High-magnetic-field transport properties of $Bi_2Sr_2CaCu_2O_8$ single crystals

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We have measured the high-magnetic-field dependences (up to 18 T) of the in-plane and out-of-plane transport properties of $Bi_2Sr_2CaCu_2O_8$ (Bi-2:2:1:2) single crystals. From *I-V* curves of *c*-axis transport we extract the magnetic field and temperature dependences of the interlayer critical current and define a decoupling line $H_D(T)$ above which $J_{c,c}$ vanishes. The temperature dependence of $J_{c,c}$ supports a first-order decoupling transition. The decoupling line lies close to the irreversibility line in the field interval 0.5–5 T. The field dependence of the in-plane vortex activation energy is $\sim B^{-0.5\pm0.1}$.

It is well established that in high-T_c superconductors nondissipative currents along CuO_2 layers exist below the irreversibility line $H_{\rm irr}(T)$.[1,2] This line separates the states with pinned vortices and a nonzero critical current density $J_{c,ab}(B)$ from those with mobile unpinned vortices. In contrast, the corresponding information concerning the critical current along the *c* axis, $J_{c,c}(B)$, in fields B parallel to the *c* axis has not been well established, nor has the existence and nature of the decoupling line $H_D(T)$, which separates the superconducting and dissipative states for interlayer currents.

One expects that the mechanisms of dissipation for currents along layers and for interlayer currents are drastically different in highly anisotropic materials. For intralayer currents, it is the motion of pancake vortices under the effect of a Lorentz force, whereas in the case of interlayer currents with $\mathbf{B} \parallel c$ (the so-called Lorentz-force-free configuration), the limitation on the critical current is imposed by its Josephson nature.[3,4] It was shown previously that these different mechanisms result in distinct behaviors of the resistivity ρ in the dissipative states,[5] above $H_{\rm irr}(T)$ and $H_D(T)$. In the Bi-2:2:1:2 superconductor, ρ_{ab} monotonically increases with T, as described by flux-flow or flux-creep models, above $H_{\rm irr}$, while ρ_c has a pronounced peak at a certain point $T_P(B)$ which shifts to lower temperature with increasing B. A recent study of transport along the *c* axis of Bi-2:2:1:2 in zero magnetic field has shown strong evidence for a model of stacked, multilayer Josephson junctions.[4]

Briceño *et al.* and Gray and Kim[5] described this peak in ρ_c as originating from two competing conductances: incoherent (dissipative) Cooper pair tunneling (coherent tunneling being suppressed by the magnetic field) and quasiparticle tunneling between layers, suppressed by the superconducting gap below T_c (and, possibly, suppressed by an activation gap for normal carriers at temperatures below 300 K). A study of the magnetic field dependence of ρ_c in synthetic MoGe/Ge multilayers[6] also suggested decoupling of layers with respect to applied magnetic field and temperature.

Suppression of the coherent Josephson current by an applied magnetic field $\mathbf{B} \parallel c$ was explained previously[7,8] by a loss of phase coherence of the superconducting order parameters in neighboring layers induced by thermal displacements of the pancake vortices from their equilibrium positions. Complete decoupling of layers with respect to the Josephson interaction was predicted to occur at a phase transition line $H_D(T)$ lying above the irreversibility line by Daemen *et al.*[8]

In the following we present experimental data which address issues about the field and temperature dependence of the interlayer critical current density $J_{c,c}$, the interplay of the decoupling line $H_D(T)$, and the irreversibility line $H_{\rm irr}(T)$, the character of the decoupling transition and the behavior of ρ_c above the decoupling line. For these purposes we have measured the *I-V* characteristics for currents along *ab* planes and along the *c* axis in fields $\mathbf{B} \parallel c$ up to 18 T. We also present data on $\rho_c(T)$ and $\rho_{ab}(T)$ over the same field range.

For this experiment, we used two single crystals with $0.925 \times 0.45 \times 0.008\,89$ mm^3 for *c*-axis currents and, with $1 \times 0.28 \times 0.0076$ mm^3 dimensions for in-plane currents, with $T_c \sim 85$ K and ~ 87 K, respectively. The contacts were made using silver paste by curing 12 h in air at 500–600 °C and subsequently quenching to room temperature. The current contacts covered most of the two crystal *ab*-plane faces for a uniform *c*-axis current density, and, for the in-plane currents, the current contacts covered the sides of the crystal to ensure a uniform in-plane current density. The measurements were done with a standard four-contact method using both ac and dc currents. For ρ_c in high magnetic field, the excitation current for the ac bridge was 30 μA. We checked the current dependence of the resistivity, and it gave identical results for currents

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up to 1 mA in either orientation. The high-magnetic-field measurements were taken in an Oxford 20 T superconducting magnet at the National High Magnetic Field Laboratory (NHMFL) at Los Alamos National Laboratory.

The critical current density along the c axis, $J_{c,c}$, with $\mathbf{B} \parallel c$ was determined from I-V characteristics by choosing the current at which the voltage deviated from the background level by ~ 1 nV in the transition to a resistive state. At zero magnetic field, we observed the critical current densities ~ 24 A/cm^2 and ~ 7.25 A/cm^2 at $T = 82$ K and 84 K, respectively, showing approximately linear dependence of $J_{c,c}$ on $(T_c - T)$. At 84 K, the I-V curve shows a hysteretic behavior, indicating characteristics of a well-coupled series of hysteretic Josephson junctions.

The typical I-V curves for different T at $H = 4$ T are shown in Fig. 1(a) (the I-V characteristics for different fields are similar). At low temperatures, $T < 30$ K, the voltage remains very low with current density up to ~ 14.5 A/cm^2; then there is a jump to the resistive state. The magnitude of this jump increases with magnetic field (not shown here). A nonvanishing critical current is observed in this low-temperature range for $B \leq 7$ T. At temperatures above 30 K the I-V curves are Ohmic at low currents, as shown in the inset of Fig. 1(a). And below the temperature T_P, where ρ_c reaches a maximum for a given field (see Fig. 3), they show concave-type behavior, and then saturation above T_P (which may be caused by the Joule heating of the crystal).

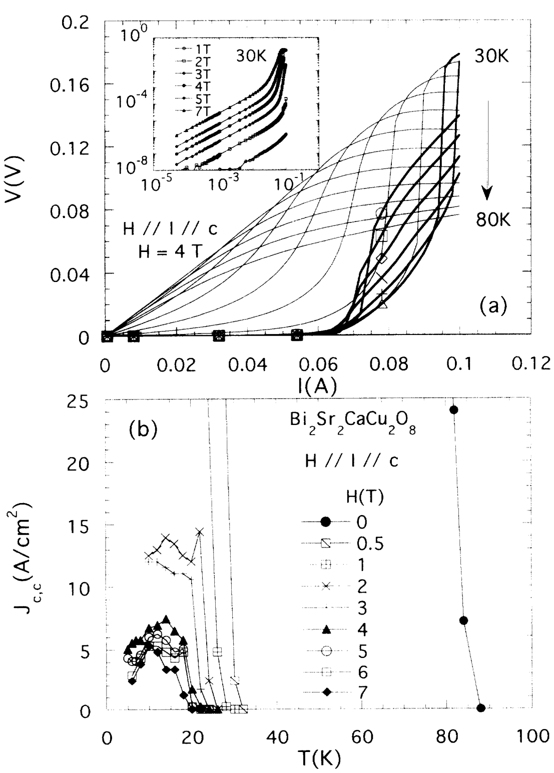

FIG. 1. (a) c-axis I-V characteristics at $B = 4$ T. Those above 30 K are shown by thin solid curves, 5-K interval from top to bottom at the right side. I-V characteristics below 30 K are shown by thick solid curves. (○) 6 K, (□) 10 K, (◇) 14 K, (×) 18 K, (+) 22 K, and (△) 26 K. Inset shows the I-V curves on logarithmic scales at 30 K and at various magnetic fields. (b) Critical current density $J_{c,c}$ vs temperature at different fields.

In Fig. 1(b), we plot $J_{c,c}$ vs T at various magnetic fields. As shown in the figure, there exists a sudden decrease of critical current with respect to temperature and magnetic field, possibly indicating a first-order phase transition. At temperatures below 30 K the critical current is strongly suppressed by the magnetic field. The critical current also exhibits a reentrant behavior with respect to temperature at high magnetic field as previously reported by Rodríguez *et al.*[9] In this low-temperature range, the I-V curves show three regimes: a zero resistance region, a small linear increase of the voltage with increasing current (only observed in a high magnetic fields), and an abrupt jump of voltage, signaling the transition to the resistive state.

Based on the data presented in Fig. 1(b), we define $H_D(T)$ as the field (temperature) below which the critical current $J_{c,c}$ becomes nonzero (with our criterion $\sim$1 nV). Extrapolations of the data in Fig. 1(b) to $J_{c,c} = 0$ introduce a maximum error 2 K, the interval of measurements, and is reflected in the error bars shown in Fig. 2. The decoupling line $H_D(T)$ is shown in Fig. 2 with the irreversibility line as obtained by Schilling *et al.*,[2] as well as one obtained in our crystal for comparison. We can see that these lines follow a similar functional dependence and are close, suggesting a relation between depinning in the ab plane and the decoupling along the c axis, which will be discussed below.

Figures 3 and 4 show the temperature dependence of the c-axis and ab-plane resistivities in different fields. Above the peak temperature (T_P), no c-axis magnetoresistance is observable in this field range. T_P is observed to decrease more rapidly as a function of B at low B. The temperature dependence of ρ_c here can be described approximately by $\rho_c \sim \exp(200/T)$. The slope of the resistivity vs T below T_P becomes sharper with

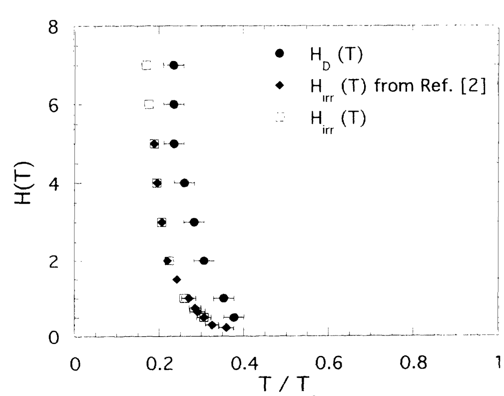

FIG. 2. The decoupling line H_D(T) as defined in the text, the irreversibility line taken from Ref. 2, and the irreversibility line obtained from the temperature dependence of zero-field-cooled and field-cooled magnetization at each field where the criterion for the in-plane critical current density at the irreversibility line is ~ 30 A/cm^2.

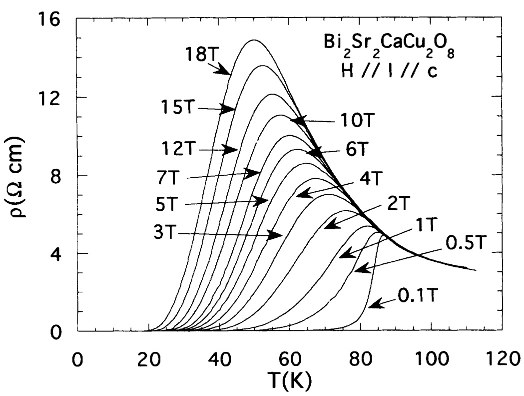

FIG. 3. The c-axis resistivity vs temperature in different magnetic fields.

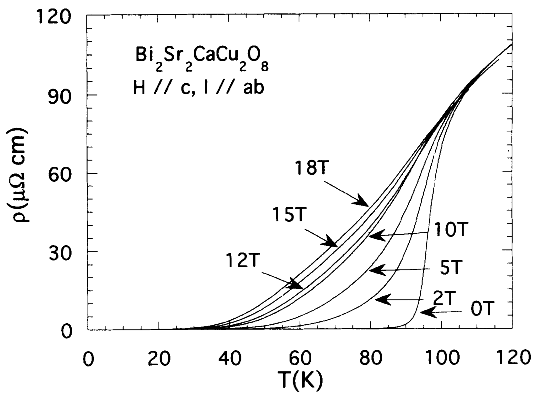

FIG. 4. In-plane resistivity vs T for different fields.

increasing magnetic field in contrast to the behavior of ρ_{ab}, where, at low temperature, higher magnetic fields broaden the transition. At low temperatures $\rho_c(T,B)$ follows $\rho_c \sim \exp(-U_{0,c}/T)$. The activation energy $U_{0,c}(B)$ is of the order 700 K at $B = 1$ T and decreases slowly with field, $U_{0,c}(B) \propto B^{-0.27}$.

In contrast to some previous results, Fig. 4 shows no low-temperature bumps in $\rho_{ab}(T)$.[5,10,11] We believe that this is due to our introduction of current into the sides of the crystal. Previous experiments with current and voltage leads on top (or bottom) mix some ρ_c into the ρ_{ab} results.[12] The effective magnetic field dependence of the activation energy for $\mathbf{B} \parallel c$, derived from $-d(\ln R_{ab})/d(1/T)$, is approximately proportional to $\sim B^{-0.5\pm0.1}$. This field dependence has also been observed experimentally in epitaxial $Bi_2Sr_2Ca_2Cu_3O_x$ thin films.[13]

In the following, we discuss the obtained results. First, the value of the zero temperature critical current density in zero field extrapolated from the data near T_c is $J_{c,c} \approx 200$ A/cm^2, where this value is very similar to the data[4] for Ar-annealed samples. Using the expression $J_{c,c} = \Phi_0 c/8\pi^2\lambda_{ab}^2\gamma^2 s$ for Josephson-coupled layered superconductors[14] where s is the CuO_2 interlayer distance, we obtain $\gamma \equiv \sqrt{m_c/m_{ab}} \approx 1000$ near T_c, taking the London penetration depth $\lambda_{ab}(0) \approx 2000$ Å. This value of γ is in rough agreement with recent estimates from irreversibility line position [$\gamma \approx 370$ (Ref. 2)] and torque measurements [$\gamma \geq 200$ (Ref. 15)]. This provides some indication that the obtained values of $J_{c,c}$ correspond to intrinsic interlayer Josephson critical current and not to the existence of Josephson junctions due to cracks or "bad" layers in the sample.

The next question is about the position of the decoupling line (determined by the sharp drop of the critical current) with respect to the irreversibility line. Our data show that both lines are almost vertical and parallel each other in fields above 3 T and the decoupling line is shifted ≈ 8 K to higher temperatures. We note that there are strong arguments for the coincidence of the irreversibility line with the melting line of the vortex lattice for a weak pinning.[2] This weak field dependence of the irreversibility line on high magnetic fields favors an almost two-dimensional (2D) Kosterlitz-Thouless-type character of the melting transition with $k_B T_m = (1/8\pi\sqrt{3})\Phi_0^2 s/16\pi^2\lambda_{ab}^2 \approx 15$ K for $\lambda_{ab} \approx 2000$ Å,[16] showing a good agreement with the Bi-2:2:1:2 irreversibility line position. This character of the melting close to 2D for Bi-2:2:1:2 was also obtained in numerical simulations done by Doniach, Ryu, and Kapitulnik[18] for high magnetic fields. It was shown[16,17] that in 2D systems the melting occurs in two steps: At T_m, the positional ordering of the vortices is lost but the orientational order remains, while at slightly higher temperature T_h [shifted by $\approx$ (8–10) K with respect to T_m according to the numerical results[17]], the orientational order is lost. At $T > T_h$ a completely random liquid phase is realized. Our high-field data show that the decoupling (defined as the vanishing of $J_{c,c}$) occurs above the irreversibility line; i.e., some correlations in pancake positions in neighboring layers remain in the hexatic phase if we associate the irreversibility line with the melting line. Then the correlations should be lost certainly at T_h, and we can speculate that T_D coincides with T_h at high fields, in the almost 2D regime. The low-field regime was explored by de la Cruz *et al.*,[18] where T_D (determined by a peak in the resistive component of the ac susceptibility) was found to lie below T_m.

Thus, at T_D where the correlation along the c axis is lost and $T > T_D(H)$, only the dissipative incoherent tunneling of Cooper pairs survives, in combination with quasiparticle tunneling at temperatures up to $\approx T_P$, while at higher T only the quasiparticle tunneling remains effective.

The I-V curves at temperatures above the decoupling line but below T_P show some resemblance to the I-V characteristics of the dc Josephson effect in a single Josephson junction as described by Ambegaokar and Halperin,[19] where the voltage below the superconducting gap is generated by thermal fluctuations of the phase. Briceño *et al.* and Gray and Kim[5] noticed that a qualitative description of the incoherent Cooper tunneling above the decoupling line in Bi-2:2:1:2 single crystals can be achieved by using the Ambegaokar-Halperin expression for the corresponding conductivity, but replacing the junction area by the area occupied by a single vortex,

B/Φ_0. Such an ansatz resembles the effect of vortex fluctuations, taking into account properly the dependence on vortex concentration. We found that this description is inadequate, especially in high fields, since it predicts an activation energy behavior $U_{0,c}(B) \propto 1/B$ and transitions to the nondissipative state which broaden below T_P with increasing magnetic field in contradiction to the data presented in Fig. 3. We believe that a more accurate description should include explicitly the slippage of phase between layers caused by thermal fluctuations of pancakes.

Below the decoupling line, the critical current density $J_{c,c}$ diminishes with increasing field with a tendency to saturate above 7 T. Note that the critical current at 7 T is suppressed $\sim$ 50 times in comparison with the zero field critical current extrapolated from the high-temperature region. In the region below $H_D(T)$ pancakes are pinned, and distortions of pancakes from their straight line positions are caused by the pinning centers in combination with thermal and quantum fluctuations. In Bi-2:2:1:2 this effect is not very strong, and this may explain the existence of substantial values of $J_{c,c}$ at high B below the decoupling line in Bi-2:2:1:2 single crystals with relatively weak disorder. Note the intriguing reentrant behavior of the critical current as a function of T in this region. It indicates the nontrivial interplay of the effects of pinning and, as well, of thermal +quantum fluctuations in this vortex state. A similar reentrant behavior due to thermal fluctuations in underdamped small single Josephson junctions has been observed.[20]

In the I-V curves shown in Fig. 1(a) jumps in voltage V_0 up to 90 mV are clearly seen. The jumps with V_0 smaller than $\approx$ 50 mV, seen below the decoupling line, can be attributed to transitions between states dominated by incoherent Cooper tunneling (low and high resistive states). Bigger jumps seen above the decoupling line may be explained by transitions from states with incoherent Cooper tunneling to states with only quasiparticle tunneling. Such a transition in a single junction should be accompanied by a jump $V_0 = 2\Delta/e$, where Δ is the superconducting gap. In Bi-2:2:1:2, V_0 is estimated as $\approx$ 50 mV using the relation $2\Delta \approx 6k_BT_c$. Note that a series of similar jumps was observed by Kleiner and Müller[4] at $B = 0$, but with a smaller ratio $eV_0/2\Delta$. They explained the small ratio by gap reduction caused by quasiparticle injection. In our case, the current densities, at which jumps are observed, are about 6 times smaller and the gap may be close to the nominal value.

To summarize, we measured the I-V characteristics for the in-plane and the out-of-plane currents in strong fields $\mathbf{B} \parallel c$. We found a decoupling line that separates nondissipative and resistive states for interlayer currents. It lies slightly above the irreversibility line, and the temperature dependence of $J_{c,c}$ supports the idea of a first-order decoupling phase transition. We invoke the Josephson-coupled model and vortex fluctuation picture to explain qualitatively the results obtained for c-axis current transport.

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