Angle-dependence of the Hall effect in Hg-Ba-Ca-Cu-O thin films

H Richter\(^1\), I Puica\(^1\), W Lang\(^1\), M Peruzzi\(^2\), J H Durrell\(^2,3\),
H Sturm\(^2\), J D Pedarnig\(^2\), D Bäuerle\(^2\),

\(^1\) Institut für Materialphysik der Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria
\(^2\) Institut für Angewandte Physik, Johannes-Kepler-Universität Linz, A-4040 Linz, Austria
\(^3\) Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge, CB2 3QZ, United Kingdom

Abstract. Superconducting compounds of the family Hg-Ba-Ca-Cu-O have evoked intensive research efforts since the current record-holder for the highest critical temperature of a superconductor belongs to this class of materials. Thin films of the compound with two adjacent copper-oxide layers and a critical temperature of about 120 K were prepared by pulsed-laser deposition of precursor films and subsequent annealing in mercury-vapour atmosphere. Like other high-temperature superconductors, Hg-Ba-Ca-Cu-O exhibits a specific anomaly of the Hall effect, a double-sign change of the Hall coefficient close to the superconducting transition. We have investigated this phenomenon by measurements of the Hall effect at different angles between the magnetic field direction and the crystallographic \(c\) axis. The results concerning the upper part of the transition, where the first sign change occurs, are discussed in terms of the renormalized fluctuation model for the Hall conductivity, adapted through the field rescaling procedure in order to take into account the arbitrary orientation of the magnetic field.

1. Introduction
The large anisotropy of the high-temperature superconductors (HTSC) due to their layered structure gives rise to important changes of the transport properties as the magnetic field orientation varies with respect to the superconducting planes. The early resistivity and critical current measurements \cite{1, 2} on HTSC as a function of the angle between the magnetic field and the \(ab\)-planes have generally shown that dissipation strongly decreases when the field is tilted towards the superconducting layers. The measurements at oblique fields were commonly analyzed in terms of the scaling approach based on the anisotropic mass model \cite{3}. According to this scaling approach, the anisotropy leads to a reduction of the effective field component parallel to the superconducting planes, such that in the limit of highly anisotropic materials, the magnetic field component along the \(c\)-axis is the only effective one, as it was indeed found experimentally in BSCCO-2212 \cite{1, 4}. For materials with moderate anisotropy, like YBCO, the field scaling was proved as valid in the flux-flow region \cite{5}, however found to work not equally well in the regime of vortex thermal activation, where the “failure of scaling” was explained as a consequence of pinning \cite{2}. For the compounds of the Hg-Ba-Ca-Cu-O family, which have an anisotropy \cite{6} that is between that of YBCO and BSCCO-2212, only few investigations regarding the angle-dependence of the transport properties have been reported. The resistivity of (Hg,Re)\(\text{Ba}_2\)\(\text{CaCu}_2\text{O}_6\) was recently \cite{7} studied under variation of the magnetic field orientation.
with respect to the c-axis, and the dependence of the depinning field on the tilt angle was inferred. In the present work we present the first investigations of the Hall-effect’s dependence on the angle $\theta$ between the magnetic field and the $ab$-planes in the (Hg,Re)Ba$_2$CaCu$_2$O$_6$ compound, and compare the experimental data to the theoretical fits based on the renormalized superconducting fluctuation model [8], adapted through the field rescaling procedure, in order to account for the tilted field orientation.

2. Sample preparation and experimental setup
Measurements were made on a (Hg,Re)Ba$_2$CaCu$_2$O$_6$ thin film sample. The sample was synthesized by a two step process, using pulsed laser deposition [9] to apply a precursor film on a SrTiO$_3$ substrate, followed by annealing in a mercury-vapour atmosphere employing the sealed quartz tube technique [10]. The film thickness, which was measured by atomic force microscopy, is 500 nm.

All measurements were done in a closed-cycle refrigerator and with an electromagnet. Data were taken in both d.c. current and magnetic field directions by a Keithley nanovolt-meter at discrete temperature points, with a stability of $\pm 0.01$ K. The sample was mounted between the electromagnet’s pole pieces in such a way that the magnetic field can be rotated in the plane spanned by the sample’s c-axis and the current direction. For all in-field measurements a magnetic field of $B = 1.13$ T was applied. The Hall voltage $V_y$ was picked up at a fixed position on adjacent side arms of the strip-shaped sample.

3. Results and comparison with theory
Figure 1 shows the temperature dependence of the longitudinal resistivity as the magnetic field $B = 1.13$ T is rotated in the plane determined by the c-axis and the current direction, at an angle $\theta$ with the latter. The current is injected parallel to the $ab$-planes of the sample. The broadening of the superconducting transition with increasing $\theta$ is qualitatively similar to the effect of an increasing magnetic field perpendicular to the layers [11]. However in the small angle region the difference becomes evident, which can be seen in Fig. 1, where the zero-field curve (dotted) is clearly different from the one corresponding to a finite field at $\theta = 0^\circ$. This indicates the three-dimensional conduction character in the Hg-Ba-Ca-Cu-O compound, since for a pure 2D in-plane conduction only the perpendicular-to-surface component of $B$ is relevant [3].

The Hall resistivity scaled with the perpendicular field component is depicted in Fig. 2. All curves exhibit the change from positive hole-like sign in the normal state to the negative electron-like one in the vortex-liquid regime, as it is common for most high-temperature superconductors [11, 12]. At $\theta = 90^\circ$ the curve reveals a double sign change (inset in Fig. 2), which has been previously seen in this compound [13]. At oblique angles this second sign reversal vanishes, which agrees with similar observations on YBa$_2$Cu$_3$O$_{6+x}$ [14].

To compare the results with a theoretical model, the Hall conductivity $\sigma_{xy} = \rho_{yx}/(\rho_{xx}^2 + \rho_{yx}^2)$ is a more appropriate choice. Figure 3 displays $\sigma_{xy}$ normalized to the out-of-plane magnetic field component $B \sin \theta$. To give a quantitative account for our data we assume:

$$\sigma_{xy} = \sigma_{xy}^n + \Delta \sigma_{xy},\quad (1)$$

where $\sigma_{xy}^n$ is the normal state contribution and $\Delta \sigma_{xy}$ the superconducting fluctuation one. For the normal-state part we assume as valid Anderson’s formula for the inverse Hall angle, and a linear temperature dependence of the resistivity. To calculate the fluctuation Hall conductivity $\Delta \sigma_{xy}$ we use the fluctuation model based on the Hartree approximation to the time-dependent Ginzburg-Landau theory [8].
Figure 1. Resistivity vs. temperature for different angles $\theta$ between the magnetic field and the current direction. The arrow indicates the curve sequence corresponding to the increasing angle $\theta$. The dotted curve shows the zero-field resistivity.

Figure 2. Hall resistivity $\rho_{yx}$ normalized to the out-of-plane magnetic field component $B\sin\theta$. The arrow shows the direction of the increasing angle $\theta$. The region of the second sign change is detailed in the inset.

Figure 3. Experimental (symbols) and theoretical (curves) normalized Hall conductivity $\sigma_{xy}/B\sin\theta$ as a function of temperature. The arrow indicates the data sequence as $\theta$ increases. The solid curves represent the theoretical fits based on the rescaled field value $\tilde{B}$, while for the dotted curves only the normal component $B\sin\theta$ is considered relevant. In the inset, the rescaled effective field $\tilde{B}$ is compared to the field component $B\sin\theta$ parallel to the c-axis.

According to the rescaled anisotropic mass model [3], we can directly relate the Hall conductivity in the oblique field to the Hall conductivity in a rescaled field $\tilde{B}$ that is applied along the c-direction

$$\frac{\sigma_{xy}(\theta, B)}{B\sin\theta} = \frac{\sigma_{xy}(0, \tilde{B})}{\tilde{B}}, \quad (2)$$

where

$$\tilde{B} = B\sqrt{\sin^2\theta + \gamma_a^2 \cos^2\theta}, \quad \tan\tilde{\theta} = \frac{1}{\gamma_a} \tan\theta, \quad \gamma_a = \frac{\xi_{0c}}{\xi_0}. \quad (3)$$

Figure 3 displays the experimental data (symbols) of the Hall conductivity in comparison to theoretical calculations (solid lines) based on a rescaled field $\tilde{B}$. The following parameters, typical for the HgBa$_2$CaCu$_2$O$_6$ compound, were used: $T_{c0} = 118.2$ K, the in-plane and out-of-plane coherence lengths $\xi_0 = 1.4$ nm and $\xi_{0c} = 0.2$ nm, respectively, the interlayer distance $s = 1.27$ nm, the Ginzburg-Landau parameter $\kappa_{GL} = 100$ and the Fermi energy $\varepsilon_F = 10^4$ K (in
$k_B$ units). The best fits were obtained for a hole-particle asymmetry parameter [15] $\alpha = 0.19$, which is comparable with the analogous value found from a similar fit [12] for Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{x}$. The dotted curves in Fig. 3 show on the other hand the calculations with the same parameters, if only the out-of-plane component $B \sin \theta$ were taken into account instead of the rescaled value $\tilde{B}$. One can notice that the two approaches give almost similar results at higher angles, but differ significantly for small angle $\theta$, where the difference between $\tilde{B}$ and $B \sin \theta$ increases, as illustrated in the inset of Fig. 3. The good quantitative agreement between the experimental data and the theoretical fits performed with the rescaled magnetic field values (solid curves) points therefore to the fluctuation origin of the Hall effect behavior in the temperature range corresponding to the first sign-change and the negative maximum of the Hall resistivity, as well as to an anisotropic three-dimensional conduction character in the Hg-Ba-Ca-Cu-O compound.

4. Conclusions

In summary, we have investigated the resistivity and the Hall effect in a (Hg,Re)Ba$_2$CaCu$_2$O$_6$ thin film when the magnetic field of fixed magnitude is rotated in the plane determined by the $c$-axis and the electric current direction. At first sight our measurements indicate a qualitative similarity with the behavior in a variable magnetic field that is applied in a fixed orientation perpendicular to the film, but with a magnitude that is given by the out-of-plane component of the oblique field. Such is also suggested by the rather good scaling of the Hall resistivity in the normal state with the out-of-plane magnetic field component. However, a difference to this two-dimensional model is revealed as the magnetic field approaches the orientation parallel to the layers, and is seen in both the resistivity and the Hall conductivity. The second sign-change of the Hall angle in the lower part of the transition is found to disappear under oblique fields, pointing thus to its vortex pinning origin. The good quantitative agreement between the measured Hall conductivity and the theoretical fits based on the renormalized superconducting fluctuation model, adapted by the field rescaling procedure in order to take into account the arbitrary orientation of the magnetic field, brings evidence for the anisotropic three-dimensional conduction character in the Hg-Ba-Ca-Cu-O compound, as well as for the fluctuation origin of the Hall effect behavior in the vortex liquid region.

Acknowledgments

Work supported by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung and the Micro@Nanofabrication Network, funded by the Ministry for Economic Affairs and Labour.

References

[1] Iye Y, Nakamura S, and Tamegai T 1989 Physica C 159 433
[2] Amirfeiz M, Cimberle M R, Ferdeghini C, Giannini E, Grassano G, D Marré, Putti M, and Siri A S 1997 Physica C 288 37 and references therein
[3] Blatter G, Geshkenbein V B, and Larkin A I 1992 Phys. Rev. Lett. 68 875
[4] Kes P H, Aarts J, Vinokur V M, and van der Beek C J 1990 Phys. Rev. Lett. 64 1063
[5] Harris J M, Ong N P, and Yan Y F 1994 Phys. Rev. Lett. 73 610
[6] Kim M S, Lee S I, Yu S C, and Hur N H 1996 Phys. Rev. B 53 9460
[7] Salem A, Jakob G, and Adrian H 2004 Physica C 402 354
[8] Ullah S and Dorsey A T 1991 Phys. Rev. B 44 262
[9] D Bäuerle 1998 Supercond. Sci. Technol. 11 968
[10] Yun S H, Pedarnig J D, Rössler R, Bäuerle D, and Obradors X 2000 Appl. Phys. Lett. 77 1369
[11] Puica I, Lang W, Göb W, and Sobolewski R 2004 Phys. Rev. B 69 104513
[12] Lang W, Heine G, Kula W, and Sobolewski R 1995 Phys. Rev. B 51 9180
[13] Kang W N, Yun S H, Wu J Z, and Kim D H 1997 Phys. Rev. B 55 621
[14] Göb W, Liebich W, Lang W, Puica I, Sobolewski R , Rössler R, Pedarnig J D, and Bäuerle D 2000 Phys. Rev. B 62 9780
[15] Fukuyama H, Ebisawa H, and Tsuchida T 1971 Prog. Theor. Phys. 46 1028