Field-induced granularity in a well-textured $(Bi,Pb)_2Sr_2Ca_2Cu_3O_y$ tape

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The magnetoresistivity of a well-textured $(Bi,Pb)_2Sr_2Ca_2Cu_3O_y$ tape is studied experimentally for a temperature range very close to T_c ($T/T_c > 0.93$) in a very low magnetic-field range ($H < 0.1$ T). In this H-T region, the dissipation associated with magnetoresistance curves seems to arise from the granularity induced by the field. As the temperature decreases, related Josephson junctions may well be coupled or even become proximity-effect superconductors, thus the dissipation is dominated by the conventional flux-creep process described by Anderson and Kim. This observation was further confirmed by the temperature dependence of the critical current density $J_c(T)$ at various magnetic fields. The $J_c(T)$ dependence seems to support the hypothesis that the Josephson coupling in the present sample is dominated by superconductor-normal-superconductor proximity-effect junctions.

INTRODUCTION

The transport properties of high-temperature superconductors (HTS) in the presence of a magnetic field have been the subject of intense research, both experimentally and theoretically over the past few years.[1] In practice most applications such as in superconducting magnets require high current-carrying capacity often in a large magnetic field, and the details of the resistive transition are the important information for the design and the protection of the magnets. Associated with the transition, two unique anomalous properties have been found. One is the existence of an "irreversibility line," reported by Muller, Takashige, and Bednorz,[2] which had led to much debate over the variety of vortex states.[3] The other is the significant broadening of the resistive transition in a magnetic field.[4] A lot of models have been proposed to explain this effect in terms of flux creep,[5] flux flow,[6] fluctuations,[7] and Josephson coupling,[8] but none of these approaches has been completely successful. The observation of the Lorentz-force-independent dissipation in highly anisotropic oxides $Bi_2Sr_2CaCuO_y$ (Bi-2212), $Tl_2Ba_2CaCu_2O_x$ (Tl-2212), and $Y_2Ba_4Cu_8O_{16}$ (Y-124) (Refs. 9–12) casts some doubts on the dissipative mechanisms based on the framework of flux motion. The Josephson coupling model[8] gives a natural explanation of the lack of any Lorentz-force dependence and is consistent with the broadened transition. But this model seems not to be so successful in explaining the magnetoresistivity data, especially for temperatures close to T_c.[13] At temperatures near T_c, Raffy *et al.*[14] have reported that the magnetoresistivity can be interpreted in terms of two-dimensional superconducting fluctuations even at temperatures well below T_c. Their results seem to be well consistent with the scaling form $\rho \sim \ln(H)$, at sufficiently high fields. But an obvious deviation can also be found in the low-field region, typically below 1 T. In an attempt to reveal the mechanism of the commonly observed "shoulder" behavior near T_c in the broadened resistive transition, more detailed studies, particularly at low fields, are clearly needed. Up to now, most authors have selected to characterize their sample with the magnetic field applied parallel to the c axis. This type of work is of great importance to explore the vortex dynamics in high-T_c superconductors. However, for most applications, such as in superconducting magnets, the field is frequently parallel to the film plane. In this paper, we present magnetoresistivity data at temperatures very close to T_c ($T/T_c > 0.93$) in a very low field with the field applied parallel to the film plane. The results are analyzed in combination with the temperature dependence of the critical current density $J_c(T)$, and represent the dissipation arising from the field-induced granularity in this temperature and field region.

EXPERIMENT

The sample for these experiments is a high-J_c silver-clad $Bi_{1.8}Pb_{0.4}Sr_2Ca_2Cu_3O_y$ (Bi-2223) film tape with dimensions of $14 \times 2.5 \times 0.04$ mm^3. The tape was prepared through a physical deposition method using the "powder in tube" technique. The details of the fabrication were reported elsewhere.[15] From the x-ray diffraction pattern for the sample, no second phase was found and much stronger (001) peaks were observed, e.g., the ratio of the strengths of the (111) and $(00\bar{1}\bar{0})$ peaks is 10%, demonstrating the high texture of the sample with a preferential grain orientation with the c axis perpendicular to the film plane.[16] The transport J_c characteristics of the sample were studied in previous work[16] and displayed practical high-field properties around 50 K. The J_c value was 2.6×10^4 A/cm^2 at 77 K and 0 T and no weak-link effect was detected through commonly used transport measurements at 77 K.[17] Magnetoresistance curves $R(H)$ were measured by the dc four-probe technique and recorded through an X-Y recorder with a sensitivity of 5 μV/cm. The contacts were soldered to the silver sheath and were so separated from one another as to ensure a uniform current flow through the region between the voltage contacts according to the calculation in Ref. 18. The field was applied parallel to the film plane and perpendicular to the current direction unless otherwise stated. To perform the $R(H)$ measurement, an excitation current of 0.5

A was used and applied along the film plane. Calibrated copper-Constantan thermocouple and Rh-Fe thermometers were utilized for $R(H)$ and J_c measurements, respectively.

RESULTS AND DISCUSSION

Figures 1(a) and 1(b) display the magnetoresistance curves at several constant temperatures very close to T_c for $H \perp I$ and $H \parallel I$, respectively. Comparing Figs. 1(a) and 1(b), it is not difficult to see that the magnetoresistivity in this temperature regime is independent of the field orientation with respect to the current direction. Since the Lorentz force is essential to understanding the dissipation in terms of magnetic flux motion, this result raises questions about the role of the Lorentz force in this loss mechanism. To analyze the magnetoresistivity of the Bi-2223 film, one has to correct the data for the influence of the silver sheath. Assuming that the normal resistance of the Bi-2223 film, R_s, is much larger than that of the silver sheath, R_n, R_n can be obtained from the $R_n(T)$ measurement above T_c and is as follows:

$$R_n = 2.2T - 73 , \tag{1}$$

where R_n and T are in $\mu\Omega$ and K, respectively. This resistivity expression for the silver sheath seems puzzling because of the negative intercept. However, our separate resistivity measurements (from 77 to 300 K) of the silver sheath without superconductor also showed similar characteristics to Eq. (1).

Supposing Eq. (1) is also effective for the temperature below T_c and neglecting the effect of the contact resistance (below $10^{-7}\ \Omega\,\text{cm}^2$) between the silver sheath and the superconductor for the present larger sample size, the resistance of the Bi-2223 film itself, R_s, can be obtained from the following simple parallel relationship:[19]

$$R_s = R_m R_n / (R_n - R_m) , \tag{2}$$

where R_m is the measured resistance.

In the process of fitting the data, we found that the $R_s(H)$ functional relationship cannot be satisfied by the

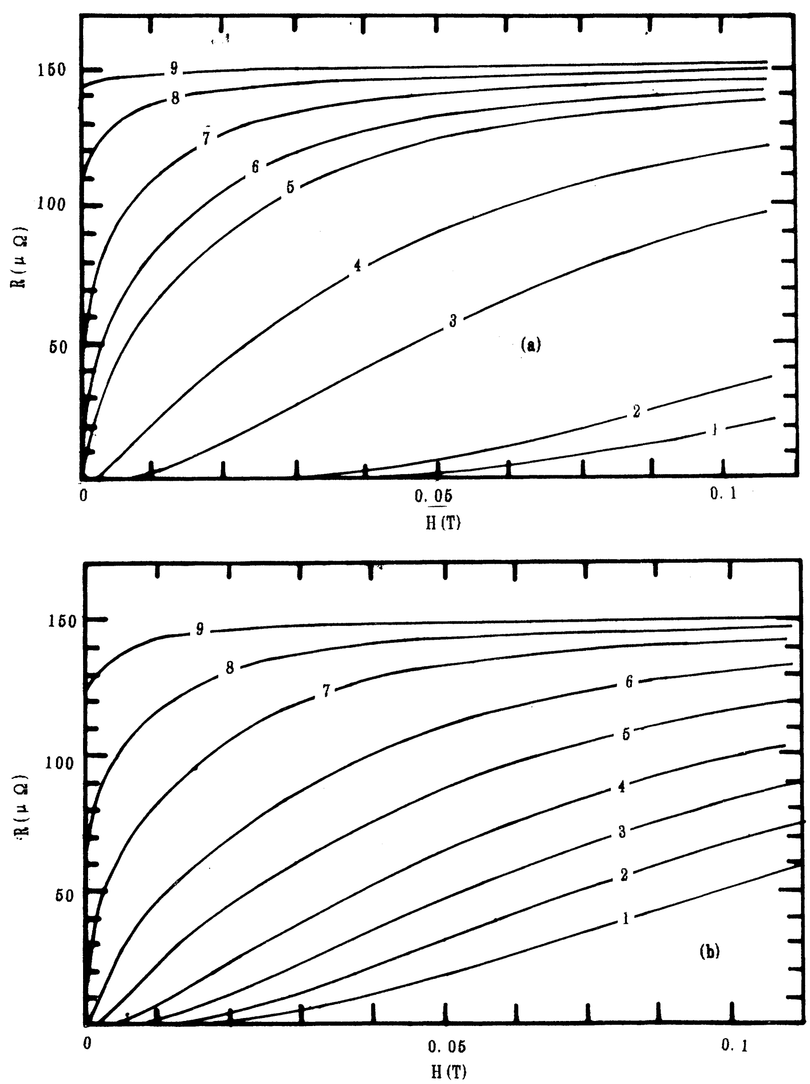

FIG. 1. (a) Magnetoresistivity of a high-J_c silver-clad Bi-2223 tape at temperature very close to T_c for $H \perp I$. Curve 1: 102.2 K; curve 2: 103.3 K; curve 3: 104.7 K; curve 4: 105.4 K; curve 5: 106.4 K; curve 6: 106.6 K; curve 7: 107 K; curve 8: 107.6 K; curve 9: 108.2 K. (b) Magnetoresistivity of a high-J_c silver-clad Bi-2223 tape at temperatures very close to T_c for $H \parallel I$. Curve 1: 103.4 K; curve 2: 103.9 K; curve 3: 104.5 K; curve 4: 104.9 K; curve 5: 105.3 K; curve 6: 106.1 K; curve 7: 106.7 K; curve 8: 107.1 K; curve 9: 107.8 K.

scaling form $\rho \sim \ln(H)$ based on thermal critical fluctuations,[20] nor by the Josephson-coupling model.[8] Therefore an alternative dissipation mechanism should be considered. Notice that the Bi-2223 films are polycrystalline, albeit being well textured and with a high degree of c-axis orientation; Josephson coupling could be formed between the grains. Furthermore, as pointed out by Daeumling, Seuntjens, and Larbalestier,[21] the field suppresses the superconductivity in regions that are already weakened by either point or extended microscopic defects, which seems to be in good agreement with their magnetization data. Although the film showed a sharp resistive transition at zero field, weak links or Josephson-coupled regions or grains could be induced as the field was increased. The grain boundaries may play a dominant role in this field-induced granularity for the present sample, but the other formation mechanisms, such as from the microscopic defects and the intrinsic weak coupling between Cu-O layers in this highly anisotropic structure, could also be important. To see this effect, experimental studies based on a high-quality single crystal are clearly necessary.

The critical currents $I_c(H,T)$ of Josephson junctions are inhomogeneous, depending on their origins. For a constant current and at given temperatures, assuming that the field H drives a number N of the junctions to the resistive-superconducting state, the number of the junctions with a resistance per unit field is N/H. Then the number dN of junctions produced in the field range $H-(H+dH)$ should be proportional to N/H and dH, i.e., $dN=n(N/H)dH$, where n is a field-independent constant. To simplify the complexity arising from the random arrangement of the Josephson junctions, we considered the simplest case that the tape is composed of a series of junctions. If there are junctions connected in parallel, they can be regarded as an equivalent junction. In that case, the resistance of the superconductor R_s would be proportional to N, and we have:

$$R_s \sim N \sim [H-H_{c0}(T)]^n \ , \tag{3}$$

where $H_{c0}(T)$ is the field above which the magnetoresistivity appears and can be obtained from the experimental results. In Eq. (3) we use $[H-H_{c0}(T)]$ rather than H because below $H_{c0}(T)$ all junctions remain well coupled and no resistance can be detected. To test Eq. (3), the magnetoresistivity data are presented again in logarithmic plots of R_s versus $[H-H_{c0}(T)]$ in Fig. 2. Power-law variations of the magnetoresistivity can be clearly found. However, it should be pointed out that at temperatures well below T_c the power-law dependence can no longer be found. The dissipation is instead dominated by a thermally activated flux-flow process.[22] This observation implies that the Josephson junctions in the present sample are so well coupled that the effect of the granularity would become secondary at low temperatures, which perhaps is the reason why this type of silver-clad tape or wire has a much higher J_c than $YBa_2Cu_3O_y$ bulk materials.

The temperature dependence of the magnetoresistivity can be analyzed by a commonly used method. As pointed out by Kim *et al.*,[8] based on the Josephson-coupling model, the resistivity can be scaled as the Arrhenius law

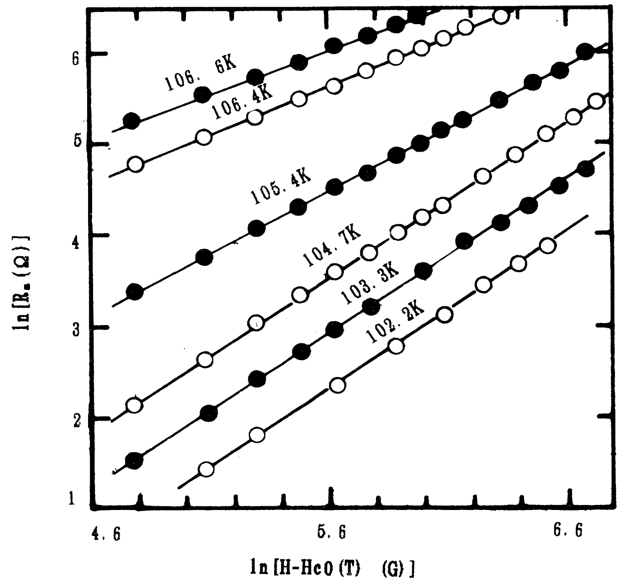

FIG. 2. Magnetoresistance curves of the Bi-2223 film itself for $H \perp I$ in logarithmic plots of R_s versus $(H-H_{c0})$, where H_{c0} is the field above which the magnetoresistivity appears.

$$\rho=\rho_0\exp(-U/kT)=\rho_0\exp[-U_0(H)(1-T/T_c)^q/kT] \ , \tag{4}$$

where the activation energy is assumed to have the form $U_0(H)(1-T/T_c)^q$. In the consideration of the field-induced granularity, combining Eqs. (3) and (4), we obtain

$$R_s=R_0(H-H_{c0})^n\exp[-U_0(H)(1-T/T_c)^q/kT] \ . \tag{5}$$

If $U_0(H)$ has the commonly used form of $1/H$,[23] then Eq. (5) can be written as

$$(1-T/T_c)^q/H=AkT\ln[R_0(H-H_0)^n/R_s] \ , \tag{6}$$

where A is a constant. Because the right-hand side in Eq. (6) is a relatively slowly varying function of T and H for T close to T_c, at the same resistance levels, Eq. (5) predicts an approximate scaling of the temperature width of the transition as

$$\Delta T=T_c(R_s,0)-T(R_s,H)\propto H^{1/q} \ , \tag{7}$$

where $T_c(R_s,0)$ is the critical temperature defined from the resistance level R_s in the transition at zero field.

Figure 3 shows ΔT versus H for several resistance levels in ln-ln plots. The scaling form of Eq. (7) can be easily found from Fig. 3. One can find that the power q is around 2, slightly decreasing at higher dissipative levels.

Further evidence of the field-induced granularity in this silver-clad sample was found from measurements of the critical current density J_c in a magnetic field. The critical current was determined with the voltage criterion of 1 μV/cm. Figure 4 indicates the temperature dependence of J_c at three fields. At a fixed field, only when the

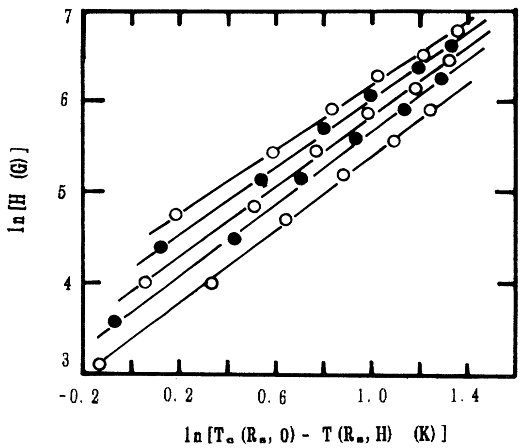

FIG. 3. Temperature width versus magnetic field for several fixed resistivity levels in logarithmic plots. From the top to the bottom, the lines are related to the resistance levels 50, 40, 30, 20, and 10 $\mu\Omega$.

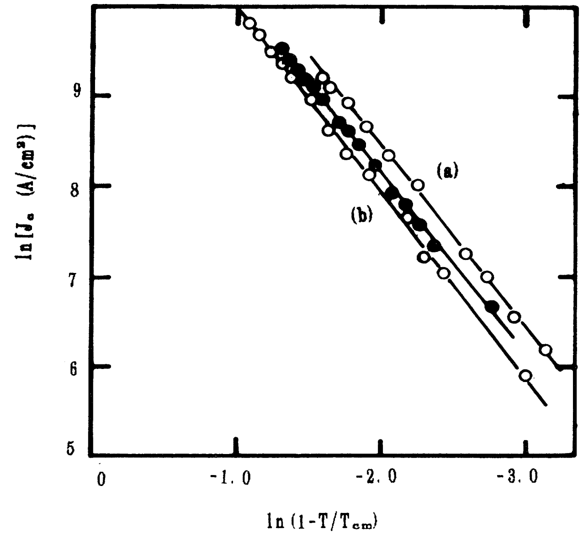

FIG. 5. Logarithmic plots of $J_c(T)$ in a temperature range close to T_{cm}. curve a: 0.5 T; solid circles: 1.0 T; curve b: 2.0 T.

temperature is well below T_c can a finite J_c be measured, as shown in Fig. 4. The boundary defined by $J_c=0$ is still a controversial issue, yielding many competing models. In our opinion, above the temperature below which J_c appears, denoted as T_{cm}, the grains in the sample are in a vortex-lattice melting state and the intergrain or intragrain Josephson junctions are decoupled. In the vicinity of T_{cm}, there may exist a transition of the vortex from the liquid to an Abrikosov vortex lattice.[23]. From the flux-creep theory of Anderson and Kim,[24] one would expect a linear temperature dependence of J_c. This linear $J_c(T)$ dependence is indeed found at temperatures well below T_{cm}. However, a nonlinear $J_c(T)$ can also be clearly observed at temperatures close to T_{cm} in Fig. 4. We think this nonlinear $J_c(T)$ characteristic is due to the effect of the field-induced granularity in the present

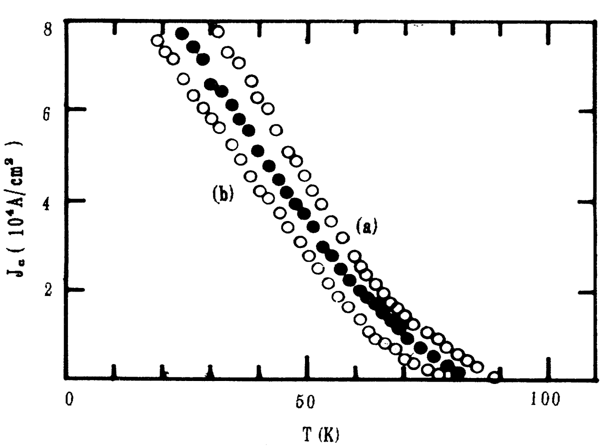

FIG. 4. Temperature dependence of critical current density $J_c(T)$ at several magnetic fields; curve *a*: 0.5 T; solid circles: 1.0 T; curve *b*: 2.0 T.

silver-clad sample. Above T_{cm}, all field-induced Josephson junctions are decoupled and lie in the resistive-superconducting state, thus resulting in a zero transport J_c. As the temperature decreases, the junctions may be coupled more and more strongly, so J_c is increased rapidly. For different types of junctions, the temperature dependence of their critical currents are also varied. For superconductor-normal-superconductor (SNS) proximity-effect junctions, according to the theory of de Gennes,[25] $I_c(T)\sim(1-T/T_c)^2$. But for an insulating boundary layer [superconductor-insulator-superconductor (SIS) junction], the calculations by Ambegaokar and Baratoff[26,27] indicate $I_c(T)\sim(1-T/T_c)$. For a high-J_c silver-clamped Bi-2223 sample, we found $J_c\sim(1-T/T_c)^{3/2}$ for T near T_c and at zero field.[17]

To examine the $J_c(T)$ dependence, the J_c data are replotted on logarithmic plots of J_c versus $(T-T_{cm})$ in a temperature region near T_{cm} in Fig. 5. The determination of T_{cm} may be a little ambiguous. Here the T_{cm} values were taken as the temperatures above which J_c tends to zero (below 50 A/cm^2) and the best fit of the data was to a power law of the type $J_c\sim(T_{cm}-T)^m$.

From Fig. 5, one finds that the power m is approximately equal to 2. This results seems to suggest that the field-induced Josephson coupling is dominated by SNS proximity-effect junctions. At low temperatures, the junctions are strongly coupled and may finally become proximity-effect superconductors.[28] Therefore the effect of such field-induced granularity would become secondary, and J_c would be dominated by the flux-creep model, resulting in a linear $J_c(T)$ dependence.

In summary, magnetoresistance curves were measured in a temperature range very close to T_c. The results seem to provide evidence that Josephson coupling can be induced by a magnetic field. The temperature dependence of the transport J_c at various magnetic fields indicated that the Josephson coupling was dominated by SNS proximity-effect junctions. At lower temperatures, this type of junction may be strongly coupled or even become proximity-effect superconductors. Further experimental studies based on a high-quality single crystal in a similar temperature and field regime would be very interesting.

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