Thermal conductivity of materials and measuring system at cryogenic temperature

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A measuring system, including the measuring setup and corresponding software, is developed to perform the measurement of the thermal conductivity of rod samples with millimeter scale in temperature range 4.2-300K. The precisions and applicability are proved by experiments on a number of materials including superconductors, SDW alloys, CMR materials, as well as engineering materials.

INTRODUCTION

The thermal conductivity of materials is of high importance in both science and engineering fields. There are several mechanisms by which heat can be transmitted through materials and many processes that limit the effectiveness of each mechanism. In a non-metal heat is conducted by means of the thermal vibrations of the atoms. In a simple metal this mode of heat transport makes some contribution, but the observed thermal conductivity is almost entirely due to the electrons. It does not follow that thermal conductivity of the two different materials must be very different in magnitude, as they are in the case of electrical conductivity, but their dependences on temperature and on the imperfections in individual specimens are rather different. In many materials, such as alloys and semiconductors, both transport mechanisms can make comparable contributions to the observed conductivity, and the relative proportions vary with composition and temperature. In superconductors the proportions are different in the moral and superconducting states, so that below the transition temperature they can be changed by an appropriate magnetic field.

In engineering, automotive, aerospace and related industries, thermal conductivity is important design parameters. These industries require access to reliable standards of thermal conductivity to facilitate material development, evaluation and improvement of component design as well as to ensure good quality control of manufactured products. There is also a demand for Certified Reference Materials and Transfer Standards for the calibration of comparative thermal conductivity apparatus that are mainly supplied by US companies. At present the manufacturers supply these apparatus with standards or reference materials that are uncertified and primarily refer to book values of thermal conductivity typical for that material. In the current climate of increasing accreditation of measurement testing facilities auditors are requiring test laboratories to have reference materials whose calibrations are traceable to national standards.

At any rate, it is necessary to measure thermal conductivity exactly. We have developed a thermal conductivity measuring system, including the measuring setup and corresponding control software, to measure the thermal conductivity of rod samples with millimeter scale in temperature range 4.2-300K. The precision and applicability of the system are proved by experiments on kinds of materials including superconductors, SDW alloys, CMR materials, as well as some engineering materials.

EXPERIMENTAL CONSIDERATIONS

Method

The method of longitudinal steady thermal flow [1] is used in the measurement. In this simplest steady-state experimental arrangement, heat is supplied at one end of a rod of uniform cross-sectional area A at a known rate $\dot{Q}$ and is removed at the other end. The temperature difference ΔT is established with a distance L. The thermal conductivity is then derived from the relation

$$K = \frac{\dot{Q}}{\Delta T} \cdot \frac{L}{A} \qquad (1)$$

Setup

A schematic view of the experimental chamber setup and sample holder is shown in Figure 1 [2]. Vacuum of the sample chamber was kept 10^{-4} Pa during the measurement. The temperature difference on the sample generated by the gradient heater is monitored directly with a differential thermocouple. The temperature difference on the sample is controlled about 1 K.

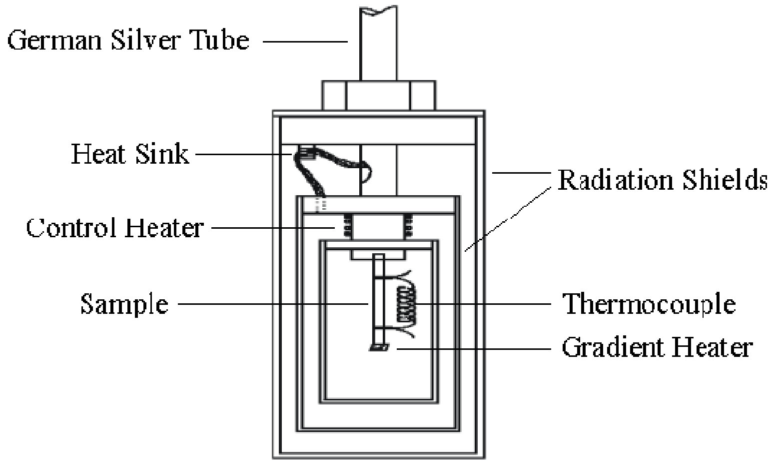

Figure 1 Schematic diagram of the experimental setup

Automation

The real-time read and write are realized by a GPIB interface board and insolated analog output boards respectively, as shown in Figure 2. The temperature instability of the sample is controlled within $\pm 2mK$ by a PID temperature controller [3]. Corresponding software is developed to collect and process the experimental data.

The Borland C++ Builder 6.0 environment is used to develop the real-time direct digital control software that practices the automation of data collection and process. We pay most attention to the convenience, security and stability of the software as BCB 6.0 provides perfect visualization component libraries (VCL). The measuring system can work properly in temperature range 4.2-300K. The experimental results of different materials are probed continuous and smooth as temperature varies.

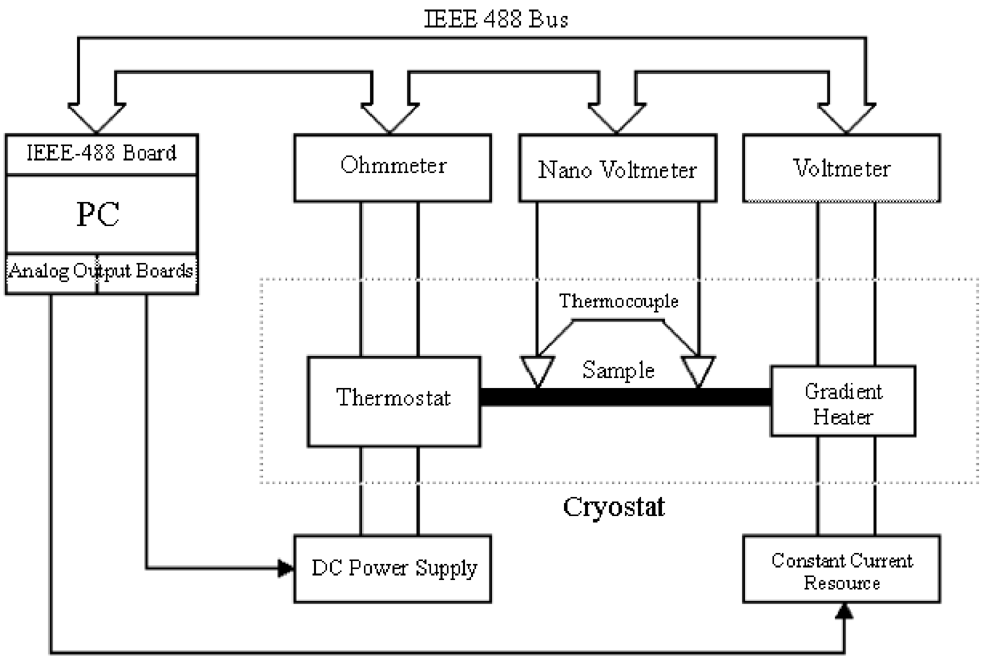

Figure 2 Schematic diagram of the real-time data collection and process

EXPERIMENTAL RESULTS

On this measuring system, we have obtained the thermal conductivity of a number of materials including superconductors [4-10], SDW alloys [11,12], and CMR materials [13, 14], as well as some engineering materials. The results meet the requirement of numerical analyses and are repeatable. Some typical thermal conductivity temperature dependences are given below.

Thermal conductivity of superconductors

The thermal conductivity peak in high T_C superconductors (HTS) has been validated [4 and its references] under T_C. Below T_C superconducting electrons condensing into Cooper pairs carry no heat, the thermal conductivity is thus ensured by normal electrons. Since the normal electron scattering rate in HTSs has been observed to decrease rapidly below T_C, thermal conductivity should increase under T_C. As temperature kept decreasing, the number of carriers decreases, that leads to the decreasing of thermal conductivity. The thermal conductivity of high T_C superconductor $Hg_{0.9}Tl_{0.2}Ba_2Ca_2Cu_3O_y$ [4] is shown in Figure 3. The thermal conductivity peak under T_C is remarkable. The thermal conductivity of new superconductor MgB_2 [6] is shown in Fig. 4. No obvious variation is observed near T_C.

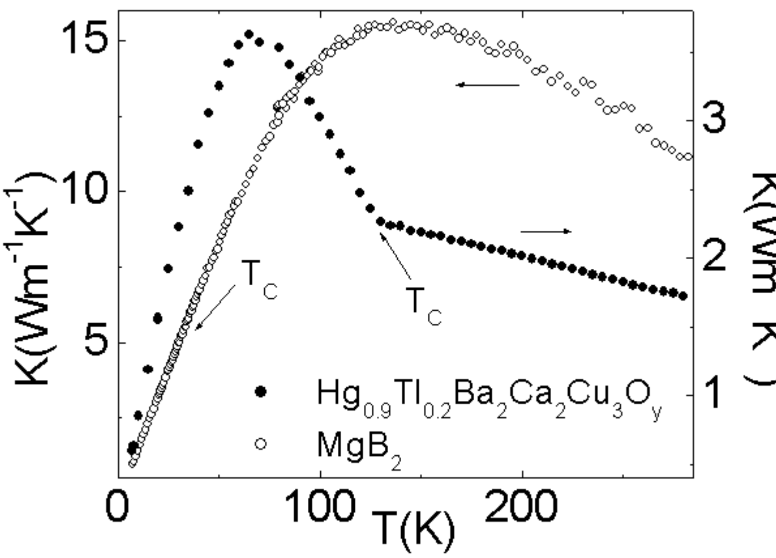

Figure 3 The thermal conductivity of high T_C superconductor Hg1223 and new superconductor MgB_2

Thermal conductivity of CMR materials

The thermal conductivity of CMR material $La_{0.7}Ca_{0.3}Mn_{0.95}Cr_{0.05}O_3$ [12] is shown in Figure 4. A minimum is observed at the Curie temperature (T_C), and a phonon-induced peak [1] is observed at about 20K. It is remarkable that the thermal conductivity and electrical conductivity show similar temperature dependence about T_C. The similarity is more interesting knowing the fact that electron contribution educed from Wiedemann-Franz law [1] is less 1%. Because of the strong electron- phonon interaction in perovskite structures, electron contributes to the thermal conductivity indirectly as well. The unusual similarity between thermal conductivity and electrical conductivity temperature dependence results from the indirect electron contribution. Above T_C, electrons are localized around phonons forming polarons. Thus modes of phonon are limited by these localized electrons. Under T_C, electrons delocalize. As temperature decreasing, more electrons become mobile. Phonons are no more bound to electrons. Thus the thermal conductivity increases with a decreasing temperature.

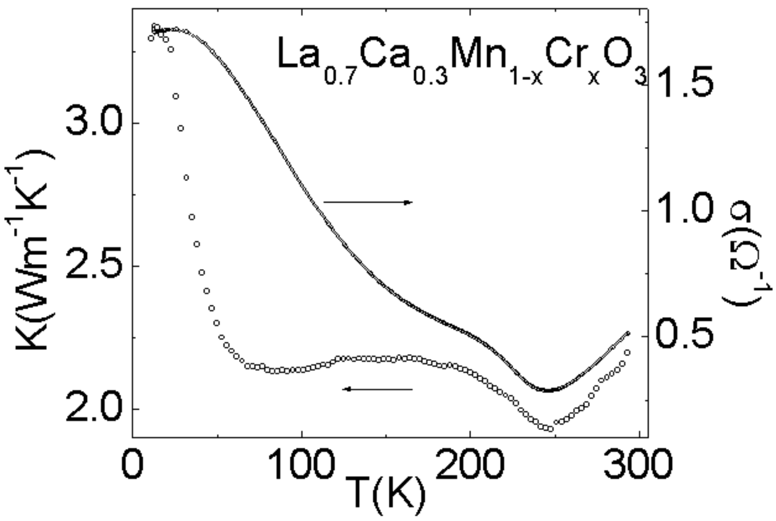

Figure4 The thermal conductivity of CMR material

Thermal conductivity of engineering materials

Both good and poor thermal conductors are demanded in different engineering fields. The thermal conductivity of Ag sheathed Bi-2223 superconducting cable and insulator in superconducting loop are shown in Figure 5. The difference in thermal conductivity is about two orders of magnitudes.

CONCLUSION

A measuring system, including measuring setup and corresponding software, is developed to measure the thermal conductivity of rod samples with millimeter scale in temperature range 4.2-300K. The precisions and applicability of the system are proved by the measurement performed on kinds of materials.

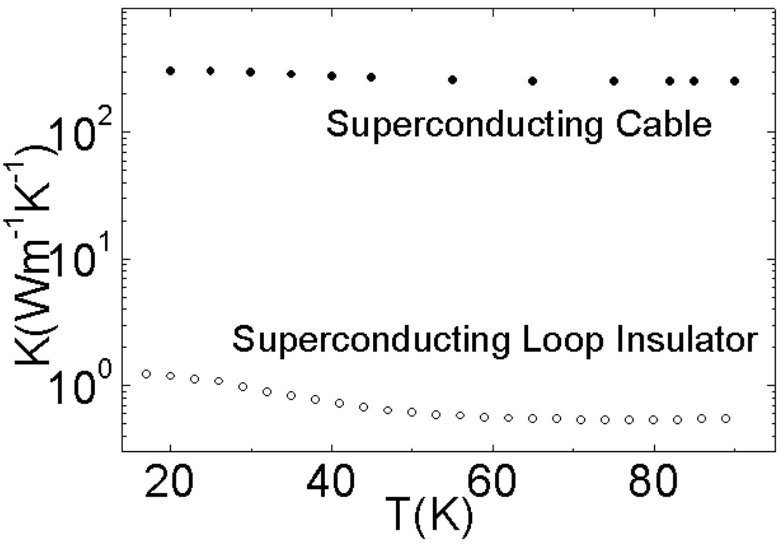

Figure 5 The thermal conductivity of some engineering materials

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