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Hall effect studies in YBCO films

A. L. Solovjov

B. Verkin Institute for Low Temperature Physics and Engineering,
National Academy of Sciences of Ukraine, 47 Lenin Ave., 310164 Kharkov, Ukraine
E-mail: solovjov@ilt.kharkov.ua

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The longitudinal, $\rho_{xx}(T)$, transverse, $\rho_{xy}(T)$, and Hall, $\rho_H(T)$ resistivities have been measured for $YBa_2Cu_3O_x$ (YBCO) films, showing positive resistivity buckling and those with usual linear $\rho_{xx}(T)$ dependence. In the former case unexpected peak on $\rho_{xy}(T)$ and unusual $\rho_H(T)$ dependence with double sign change just above transition temperature T_c have been revealed. The data are analyzed using recent theory for the sign of the Hall conductivity in strongly correlated systems.

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1. Introduction

Investigation of the Hall effect is known as a useful method in getting reliable information about specific normal-state properties of high-T_c superconductors (HTS's) [1], which are believed to be of primary importance in deciphering their behavior in the superconducting-state. Despite of a huge amount of papers published on this problem, unusual temperature dependence of the Hall resistivity with sign reversal (SR) at the resistive transition [2] still remains controversial. Besides, there is an evident dependence of the properties of HTS's on the carrier density in the CuO_2 planes, n_h , which is determined by oxygen doping and which leads to spin gap opening [3] in the underdoped regime. Another phenomenon in HTS's, which also depends on doping, is the enhanced electron-electron correlation [4,5]. In slightly underdoped regime (80 K < T_c < 90 K), where the features of the spin scattering are not so pronounced, effects due to electron-electron correlation are believed to be observable, both in the resistivity and Hall effect measurements. However, the role of both mechanisms in superconducting coupling in HTS's is still questionable.

2. Results and discussion

To further investigate this point, we carried out resistivity and Hall effect measurements of YBCO films with different oxygen content. In this paper we report the results obtained on two YBCO films, designated below as samples S1 and S2, and on a reference film (S3). The films were epitaxially grown by pulsed laser deposition on $SrTiO_3$ (100) substrates and patterned into well-defined 4×0.2 mm Hall-bar structures by standard lithography and chemical etching techniques [6]. The Hall-bar geometry consists of current leads and three pairs of transverse voltage contacts. To exclude uncertainties due to geometric effect, the Hall data reported here have been acquired using both the first and the third pair.

The reference film with $T_c \simeq 90$ K shows a typical dependence for such YBCO systems, which is almost linear $\rho_{xx}(T)$ dependence in the normal state. But S1 ($T_c \simeq 86$ K) and S2 ($T_c \simeq 84$ K) demonstrate enhanced resistivity and slightly positive resistivity buckling just above 120 K (S1) and 110 K (S2), respectively. Here T_c is defined as the temperature at which the approximated $\rho_{xx}(T)$ drops to zero. The enhancement of the resistivity and lowering of T_c suggest that the films are in a slightly underdoped regime. On the other hands unusual buckling can be attributed to the changes in spin-fluctuation parameters, as it has been studied extensively by Stojkovich and Pines [7].

The longitudinal resistivity $\rho_{xx}(T)$ was measured and the transverse resistivity $\rho_{xy}(T) \sim V_{xy}/I_{xx}$, which simultaneously has been observed on the transverse pairs of contacts even in the absence of a magnetic field, was investigated. Simple algebra yields (2–4) μm misalignment of opposite transverse strips is enough to produce $R_{xy}(100\ \text{K}) \simeq (0.5-1)\Omega$,

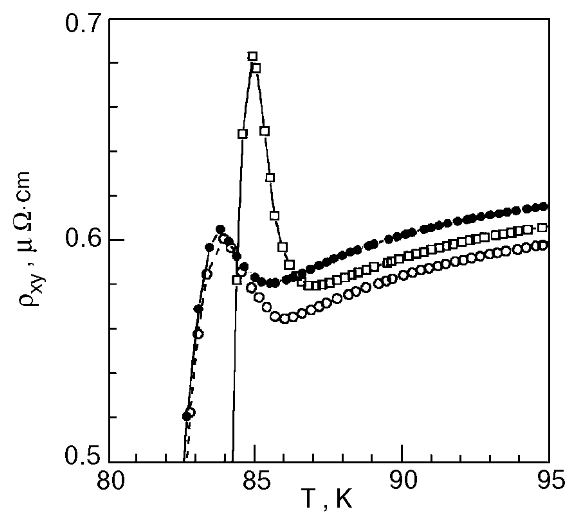

Fig. 1. Effect of magnetic field, $B_z = 600$ mT, applied parallel to the c axis in opposite directions, in the ab plane transverse resistivity, $\rho_{xy}(T)$, for sample S2 (dots and circles). Squares correspond to $\rho_{xy}(T)$ without a magnetic field.

which is usually observed experimentally. To avoid a suspicion of thermo-emf origin of the transverse signal, we performed measurements with a very small transport current, $I_{xx} = 10^{-7}$ A. No transverse voltage has been observed in this case. Any other intrinsic reasons that may cause the transverse signal have not yet been identified.

No unexpected peculiarities are revealed on the $\rho_{xx}(T)$ dependences of the reference film and S1, whereas S2 exhibits a pronounced ρ_{xy}-vs-T peak at the beginning of the resistive transition (Fig. 1, squares). The peak starts to grow at $T_{co} > T_c$, which is the temperature at which the magnetic field begins to broaden the resistive transition (Fig. 2, solid and dashed lines). The peak is clearly seen on both pairs of contacts, suggesting its intrinsic nature. The magnetic field B_z, of opposite directions, along the c axis and vice versa, noticeably suppresses the peak and shifts it slightly towards low temperatures (Fig. 1, dots and circles).

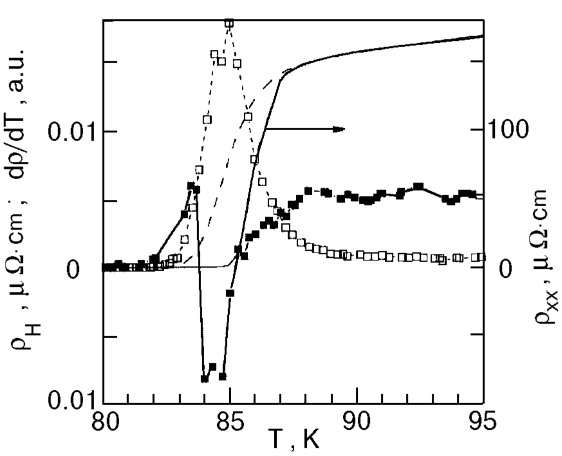

Fig. 2. ρ_H (solid squares), ρ_{xx} (solid line — $B_z = 0$, dashed line — $B_z = 600$ mT) and $d\rho_{xx}/dT$ (squares — $B_z = 600$ mT) vs T dependences for sample S2.

There are several theoretical models [8,9] to describe the appearance of the transverse voltage in HTS's. According to Glazman [8], vortices and antivortices produced by the transport current can attract each other at a relatively small current, when the number of vortices is not too large. The interaction gives rise to deformation of the vortex trajectories. As a result, a nonzero transverse voltage should appear on the film since the trajectories intersect the measurement contour. Unfortunately, no dependence on the external magnetic field is analyzed. The effect must disappear with increasing transport current, which leads to the enhancement of the number of vortices. However, no expected dependence on current has been observed in our experiments.

Another theoretical approach to the problem has been proposed by Doornbos et al. [9]. They have shown that inhomogeneity of oxygen impurity concentration in high-T_c oxides leads to spatial fluctuation in the charge carrier density and, consequently, to fluctuation in T_c. Because of the very short coherence length in HTS's, different inhomogeneities, even with very small characteristic lengths, may deeply affect the superconducting properties. To model an inhomogeneous high-T_c superconductor they considered a square, two-dimentional, random resistor network (RRN). Because the resistivities and T_c's of the resistors are expected to be different, there must be a transverse component of the transport current producing the peak just at the beginning of the resistive transition. When activation energy U is considered to be constant, but T_c is randomly distributed, the anomalous peak must decrease with increasing magnetic field, as we observed in our experiments. It has been shown [10] that very moderate T_c difference, of the order of 1 K or less, is large enough to produce the effect.

Mosqueira et al. [10] used a model [11] similar to RRN to account for their results obtained in measuring the longitudinal resistivity, $\rho_{xx}(T)$, in YBCO single crystals. The oxygen-deficient crystals, with T_c between 85 K and 90 K, showed a similar resistivity peak being quenched by a magnetic field in the same manner as in our measurements. The only difference is that the value of the transverse voltage measured in our experiments is much smaller. In the framework of the RRN model this suggests the fact that a transverse component of the transport current, I_{xx}, which produces the transverse voltage, is rather small, approximately $(1-5)\cdot 10^{-4} I_{xx}$, which seems to be a reasonable value. Thus the RRN model [9] enables us to physically reasonably explain the appearance of the transverse resistivity peak. We also think that observation of the peak may be viewed as additional evidence that the sample is underdoped. No peaks have been observed on films with $T_c \simeq 90$ K. Moreover, as has been demonstrated by Mosqueira et al. [10], after re-oxygenation the crystals showed $T_c \geq 90$ K and all peaks disappeared.

As Fig. 1 shows, magnetic field of both opposite direction noticeably affects the resistivity curve in the normal state (Fig. 1, dots and circles). One-half of the distance between these two curves determines the Hall-resistivity,

$$\rho_H(T) \sim (V_{xy}/I_{xx}) = R_H(T) d^{-1} B_z \,, \qquad (1)$$

where d is the sample thickness. Thus, the Hall coefficient R_H can be easily determined. In high-T_c oxides R_H turnes out to be temperature dependent [12]. Usually measured experimentally, $\rho_H(T) \sim R_H(T)$ starts to noticeably grow at about 240 K and reaches its maximum level just above T_{co}, as the temperature is lowered. Below T_{co}, $\rho_H(T)$ rapidly decreases, becomes negative, and then comes to zero at $T_c(H)$, thus giving rise to the sign reversal (SR) of the Hall resistivity. Both S1 and S3 show the usual $\rho_H(T)$ dependence with the SR effect. But S2 exhibits unusual, almost linear, $\rho_H(T)$ dependence with a positive slope and unexpected double sign reversal (Fig. 2, solid squares), which was observed experimentally on YBCO films for the first time. As has recently been shown [13], the linear $\rho_H(T)$ dependence can be considered as additional evidence for enhanced electron-electron correlation in the sample.

To account for the SR effect different flux-flow-based models (see, for example, Hagen et al. [2] and the bibliography cited there), are commonly used. The authors [2] have concluded that due to the specific interplay between the Magnus force and the drag force, vortex velocity $\mathbf{v}_L$ should generate a Hall voltage, whose sign is opposite to that of the normal state. But the double sign reversal effect does not seem to be explained by the models. Moreover, recent theory concerning the Hall effect in strongly correlated (SC) systems [14] is believed to be more appropriate. Using the Hubbard $t-J$ model, Rojo et al. [14] have analyzed the Hall current as a function of the filling fraction, $n = N_p/N_s$, where N_p and N_s are the total particle number and the number of sites in the considered lattice, respectively. In the framework of this approach, the $t-J$ Hamiltonian have to include the Hubbard repulsion,

$$H' = G \sum_{\langle i,j \rangle} (n_i - \langle n \rangle)(n_j - \langle n \rangle) \,, \qquad (2)$$

which suggests a clear dependence on n_h with $\langle n \rangle$ being the mean particle number. Finally, the result was found to be strongly dependent on the correlation parameter G/t. When $G/t = 0$, the equilibrium Hall current changes sign at half filling as the Fermi surface changes its shape from electron-like to hole-like shape. As a result, the usual SR effect is observed. In the strongly correlated limit ($G/t >> 1$) an additional sign change should occur below half filling, which is entirely due to the correlation, as we have observed experimentally. The results are found to be the same for fermionic and bosonic systems.

To see the applicability of the SC theory to real samples, we should remember that there are many Cooper pairs, which are bosons, in the superconducting state, whereas there are no Cooper pairs in the normal state. Thus, a strong rearrangement of the filling fraction of bosons is expected at the resistive transition, which gives rise to the SR effect. As Fig. 2 illustrates, the Hall resistivity always changes sign at the mean-field transition temperature T_c^{mf}, which is defined as the temperature at which $d\rho_{xx}/dT$ vs T (Fig. 2, hollow squares) has a maximum or $\rho_{xx}(T)$ has the inflection point. This result suggests a half filling of the bosonic lattice at T_c^{mf}, which seems reasonable. In accordance with the SC theory, the observation of the double sign reversal with an additional positive peak below half filling (Fig. 2) should be considered as an indication of enhanced electron-electron correlation in the sample with $G/t \sim 2-3$. Moreover, we consider the other observed peculiarities demonstrated by S2 as additional clear signs of enhanced electron correlation in the sample.

In conclusion, the observed phenomena were found to be in good agreement with the RRN and SC theories. Consequently, the enhanced electron correlations [1,5] should definitely be taken into account in the consideration of scattering and coupling mechanisms in high-T_c superconductors.

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