A new technique for measuring thermal conductivity at low temperature

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Abstract

The measurement of thermal conductivity of materials with very small thermal conductance has always been a challenge, as the acceptable value for the parasitic power dissipation during the measurement decreases with decreasing thermal conductance. At very low temperatures this problem naturally intensifies since the thermal conductivity of most materials becomes very low. For example, the measurement of thermal conductivity of insulating glasses at temperature below 10 mK has been prevented sofar by this shortcoming. We introduce a new technique for thermal conductivity investigations, which allows for a contact-free measurement and utilizes thermometry with very low parasitic power dissipation. We present preliminary results on BK7 glass down to about 5 mK.

Key words: thermal conductivity; glasses; tunneling states;

To measure properties of matter in the limit of very low temperatures has always been of fundamental importance since it often serves as a valid test for theories. However, due the nature of some experiments, the achievement of this goal can be a challenge. In the case of thermal conductivity measurements one faces usually the limit of allowed parasitic heat dissipation and the problem of thermal shunt through the electrical lead connected to the specimen. As the temperature decreases the situation worsens since the thermal conductivity of most materials decreases rapidly. Despite of these difficulties, in a recent experiment the temperature dependence of the thermal conductivity of the multi-component glass BK7 was measured for the first time down to about 10 mK [1]. This was made possible, by using the dielectric constant of the glass sample itself for thermometry and by reducing the power dissipation to about 0.1 pW.

Here we discuss a new contact-free technique for measuring the thermal conductivity that makes use of SQUID-based inductive thermometry with extremely low intrinsic power dissipation. The basic idea of this concept is, to heat the sample optically and to measure the temperature via the change of the dc magnetization of a paramagnetic material attached to the sample in a small magnetic field. The schematic diagram of the experimental setup, used for our measurements is shown in Fig. 1. The sample holder consisted of a copper base, to which the cylindrical glass sample (6 mm diameter and 16.5 mm long) was attached, a cylinder made of STYCAST around the sample, carrying the pickup coils, and an outermost aluminum tube, that was used to freeze in a small static magnetic field, produced by a superconducting coil wound around the aluminum cylinder. Two strips each of Au:Er (~ 500 ppm) $(11 \times 0.25 \times 1)\mathrm{mm}^3$ in size were glued circularly around the glass sample and were separated by about 6 mm. These two strips were used to measure the temperature of the sample at different positions in order to determine the temperature gradient ΔT. Gold containing small amounts of erbium is paramagnetic and thus its susceptibility changes with temperature roughly corresponding to the Curie law $\chi \propto 1/T$ [2]. Its change of magnetization in a field of 0.5 mT was used to determine the temperature. The change of magnetization of both Au:Er strips were measured via the change of flux

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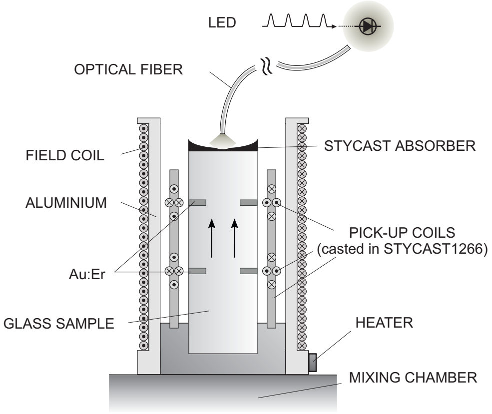

Fig. 1. Schematic diagram of the experimental setup.

through superconducting pick-up coils, each connected to the input coil of a dc SQUID. The pick-up coils are designed as second order gradiometers to reduce external disturbances. Prior to measurements the Au:Er thermometers had been calibrated against the temperature of the mixing chamber, where the experiment was mounted. The heat input $\dot{Q}$ for the glass was provided by light pulses from an LED through an optical fiber. The LED was mounted at the 1K pot of the dilution refrigerator and excited by positive voltage pulses with constant width and amplitude. The repetition rate of the pulses controlled the amount of heat deposited on the glass. As a light absorber, a small amount of STYCAST 2850 formed a black cap attached to the upper end of the glass.

The insert of Fig. 2 shows a typical measuring sequence starting at a temperature of 27.9 mK with the LED off. Both Au:Er thermometers are reading the same temperature. After 12 min. the LED was switched on for 12 min and the temperatures increased correspondingly. The total change of the temperature at the upper Au:Er thermometer was about 5% of the base temperature. The temperatures of the two thermometers during the heating process were different as expected. The temperature gradient, which is used to determine the thermal conductivity, is easily obtained. After switching off the LED, the temperature at both Au:Er thermometers returned to the mixing chamber temperature. Next the mixing chamber temperature was changed to 25.1 mK and the procedure was repeated. The resulting temperature dependence of the thermal conductivity of BK7 is shown in Fig. 2 together with the data from [1] and [3].

The data obtained with the new contact-free method agree well with previous investigation in the temperature range above 10 mK. Due to the extremely low parasitic power dissipation of the new technique it was possible for the first time to measure the thermal conductivity of an insulating glass even below 10 mK, down to the minimum temperature of the dilution refriger-

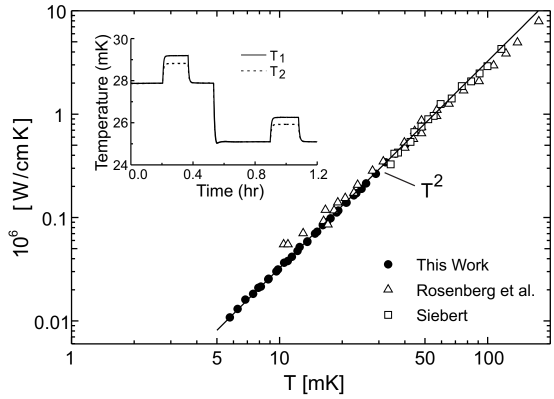

Fig. 2. Thermal conductivity of BK7 as determined with the contact-free method compared with previous results [1] and [3]. The insert illustrates the experimental procedure.

ator of about 5 mK. We estimate the power dissipation in our thermometers due to the SQUID measurement to be less then 10^{-20} W. The main contribution of this power dissipation stems from eddy current heating in the Au:Er caused by flux noise and Josephson oscillations in the SQUID. A detailed discussion of this so-called back action in SQUID measurements can be found for example in [4]

The thermal conductivity of insulating glasses is determined by the flow of thermal phonons which are scattered resonantly by atomic tunneling systems [5]. Due to the irregular structure of amorphous solids the parameters of the tunneling systems are widely distributed. Because of this one expects that the thermal conductivity of glasses varies proportional to T^2 at low temperatures. Our preliminary data agree roughly with this expectation, indicating that the mentioned mechanism of heat transport in glasses dominates down to temperatures of about 5 mK in BK7.

We believe that this new method for measuring thermal conductivity opens up many possibilities for experiments on samples with very low thermal conductivity and in particular at ultra-low temperatures.

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