Negative in-plane and out-of-plane magnetoresistivities in an optimally doped $Bi_2Sr_2Ca_{0.8}Y_{0.2}Cu_2O_{8+\delta}$ single crystal

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Both the in-plane and out-of-plane magnetoresistivities have been measured in the normal state of an optimally doped $Bi_2Sr_2Ca_{0.8}Y_{0.2}Cu_2O_{8+\delta}$ single crystal with a magnetic field applied parallel and perpendicular to the CuO_2 planes. Whatever the magnetic field and the current directions are, a negative magnetoresistivity is obtained over a wide range of temperature above the critical temperature T_c. For the in-plane and out-of-plane measurements, the nondominant orbital contribution to magnetoresistivity suggests the substantial role played by the spin degrees of freedom.

One of the most interesting issues of the high-T_c superconducting cuprates is the understanding of their normal-state properties. In particular, there is a great deal of experimental evidence for the spin gap opening and the carrier confinement effect.[1–3] Among the many unusual transport properties that have been reported in these systems, the coexistence of a nonmetallic out-of-plane resistivity ρ_c with a metallic temperature dependence for in-plane resistivity ρ_{ab} have raised numerous questions concerning the electronic processes involved in the conduction mechanisms in and across the planes.[4–12] To get further insight into the anomalous charge transport properties and in the possible spin effects on the out-of-plane and in-plane charge dynamics of high-T_c cuprates, in-plane and out-of-plane magnetoresistance (MR) measurements with B parallel and perpendicular to the c axis are very useful. An important amount of magnetotransport experiments in anisotropic superconducting cuprates has been achieved; for instance, in the two CuO_2 layers $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212), a negative anisotropic out-of-plane MR has been observed and interpreted in terms of field dependence of a pseudogap in the spin system.[9] In $La_{2-x}Sr_xCuO_4$ (La-214), the same feature has been reported in the underdoped state.[11] Besides, in $Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201) single crystals, positive transverse and longitudinal out-of-plane MR has been found and an explanation in terms of anisotropy of the in-plane mean free path is given.[13] Results for in-plane MR measurements are more contrasting. Indeed, a slight negative longitudinal MR is observed in optimally doped $Bi_2Sr_2CuO_{6+\delta}$ (Bi-2201) (Ref. 14) and underdoped La-214 (Ref. 15) whereas such a phenomenon is not reported in the studies of Kimura *et al.*[11] in La-214 and Heine *et al.*[16] in Bi-2212. In these latter cases, the authors have interpreted the positive in-plane MR as a result of superconducting fluctuations. It is worthy to note that, in La-214 single crystals, an isotropic negative in-plane MR has been measured by Preyer *et al.*[17] However, none of those papers report measurements of the anisotropic MR with various field orientations in the same Bi-2212 single crystal. In this work, we report magnetoresistance (MR) measurements with current flow $J\|ab$ and $J\|c$ and with the magnetic field oriented parallel ($B\|J$) and perpendicular ($B\perp J$) to the current. This study is achieved on the *same* optimally doped $Bi_2Sr_2Ca_{0.8}Y_{0.2}Cu_2O_{8+\delta}$ (Bi-2212) single crystal. We observe that the MR is almost independent of the transverse or longitudinal configurations not only for the out-of-plane current but also for the in-plane current. This feature implies an essential role of the spin correlation in the out-of-plane transport phenomena and the negative MR is discussed in terms of formation of a pseudospin gap. The in-plane MR is also found negative in sign and almost isotropic. We account for this feature considering a strong coupling between Cu spins and the charge carriers.

The crystals of $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ used in this study were grown by a self-flux method which has been described elsewhere.[18,19] The structural investigations undertaken to check the quality of crystals, in particular their actual cationic compositions are reported in an earlier paper;[20] it is demonstrated that substitutions of low concentrations of Y^{3+} on the Ca^{2+} site lead to a set of samples with different doping states. The actual cations contents were checked by energy dispersive spectroscopy (EDS) x-ray spectroscopy with a Kevex analyzer mounted on a 200-kV electron microscope following the procedure described in Ref. 15 for each batch. In this work, we investigate charge transport in $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ with $x_{EDS}=0.2$ which corresponds approximately to the optimum doping state.[20] The typical dimensions of the sample are $1\times1\times0.01$ mm^3. We have evaporated six ‘‘silver pads’’ as described in Fig. 1: two on the top face, two others on the bottom face, and one silver pad on each ac plane. Voltage and current contacts were established by thin gold wires attached to the evaporated-silver pads with silver paint. The sample was then annealed in air at 400 °C for 10 min in order to reduce the contact resistance. This simple contact geometry allows measurements of the in-plane, ρ_{ab}, and the out-of-plane, ρ_c, resistivities on the same crystal. It has been checked that the evaporation of silver pads on the ac planes does not affect the ρ_c data. To measure the ρ_c resistivity, the current is applied along the c-axis direction and the voltage drop is measured parallel to it. This yields good estimate of ρ_c, as discussed in Ref. 21 for Bi-2212 single crystals. On the other hand, to measure the in-plane resistivity, the current is applied within the ab plane and the voltage drop is measured with either the two contacts on the top face or the two other

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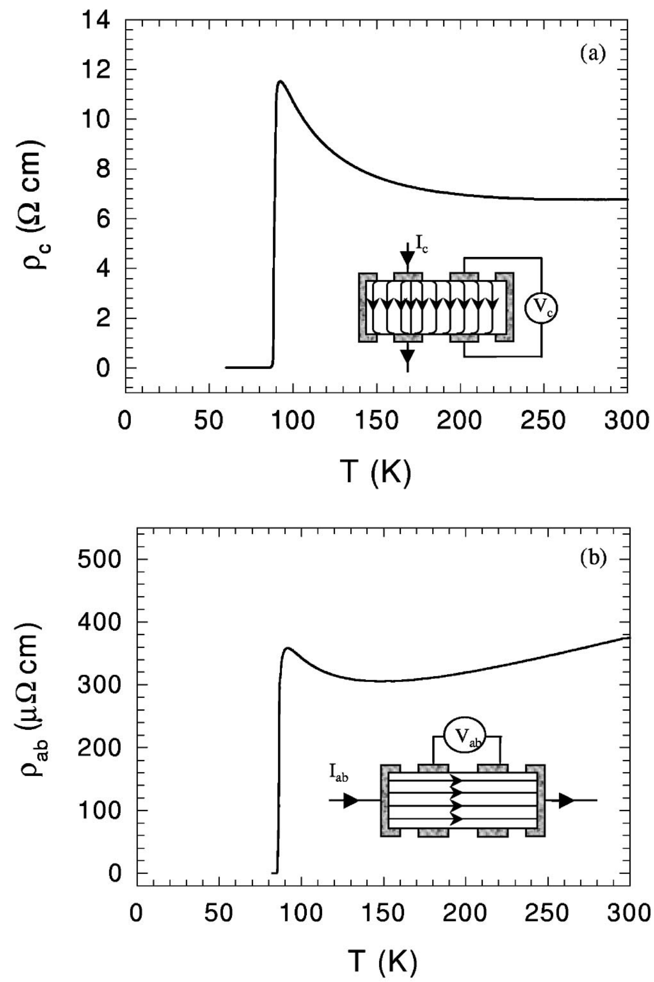

FIG. 1. Zero-field out-of plane (a) and in-plane (b) resistivity curves. In the inset, we have schematically drawn the contact configurations. The solid lines correspond to the current lines.

ones on the bottom face. For the MR measurements, the sample was aligned with the magnetic field parallel and perpendicular to the c axis to an accuracy of 0.1°. According to previous results,[12,21] the zero-field out-of-plane resistivity temperature dependence shows a strong semiconducting behavior [Fig. 1(a)]. The zero-field in-plane resistivity measurements exhibit a metalliclike temperature dependence with a slight upturn just above $T_c \simeq 88$ K [Fig. 1(b)]. At room temperature, the zero-field resistivity values are $\rho_{ab}(300\text{ K}) \approx 400\ \mu\Omega$ cm and $\rho_c(300\text{ K}) \approx 7\ \Omega$ cm. These values are in perfect agreement with those reported in Ref. 12 for an optimally doped Bi-2212.

First, we focus on the out-of-plane MR. Figure 2 shows the temperature dependence of the longitudinal ($B \| J$) and transverse ($B \perp J$) out-of-plane MR, represented as LMR and TMR, respectively, in the following. A change of sign, from positive just above T_c to negative up to 150 K, is found for both field orientations. Moreover, the LMR and TMR are essentially equivalent implying that the out-of-plane MR is ''isotropic,'' i.e., independent of the field direction. Such an isotropic negative out-of-plane MR is a common feature that has already been observed in Bi-2212,[9] Bi-2201,[14] Sr_2RuO_4,[22] and underdoped La-214.[11] It is important to note that the magnitude of our experimental MR matches perfectly the magnitude of the one reported by Yan *et al.*[9] in Bi-2212 single crystals. However, in this latter paper, the authors consider a slightly underdoped compound whereas ours is optimally doped. Qualitative and/or quantitative comparison with the experimental features we have observed would be difficult.

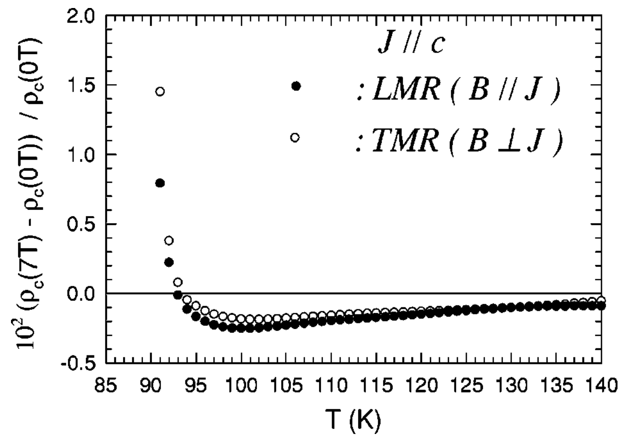

FIG. 2. Temperature dependence of transverse ($B \perp c \| J$) (open circle) and longitudinal ($B \| c \| J$) (black circle) out-of-plane magnetoresistivity at 7 T.

The result exhibited in Fig. 2 implies that the positive orbital contribution to the TMR, arising from a bending of the carrier trajectory by the magnetic-field-induced Lorentz force when $B \perp J$, is absent. This suggests that a spin part, rather than an orbital part, is strongly involved in the observed negative out-of-plane MR.

More interesting are the results of the Fig. 3, which show the temperature dependence of the longitudinal ($B \| J$) and transverse ($B \perp J$) in-plane ($J \| ab$) MR. This current configuration also gives rise to a noticeable, but negative, amount of MR for both field directions. Let us note again that the MR changes in sign and becomes positive near T_c as for the out-of-plane MR (see Fig. 2). This is attributed to the onset of superconducting fluctuations that give rise to an additional positive MR term as approaching to T_c. At this point, it is important to note that the negative MR occurs regardless of the respective field and current directions. Moreover, when $J \| ab$, despite the fact that the TMR is

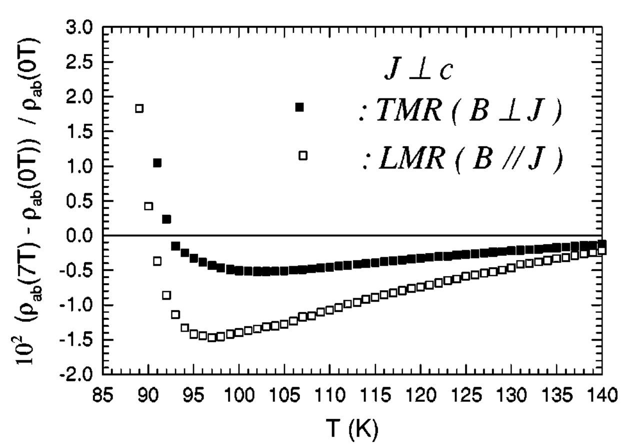

FIG. 3. Temperature dependence of transverse ($B \| c \perp J$) (black square) and longitudinal ($B \| c \perp J$) (open square) in-plane magnetoresistivity at 7 T.

found ''*more positive*'' than the LMR, in agreement with the additional positive orbital contribution expected in this transverse configuration, only a weak in-plane MR anisotropy is observed.

Our experiments report negative in-plane LMR *and* TMR in Bi-2212 single crystals. In La-214, Kimura *et al.*[11] observe a positive in-plane MR whatever the field direction and the doping state are. At least for the underdoped compound, they account for this result considering the excess of conductivity arising from superconducting fluctuations of an Aslamasov-Larkin type. For other doping states, they assume that the normal-state MR is involved. Contrasting results are reported by Ando *et al.*[15] for underdoped La-214. The authors have observed a negative in-plane TMR at low temperature for very high magnetic fields. In the same way, for the same compound, Preyer *et al.*[17] have observed a negative, but isotropic, in-plane MR. The authors give such a result as evidence for spin scattering effect in limiting the conductance. Besides, no evidence for a negative MR term when $J\|ab$ is found for Sr_2RuO_4 (Ref. 22) and $YBa_2Cu_3O_{7-\delta}$ (YBCO).[23,24] The bismuth system exhibits an important discrepancy in the behavior of the in-plane MR. Heine *et al.*[16] have measured positive TMR which has been analyzed in terms of superconducting order-parameter fluctuations and interactions of carrier spins with magnetic field. In Bi-2201 single crystals,[14,25] a slight negative MR is observed only when the field is perpendicular to the CuO_2 layers. Nevertheless, in the same compound, Ando *et al.*[7] have reported only little positive MR.

Actually, the question is to know how to account for the nonconventional behavior presented above for both in-plane and out-of-plane MR. In many papers, the existence of a negative out-of-plane MR is often interpreted in terms of a field-dependent pseudogap.[9,26] The out-of-plane charge transport is blocked by this normal-state gap which plays, in such a picture, a central role in the temperature dependence of *c*-axis resistivity and magnetoresistivity. When one applies a magnetic field, this pseudogap is suppressed promoting the conduction along the *c* axis. This naturally leads to a negative out-of-plane MR. The isotropy shown on Fig. 2 is usually considered as an evidence suggestive of the role of the field on the MR through the spin degrees of freedom.[9] An attractive scenario may be that the interlayer charge transport is prevented by spin-singlet state pairing associated with a spin gap. The presence of a magnetic field would break up the singlet state between spins. Therefore the concomitant reduction of the gap induces an increase of the tunneling amplitude and leads naturally to the observed isotropic negative out-of-plane MR. According to Yan *et al.*,[26] the gap is not supposed to affect the in-plane charge transport. Thus the argument presented above cannot account for the experimental results concerning in-plane measurements. For the in-plane transverse configuration, the orbital contribution is expected to be important. The negative transverse MR and the weak anisotropy found between the transverse and the longitudinal configurations might indicate that the orbital part does not dominate the in-plane MR. This weak Lorentz-force dependent property suggests a spin dominated origin of the in-plane MR. As noted previously, Preyer *et al.*[17] have also observed an isotropic negative in-plane LMR and TMR. The authors have emphasized that such experimental features are inconsistent with coherent backscattering (weak localization)[27] or conventional interaction effects.[28] They have suggested that the charge carriers are strongly scattered by the fluctuating Cu spin system which in such a case limits the conductance. If an intense field is applied, a reduction of these spins fluctuations is obtained as proposed by N. P. Ong.[29] For explaining the in-plane experimental results presented above, we can expect that a similar mechanism is at work in our optimally doped Bi-2212 single crystal.

In numerous papers, magnetic field suppression of superconducting fluctuations are used to describe in-plane and out-of-plane MR data.[16,30–33] However, even when orbital *and* spin contributions are considered, one cannot account for a negative longitudinal and transverse in-plane MR. For the *c*-axis transport properties, it has been shown that the decrease of the one-electron density of state (DOS) at the Fermi level induced by the formation of Cooper pairs in the normal state can lead to a negative LMR. However, the isotropy revealed by the measurements reported in this paper is not yet understood in such a framework.

Besides, several magnetotransport experiments suggest that the *c*-axis LMR contribution has the same origin as the in-plane orbital MR contribution. Indeed, in Tl-2201 (Ref. 13) and optimally doped La-214,[34] where no negative *c*-axis MR contribution is observed, the *c*-axis LMR is found to follow the orbital in-plane MR *T* dependence. Apparently, our experiments are not consistent with such a behavior and do not suggest that *c*-axis transport is dominated by scattering process within the planes.

In conclusion, we have measured both the in-plane and out-of-plane MR with a magnetic field oriented parallel and perpendicular to the current. We have obtained a negative MR regardless of the field and the current directions. An isotropic *c*-axis MR and a slightly anisotropic in-plane MR have been found. These results are qualitatively in agreement with a field-dependent spin gap picture for the *c*-axis transport. We also show that the spins seem to play a substantial role in the in-plane magnetoresistivity. We have also discussed our results in terms of superconducting fluctuations and two-component picture models where the *c*-axis conduction is governed by the in-plane one.

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