The Hall effect and the thermal emf of single-crystal films $YBa_2Cu_3O_{7-x}$ and $HoBa_2Cu_3O_{7-x}$

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The temperature dependence of the Hall coefficient R_H, the mobility of current carriers μ, the thermal emf α of $Y(Ho)Ba_2Cu_3O_{7-x}$ single-crystal films, and the dependence of R_H on the magnetic field strength were studied experimentally. The quantities R_H and α were found to have a positive sign. The number of carriers per cell was found to be 0.9 (120 K)–1.7 (300 K).

The kinetic phenomenon in high-temperature superconductors have been studied extensively.[1–6] Most of the studies, however, utilized ceramic samples, causing a large scatter in the values of μ and α, to the point of a disagreement in the sign of the thermal emf. The use of single-crystal samples to carry out these experiments makes it possible to obtain additional information on the properties of the electron gas, information which is necessary to determine the nature of the high-T_c superconductivity. We have measured the temperature dependence of the Hall coefficient R_H and the thermal emf α of $YBa_2Cu_3O_{7-x}$ and $HoBa_2Cu_3O_{7-x}$ single-crystal films with the [001] axis oriented perpendicular to the plane of the substrate.

The films 0.2–1.3 μm thick, grown on $SrTiO_3$ single-crystal substrates according to a method described in Ref. 7, had a critical temperature T_c of the superconducting transition in the range from 87 K to 91 K, with a transition width of 0.5 K. At $T = 100$ K the resistivity was in the range 60–150 $\mu\Omega\cdot$cm. The Hall voltage and thermal emf were measured with an accuracy of 50 nV, using a compensation method. The thermal emf was measured between the copper sides of the copper-constantan thermocouples at a temperature gradient of 1–3 K. The absolute values of α of the samples were determined with allowance for the additive contribution of the temperature-dependent thermal emf of copper.[8]

Figure 1 is a plot of the Hall coefficient as a function of the strength of the magnetic field H at $T = 300$ K. Within the experimental error, R_H does not depend on H, is positive, and is equal to 6×10^{-4} cm^3/C (for $HoBa_2Cu_3O_{7-x}$) and 6.5×10^{-4} cm^3/C (for $YBa_2Cu_3O_{7-x}$). At $T = 300$ K the concentration of the carriers $p = r/R_He$ amounts to 1×10^{22} cm^{-3} and 9.6×10^{21} cm^{-3}, respectively, under the assumption that the "Hall factor" $r = 1$. The temperature dependence of R_H for the $HoBaCu_3O_{7-x}$ film in the field $H = 10$ kOe is shown in Fig. 2. We see that R_H increases with decreasing T from 300 K to 120 K roughly by a factor of 2 (from 0.9 to 1.7 holes/cell). This result is in good agreement with the data of the studies on $YBa_2Cu_3O_{7-x}$ ceramic samples.[3] Shown also in this figure is the temperature dependence of the Hall mobility $\mu = R_H\sigma$, where σ is the resistivity of the $HoBa_2Cu_3O_{7-x}$

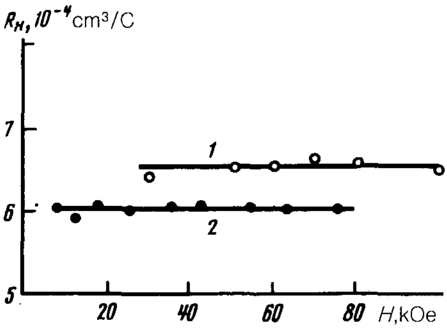

FIG. 1. The Hall coefficient vs the magnetic field for single-crystal films. 1—$YBa_2CU_3O_{7-x}$; 2—$HoBa_2Cu_3O_{7-x}$.

sample. As the temperature is raised, μ decreases from 6.5 to 1.4 cm²/(V·s) in accordance with $\mu \propto T^{-1.7}$.

At such low values of μ the question arises as to whether the Boltzmann kinetic equation can be used for high-T_c superconductors. The linear nature of the temperature variation of the resistivity of the lanthanum and yttrium superconductors, which is retained to 1000 K and 600 K (Ref. 4), respectively, leads us to assume that at temperatures below 300 K the mean free path is greater than the distance between the nearest Cu–O atoms. The fact that the calculated kinetic coefficients for lanthanum superconductors are in qualitative agreement with experiment is evidence in favor of the applicability of the kinetic equation.[9]

To determine the sign of the charge carriers, which may not be the same as that of the Hall coefficient when the mean free path is comparable to the lattice constant,[10] we

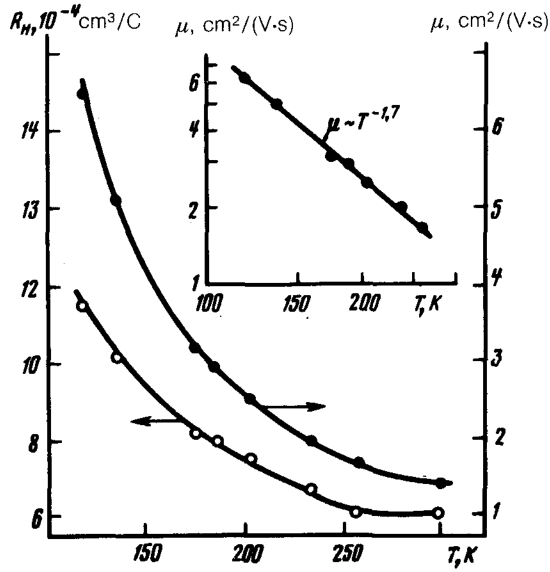

FIG. 2. Temperature dependence of the Hall coefficient and of the mobility of the current carriers for an $HoBa_2Cu_3O_{7-x}$ single-crystal film.

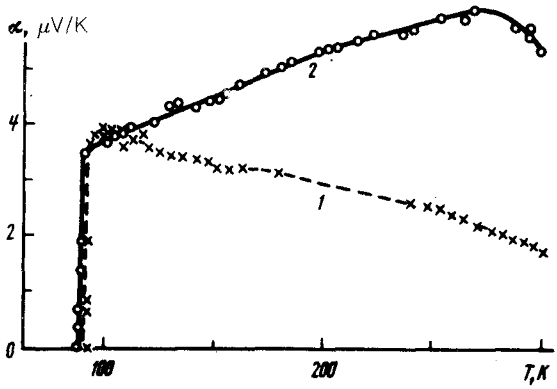

FIG. 3. Temperature dependence of the thermal emf coefficient of the single-crystal films. 1—$HoBa_2Cu_3O_{7-x}$; 2—$YBa_2Cu_3O_{7-x}$.

have carried out additional measurements of the thermal emf. Experimental studies of the $HoBa_2Cu_3O_{7-x}$ and $YBa_2Cu_3O_{7-x}$ films have shown that the sign of α is positive in the temperature interval from T_c to 300 K. Near T_c the thermal emf decreases sharply and at $T \leqslant T_c$ it vanishes, indicating that there is no parasitic thermal emf in the circuit. The value of α of the more perfect samples of both compounds ($\rho \approx 60$ $\mu\Omega \cdot$cm) decreases with increasing temperature (curve 1 in Fig. 3). The samples with large values of ρ exhibit a different behavior of $\alpha(T)$ until α begins to increase as a result of increasing T (curve 2 in Fig. 3).

If the phonon drag is disregarded, we can describe the thermal emf of metals by

$$\alpha = \frac{\pi^2 k^2 T}{3e} \left[N(E)/p + \frac{d \ln \mu(E)}{dE} \right]_{E = E_F} \quad (1)$$

Here $N(E)$ is the state density of the current carriers, k is Boltzmann's constant, and E_F is the Fermi energy. Since the second term in parentheses is much smaller than the first term, it can be ignored. In this case we have

$$\alpha(T) \sim TN(E_F)/p. \quad (2)$$

The experimentally observed functional dependence $\alpha(T)$, which differs markedly from (2), indicates that a strong phonon drag due to a high Debye temperature and a strong electron-phonon interaction is typical of high-T_c metal-oxide superconductors right up to $T \sim 300$ K. The shape of the $\alpha(T)$ curve can also be affected by the change in $N(E_F)$, which is related to the temperature dependence of the electron-phonon renormalization of this value. The sensitivity of α to the structural perfection of the samples and its dependence on the temperature may stem from the partial suppression of the phonon drag as the phonon mean free path is reduced. The change in the concentration of the carriers p with temperature should also be taken into account. The observed increase in R_H suggest that p decreases with decreasing temperature. A possible increase in R_H may be due to a decrease in the concentration of holes as a result of thermal activation to a narrow auxiliary band which is situated near E_F. This assumption is consistent with the data obtained by Ong *et al.*,[3] who observed a slight x dependence of R_H for $YBa_2Cu_3O_{7-x}$ with $0.1 \leqslant x \leqslant 0.5$ and a strong $R_H(x)$ dependence for $x > 0.5$, which they attributed to the stabilization of the Fermi level by a narrow band of localized states, which corresponds to E_F at $x \approx 0.4$. A similar conclusion was reached by Kapitulnik[11] and Forro *et al.*[12] This phenomenon can be explained unambiguously by obtaining additional data on the band structure and the shape of the Fermi surface in such superconductors.

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