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# Hall conductivity in $Tl_2Ba_2CaCu_2O_8$ films in the mixed state

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We present data on the Hall conductivity $\sigma_{xy}$ in $Tl_2Ba_2CaCu_2O_8$ thin films. It has been found that the Hall conductivity consists of two terms. The first one is inversely proportional to the magnetic field strength, in agreement with theories for motion of a single vortex. This term changes sign from negative near $T_c$ to a positive value at low temperatures. The second term is field independent and has been attributed to be due to the normal Hall effect in the vortex cores.

A number of theoretical predictions[1–4] have been made concerning the behavior of the flux-flow electric transport coefficients in type-II superconductors. In real systems, the vortices can be pinned by disorder which prevents the flux to flow. Even in highly anisotropic Bi- and Tl-based high-temperature superconductors, pinning becomes important as temperature ($T$) and/or magnetic field ($H$) decrease. As a result, the vortices become immobile, and both the longitudinal and Hall resistivities, $\rho_{xx}$ and $\rho_{xy}$, respectively, decrease rapidly. This makes it difficult to compare data on $\rho_{xx}$ and $\rho_{xy}$ with theory for the viscous flux flow (VFF).[1–4]

A brilliant way to get information about the VFF over the whole $H$-$T$ diagram in the mixed state has been provided by Vinokur, Geshkenbein, Feigel'man, and Blatter[5] who have shown that the Hall conductivity $\sigma_{xy} = \rho_{xy}/\rho_{xx}^2$ ($|\rho_{xy}| \ll \rho_{xx}$) is independent of disorder. In particular, it follows from their theory[5] that

$$\rho_{xy} = \frac{\alpha}{\Phi_0 B}\rho_{xx}^2, \tag{1}$$

where $B$ is the magnetic induction, $\Phi_0 = \pi\hbar/e$ is the flux quantum, $\alpha$ is the *bare* Hall drag coefficient, and thus all pinning effects are located in $\rho_{xx}^2$ term.

For epitaxial $YBa_2Cu_3O_7$ films Luo *et al.*[6] observed a scaling behavior $\rho_{xy} \sim \rho_{xx}^{\beta}$, with $\beta$=1.7±0.2, and interpreted this result in terms of the glassy scaling near the vortex-glass transition. In Ref. 5, the scaling of the Hall resistivity was viewed as a general feature of any disorder-dominated vortex dynamics, and the deviation of $\beta$ from 2 was attributed to the temperature dependence of $\alpha$ near the transition temperature $T_c$. Using $Bi_2Sr_2CaCu_2O_8$ single crystals, the resistivities were probed at temperatures significantly below $T_c$ (Ref. 7) but still above the vortex-glass critical regime. It was found[7] that $\beta$=2±0.1, in excellent agreement with Eq. (1).

In this paper we report data on the Hall conductivity of $Tl_2Ba_2CaCu_2O_8$. Our key finding is the low-field behavior of the Hall conductivity, $\sigma_{xy} \sim 1/H$, which is consistent with the theoretical results for the viscous motion of a single vortex.[3,4] Also, there is another, field-independent contribution which is related to the normal Hall effect in the vortex cores. Besides, we find out the interrelation between the field-independent component of the tangent of the Hall angle (as determined from the high-field data) and the low-field behavior of the Hall conductivity.

The $Tl_2Ba_2CaCu_2O_8$ films with thickness of 300 nm were grown by laser ablation on (001) $LaAlO_3$ substrates (Ref. 8). X-ray $\theta$-$2\theta$ scans showed that the films are single 2:2:1:2 phase and $c$-axis oriented. A small broadening, less than 1°, in film peaks detected by $\Phi$ scans indicated almost perfect alignment in the $a$-$b$ plane. Compositional element analysis was performed by secondary ion mass spectroscopy through the film and indicated uniform distribution of all elements up to the substrate interface. Critical current density at 77 K was $2\times10^6$ A/cm$^2$. A $3.5\times0.75$ mm$^2$ strip with six gold covered contacts for in-plane resistivities measurements was patterned. Two samples were made under identical conditions and had shown similar results. Data presented below are those for one of the films. The magnetic field (ranging from 0.1 to 5 T) was directed perpendicular to the film surface. The Hall resistance was obtained by switching the pairs of contacts, see Ref. 7. This procedure is equivalent to a reversal of the magnetic field. We measured $\rho_{xy}$ and $\rho_{xx}$ at direct current up to 4 mA, with reversal of the current. Both the Hall and longitudinal resistivities were Ohmic at these currents. No signs of inhomogeneity were observed as checked by resistivity measurements for different combinations of leads. Because $\rho_{xy}^2 \ll \rho_{xx}^2$, the Hall and longitudinal conductivities have been calculated as $\sigma_{xy} = \rho_{xy}/\rho_{xx}^2$ and $\sigma_{xx} = 1/\rho_{xx}$, respectively.

Figure 1 depicts the temperature dependence of the longitudinal resistivity for magnetic fields up to 5 T. At zero magnetic field, the longitudinal resistivity drops to

 

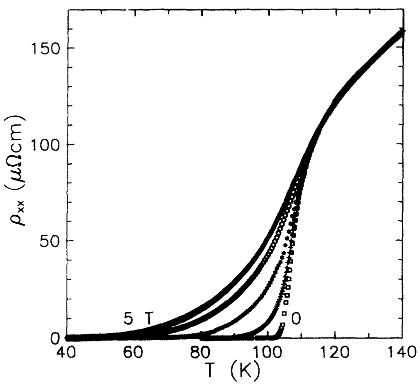


FIG. 1. $\rho_{xx}$ vs $T$ in magnetic fields of 0, 0.15, 1, 3, and 5 T.

$10^{-3}$ $\mu\Omega$ cm at $T \approx 101$ K, the transition width is of about 5–7 K. No contribution due to the $c$-axis conduction in form of a "knee" in the $\rho_{xx}(T)$ dependences has been observed.

In Fig. 2 (lower part) we plotted $\log\rho_{xy}$ vs $\log\rho_{xx}$ at different magnetic fields, with a slope reaching 2 under resistivity (and temperature) decrease. Very similar curves have been obtained previously on $Bi_2Sr_2CaCu_2O_8$ single crystals[7] and together with Fig. 2 deliver strong experimental support to the theory by Vinokur *et al.*[5]

We would like to emphasize here that the theory[5]

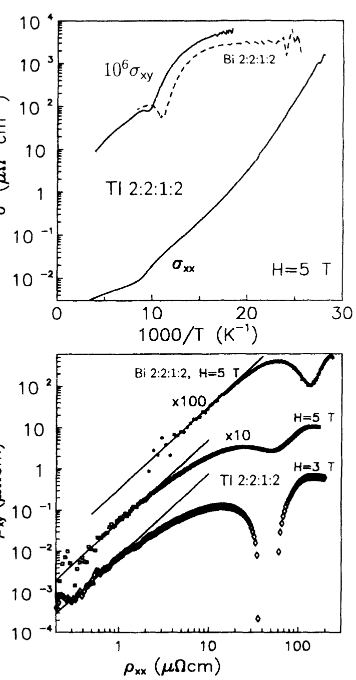


FIG. 2. Top: The Arrhenius plots of the longitudinal and Hall conductivities at $H$=5 T. Data for $Bi_2Sr_2CaCu_2O_8$ single crystal (sample 1 from Ref. 7) are depicted by the dashed line. Note that $\sigma_{xy}$ is multiplied by the factor of $10^6$. Bottom: The log-log plots of $\rho_{xy}$ vs $\rho_{xx}$ dependences in magnetic fields of 3 and 5 T. Also shown are data for $Bi_2Sr_2CaCu_2O_8$ single crystal (sample 1 from Ref. 7). Curves are shifted along the vertical axis for the sake of clarity. Solid lines represent a fit to the resistivity squared dependence [Eq. (1)].

does not predict the independence of the Hall conductivity upon *temperature* but states that *in the pinned regime* $\sigma_{xy}$ should be a much weaker function of temperature than the longitudinal conductivity. This is illustrated by upper part of Fig. 2 where we show the Arrhenius plots for the Hall and longitudinal conductivities, $\sigma_{xy}$ and $\sigma_{xx}$, respectively, in a field of 5 T. Upon cooling, $\sigma_{xy}$ increases in the normal state, exhibits a minimum (which evolves into the sign-change behavior at lower magnetic fields), and then increases rapidly as expected for the VFF regime near $T_c$.[5] As the temperature is lowered to the thermally activated flux-flow (TAFF) regime where $\sigma_{xx}$ exponentially grows (with the activation energy $U \approx 70$ meV), the Hall conductivity becomes a weaker function of $T$ and apparently does not demonstrate activation behavior.

The temperature range available for the measurements of $\rho_{xy}$ is much narrower than that for $\rho_{xx}$ because in the TAFF regime the Hall angle scales to the longitudinal resistivity [see Eq. (1)] and therefore exponentially goes to zero: $\tan\theta_H = \rho_{xy}/\rho_{xx} \propto \rho_{xx} \propto \exp(-U/T)$. That is why we are not able to present data for $\sigma_{xy}$ of $Tl_2Ba_2CaCu_2O_8$ films over the whole TAFF region. For single crystalline $Bi_2Sr_2CaCu_2O_8$ used by one of us previously[7] the activation energy was $U \approx 35$ meV at $H$=5 T which is lower than for $Tl_2Ba_2CaCu_2O_8$ films used in this study. This allowed measurements down to lower temperatures. The Hall conductivity for $Bi_2Sr_2CaCu_2O_8$ depicted by the dashed line in the upper part of Fig. 2 is similar to that for $Tl_2Ba_2CaCu_2O_8$ for $1000/T<50$ $K^{-1}$. There is definitely no reason for $\sigma_{xy}$ of these two compounds to have different temperature dependences at lower temperatures, while the tendency to saturate can be easily understood for both compounds.[9]

In Fig. 3 (lower part) the temperature dependences of the Hall conductivity at magnetic fields below 1 T are shown. While in the normal state $\sigma_{xy}$ is positive and proportional to the magnetic strength, it is negative in the mixed state and its magnitude increases approximately as $H^{-1}$ at low fields as seen in the inset in Fig. 3 where data for $\sigma_{xy}H$ at $H<0.22$ T collapse, within experimental error, onto a single curve.

Analysis of the magnetic field dependences of the Hall conductivity (Fig. 3, top) over the whole mixed state region reveals that $\sigma_{xy}$ contains a $H^{-1}$ term that is negative near $T_c$ and changes sign on cooling between 85 and 80 K and a field-independent positive contribution. A fit represented by solid lines in the top panel of Fig. 3 describes very well the whole set of data for $\sigma_{xy}$ as a sum of these two components. The first component varies from $-119/H$ $\Omega^{-1}\,cm^{-1}$ at 98 K to $9800/H$ $\Omega^{-1}\,cm^{-1}$ at 70 K. The second component increases from zero on cooling below $T_c$. Below 80 K it is nearly temperature independent and equals to $750 \pm 50$ $\Omega^{-1}\,cm^{-1}$.

Such a behavior of the Hall conductivity was predicted in Refs. 3 and 4. Theories[3,4] start from the time-dependent Ginzburg-Landau (TDGL) equations in which the order parameter relaxation time is taken to be complex. The Hall conductivity is related to the dimensionless Hall coefficient $\alpha_2 = \alpha/(\pi\hbar n_s)$ (where $n_s$ is the superfluid density) as[3]

$$\sigma_{xy}=\frac{m}{\hbar}\frac{\alpha_2}{4\pi\kappa^2}\frac{H_{c2}(T)}{B}, \quad (2)$$

with $m$ the effective mass of the Cooper pair, $\kappa$ the Ginzburg-Landau parameter, $H_{c2}(T)$ the second critical field. The coefficient $\alpha_2$ in turn is a linear combination of the imaginary part of the order parameter relaxation time ($\gamma_2$) and the normal-state Hall conductivity $\sigma_{xy}^n(h_0)$, where $h_0$ is the field in the vortex core. We can ascribe the first component of $\sigma_{xy}$ to be due to nonzero $\gamma_2$. The normal Hall effect in the vortex cores gives a contribution $\sigma_{xy}^n(h_0)\frac{H_{c2}}{H}$ (Refs. 1 and 3) that is field independent at large magnetic fields and can be associated with the second component of $\sigma_{xy}$.

It is interesting to compare data on the Hall conductivity with the high-field behavior of the Hall angle $\theta_H$. The temperature dependences of the tangent of the Hall angle are shown in Fig. 4. $\tan\theta_H$ increases in the normal state (see remark 9), passes through a minimum and increases again with decreasing temperature in the VFF regime. On further cooling, the pinning tends to decrease the Hall angle from its VFF value because in strongly pinned regime the vortices creep in the direction of the Lorentz force only. It has been previously established[10,11] that in strongly anisotropic Tl- and Bi-based superconductors in the VFF regime $\tan\theta_H$ consists of two terms: $\tan\theta_H=a+bH$, where $a$ is strongly $T$ dependent, while $b$ weakly depends upon the temperature. Such a behavior is clearly seen in Fig. 4.

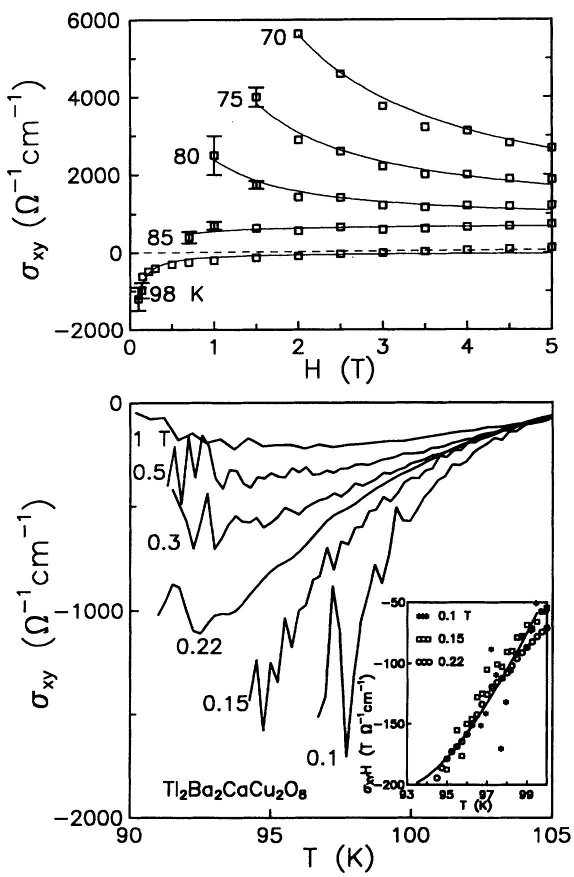


FIG. 3. Top: The magnetic field dependences of the Hall conductivity at various temperatures as indicated. Solid lines represent a fit to the data as described in the text. Bottom: The temperature dependences of the Hall conductivity in magnetic fields as indicated. Inset: The temperature dependences of $\sigma_{xy}H$ at $H$=0.1, 0.15, and 0.22 T. Solid line is a fit to the data on the Hall angle as described in the text.

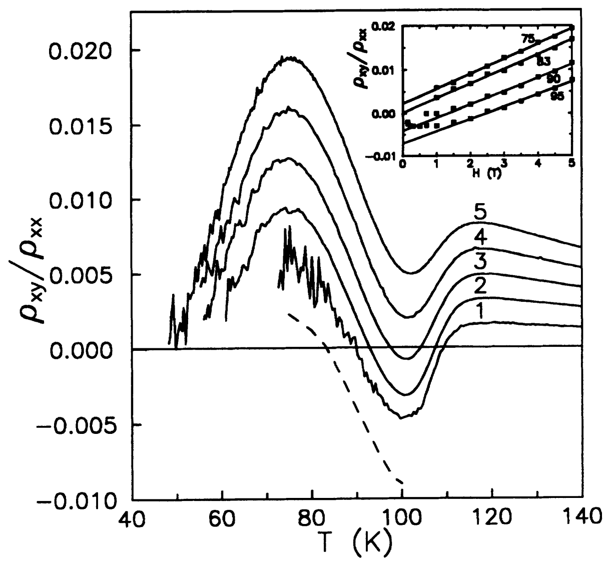


FIG. 4. The temperature dependences of the tangent of the Hall angle in magnetic fields ranging from 1 to 5 T. Dashed line represents the behavior of the "zero-field" Hall angle obtained from the extrapolation of the high-field data (see in the text). Inset: The $\tan\theta_H(H)$ dependences at $T$=75, 83, 90, and 98 K. Solid lines are linear fits of the high-field data.

The dashed line in Fig. 4 represents the behavior of the "zero-field" component of $\tan\theta_H$ [$a(T)$ dependence] obtained as the intersections of the $\tan\theta_H(H)$ dependences linearly extrapolated from high magnetic fields, with the ordinate axis (Fig. 4, inset). The inset in Fig. 4 shows that at low fields, the vortex dynamics is dominated by disorder which makes the Hall angle to go to zero. One can think, however, that data on the coefficient $a$ obtained as described above are not strongly influenced by disorder and can be compared to the VFF low-fields value:[3,4]

$$\tan\theta_H=\frac{\alpha_2}{\alpha_1}, \quad (3)$$

where $\alpha_1$ is the dimensionless viscous drag coefficient which is temperature and field independent (see Ref. 3). As the component of $\alpha_2$ arising from the normal Hall effect can be neglected at low magnetic fields,[12] the dashed line gives the temperature dependence of the imaginary part of the order parameter relaxation time $\gamma_2$. Comparing Eqs. (2) and (3), we see that the coefficient $a(T)$ ("zero-field" component of the tangent of the Hall angle) should be proportional to $\sigma_{xy}H/H_{c2}(T)\propto\sigma_{xy}H/(1-T/T_c)$. It seems to be confirmed by findings of Figs. 3 and 4: (i) As temperature increases, the coefficient $a(T)$ changes sign from positive to negative at 83 K, just where the $H^{-1}$-term in the Hall conductivity (see Fig. 3, top panel) changes sign. (ii) The solid line in the inset of Fig. 3 represents a fit of $\sigma_{xy}H$ to a form $\Upsilon a(T)(1 - T/T_c)$ (with the coefficient $\Upsilon$=3.5×10$^5$ T $\Omega^{-1}$ cm$^{-1}$ and $T_c$=101.5 K) which describes well the low-field data on the Hall conductivity in the mixed state.

Finally, we would like to note that the Nozières-Vinen model[2] also predicts the $H^{-1}$ dependence for the Hall conductivity. However, this model is not able to get the sign reversal of the Hall conductivity and, strictly speaking, is valid at $T$=0 only. In Refs. 3 and 4 the sign reversal of $\sigma_{xy}$ is related to negative value of $\alpha_2$—a parameter which appears in the TDGL equations and can be obtained from comparison with our experimental data.

To sum up, the presented data on the Hall conductivity in $Tl_2Ba_2CaCu_2O_8$ superconductor provide evidence that $\sigma_{xy}$ in the mixed state is in agreement with the theories of the viscous flux motion and is not influenced by disorder. We have found that the Hall conductivity at low magnetic fields is approximately proportional to the inverse magnetic field strength. We have shown that analyzing either high-field data on the Hall angle or low-field data on the Hall conductivity, one can get a consistent description of the behavior of the imaginary part of the order parameter relaxation time, within the TDGL approach to the motion of a single vortex.

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[1] J. Bardeen and M. J. Stephen, Phys. Rev. **140**, A1197 (1965).

[2] P. Nozières and W. F. Vinen, Philos. Mag. **14**, 667 (1966).

[3] A. T. Dorsey, Phys. Rev. B **46**, 8376 (1992).

[4] N. B. Kopnin, B. I. Ivlev, and V. A. Kalatsky, Pis'ma Zh. Eksp. Teor. Fiz. **55**, 717 (1992) [JETP Lett. **55**, 750 (1992)]; N. B. Kopnin, B. I. Ivlev, and V. A. Kalatsky, J. Low Temp. Phys. **90**, 1 (1993).

[5] V. M. Vinokur, V. B. Geshkenbein, M. V. Feigel'man, and G. Blatter, Phys. Rev. Lett. **71**, 1242 (1993).

[6] J. Luo, T. P. Orlando, J. M. Graybeal, X. D. Wu, and R. Muenchausen, Phys. Rev. Lett. **68**, 690 (1992).

[7] A. V. Samoilov, Phys. Rev. Lett. **71**, 617 (1993).

[8] L.-G. Johansson, T. Claeson, Z. G. Ivanov, H. Olin, E. Olsson, and D. Erts, in *Proceedings of the Conference on Molecular and Oxide Superconductors, Eugene, 1993* [J. Supercond. (to be published)].

[9] We can understand the fact that at $T \to 0$ $\sigma_{xy}$ tends to a constant value in the following way. Namely, as magnetic field increases, the normal Hall effect in the vortex cores becomes increasingly important (see Refs. 1 and 3). In the normal state, $\cot\theta_H = c + dT^2$ ($c$ and $d$ are positive constants) is a well-documented behavior for the cotangent of the Hall angle $\theta_H$ which is also valid for our samples. Then as temperature tends to zero, $\sigma_{xy} = (\cot\theta_H \rho_{xx})^{-1}$ tends to a value $(c\rho_0)^{-1}$, where $\rho_0$ is the residual resistivity, and the $\sigma_{xy}(T)$ dependence at large fields in the mixed state reflects the temperature dependence of the normal-state Hall conductivity.

[10] S. J. Hagen, C. J. Lobb, R. L. Greene, and M. Eddy, Phys. Rev. B **43**, 6247 (1991).

[11] N. V. Zavaritsky, A. V. Samoilov, and A. A. Yurgens, Physica C **180**, 417 (1991).

[12] As it follows from Eqs. (3.49), (3.50) of Ref. 3, if $-\sigma_{xy} \gg \frac{1}{2}\sigma_{xy}^{(n)}(h_0)h_0(0)/B$, the contribution to $\alpha_2$ from the normal-state Hall conductivity can be neglected.