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IN A MAGNETIC FIELD\***

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# DISSIPATION IN HIGH-TEMPERATURE SUPERCONDUCTORS IN A MAGNETIC FIELD

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## Abstract

The absence of a Lorentz force dependence on dissipation in the highly anisotropic high-temperature superconductor,  $Tl_2Ba_2CaCu_2O_x$ , has been measured over a wide range of current densities in broadened resistive transitions, current-voltage characteristics, magnetoresistances, and critical current densities,  $J_c$ . The magnetoresistances are very useful to find out the correct temperature and field dependences of the activation energy. As an alternative to flux motion, we consider a Josephson-coupling model which is consistent with the broadened resistive transitions and the lack of Lorentz-force dependence. We found that the Josephson-coupling model agrees with the temperature dependences of the activation energy and  $J_c$  and is better matched to the weak field dependence of  $J_c$  than the flux creep model. Possible origins of Josephson junctions in high-quality films and single crystals are discussed.

## Introduction

Recent studies of the broadened resistive transitions of high-temperature superconductors (HTS) in a magnetic field,  $H$ , have shown<sup>1-3</sup> essentially no macroscopic Lorentz force dependence in the highly anisotropic HTS,  $Bi_2Sr_2CaCu_2O_x$ ,  $Tl_2Ba_2CaCu_2O_x$  and recently<sup>2</sup> in  $YBa_2Cu_4O_7$ . Since the Lorentz force is essential to understand such dissipations in terms of magnetic flux motion, these results questioned the role of the Lorentz force in this loss mechanism. We have measured the broadened resistive transitions, magnetoresistance, current-voltage characteristics,  $I(V)$ , and critical current densities,  $J_c$ , in highly-oriented films of  $Tl_2Ba_2CaCu_2O_x$  for both orientations of the field with respect to the transport current for field parallel to the  $CuO$  plane ( $H||a$ ). These measurements span the temperature range from 4.2 K to 100 K in fields up to 10 T, and *no significant dependence on the macroscopic Lorentz force is ever found.*

As an alternative to flux motion, we consider a Josephson coupling model for dissipation which has satisfactorily explained similar results in granular  $NbN$  films<sup>4</sup>. This model gives a natural explanation of the lack of *any* Lorentz-force dependence and is consistent with the broadened resistive transitions. A detailed comparison of the predictions of Josephson-coupling and flux creep models to  $Tl_2Ba_2CaCu_2O_x$  shows that the Josephson-coupling model is consistent with the temperature dependences of  $J_c$  and the activation energy,  $U$ , and is better matched to the weak field dependence of  $J_c$ . Although the flux creep model fits the experimental result for  $U$ , it predicts a much stronger temperature and field dependence of  $J_c$  than is found. Possible origins of Josephson junctions in high-quality films and single crystals are discussed.

## Sample Preparation

Sputtered films of  $Tl_2Ba_2CaCu_2O_x$  were prepared in a three-gun dc magnetron sputtering system. Three targets of Tl, Cu, and a 1:1 Ba/Ca mixture are simultaneously sputtered in 20 m Torr of Ar and  $4 \times 10^{-5}$  Torr of  $O_2$ . The films were deposited onto (100) single-crystalline substrates of MgO, which were kept at 210 °C during deposition. The films were wrapped in gold foil together

with  $TlBaCaCuO$  bulk materials and annealed in flowing  $O_2$  at 870 °C for 6 min, then slowly cooled at a rate of 10 °C/min. X-ray diffraction analysis indicated a high degree of orientation of the 2212 phase with its  $c$ -axis perpendicular to the substrate, with the full-width at half maximum (FWHM) of the rocking curve for  $Tl_2Ba_2CaCu_2O_x$  films consistently being  $\leq 0.7^\circ$  for the (0010) peak. Resistance,  $J_c$  and  $I(V)$  measurements were performed in a  $^4He$  gas-flow cryostat equipped with 13.5-T superconducting solenoid.

## Resistive transitions and Magnetoresistivity

### $H||a$

The resistive transitions,  $\rho(T,H)$ , for  $Tl_2Ba_2CaCu_2O_x$  films for field perpendicular to the  $c$ -axis display just minor differences between the data for  $H||I$  and  $H \perp I$  compared to the overall effect as shown in Fig. 1. The resistivity for  $H \perp I$  is higher for all field values, but the difference in resistivity between two orientations decreases with the field strength as  $H^{-0.5}$ , which is unlikely to be the case of a flux-motion induced dissipation. As an alternative to flux motion, the Josephson coupling model can give a natural explanation of the lack of *any* Lorentz-force dependence and is consistent with the broadened resistive transitions. In order to shed further light on this issue, the resistivities for  $H||a$  for the  $Tl_2Ba_2CaCu_2O_x$  films were fit to:

$$\rho(T,H) = \rho_0 \exp\left(-\frac{U(T,H)}{T}\right) = \rho_0 \exp\left(-\frac{U_0(H)(1-t)^q}{T}\right), \quad (1)$$

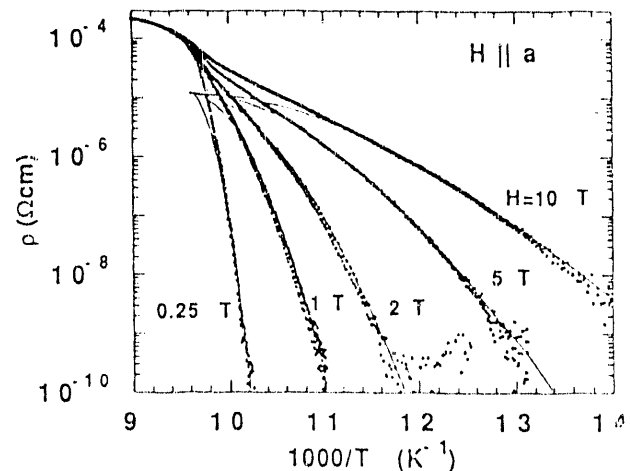


Fig. 1. Resistive transitions for  $H||I$  and  $H \perp I$  for field parallel to the  $CuO$  plane. Solid curve shows a one-parameter fit to Eq 1 for  $H||I$ . The parameters used are  $\rho_0 = 1.2 \times 10^{-5} \Omega cm$ ,  $T_{c0} = 104.2 K$  and  $q=2$ .

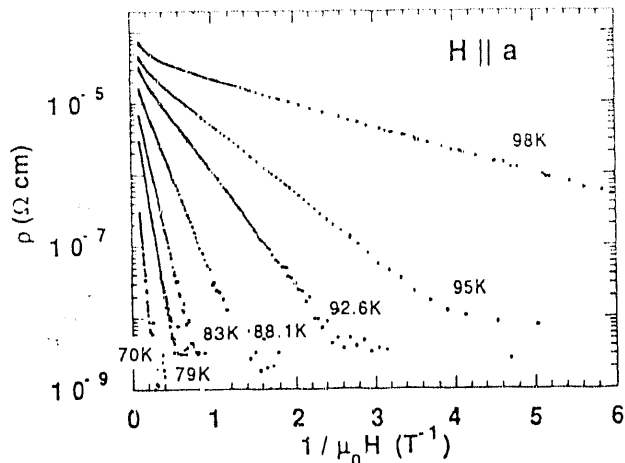


Fig. 2. Magnetoresistivities below  $T_{c0}$  for Hlla.

where the activation energy  $U(T,H)$  is assumed to have the form  $U_0(H)(1-t)^q$ , and  $t \equiv T/T_{c0}(H)$ . All fitting of the resistive transitions are done over three orders-of-magnitude in fixed ranges of  $\rho$  between  $10^{-9}$  to  $10^{-5}$   $\Omega\text{cm}$  as a compromise between the double transitions and noise.

We selected  $q=2$ ,  $T_{c0}(H)=104.2$  K,  $\rho_0 = 1.2 \times 10^{-5}$   $\Omega\text{cm}$  and found the excellent agreement with experiments shown in Fig. 1. The only free parameter is given by:

$$U_0(H) = 64500 \text{ [K]} / (\mu_0 H)^{1.09}. \quad (2)$$

A detailed description of the fitting procedure will be published elsewhere.<sup>5</sup>

Given a number of free parameters, there are many degrees of freedom to fit the resistive tails. Therefore, an independent measurement is needed to check whether the results of the fit are the correct description of the experiments, not due to an arbitrary selection of free parameters. Magnetoresistivities, which is another way of viewing the resistive tails, can be used for this purpose.

The magnetoresistivities,  $\rho(H)$ , below  $T_{c0}$  were measured up to 9T to further understand the functional form of  $U$ . The log of  $\rho(H)$  is plotted in Fig. 2 as a function of  $1/\mu_0 H$ , (the unit area of the flux line lattice is proportional to  $1/H$ ). They display a linear dependence of  $U$  on  $1/H$  over the whole ranges of  $T$  and  $H$  where the fits of Eq 1 were performed in resistive transitions. Such linear dependence of  $U$  on  $1/H$  is consistent with the result of the above fit, i.e., Eq 2. Moreover we found that the slopes of the log of  $\rho(H)$  vs  $1/H$  in Fig. 2 in turn were well described by the temperature dependence of  $(1-t)^2$ .

The resistive tails were also measured as a function of current in films of  $\text{Ti}_2\text{Ba}_2\text{CaCu}_2\text{O}_x$ . At higher current densities, the tails are stretched out to the lower temperatures, but the minor differences between HLI and HIII remain unchanged. These results at higher current densities clearly demonstrate that the lack of a macroscopic Lorentz force dependence does not depend on  $J$ .

### Hllc

In the case of Hllc, the resistive transitions shown in Fig. 3 are significantly broader, and the magnetoresistivities shown in Fig. 4 are quite different from the case of Hlla. A structure is clearly seen in the log of  $\rho(H)$  vs  $1/H$  plot. This suggests that the activation energy is no longer a simple form of  $1/H$  as for Hlla. All  $\rho(H)$  curves display downward curvatures below  $\rho(H) \sim 5 \times 10^{-6}$   $\Omega\text{cm}$ , and they show upward curvatures above that. This demarcation value is closely related to a sharper drop found in the resistive tails. Indeed in a fit of the resistive tails to Eq 1, a larger value of  $q$  was needed to fit the sharper drop of the  $\rho(T)$  below about  $10^{-7}$   $\Omega\text{cm}$ . This sharper drop could result from a change in the dissipation. To address this possibility, a fit of the tails was performed excluding the portions below  $10^{-7}$   $\Omega\text{cm}$ , and the results with  $U=2200(1-t)^{1.5}/H^{0.71}$  are shown as the solid curves in Fig. 3. The  $U \sim H^{-0.71}$  dependence agrees with the upward curvatures found in Fig. 4. The qualitative difference of the resistive tails and

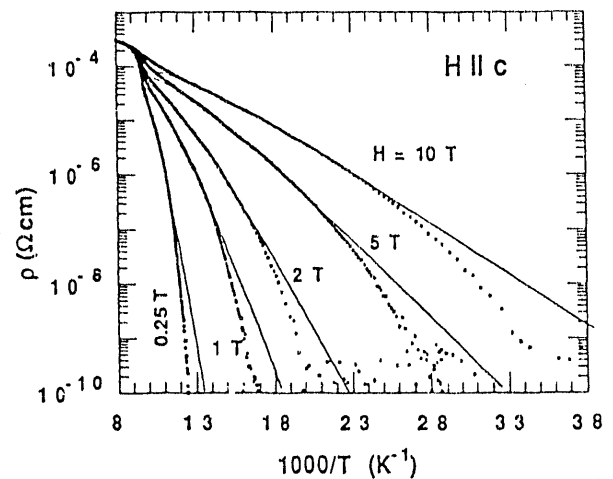


Fig. 3. Resistive transitions for Hllc. The parameters used are  $q=1.5$ ,  $T_{c0}(0) = 104.2$  K and  $\mu_0 dH_c2/dT = 2\text{T/K}$ .

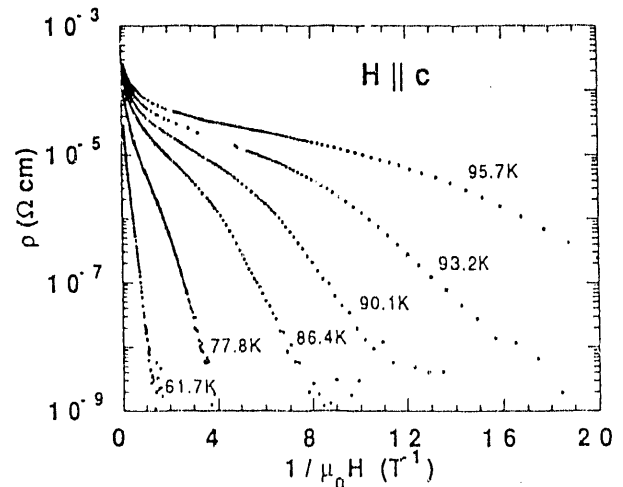


Fig. 4. Magnetoresistivities below  $T_{c0}$  for Hllc.

magnetoresistivities from those for HIIa probably indicates that the mechanism of dissipation could be different in this orientation. Since this paper is mostly concentrated on the Lorentz force dependence for HIIa, the data for HIII will not be discussed any further.

#### Current-voltage Characteristics and Critical Currents

For HIIa, the  $I(V)$  near the resistive tail region display only minor differences between HII and HIII for all H and T indicating no Lorentz-force dependence. At the lower temperatures, the  $I(V)$  show a characteristically different shape exhibiting negative curvature. This negative curvature allows a natural definition of  $I_c$  without requiring an ambiguous voltage criterion. However, a voltage criterion for determining the  $J_c(H,T)$  is more convenient, and the customary  $1 \mu\text{V}/\text{cm}$  was used to define  $J_c$ . For HIIa, these data are shown in Fig. 5, superimposed for both orientations of H with respect to current; there is no evidence for a macroscopic Lorentz-force dependence from 4.2 K to 93 K in fields up to 10 T.

Since the  $J_c(H,T)$  shown in Fig. 5 are determined from a voltage criterion, a value is always measured whether the  $I(V)$  exhibits negative curvature or just represents a continuous spreading of the resistive transition. Thus, we display the onset of negative curvature of  $I(V)$  in Fig. 5 with the solid line, and point out that it corresponds closely to the rapid decreases of  $J_c$  with field, found at the higher temperatures.

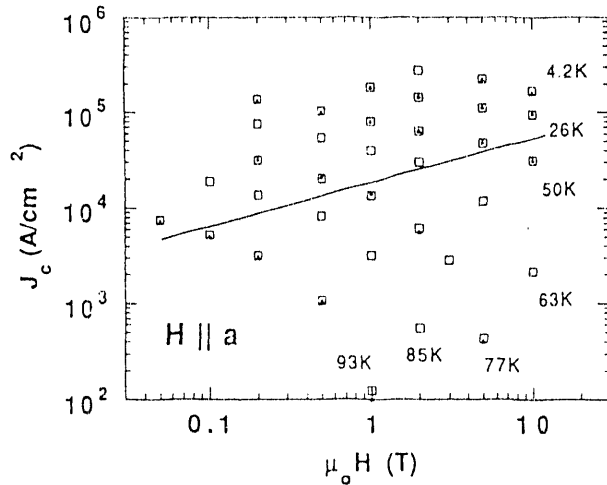


Fig. 5. The critical current densities,  $J_c$ , for HII (open squares) and HIII (solid triangles) versus magnetic field at the temperatures indicated for HIIa. These clearly indicate no macroscopic Lorentz-force dependence of  $J_c$ . The  $I(V)$  for data above the solid line show negative curvature.

Figure 6 shows the temperature dependence of  $J_c$  using only values for which the  $I(V)$  exhibit negative curvature, and the best fits are for  $q=2$ . The dependence of  $J_c(H,T)$  can be parameterized as:

$$J_c(H,T) = \frac{300000 \text{ A/cm}^2}{(\mu_0 H)^{0.24}} \left(1 - \frac{T}{T_{c0}}\right)^2, \quad (3)$$

for which we forced the exponent to be 2 and  $T_{c0} = 104.2 \text{ K}$ .

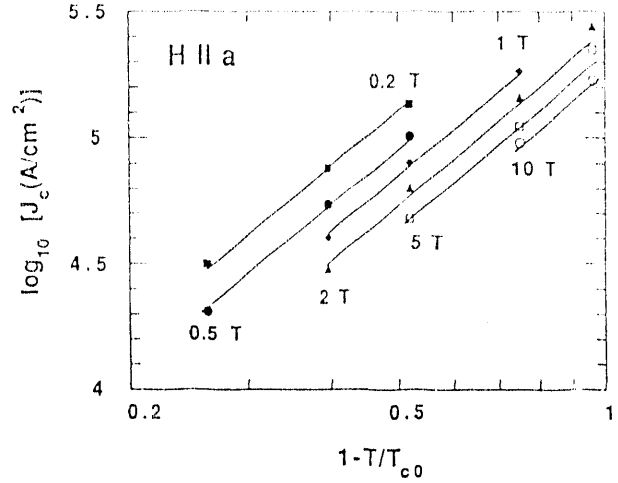


Fig. 6. The temperature dependence of  $J_c$  at the various indicated field values.

#### Comparison with Josephson Coupling and Flux Creep Model

All the transport measurements reported in this paper,  $\rho$ ,  $I(V)$  and  $J_c$ , as a function of temperature and HIIa, show little or no dependence on the macroscopic Lorentz force. Even if the small differences shown in Fig. 1 are real, the broadened resistive transitions, magnetoresistivities,  $I(V)$  and  $J_c$  for HIII are so similar to HII that the Lorentz force is at most a perturbation. Such absence of the Lorentz force in all the measurements favors another mechanism than flux flow for the dissipation in  $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_x$  films. We consider a Josephson-coupling model which is consistent with the broadened resistive transitions and the lack of Lorentz-force dependence on all properties reported in this paper. At this point, it is valuable to perform a detailed comparison of the experiments with the Josephson-coupling and flux creep models.

In classical Josephson junctions,  $U$  is proportional to the Josephson critical current,  $I_c$ , in zero field.<sup>6</sup> In finite field using Abrikosov solution for the vortex lattice,  $U$  near  $T_{c0}$  is given as  $U \sim (1-B/\mu_0 H_{c2}) (1-t)^q$ , where  $I_c \sim (1-t)^q$ . For  $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_x$ , the  $U(H,T) \sim (1-t)^2 / H^{1.09}$  was obtained from the fit of  $\rho(T,H)$  shown in Fig. 1, and  $J_c(H,T) \sim (1-t)^2 / H^{0.24}$  was obtained using only values for which the  $I(V)$  exhibit negative curvature (above the solid line in Fig. 6). This  $T$  dependence is consistent with SIS junctions in which the boundary conditions of Deutscher and Müller<sup>7</sup> are applied to the order parameter at the insulator boundary or the superconductor-normal-superconductor (SNS) proximity junctions in which  $U \sim (1-t)^2 \exp(-\alpha t)$  with a material dependent constant  $\alpha$ <sup>8</sup>.

The flux creep model of Tinkham<sup>9</sup> predicts  $U(T,H) \sim \mu_0 H_{c2}^2 V_a$ , where the superconducting condensation energy is multiplied by the volume triggering the flux jump,  $V_a \sim \xi \Phi_0 / B$ . Hence,  $(1-t)^{1.5} / B$ . However, for the very weak coupling between  $\text{CuO}_2$  planes in  $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_x$ , it is more appropriate to use a temperature-independent length of the order of the  $\text{CuO}_2$  planar spacing in place of  $\xi$  as the length along the  $c$ -axis of the region triggering the flux jump, and then  $U(T,H) \sim (1-t)^2 / B$  consistent with the experiment for HIIa. This model<sup>9,10</sup> also derives  $J_c \sim U / BV_d L$ , where  $V_d$  is the volume of the minimum region triggering an activated event and  $L$  is the typical distance moved. The

interpretation of results on YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films<sup>10</sup> led to an evaluation of  $V_0$  and  $L$  leading to  $J_c \sim (1-t)U$ , then  $J_c \sim (1-t)^3/B$ . This is clearly too strong a dependence for both temperature and field when compared to our measurements. This result is the main difference with the Josephson coupling models, for which  $J_c \sim U$ .

The above comparisons are not sufficient to rule out any mechanism considered for dissipation in Tl<sub>2</sub>Ba<sub>2</sub>CaCu<sub>2</sub>O<sub>x</sub> for Hllc. Our results indicate that the temperature dependences of  $J_c$  and  $U$  are the same, favoring the Josephson-coupling model. However, it would be useful to have more specific predictions about the parameters for the flux creep model. In addition, it is possible that the dissipation mechanisms for  $J_c$  and the resistive tails (through  $U$ ) are different: this is unappealing since they both exhibit the same Lorentz-force independence, but, e.g., they could be inter- and intra-granular Josephson junctions since  $J_c$  was not checked in the single crystal work<sup>3</sup>.

### Discussion

The Josephson coupling model has satisfactorily explained similar results in granular NbN films<sup>4</sup>. In this case, the junctions occurred laterally in the film plane, across insulating boundaries between the columnar grains. However, it should be emphasized that the measurements on HTS were made on single crystals or very large-grained thin films which do not have obvious structural defects to produce Josephson junctions as do the granular NbN films. Daeumling *et al.*<sup>11</sup> have recently proposed a model of *field-induced* granularity in single crystals of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> which convincingly explains their magnetization data. In this model, the field suppresses the superconductivity in regions that are already weakened by either point or extended microscopic defects, which are not seen in conventional analyses of these crystals. Oxygen vacancies were postulated<sup>11</sup> for single crystals of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>.

Another possible origin is Josephson coupling between superconducting layers<sup>12</sup>, in this case the intrinsic CuO<sub>2</sub> planes. These interlayer junctions play a role in transport properties if current flow is not confined to individual CuO<sub>2</sub> planes, but must cross to other planes by Josephson tunneling. The probability of microscopic defects, stacking faults in CuO<sub>2</sub> planes, or fluctuations blocking the current flow is drastically increased in the two-dimensional (2D) CuO<sub>2</sub> planes compared to 3D superconductors. For a very weak coupling in Tl<sub>2</sub>Ba<sub>2</sub>CaCu<sub>2</sub>O<sub>x</sub>, *thermal fluctuations* in the Josephson coupling between CuO<sub>2</sub> planes could be important in transport properties of the system, such as resistive losses.

Both the Josephson junction and flux creep models are rather vague, and a better prediction for the field dependence of the Josephson coupling model in the highly anisotropic HTS like Tl<sub>2</sub>Ba<sub>2</sub>CaCu<sub>2</sub>O<sub>x</sub> is still needed. Nonetheless, presuming that both  $J_c$  and  $U$  are limited by the same Josephson junctions, the different field dependences of  $J_c$  and  $U$ , which is strictly proportional to  $J_c$  in the Josephson coupling model, means that the relevant area of the junctions,  $A_j$ , must depend on field as  $H^{-0.85}$ . The *magnitude* of  $A_j(H)$  is harder to assess since we cannot assume  $I_c = J_c A_j$ , as for the columnar grains of NbN<sup>4</sup>, because the specific junction geometry is not known and it could be between CuO<sub>2</sub> planes.

Note that since the Tl<sub>2</sub>Ba<sub>2</sub>CaCu<sub>2</sub>O<sub>x</sub> films are polycrystalline, albeit with a high degree of *c*-axis orientation, Josephson coupling could be between the grains. However, similar results<sup>3</sup> obtained on single crystals of Tl<sub>2</sub>Ba<sub>2</sub>CaCu<sub>2</sub>O<sub>x</sub> suggest that the Lorentz-force-independent characteristics are not a result of thin-film grains.

### Summary

The universal lack of a Lorentz force dependence on dissipation in the highly anisotropic HTS like Tl<sub>2</sub>Ba<sub>2</sub>CaCu<sub>2</sub>O<sub>x</sub>, are measured for Hllc by the broadened resistive transitions, magnetoresistances, current-voltage characteristics and critical current densities. We found that the magnetoresistivities are very useful to view the resistive tails from a different angle. As an alternative to flux motion, we consider a Josephson-coupling model

which is consistent with the broadened resistive transitions and the lack of Lorentz-force dependence on all properties reported in this paper. The main difference between the Josephson-coupling and flux-flow models is the ratio  $J_c/U$ : it is temperature independent in the Josephson-coupling model, but proportional to  $1-t$  for the modified flux creep model<sup>9,10</sup>. Our results of the same temperature dependences of  $J_c$  and  $U$  better agree with the Josephson coupling model. The weak field dependence measured for  $J_c$  is better matched to the Josephson-coupling model. Although no definitive choice of model can be made, the Josephson-coupling model agrees at least as well as flux creep. For Hllc, the qualitative difference of the resistive tails and magnetoresistivities from those for Hlla probably indicates that the mechanism of dissipation could be different in this orientation.

### Acknowledgement

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