# Anisotropic Hall mobility in slightly overdoped $YBa_2Cu_3O_{6.92}$ from magnetoresistance and Hall-coefficient measurements

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(Received 16 December 1996)

Hall mobilities of slightly overdoped $YBa_2Cu_3O_{6.92}$ crystals were evaluated from the measurements of the in-plane magnetoresistance (MR) and the Hall effects. While MR for $H\|c$ is consistently understood in terms of the in-plane Hall mobility, MR for $H\|ab$ has shown no detectable orbital contribution, which strongly suggests that the Hall mobility involving the $c$-axis hopping is seriously suppressed. The Hall conductivities are found to be also highly anisotropic, and the anisotropy becomes larger with decreasing temperature, as is similar to the anisotropy of the dc resistivity. [S0163-1829(97)03622-9]

As is widely accepted, the temperature ($T$) dependence of transport parameters represented by resistivity is a hallmark of high-temperature superconducting cuprates[1] (HTSC's), which is rarely seen in conventional metals or layered superconductors like $Sr_2RuO_4$ (Ref. 2) or organic BEDT salts.[3] This naturally implies that scattering time ($\tau$) characterizes their unusual electronic states, and a large number of studies have been devoted to understanding $\tau$ or the charge dynamics.[4] We have proposed that the electronic states are two-dimensional (2D) even in $YBa_2Cu_3O_{6.92}$—the least anisotropic HTSC—and that the 2D nature is mainly determined by $\tau$, not by effective mass ($m^*$).[5,6] The $c$-axis conduction then proved to be incoherent, i.e., the $c$-axis mean free path is shorter than the $c$-axis lattice parameter. Although this may be often observed in layered materials, the incoherent nature of $YBa_2Cu_3O_{6.92}$ is quite unique, which leaves the $c$-axis resistivity ($\rho_c$) metallic.

An important concept about $\tau$ is the possible existence of two kinds of in-plane $\tau$, i.e., $\tau_{\rm tr}$ ($\propto T^{-1}$) and $\tau_H$ ($\propto T^{-2}$), which give the different $T$ dependence of the resistivity ($\rho_{ab}$) and Hall coefficient ($R^H_{ab}$) along the $ab$ plane.[7] Even though their microscopic origin is still an open question, it has been experimentally established that $\tau_{\rm tr}$ and $\tau_H$ successfully explain the $T$ dependence of $\rho_{ab}$ and $R^H_{ab}$ for almost all HTSC's.[8] Recently Harris *et al.*[9] have found that the in-plane normal-state magnetoresistance (MR) for magnetic field parallel to the $c$ axis ($H\|c$) is understood as classical MR characterized by $\tau_H$. This can be further evidence for the coexistence of $\tau_{ab}$ and $\tau_H$; however, their interpretation is seriously incompatible with the previous explanation of MR in terms of superconducting fluctuation (SF).[10,11] The best way to see which is more plausible is to study MR of samples with less SF such as overdoped HTSC's.

In this study we measured and analyzed in-plane normal-state MR of slightly overdoped $YBa_2Cu_3O_{6.92}$ crystals for three orientations of $H$, together with their anisotropic Hall coefficients. The purpose of the present study is twofold. One is to address the question whether MR for $H\|c$ of HTSC's arises from classical MR or from SF. As was reported in a previous paper,[5] our single crystals of $YBa_2Cu_3O_y$ are slightly overdoped when highly oxygenated. Consequently SF-induced MR will be much reduced in our samples than in Refs. 9–11. The other purpose is to study the anisotropy of Hall mobility and/or Hall conductivity. The concept of $\tau_{\rm tr}$ and $\tau_H$ suggests that resistivity and Hall mobility probe different scattering processes. In this conjecture the anisotropy of Hall mobility should be studied in addition to the anisotropy of dc resistivity. Here we evaluate the anisotropy of the Hall mobility ($\mu^H$) from MR and Hall coefficient measurements.

Single-crystal samples of $YBa_2Cu_3O_{6.92}$ prepared by a crystal-pulling technique[12] are the same as were used in Ref. 5. Samples were cut from an as-grown crystal with a typical dimension of $4\times4\times2$ mm$^3$, and were annealed in oxygen flow at 400 °C for 10 days. All the quantities presented here were measured using the samples from the same crystal. They are slightly overdoped with $T_c$ of 90 K and low $\rho_{ab}$ of 30 $\mu\Omega$ cm at 100 K. Magnetoresistance was measured in sweeping magnetic field ($H$) up to 8 T with current ($I$) parallel to the $ab$ plane, by employing an ac-bridge-type nano-ohmmeter (Linear-Research LR201) with a typical uncertainty of 20–50 ppm. Temperature was stabilized within $\pm5$ mK during sweeping $H$ using a cernox resistance thermometer.

The magnetoresistance for $H\|c$ is found to be roughly proportional to $H^2$, as shown in Fig. 1. Because of the slightly overdoped nature, $\rho_{ab}$ of our sample is about half of that in the optimally doped $YBa_2Cu_3O_y$, and consequently the SF-induced MR $\Delta\rho_{\rm SF}\sim\Delta\sigma_{\rm SF}/\sigma^2_{ab}\sim{\rho_{ab}}^2\Delta\sigma_{\rm SF}$ is expected to be at most 25% of that in optimally doped crystals. In spite of this expectation, the observed MR above 100 K is as large as, or even slightly larger than, that in the optimally doped YBCO. This strongly suggests that the MR above 100 K mainly comes from classical MR rather than SF. In the framework of SF, MR from the Maki-Thompson (MT) term would be dominant above 100 K. Thus the present results also imply that MT term is negligibly small in HTSC's, as is naturally expected in the case of non-$s$-wave superconductivity.[13] It should be noted that Kimura *et al.*[14] have obtained the same conclusion from the anisotropic MR of $La_{2-x}Sr_xCuO_4$.

 

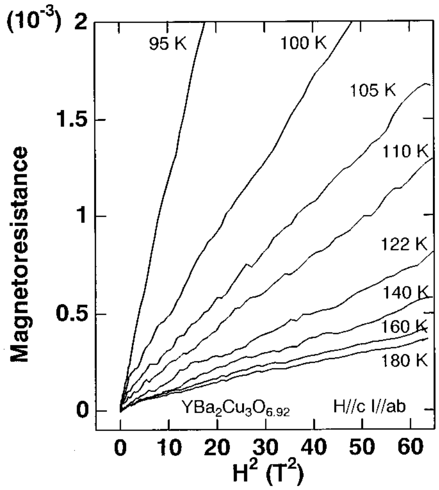


FIG. 1. Magnetic field ($H$) dependence of the magnetoresistance of single-crystal $YBa_2Cu_3O_{6.92}$ plotted as a function of $H^2$. The current is applied along the $ab$ plane, and the magnetic field is applied along the $c$ axis.

Under the lowest approximation, classical MR in metals is roughly equal to $(\omega_c\tau)^2$, where $\omega_c$ and $\tau$ are cyclotron frequency and cyclotron scattering time $(=\tau_H)$, respectively. $\omega_c\tau$ can be expressed by $\rho$ and $R^H$ as

$$\frac{\Delta\rho}{\rho}\sim(\omega_c\tau)^2=(H\mu^H)^2=\left(\frac{HR^H}{\rho}\right)^2. \tag{1}$$

If $R^H$ is independent of temperature, as in the case of conventional metals, Eq. (1) reduces to Kohler's rule of $\Delta\rho/\rho \propto(H/\rho)^2$. In HTSC's, however, $R^H$ depends on temperature, which no longer allows us to regard $R^H$ as constant in Eq. (1). Harris *et al.*[9] claimed the violation of Kohler's rule in HTSC's from the fact that MR does not scale with $(H/\rho)^2$, but we think that they should have employed the original relation given by Eq. (1) instead of $(H/\rho)^2$.

Equation (1) tells us two ways to evaluate in-plane $\omega_c\tau$, i.e., $(\Delta\rho_{ab}/\rho_{ab})^{0.5}$ and $HR^H_{ab}/\rho_{ab}$. To see the consistency between these two, we plotted $1/(\Delta\rho_{ab}/\rho_{ab})^{0.5}$ and $\rho_{ab}/HR^H_{ab}$ for $H=8$ T as a function of $T^2$ in Fig. 2. Except for the data near $T_c$ where SF is significant, the two sets of data show identical $T$ dependence $(1/\omega_c\tau\propto T^2+C)$. Although this scaling is the same as Harris *et al.* did in Ref. 9,

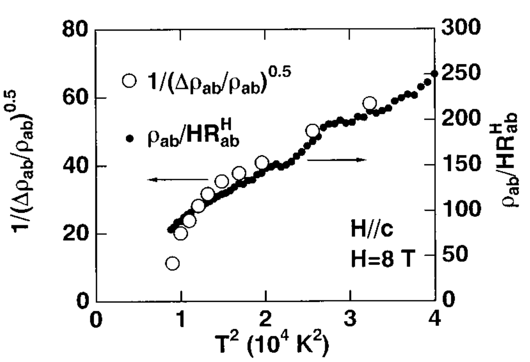


FIG. 2. Temperature ($T$) dependence of the in-plane $\omega_c\tau$ plotted as a function of $T^2$. Note that $1/\omega_c\tau$ is evaluated in two ways, $1/(\Delta\rho_{ab}/\rho_{ab})^{0.5}$ and $\rho_{ab}/HR^H_{ab}$ (see text).

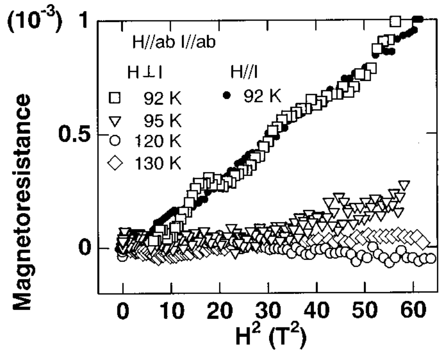


FIG. 3. Magnetic field ($H$) dependence of the magnetoresistance of single-crystal $YBa_2Cu_3O_{6.92}$ plotted as a function of $H^2$. The current and magnetic field are applied along the $ab$ plane.

our interpretation is different from theirs. It does not necessarily mean the violation of Kohler's rule, but means that the in-plane MR for $H\|c$ is well understood by a "generalized" Kohler's rule described by Eq. (1). In other words, the in-plane MR is determined by the in-plane $\mu^H$. We comment here on the different magnitudes between $1/(\Delta\rho_{ab}/\rho_{ab})^{0.5}$ and $\rho_{ab}/HR^H_{ab}$. In the Boltzmann theory, $\tau$ is averaged around the Fermi surface in different manners between Hall conductivity and MR.[15] In the language of statistics, Hall conductivity and classical MR correspond to the median and variance of local Hall mobility $\mu^H(k)$, respectively.[9] Accordingly the present data suggest that the magnitude of $\mu^H(k)$ might more or less vary in $k$ space.

Next we discuss $\mu^H$ involving the $c$-axis hopping. Figure 3 shows transverse $(H\perp I)$ and longitudinal $(H\|I)$ MR for $H\|ab$. The longitudinal MR above 92 K is not shown, because it was too small to be detected. As shown in the data of 92 K,[16] the transverse MR is nearly equal to the longitudinal MR within experimental accuracy. This indicates that the orbital contribution, including classical MR and SF, is negligibly small for $H\|ab$, and also that $\mu^H$ involving the $c$-axis hopping is quite small.

In spite of the relatively small $m^*_c$ of slightly overdoped $YBa_2Cu_3O_{6.92}$, the Hall mobility for $H\|ab$ in Fig. 3 is unusually small. From the effective-mass anisotropy $m^*_c/m^*_{ab}$ $(\sim 7)$ evaluated from the Drude weights of the optical conductivity,[6] MR for $H\|ab$ is expected to be as large as 14% of MR for $H\|c$.[17] The observed MR for $H\|ab$ is much smaller than this expectation, suggesting that the anisotropy of $\mu^H$ is larger than $m^*_c/m^*_{ab}$ to make the $c$-axis conduction seriously suppressed. A similar anisotropy in $\tau$ is observed in the dc resistivity and optical conductivity.[5,6] Thus we propose that the present result is further evidence of anomalously short $\tau_c$.[18,19] It should be noted that MR for $H\|ab$ of $YBa_2Cu_3O_y$ thin films goes to negative in high fields,[20] which seriously contradicts the conventional picture of classical MR.

Another way to evaluate the anisotropy of $\mu^H$ is to analyze the anisotropy of the Hall conductivity $\sigma_{xyz}\sim R^H_{xy}/\rho_{xx}\rho_{yy}$ where $I\|x$ and $H\|z$. It should be emphasized that $\sigma_{xyz}$ is a more fundamental quantity than $R^H_{xy}$ in the sense that the Boltzmann theory and the Kubo fomula give a direct expression for $\sigma_{xyz}$. The $c$-axis Hall coefficient $R^H_c$ (Ref. 21) for various HTSC's has been measured and

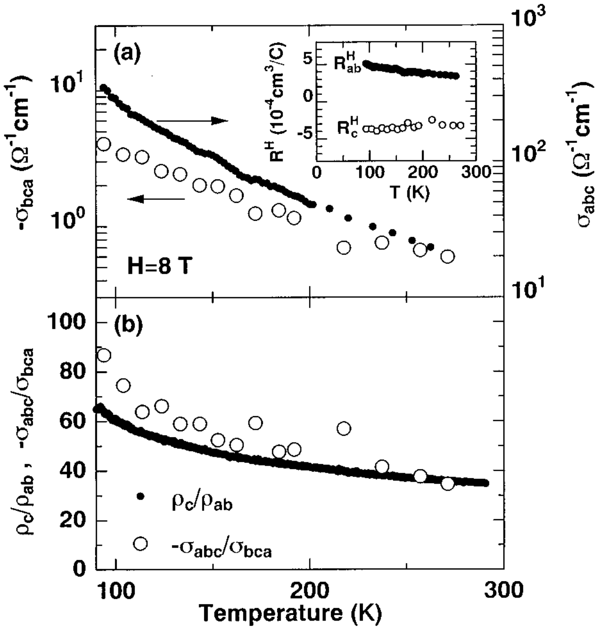


FIG. 4. (a) The Hall conductivities, $\sigma_{abc}$ ($H\|c$) and $\sigma_{bca}$ ($H\|ab$), of single-crystal $YBa_2Cu_3O_{6.92}$. The inset shows the anisotropic Hall coefficients (from Ref. 5). (b) Temperature dependence of the anisotropy of the Hall conductivity (open circles) and that of the resistivity (closed circles) for single-crystal $YBa_2Cu_3O_{6.92}$.

analyzed,[5,22] and $R_c^H$ is found to be nearly independent of $T$. Although the $T$ independence has attracted attention before, a more important fact is that the $T$ independent $R_c^H$ is observed together with the unusual $T$ dependence of $\rho_c$. In other words, the Hall conductivity cancels the unusual $T$ dependence of $\rho_c$ to make $R_c^H$ $T$ independent. This implies that the Hall conductivity involving the $c$-axis hopping includes semiconducting nature as $\rho_c$ does.

Figure 4(a) shows the anisotropic Hall conductivities $\sigma_{abc}$ and $\sigma_{bca}$, calculated from the measured $\rho_{ab}$, $\rho_c$, $R_{ab}^H$, and $R_c^H$. $\sigma_{abc}$ and $\sigma_{bca}$ show a remarkable anisotropy strongly depending on temperature. In the Boltzmann theory, since $\sigma_{xyz}$ is roughly proportional to $\mu_x^H\mu_y^H$, $\sigma_{abc}/|\sigma_{bca}|$ reduces to the anisotropy of $\mu^H$. Hence $\sigma_{abc}/|\sigma_{bca}|\sim 80$ at 100 K means that $\mu^H$ involving the $c$-axis hopping is 2 orders of magnitude smaller than the in-plane $\mu^H$. This is well consistent with the very small MR for $H\|ab$.

In Fig. 4(b), $\sigma_{abc}/|\sigma_{bca}|$ and $\sigma_{ab}/\sigma_c$ $(=\rho_c/\rho_{ab})$ are plotted as a function of temperature, where they show a similar $T$ dependence. By definition, $\sigma_{abc}/|\sigma_{bca}|$ can be rewritten as

$$\frac{\sigma_{abc}}{|\sigma_{bca}|}\sim\frac{R_{ab}^H/(\rho_{ab})^2}{|R_c^H|/\rho_{ab}\rho_c}=\frac{R_{ab}^H}{|R_c^H|}\,\frac{\rho_c}{\rho_{ab}}, \tag{2}$$

which means that $\sigma_{abc}/|\sigma_{bca}|$ increases with decreasing $T$ as $\rho_c/\rho_{ab}$ [The temperature dependence of $R_{ab}^H/|R_c^H|$ is relatively weak. See the inset of Fig. 4(a).] We therefore conclude that *the Hall conductivity becomes more anisotropic with decreasing temperature, as is similar to the dc resistivity*. If the larger $\rho_c/\rho_{ab}$ at lower $T$ can be regarded as a piece of evidence for the carrier confinement, we can say that the motion of carriers induced by the Lorentz force feels the confinement in a similar way.

Finally we point out two possible scenarios about the $T$ dependence of $\sigma_{bca}$. One is that the concept of $\tau_{\rm tr}$ and $\tau_H$ is broken down in the $c$-axis hopping process. Instead, $\tau_{ab}(=\tau_{\rm tr})$ and $\tau_c$ are defined in the $c$-axis hopping, where $\sigma_{bca}\propto\tau_{ab}\tau_c$ and $R_c^H\sim$const. This scenario is based on the assumption that only $\tau$ is anomalous in the $c$-axis transport.[5] Hussey *et al.*[19] have also claimed $\tau_{\rm tr}=\tau_H$ in the $c$-axis hopping from the anisotropic MR in overdoped $TlBa_2CuO_6$. The other scenario is that $\sigma_{bca}$ is characterized by another scattering time or by a different process, which makes $R_c^H$ accidentally $T$ independent. Recently Nagaosa[23] has calculated $\sigma_{bca}$ in the framework of the $t$-$J$ model, where $\sigma_{bca}$, unlike $\rho_c$, cannot be expressed by simple electron operators, but consists of spinon and holon parts.

In summary, we have measured and analyzed the anisotropy of in-plane magnetoresistance and the Hall effect in slightly overdoped $YBa_2Cu_3O_{6.92}$ crystals. The in-plane magnetoresistance above 100 K is mainly due to classical magnetoresistance, and is well understood in terms of the in-plane Hall mobility. Furthermore, we have evaluated the anisotropy of Hall mobility and Hall conductivity between the in-plane and out-of-plane directions. The anisotropy of the Hall mobility is larger than the effective-mass anisotropy, and strongly depends on temperature, just like the anisotropy of resistivity. This is further evidence for anomalously short scattering time in the out-of-plane direction.

We would like to thank Y. Yamada and Y. Shiohara for technical help on the crystal growth by the crystal-pulling technique. We also appreciate H. Takagi, K. Kimura, K. Semba, and N. Nagaosa for fruitful discussions. This work was partially supported by NEDO for R&D of Industrial Science and Technology Frontier Program.

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