Fast-Time Heat Pulse Measurements in High- and Low-Diffusivity Materials*

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1. Introduction

In this paper we discuss two sample geometries which we have used for low-temperature thermal measurements on high- and low-diffusivity materials respectively. In the first geometry, our data reveal features of the response at early times which we ascribe to causality effects. The second geometry gives one the opportunity to investigate both heat capacity and thermal diffusivity on different time-scales in the same sample. Data on vitreous silica, which so far are restricted to temperatures above 0.6 K, do not reveal any large differences from the predictions of standard diffusion theory. However, we discuss an anomaly which may be related to the time-dependent heat capacity of the standard two-level-systems model.

2. High-diffusivity Experiments

The geometry which we have used for studies on crystals is shown in the inset of Fig. 1 [1]. The samples, typically 30 x 10 x 0.1 mm, are clamped at one end and suspended in vacuum with thin-film heater (gold) and thermometer (indium) 10 mm apart as shown. In the boundary scattering regime of our experiment, the response of the thermometer to an instantaneous heater pulse of energy Q can be compared to a one-dimensional solution of the thermal diffusion equation [1]:

$$\delta T = \left(\frac{Q}{AC\sqrt{2Dt}}\right) \exp(-x^2/4Dt).$$  \hspace{1cm} (1)

Fig. 1. The geometry for "high-diffusivity" samples is shown in the inset. The temperature pulse, for a roughened sapphire sample at 3.4 K, is fitted to a one-dimensional solution of the diffusion equation in the range indicated by arrows. The early-time discrepancy is discussed in the text.

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In (1), L, A and x are the sample length, cross-sectional area, and heater-thermometer separation respectively; the solution is accurate to one percent for times less than \( L \cdot (1-x/L)/5D \). The parameters of the fit are the heat capacity, \( C \), and thermal diffusivity, \( D \), of the sample. We have carried out experiments on single-crystal sapphire with both roughened and smooth surfaces. The values obtained for the heat capacity and for the thermal diffusivity on the roughened samples are in excellent agreement with bulk heat capacity measurements and with steady-state thermal conductivity data on the same specimens. In the case of the smooth samples, specular scattering at the sample surfaces appears to require a more sophisticated analysis, which is presently being developed.

Here we would like to discuss the discrepancy between our data and the predictions of classical diffusion theory at early times. As shown, the data at earlier times always lie low relative to extrapolations of the later-time fits. When measured on faster time scales, the effects are even more pronounced and too large to be explained by thermometer response times, addenda, or other artifacts. However, the observation is consistent with the fact that (1) is acausal, since it predicts that the response to an impulse will begin instantaneously everywhere. The problem has been realized since the beginnings of diffusion theory, and a number of modified equations have been developed to account for it [2]. We are not aware of any previous experiments which have tested these equations. Since the expected minimum propagation time is about two microseconds, our data can provide such a test. We are presently developing a more complete description of fast-time thermal diffusion to explain the observed behavior.

3. Low-Diffusivity Experiments

The geometry which we have described is inappropriate for early-time studies on low-diffusivity materials with slow temporal response such as glasses. Instead, we have adopted the new arrangement shown in the inset of Fig. 2. The sample dimensions are similar to those of Fig. 1 except that the thickness is now typically 1 mm or more. In this case the heat diffusion is initially in two dimensions, and the time scale is determined by the heater-thermometer separation, usually 0.5 mm.

![Fig. 2. The geometry for "low-diffusivity" samples with heater and one thermometer shown. The temperature pulse was taken on a sample of Suprasil-W2 at 0.66 K. The small dots indicate the fit to (2).]