Low-field magnetoresistance of $Bi_2Sr_2CaCu_2O_8$ single crystals in the vicinity of T_c

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We report a systematic study of the magnetoresistance of Bi-2:2:1:2 single crystals using a small transport current and in magnetic fields less than 1 T. A few kelvin below the transition temperature we find excellent agreement with the theory of superconducting order-parameter fluctuations in two-dimensional systems. The critical temperature of an isolated double CuO_2 sheet is estimated at 37 K, and the field which decouples CuO_2 sheets at 0.1–0.2 T. By measuring the magnetoresistance in weak applied fields it is possible to determine the presence of small amounts of the Bi-2:2:2:3 phase. The presence of this latter phase makes the analysis of the fluctuation-enhanced conductivity above T_c very complicated.

I. INTRODUCTION

The high-T_c superconducting cuprates are characterized by quasi-two-dimensional superconducting properties (due to the weakly coupled CuO_2 planes), short coherence lengths, and high transition temperatures. These properties greatly enhance fluctuation phenomena both above and below T_c, leading to a strong fluctuation contribution to the magnetoresistance. The fluctuation contribution to conductivity above T_c and related suppression of fluctuations by the magnetic field are in many cases successfully analyzed in the framework of the Aronov-Hikami-Larkin[1] model based on the Aslamazov-Larkin[2] and Maki-Thompson[3,4] fluctuation enhancement of conductivity in layered high-T_c compounds.

Below T_c the situation seems to be much more complicated. Dissipation in the magnetic field at low resistivity values ($\rho < 10^{-2}\rho_n$, where ρ_n is the normal-state resistivity immediately above T_c) is in good agreement with thermally activated flux motion[5] and can be described by an Arrhenius law $\rho=\rho_0\exp(-U/T)$, where U is the depinning activation energy and the prefactor ρ_0 is essentially magnetic-field and orientation independent. At higher resistivities ($\rho \rightarrow \rho_n$), the magnetoresistance curves are ordinarily related to the Lorentz-force-dependent flux flow, but the expected linear dependence of the resistivity on magnetic field is not observed in high-T_c compounds. This discrepancy has indicated the possibility that an alternative mechanism causes the dissipation in the magnetic field below T_c.

Recently high-field (above 1 T) magnetoresistance curves of Bi-2:2:1:2 thin films[6] and single crystals[7] were analyzed in the framework of the superconducting order-parameter fluctuations below T_c. This approach was based on the fact that the magnetoresistance curves are much better described by a logarithmic dependence of dissipation on the magnetic field than by any kind of power law. $Bi_2Sr_2CaCu_2O$ (BISCO) superconductors are compounds with a high degree of anisotropy, and decoupling of the superconducting planes is possible even in fields less than 1 T,[8,9] leading to two-dimensional behavior and the Kosterlitz-Thouless (KT)[10] transition. Above the KT melting temperature of the two-dimensional (2D) vortex lattice T^m_{2D}, which is only weakly field dependent for $H_{c1} \ll H \ll H_{c2}$, long-range off-diagonal superconducting order is absent, which means that intrinsic superconducting transition temperatures of the single CuO_2 plane and double and triple CuO_2 sheets differ from the measured T_c of the whole sample. Small coupling between superconducting sheets destroys the KT transition and the transition temperature is thus raised toward the T_c of the whole three-dimensional sample.

It is predicted[9] that in high-T_c compounds with a high degree of anisotropy and in which the Josephson coupling between superconducting sheets dominates over the magnetic one (such as BISCO), the critical field which causes decoupling of these sheets essentially does not depend on temperature, so that in fields higher than the critical one superconductivity is two dimensional. In such cases, it is possible to analyze the magnetoresistance curves in terms of superconducting fluctuations in two-dimensional systems with a superconducting transition temperature T^* lower than T_c. For the applied field perpendicular to the ab planes, the magnetoresistance is expressed as[11]

$$\Delta R(T,H)=A\left[\frac{T}{T^*}\right]f_2\left[\frac{H}{H_\varphi}\right], \tag{1}$$

where $H_\varphi=\hbar/4eL^2_\varphi$ is the phase-coherence-breaking field, L_φ the inelastic diffusion length, and

$f_2(x)=\Psi(\frac{1}{2}+1/x)+\ln(x)$, where Ψ is the digamma function. The function $A(T/T^*)$ is directly proportional to the Larkin function $\beta(T/T^*)$:[12]

$$A\left(\frac{T}{T^*}\right)=\frac{e^2}{2\pi^2\hbar}R_L^2\beta\left(\frac{T}{T^*}\right), \tag{2}$$

where R_L is an effective fluctuation sheet resistance. The temperature dependence of the Maki-Thompson contribution to the superconducting fluctuations is included in the Larkin function $\beta(T/T^*)$, which measures the strength of fluctuations. In the case of an attractive interaction, the β function increases with decreasing temperature as $1/\ln(T/T^*)$ and diverges at T^*. The phase-coherence-breaking field is scaled according to the phenomenological law $H_\varphi=H_0\exp(-T/T_0)$.

In this paper, we report a systematic study of the magnetoresistance of Bi-2:2:1:2 single crystals with a small transport current applied and in weak magnetic fields (up to 1 T), and find an excellent agreement with the above-mentioned model over a temperature range of 2.5 K (78.5–81 K). By fitting the experimental results, we estimate the value of T^* at 37 K and the decoupling field approximately at 0.1–0.2 T. We also note the difficulties in determining the fluctuation-enhanced conductivity above T_c corresponding to the Bi-2:2:1:2 phase due to the mixing of the Bi-2:2:1:2 and Bi-2:2:2:3 phases. Although the presence of the former can be reduced to very small values, it cannot be excluded entirely, and this makes the analysis very complicated.

II. EXPERIMENTAL

Single crystals were grown by the KCl-flux method described elsewhere.[13] The critical temperature of the measured sample (defined by the linear extrapolation of the steep part of the transition curve to the value $R=0$) is 84.5 K. Measurements were carried out using a low-frequency (33 Hz) ac method in a standard four-contact configuration. The contacts were made with silver paste and 21-μm gold wires. The applied current was 24 μA, which corresponds to a current density of approximately 0.2 A/cm.^{2} Magnetic fields in the range 0.1–0.8 T were produced by an iron-core magnet and with a level of precision of 0.1%; the remanent magnetism of the iron core was canceled by a small opposite current through the magnet coils before each run. The magnetic field was applied perpendicular to the ab planes in all the measurements. Accurate crystal orientation with respect to the magnetic field was achieved by taking measurements at several angles in the vicinity of the desired values. For measurements of the small magnetoresistance in the fully resistive state above 90 K, the method of compensation was used in order to separate signals as low as 5–10 nV from the total signal of 30–40 μV.

We note that all the samples undoubtedly contain small amounts of the Bi-2:2:2:3 phase, as was confirmed by the magnetoresistance measurements above 90 K, where the contributions of the Bi-2:2:1:2 phase (above T_c) and Bi-2:2:2:3 phase (below T_c) are mixed (Fig. 1) (the magnetoresistance measurements in a weak field is thus a very simple but powerful method for determination of the presence of the Bi-2:2:2:3 phase in a predominantly Bi-2:2:1:2 sample). If the amount of Bi-2:2:2:3 phase is appreciable, a small kink in a zero-field resistance curve occurs, but if the higher-temperature phase is only slightly present, the kink might be hidden in the large normal-state resistance of the Bi-2:2:1:2 phase. X-ray analysis is probably in many cases not sensitive enough for an accurate determination of the inclusions of the Bi-2:2:2:3 phase. This conclusion is confirmed by our measurements of the magnetoresistance of single crystals grown by the self-flux method with the starting composition [Bi]:[Sr]:[Ca]:[Cu] = 2:2:1.2:2.6. This composition has been reported[14] to yield phase-pure Bi-2:2:1:2 single crystals, but this assertion is also based on the analysis of characteristic diffraction lines. However, the magnetoresistance of samples produced by the same method by us also shows the characteristic mixing in the temperature region between the critical temperatures of the two phases (Fig. 2). As the field is increased, $\Delta R(H,T)$ also

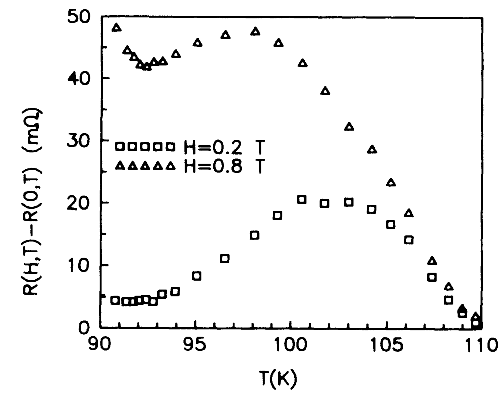

FIG. 1. Magnetoresistance $R(H,T)$-$R(0,T)$ of a sample produced by the KCl-flux method in the region between the critical temperatures of the Bi-2:2:1:2 and the Bi-2:2:2:3 phases, for applied fields of 0.2 and 0.8 T. The total signal is a combination of the magnetoresistance of the Bi-2:2:1:2 phase above and the Bi-2:2:2:3 phase below the corresponding critical temperatures.

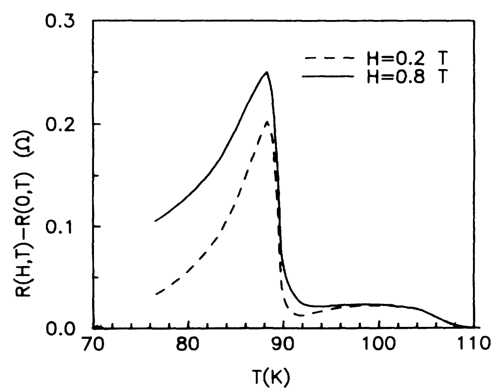

FIG. 2. Magnetoresistance $R(H,T)$-$R(0,T)$ of a sample produced by the self-flux method with a starting composition [Bi]:[Sr]:[Ca]:[Cu]=2:2:1.2:2.6 (which has been reported to yield pure Bi-2:2:1:2 crystals), for applied fields of 0.2 and 0.8 T. The presence of the Bi-2:2:2:3 phase is obvious.

increases in the intermediate region, and in strong fields this curve will ultimately show the monotonic fall with increasing temperature which apparently represents the pronounced fluctuation contribution solely by the Bi-2:2:1:2 phase above the corresponding T_c. It must be emphasized that ΔR is strongly field dependent in the intermediate region mentioned. Since the two phases have different parameters, large errors can arise if strong-field data alone are carelessly analyzed. On the other hand, we find that the magnetoresistance below T_c(2:2:1:2) corresponds to the Bi-2:2:1:2 phase. The influence of the Bi-2:2:2:3 phase is negligible in this temperature region for two reasons: first, the amount of the Bi-2:2:2:3 phase is in most cases (such as ours) very small, and second, measurements are performed well below $T_c(2:2:2:3) \simeq 105-110$ K.

III. RESULTS AND DISCUSSION

An excellent fit to the model of superconducting fluctuations below T_c was obtained for eight temperatures in the temperature range 78.5–81 K (Figs. 3 and 4), differing slightly only for the field of 0.1 T at each inspected temperature. Curves were fitted to the complete expression for $\Delta R(T,H)$ and not only to the logarithmic part of the formula. Since the computed H_φ is very small compared to the lowest applied field (0.1 T), the magnetoresistance curves show a logarithmic behavior, which is the consequence of the saturation of the Ψ function. We obtained much better results by taking into account small corrections due to the finite dependence of the Ψ function on the field. Above 81 K, H_φ starts to decrease rapidly with increasing temperature (Fig. 5), which is the manifestation of an increased contribution of the flux flow to the total dissipation. In spite of the fact that linear dependence of the longitudinal magnetoresistance on magnetic field has not been observed in high-T_c materials, the flux-flow contribution to the total dissipation cannot be disregarded easily. The remarkable change of sign of the Hall voltage we observed in the vicinity of T_c (Fig. 6) can be qualitatively explained in terms of the Nozières-Vinnen flux-flow model,[15,16] indicating that flux flow is an important dissipation mechanism at least very close to the transition temperature. In Hall-effect measurements, much stronger currents are usually used (in our present case 600 μA) than in magnetoresistance measurements; these relatively strong currents are responsible

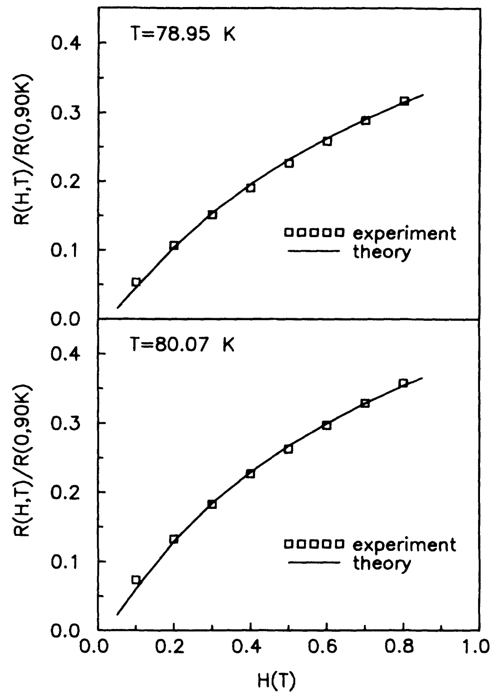

FIG. 4. Normalized magnetoresistance $R(H,T)/R(H,90\text{ K})$ versus applied field for two different temperatures. The fit deviates slightly for the lowest applied field of 0.1 T at all temperatures investigated.

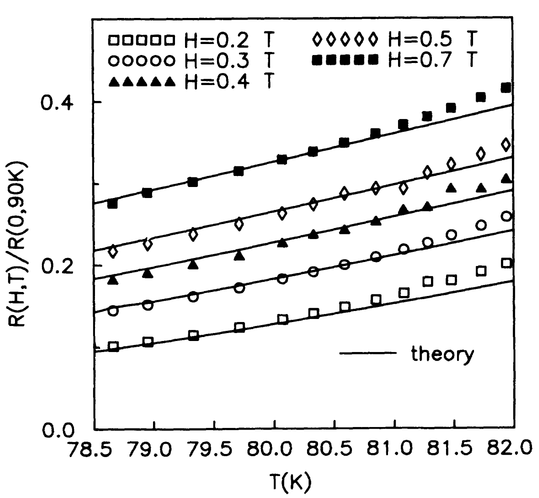

FIG. 3. Normalized magnetoresistance $R(H,T)/R(0,90\text{ K})$ versus temperature, at various applied fields, in the temperature region 78.5–82 K. Above 81 K, the flux-flow contribution becomes significant, while below this temperature the curves fit well to the theory of superconducting fluctuations below T_c.

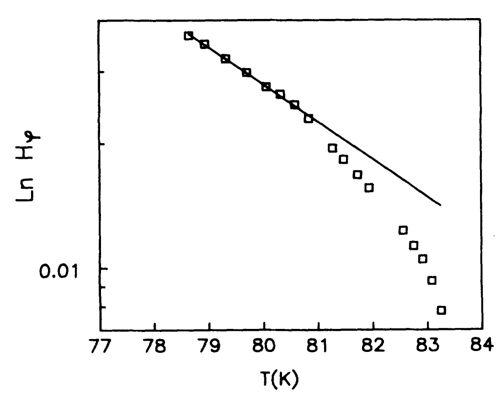

FIG. 5. Temperature dependence of the phase-coherence-breaking field H_φ in a linear-log plot. Above 81 K, it starts to deviate from an exponential law, which is an indication of increased contribution of flux flow.

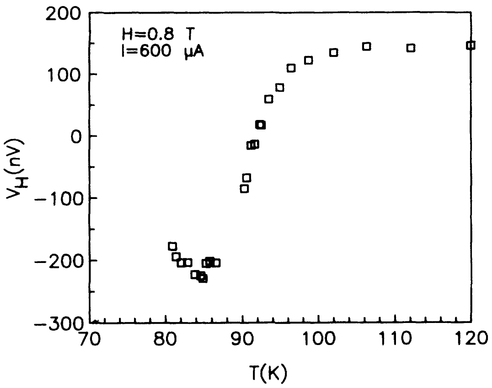

FIG. 6. Change of the Hall-voltage sign in the vicinity of T_c in the Bi-2:2:1:2 single crystal. The magnetic field is 0.8 T and it is perpendicular to the ab planes. The applied current is 600 μA.

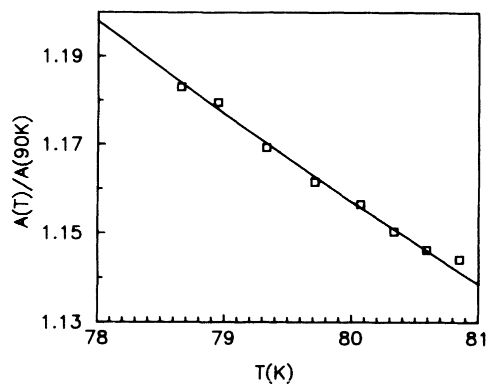

FIG. 7. Function $A(T)/A(90\ \mathrm{K})$; it follows well the predicted dependence and diverges at $\simeq 37$ K.

for an increased Lorentz force on vortices, leading to the enhanced flux-flow contribution to the total dissipation. However, a few degrees below T_c the negative Hall voltage increases toward zero, but the longitudinal magnetoresistance remains an appreciable fraction of the normal-state resistance even for the much smaller currents. This indicates the strong competition between the two mechanisms, which in fact always exists. Depending on the phenomenon and the temperature range investigated, one can contribute more than the other, so that our analysis in terms of the superconducting fluctuations does not mean that flux flow is absent, but only that its contribution is masked by the strong dissipation due to the suppression of the long-range superconducting order. At temperatures higher than 81 K, the phase-coherence-breaking field apparently deviates from the exponential law and becomes very small, but this is only a reflection of the increased flux-flow contribution.

The best agreement with experimental results has been obtained with $T^* \simeq 37$ K, $\ln H_0 \simeq 13.2$, and $T_0 \simeq 4.8$ K. The parameters which describe H_φ are in good agreement with the previously reported results for single crystals in strong fields,[7] where the estimated values were $\ln H_0 \simeq 12.1$ and $T_0 \simeq 6.8$ K. But our estimate of $T^* \simeq 37$ K is much closer to the result for thin films,[6] for which the value of 30 K was reported, while for the single crystal this temperature was estimated to be approximately 71 K. As we mentioned before, T^* can be interpreted as the melting temperature of a two-dimensional vortex lattice in the Kosterlitz-Thouless sense, and some models[9] predict that this temperature can be between 30 and 40 K for the Bi-2:2:1:2 compound and consequently for a double CuO_2 sheet. The other high-T_c superconductors may have different T^*, depending on the arrangement of CuO_2 planes, i.e., whether they have single, double, or triple planes. Because fluctuation effects are enhanced in systems with lower dimensionality, T^* should be the highest for the triple CuO_2 sheet and the lowest for the single CuO_2 plane; some analyses confirm this conclusion.[6]

Strong applied fields, well above 1 T, surely decouple superconducting sheets, but in our work we show that an agreement of experiment and the theory of dissipation due to superconducting fluctuations below T_c is also achieved in much weaker fields. This indicates that the value of the decoupling field for Bi-2:2:1:2 is very low indeed. The observed discrepancy of fit at the field of 0.1 T at all inspected temperatures could indicate that the value of the decoupling field is approximately 0.1–0.2 T. If we take into account the highly layered structure of Bi-2:2:1:2, this rather low value is not surprising, even though it is even lower than that predicted by theoretical models.[8,9]

The function $A(T/T^*)$ follows well the characteristic inverse logarithmic dependence on temperature, as can be seen in Fig. 7. We have to note that the value of T^* is computed by extrapolation to the much lower temperatures, which may cause some error. But for the range of fields used, low resistivity values are attained after a very small decrease of temperature and the magnetoresistance in this region is strongly modified by thermally activated flux creep.

IV. CONCLUSION

We show that it is possible to analyze the magnetoresistance of Bi-2:2:1:2 single crystals in terms of superconducting fluctuations below T_c for applied fields lower than 1 T, at temperatures of at least a few degrees below the transition temperature. Closer to T_c, dissipation due to the superconducting fluctuations is modified by the flux-flow contribution. Since the fit deviates for the field of 0.1 T at all temperatures investigated, the decoupling field of the superconducting sheets is estimated to be 0.1–0.2 T. The critical temperature of the double CuO_2 sheet is estimated to be approximately 37 K.

The analysis of the magnetoresistance above T_c that corresponds to the Bi-2:2:1:2 phase is extremely difficult due to the mixing of the contributions of Bi-2:2:1:2 and

Bi-2:2:2:3 phases above and below T_c, respectively. The presence of very small amounts of the Bi-2:2:2:3 phase in predominantly Bi-2:2:1:2 samples can thus be determined by magnetoresistance measurements in weak magnetic fields. To obtain a wider understanding of these phenomena we intend to extend our investigation to some other well-characterized systems that exhibit similar layered structures to that found in the Bi-2:2:1:2 compound.

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