much weaker than is desirable or necessary for a practical calorimeter.

A more detailed and quantitative analysis of these results will be presented in a subsequent paper.

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