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Thermal conductivity of the high-T_c superconductors

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In honor of Martin Peter's 60th birthday.

Abstract. The measurements of thermal conductivity λ of $GdBa_2Cu_3O_{7-x}$, $YBa_2Cu_3O_{7-x}$ and $SmBa_2Cu_3O_{7-x}$ are presented. For the transition temperature T_c there is a pronounced change of the slope on the $\lambda(T)$ dependence. For the temperatures lower then T_c the broad maximum occur, which height depend on the magnitude of the electronic component λ_e of the thermal conductivity.

From the transport properties of the new class of high-T_c materials, electrical conductivity measurements are widely used by all the researchers. Thermal conductivity measurements, which are much more time consuming and need some experience, were presented only in few papers [1, 2, 3] for the Y–Ba–Cu–O samples.

In this paper we present the results of the thermal conductivity measurements for the samples of Gd–Ba–Cu–O, Y–Ba–Cu–O and Sm–Ba–Cu–O in the temperature range from 5 to 100 K. The $\lambda(T)$ dependences show the similar features for all the samples.

Polycrystalline samples were prepared from high purity powders of Gd_2O_3, Sm_2O_3, Y_2O_3, Ba_2CO_3 and CuO. After mixing and pressing into pellets the samples were calcinated in air at 950°C for 10 hours. Then after pulverisation and pressing they were heat treated in flow oxygen atmosphere at temperature about 650°C for about 6 hours. This procedure was repeated several times.

X-ray analysis proved that all the samples were single phased but their lattice parameters differ slightly. It was connected with the little different amount of oxygen.

The resistive transitions of the samples were measured by the standard four probe method. The results are summarized in Table I. The resistivity of the Y–Ba–Cu–O decreases linearly with temperature from the room temperature down to about 100 K whereas for all the other samples resistivity was proportional to $T^{0.5}$. As the example the resistivity temperature dependence is shown in

Table I

Sample	Gd-1	Gd-2	Gd-3	Gd-4	Sm	Y
T_c [K]	91.8	92.7	90.0	92.3	92.0	89.5
ΔT_c [K]	3.7	2.5	6.1	3.2	2.2	4.2
ρ_{300} (mΩcm]	2.2	2.4	21.5	21.0	1.5	0.74
ρ_{300}/ρ_{100}	2.1	1.8	1.2	1.4	1.5	3.1

Fig. 1. In the insert the same plot is presented but as the $\rho(T^{0.5})$ dependence. Such a behaviour may result from our method of preparing samples.

Thermal conductivity measurements were carried on by a stationary state method in the temperature range 5–300 K. The sample chamber temperature was stabilized with the accuracy better then $\pm 3 \times 10^{-3}$ K. The sample temperature was measured by a constantan-manganin thermocouple, with the liquid nitrogen and liquid helium temperatures as reference points. Particular care was taken to avoid the heat transfer between the sample and its environment. The samples were placed inside the cylindrical screen, made of material with the similar thermal conductivity as the samples along which the temperature gradient was maintained identical as along the sample. Mean temperatures of the sample and the screen were identical. All current and voltage leads were thermally anchored to the screen. The measurements were carried on for different temperature gradients (from 0.1 to 1 K). Although the typical sample dimensions were $1.8 \times 2.5 \times 10\ \text{mm}^3$, some measurements were repeated for the samples with different dimensions. The measurement error was below 1.5%.

The total thermal conductivity temperature dependence for three $GdBa_2Cu_3O_{7-x}$ and one $YBa_2Cu_3O_{7-x}$ and $SmBa_2Cu_3O_{7-x}$ samples are presented

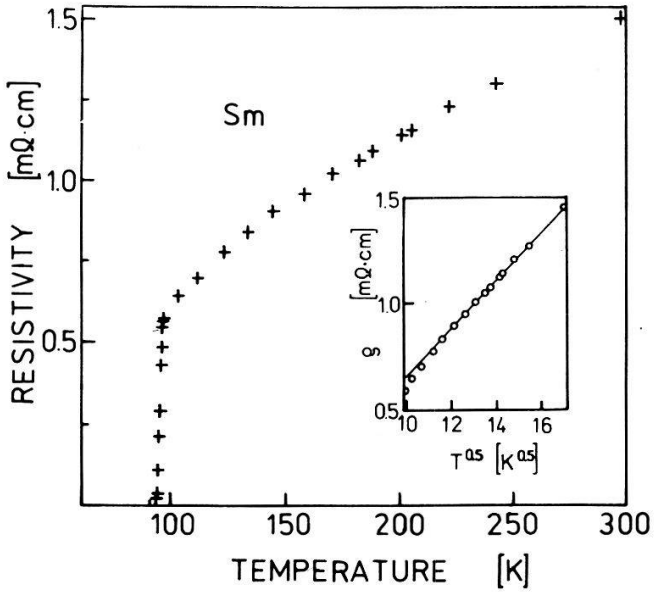

Figure 1
Temperature dependence of the resistivity of the sample Sm. In the insert-resistivity of the sample Sm versus $T^{0.5}$.

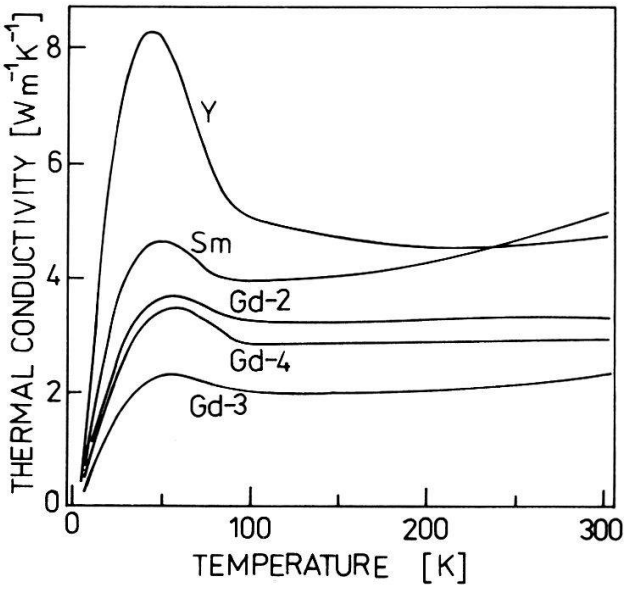

Figure 2
Total thermal conductivity temperature dependence.

in Fig. 2. For the better clarity the results are plotted as solid lines which are drawn through the measured points. The scatter of the experimental points around these smoothed lines did not exceed ±0.1%.

It is seen that the $\lambda(T)$ dependences are similar for all the samples. For the transition temperature there is an abrupt change of the slope of the curves. For the temperatures lower then T_c there is a linear increase of λ up to temperatures about 45–55 K where the maxima on the $\lambda(T)$ dependence occur. Below the $T_{\lambda max}$ there is almost linear decrease of λ down to temperatures of about 10 K. Below this temperature the dependence becomes quadratical with temperature. This behaviour is depicted in Fig. 3 where experimental points are presented

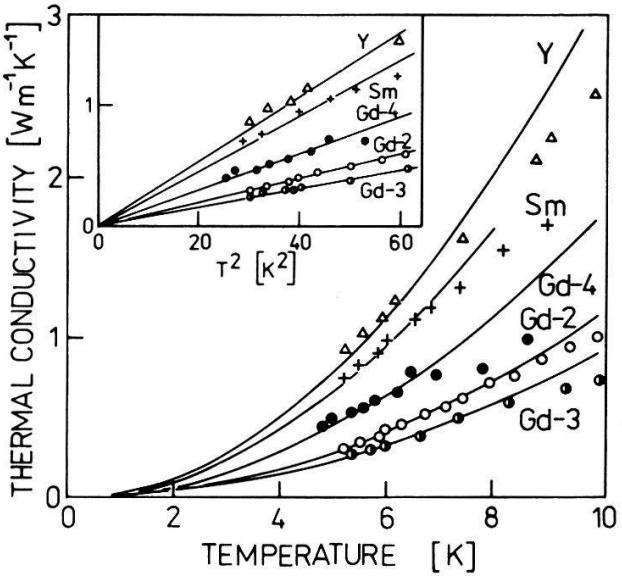

Figure 3
Total thermal conductivity for the low temperature region (solid lines represent quadratic fit to the experimental points). Insert-thermal conductivity versus T^2.

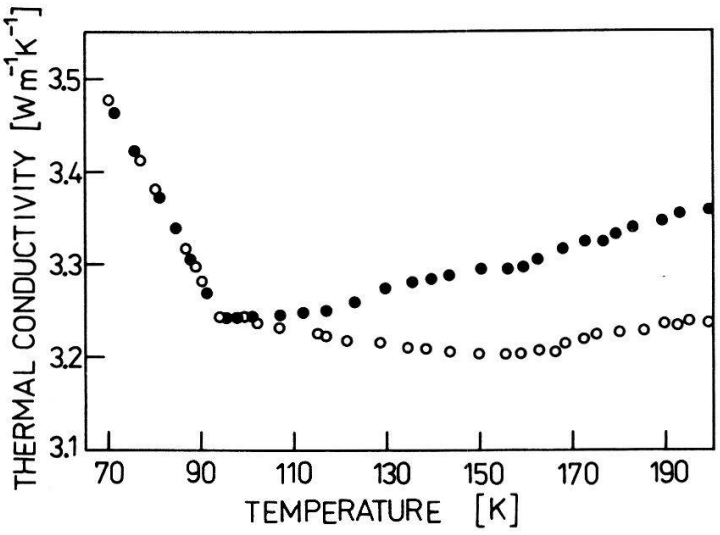

Figure 4
Thermal conductivity temperature dependence for the sample Gd-2 before- (open circles) and after (closed circles) heat treatment.

together with the solid curves proportional to T^2 fitted to them. For the better visibility of this dependence it is replotted in quadratic scale of the temperature in the insert of Fig. 3.

For the temperatures above the transition there is a wide 'plateau' on the $\lambda(T)$ dependence with the slight increase of λ above about the 180 K. This behaviour is characteristic for anisotropic, layered crystals with the large number of different atoms in the unit cell and the high anisotropy of interatomic interactions [4].

For the Sm–Ba–Cu–O sample above the transition temperature a pronounced increase of λ may be observed. In our opinion such a behaviour is probably connected with the existence of the gas inside the deep pores of this ceramic. Recondensation of this gas from the hot to the cold wall of the pore may give the additional mechanism for transporting the heat in higher temperatures.

Our view may be supported by the observation of the change of the $\lambda(T)$ dependence for the sample Gd-2 after heating it in helium gas above 150°C. This change is presented in Fig. 4. It is seen that for the temperatures close to the transition one the $\lambda(T)$ dependence is identical for heated and nonheated sample. But above about 100 K thermal conductivity of the heated sample increases with the temperature. It is interesting, that the resistivity temperature dependence of the sample was identical before and after heat treatment. It is also difficult to imagine that the structure of the sample was changed after heat treatment in rather low temperature. All this seems to support our view that the increase of the thermal conductivity for the temperatures higher than about 180 K for some samples is connected with the gas present in the deep pores of the sample.

Making use of the electrical resistivity values and according to the Wiedeman–Franz law, we are able to evaluate the electronic component λ_e of the thermal conductivity of the samples. It is equal to about 20% for Y–Ba–Cu–O sample about 8% for the Gd-2 sample, about 10% for Sm–Ba–Cu–O sample,

about 2% for Gd-3 sample and changes from about 2% for $T = 100$ K to 10% for $T = 300$ K for Gd-4 sample. It is seen that the height of the maximum is connected with the value of the electronic component λ_e of thermal conductivity.

It is interesting to compare our results with the other obtained for Y–Ba–Cu–O samples [2, 3]. It turns out that the $\lambda(T)$ dependences are very similar and the measured values of λ are very close to the samples with the similar value of the electronic component λ_e of the thermal conductivity.

In conclusion we can state that for all the samples the dominant role is played by the phonon mechanism of thermal conductivity. All the measured samples exhibit a maximum on the thermal conductivity temperature dependence which is similar to the one observed for dielectrical samples but which in our opinion is connected with the transition to superconducting state for which the scattering phonons on electrons is much lower. The height of this maximum is closely related to the value of the electronic component of the thermal conductivity of the samples.

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