Mixed-state Hall effect in high-temperature superconductors in small and large magnetic fields

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In many high-temperature superconductors, the Hall effect in the mixed superconducting state has a sign opposite to that in the normal state. Some highly anisotropic materials exhibit even a double sign reversal of the mixed-state Hall effect. We investigate this anomaly in precisely-patterned thin films of YBa₂Cu₃O₇₋₄ (YBCO) in a large range of magnetic fields from 32 mT to 13 T. The Hall conductivity appears to decompose into two contributions of different sign. The positive (hole-like) part increases steeply below the critical temperature and indicates that the scattering rate of the quasiparticles in the superconducting state is drastically reduced. The negative contribution is present around the critical temperature and becomes important in low fields only. The delicate interplay between these two contributions, together with the cutoff of the experimental window by pinning, leads to the various experimental observations, and eventually to a double sign change in fields below 0.25 T that has not been observed previously in YBCO.

1. INTRODUCTION

The unusual behavior of the Hall effect in high-temperature superconductors (HTS) both in the normal and in the mixed state continues to attract considerable interest. In particular, the sign change of the Hall angle below the critical temperature $T_c$, in the vortex-liquid region, is in contrast to traditional models for the vortex Hall effect and still is an unresolved issue. Several theoretical approaches have been attempted to explain this phenomenon. It has been proposed that vortex pinning [1,2] or the dimensionality of the vortex-pinning disorder [3] are responsible for the sign change, but that notion was challenged by the argument that the Hall conductivity is independent of pinning [4]. The importance of vortex many-body effects has been also emphasized [5]. Other models, based either on a microscopic calculation [6], or on the general framework of the time-dependent Ginzburg-Landau theory [7-10], suggest that the Hall anomaly is an intrinsic electronic property of HTS. Finally, some groups have stressed that the sign change takes place in a temperature region, where critical thermodynamic order-parameter fluctuations have to be considered [10].

The experiments revealed that the Hall anomaly is only observed in moderate magnetic fields of about $B < 6$ T and attains its maximum within the vortex liquid and superconducting fluctuation range [11,12]. The sign change was detected in many different HTS [13,14] and even in some conventional superconductors [15], and its presence appears to be connected with the carrier concentration [16]. Most studies have been performed in moderate magnetic fields (between about 1 and 20 T) and applying small current densities, thus, on a limited range of Lorentz forces on the vortices. Some authors have explored the vortex Hall effect of YBa₂Cu₃O₇₋₄ (YBCO) [17,18] and Bi₂Sr₂CaCu₂O₈ (BSCCO)
Figure 1. Resistivity of a YBCO thin film in various magnetic fields.

[19] in the free-flux-flow limit, employing a pulsed-current method. On the contrary, several groups [20,21] have enhanced the pinning forces in their samples by artificial defects and claimed that the Hall conductivity was independent of pinning [20]. Another issue is the double sign change of the vortex Hall effect in BSCCO [23] that is possibly present in YBCO too, but has been so far only detected at high current densities [24].

In this paper, we report measurements of the vortex Hall effect in YBCO thin films in a large range of magnetic fields, with particular emphasis put on small magnetic fields.

2. EXPERIMENTAL TECHNIQUES

We present data collected from 100 ± 10-nm-thick, epitaxial YBCO films, deposited by single-target rf sputtering on LaAlO$_3$ substrate. The sample’s critical current density exceeded 3 MA/cm$^2$ at 77 K. A test structure with three precisely oriented voltage probe pairs was patterned into the film, using our laser processing method [25]. The strip sample was 0.4-mm wide with the voltage-probe distance of 4.4 mm.

The experiments were performed with 17-Hz ac currents at $j = 250$ A/cm$^2$ together with lock-in detection. Measurements from 1 to 13 T were made in a superconducting solenoid using standard cryogenic techniques. The low-field measurements from 32 mT to 1 T were performed in a closed-cycle cryocooler and with an electromagnet. The high sensitivity was achieved by selecting thin film structures with excellent alignment of the Hall probes. Particular care was exercised to exclude spurious signals from the earth’s magnetic field and the remanence of the magnet’s pole pieces. As an additional check, the sample was reversed with respect to the electromagnet and equivalent data were collected from the other Hall probes. Independently, the results were confirmed on a second, similar sample.

3. RESULTS AND DISCUSSION

The resistivity of a YBCO thin film in various magnetic fields is shown in Fig. 1. The transition is typical for thin-film samples with a vortex-glass behavior at low temperatures, and different from the vortex melting observed in clean single crystals. The shape of the upper part of the transition is common to both thin films and single crystals [26] and can be well characterized by renormalized superconducting order-parameter fluctuations [27].

Fig. 2 presents the Hall coefficient of YBCO for a wide range of magnetic fields from 32 mT to 13 T. Fig. 2(a) demonstrates that $R_H$ is always positive for $B \geq 4$ T and the sign reversal at lower fields, in accordance with previous investigations that have been performed in a similar magnetic field range. Comparing Figs. 1 and 2 it is evident that the minimum of $R_H$ occurs in the vortex-liquid regime. The Hall anomaly increases significantly when the magnetic field is reduced below 1 T, as shown in Fig. 2(b). Surprisingly, a second sign change appears below 0.25 T. Measurements of the Hall effect in high current densities to reduce pinning suggest that a second sign change appears in YBCO in moderate magnetic fields in the irreversible regime [24]. In Fig. 2(b) however.
the second sign change already develops in the vortex-liquid regime.

It is instructive to plot the Hall conductivity $\sigma_{xy} = \rho_{yz} / (\rho_{xx}^2 + \rho_{yz}^2)$, normalized to $B$, as shown in Fig. 3. Since $\rho_{yx} = R_H B$, $\sigma_{xy}/B$ is independent of $B$ in the normal state above 90 K and roughly follows $\sigma_{xy} \propto T^{-3}$ temperature dependence. This trend extends into the vortex-liquid region at $B = 13$ T, followed by a gradual increase of the exponent as $T$ is reduced. At lower magnetic fields, however, a negative contribution appears to gain importance with the $B$ decrease. At 8 and 6 T range, the positive contribution prevails, but at $B \leq 3$ T, the negative part increases rapidly and $\sigma_{xy}$ eventually changes its sign. The inset in Fig. 3 shows that the negative contributions is limited to a temperature range and narrows with decreasing $B$. Thus, at low fields, it leads to a sharp minimum and the positive part again becomes dominant at lower $T$'s.

The observed behavior is tentatively explained by two contributions to the Hall conductivity. One has the same sign as the normal-state effect and rapidly increases below $T_c(B)$, indicating reduced carrier scattering in the superconducting state. The other contribution exhibits an opposite sign in the case of fully-oxidized YBCO, and is limited to a rather narrow temperature range below $T_c(B)$. The second sign change observed in high-current measurements in moderate magnetic fields [24] fits into this picture. It indicates that when transport current is high enough (not accessible in our low-current data in Fig. 3) $\sigma_{xy}$

Figure 3. $B$-field-normalized Hall conductivity of YBCO for various magnetic fields.
turns positive again at lower temperatures.

Finally, we discuss our experimental observations in the context of the currently proposed physical models. Several theories [1,2] associate the negative Hall anomaly with the backflow current due to pinning. The large negative Hall peak in low magnetic fields and its eventual disappearing at larger fields is, in this picture, simply in accordance with the decrease of the effective pinning force with larger $B$. However, the steep decrease of $R_H$ that starts above the mean-field $T_c$ in the fluctuation region [28] is a precursor of the sign change and is not compatible with pinning. Several other experimental results also indicate that pinning determines the shape of the low-temperature cutoff of the Hall voltage near the vortex-glass or melting transition, but does not appreciably affect the Hall anomaly on its high-temperature side [14,17,18,20–22].

Many of the intrinsic models decompose $\sigma_{xy} = \sigma^N_{xy} + \sigma^S_{xy}$, where $\sigma^N_{xy}$ represents a quasiparticle or vortex-core contribution, associated with the normal-state excitations, and $\sigma^S_{xy}$ a superconducting contribution, resulting from superconducting fluctuations or hydrodynamic vortex effects, respectively [6–10]. The sign of $\sigma^N_{xy}$ is the same as that of the normal-state Hall effect, but the sign of $\sigma^S_{xy}$ depends on details of the Fermi surface. In particular, the fluctuation models [10,12] allow for a natural explanation of the observed $B$ dependence of the negative contribution in Fig. 3.

The second sign change, on the other hand, requires the additional contribution from the vortex cores [6]. Another intriguing possibility, in particular regarding our films, is a contribution from vortex-glass fluctuations with line-like disorder [3] that might evoke the rapid positive divergence of $\sigma_{xy}$ observed in low fields.

Acknowledgement. Work supported by the Fonds zur Förderung der wissenschaftlichen Forschung, Austria, and by the US Office of Naval Research grant N00014-98-1-0080, Rochester.

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