Physical and geometrical origins of the normal–state magnetoresistance in YBa$_2$Cu$_3$O$_7$

W. Göb$^a$, W. Lang$^a$, and Roman Sobolewski$^b$

$^a$Ludwig Boltzmann Institut für Festkörperphysik, Kopernikusgasse 15, A-1060 Wien, Austria, and Institut für Materialphysik der Universität Wien, Austria.

$^b$Department of Electrical Engineering and Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14627, USA.

The transverse magnetoresistance (MR) of YBa$_2$Cu$_3$O$_7$ thin films is analyzed with respect to the geometric magnetoresistance (GEMR), which is introduced to the measurements in a transverse magnetic field by a finite length-to-width ratio of the sample structure. We show that this effect becomes important in high-temperature superconductors (HTSC) at temperatures far above $T_c$ in sample geometries typically used for single crystal measurements. The GEMR adds to the physical MR, which may lead to a misinterpretation of the high temperature part of the MR. Measurements of the MR and the Hall effect employing two different sample geometries, patterned in the same YBa$_2$Cu$_3$O$_7$ thin film, which allow for a separation of GEMR from physical MR are presented.

The interpretation of the transverse in-plane MR of HTSC materials above their superconducting transition temperature $T_c$ has attracted much interest over the past few years from both experimental and theoretical point of view (e.g. [1-5]). Experimental data do not give a consistent picture, since the effect itself is small (on the order of $10^{-5}$) and difficult to measure. Thus, extreme care must be taken to eliminate experimental errors.

The aim of this paper is to examine a source of an additional systematic error in measurements of the transverse MR, which cannot be neglected in single-crystal HTSC studies, namely the geometric contribution to MR (GEMR), resulting from bending of the current trajectories in a magnetic field.

We compare two sample geometries with different contributions of GEMR. By “sample geometry”, we denote the area of the sample used for electrical measurements. Usually, this area is either defined by a geometry patterned into a thin film, or, in the case of a single crystal or bulk sample, by the geometry of the sample and the arrangement of the contact electrodes. We characterize the geometry of a rectangular sample by its length-to-width ratio $n = l/w$.

Theoretically, only a sample with $n \to \infty$ has zero GEMR and, thus, allows for a direct measurement of the physical MR $\Delta \rho_{\text{phys}} / \rho_0 = [\rho_{xx}(B) - \rho_{xx}(0)] / \rho_{xx}(0)$. On the other hand, the GEMR is maximized in the Corbino disk arrangement [6], where $n = 0$. In the case of a small Hall angle $\theta_H$, the total MR $\Delta R / R_0 = \Delta \rho_{\text{phys}} / \rho_0 + \Delta \rho_{\text{geom}} / \rho_0$ of an arbitrarily shaped sample [6] is given by

$$\frac{\Delta R}{R_0} = \frac{\Delta \rho_{xx}(B)}{\rho_{xx}(0)} + \left[1 + \frac{\Delta \rho_{xx}(B)}{\rho_{xx}(0)}\right] \tan^2 \theta_H \cdot g(n).$$

(1)

For rectangular-sample geometries, the function $g(n)$ can be approximated for $n > 1$ by

$$g(n) = \frac{14S}{\pi^3} \cdot \frac{1}{n},$$

where $S = \frac{8}{7} \sum_{k=0}^{\infty} \frac{1}{(2k+1)^3} \approx 1.2021$.

For the Corbino disk, $g(0) = 1$. In HTSC materials, far above $T_c$, we find that the in-plane MR $\Delta \rho_{xx}(B) / \rho_{xx}(0) << 1$ [3-5] and, thus, the second term in the square bracket in Eq. (1) can be neglected. Hence, the GEMR is approximately

$$\Delta \rho_{\text{geom}} / \rho_0 \approx \tan^2 \theta_H \cdot g(n).$$

(2)

We note that the importance of GEMR compared to the physical MR primarily depends on the sample
Figure 1. MR of a strip (MRS) and a Corbino disk (MRD) of YBa$_2$Cu$_3$O$_7$. The triangles represent the difference between MRD and MRS and are compared to tan$^2\theta_H$. The dotted and broken lines represent fits to power laws for MRS and MRD, respectively.

geometry. In Fermi-liquid transport theory, tan$^2\theta_H$ and the magnitude of physical MR are related. Thus, a small $\theta_H$, which implies a reduced GEMR is commonly associated with small physical MR. The GEMR is, like the physical MR, proportional to $B^2$ in moderate magnetic fields and cannot be separated from the latter experimentally. For a given sample geometry and known $g(n)$, only a complementary measurement of the Hall angle allows for an evaluation of the physical MR according to Eq. (1).

We present an analysis of MR and Hall effect data obtained on YBa$_2$Cu$_3$O$_7$ thin films in a magnetic field $B = 1$ T. The 100 $\pm$ 10-nm-thick epitaxial films were deposited by single-target rf sputtering on LaAlO$_3$ substrates. Two independent sample shapes, a strip-like geometry with six potential probes ($n = 11$) and a Corbino structure, were patterned in the same film, using a special laser processing method [7]. The experimental procedure for the MR measurements has been described in [5].

Figure 1 compares the MR of the strip (MRS) with the MR of the Corbino disk (MRD). The solid line represents the prediction for the GEMR in the Corbino disk, calculated from the Hall data obtained on the strip-shaped sample according to Eq. (2). We wish to point out that the difference between the MRD and MRS (triangles in Fig. 1) — the GEMR of the Corbino disk — is in excellent agreement with the prediction calculated from $\theta_H$. On the other hand, a calculation using $g(11) \approx 0.05$ reveals that the GEMR of our strip-shaped sample is more than two orders of magnitude smaller than the physical MR over the whole investigated temperature range and can be safely neglected in this sample geometry.

Finally, we note that for a square-shaped sample ($n = 1$), which is not studied here but represents a typical geometry for single crystal studies of HTSC, $g(1) \approx 0.5$ [6]. Thus, the GEMR is about half the value observed for the Corbino disk. As can be noted in Fig. 1 this may lead to a significant error in MR measurements of HTSC single crystals. In previous MR investigations of HTSC single crystals in the normal state, a violation of Kohler’s rule and an unconventional temperature dependence of $\Delta \rho / \rho_0$ was revealed [4]. It was argued that the normal-state MR probes the variance of the local Hall angle over the Fermi surface and, thus, $\Delta \rho^{\text{phys}} / \rho_0 \propto \tan^2 \theta_H$. Since in the most of the HTSC materials, the Anderson relation [8] $\cot \theta_H = AT^2 + C$ is closely obeyed, the physical MR is approximately proportional to $T^{-4}$ in the normal state (assuming $C \approx 0$). According to Eq. (2), the same temperature dependence applies for GEMR. Thus, GEMR enhances the magnitude of MR but does not alter the MR’s temperature dependence significantly. In fact, our MRS results, which are essentially free of GEMR indicate that indeed $\Delta \rho^{\text{phys}} / \rho_0 \propto T^{-4.0}$ at high temperatures.

REFERENCES