Flux-creep dissipation in epitaxial $YBa_2Cu_3O_{7-\delta}$ film: Magnetic-field and electrical-current dependence

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We have investigated the dissipation characteristics in the mixed state of $YBa_2Cu_3O_{7-\delta}$ film, grown epitaxially on the $SrTiO_3(100)$ substrate, in terms of external transport current as well as magnetic field applied parallel to the c axis of the film. The dissipation fits well the thermally activated flux creep model, $R = R_0 \exp(-U/k_BT)$, where U is a function of electrical current, magnetic field, and temperature. In the range of current density $\sim$20–4000 A/cm^2, the current dependence of the activation energy U scales with $\ln(I/I_0)$, as observed recently by Zeldov *et al.* U shows a power-law dependence on magnetic field as $H^{-\beta}$ with $\beta = 0.73 \pm 0.002$. We obtain the resistance prefactor R_0 proportional to the applied magnetic field, provided the Ginzburg-Landau-type magnetic-field suppression of the mean-field transition temperature T_{c0} is taken into account. In addition, we present the magnetoresistance at various temperatures below T_{c0}, in good accordance with the flux-creep model.

I. INTRODUCTION

We report the results of a comprehensive experimental study on the dissipation due to flux motions in the mixed state of an epitaxial $YBa_2Cu_3O_{7-\delta}$ superconducting film in a magnetic field applied parallel to the c axis of the film. We found that the dissipation, in the electrical current range used in this study, can be well described by the thermal activation of the form $R = R_0 \exp(-U/k_BT)$. The effective activation energy barrier U turned out to have a functional dependence on temperature T, magnetic field H, and transport current I as $U = AH^{-\beta}\ln(I/I_0)g(T)$, where A is a constant depending weakly on applied magnetic field, β is a constant with value close to 1, and I_0 and $g(T)$ are the threshold current and the temperature function, respectively, to be described below. In this study we concentrated our effort on differentiating the dependence of U on variables H, I, and T from the measurements of resistive transition as a function of both magnetic field and current, and magnetoresistance as a function of temperature.

The dissipation due to thermally activated flux creep can be expressed as[1]

$$R = 2R_0 \exp\left[-\frac{U_0}{k_BT}\right] \sinh\left[\frac{JBV_dL}{k_BT}\right], \qquad (1)$$

where R_0 is the resistance prefactor with B/J dependence on magnetic field and current density, U_0 is the energy barrier arising from spatial variations of the condensation energy over which a flux bundle of volume V_d should be activated to hop an average distance L, J is the external transport current density, and B is the magnetic flux density in the sample. We rewrite Eq. (1), following Hettinger *et al.*,[2] as

$$R = 2R_0 \exp\left[-\frac{U_0}{k_BT}\right] \sinh\left[\frac{U_0}{k_BT}\frac{I}{I_0}\right], \qquad (2)$$

where $I_0 = J_0wd$ is the threshold current, for a film of width w and thickness d, that drives the flux motion from the flux-creep behavior into the flux-flow behavior by tilting the pinning potential, thereby reducing the activation energy to zero. Here the threshold current density is given by $J_0 = U_0/BV_dL$. In Eqs. (1) and (2) the exponential term represents the random thermal equilibrium activation of the flux bundles from the random pinning potentials in the absence of the external transport current and the sinh term represents the unidirectional depinning effect caused by the Lorentz force exerted by transport current on the flux bundles.

In the low-current limit, from Eq. (1) or (2) we obtain the current-independent dissipation R of Arrhenius form. If the argument of the sinh function is order unity or larger in the high-current limit, however, the sinh term in Eq. (2) can be replaced by the corresponding exponential expression. In this limit, Eq. (2) is given in terms of the effective activation energy U by

$$R = R_0 \exp[-U(T,H,I)/k_B T] \ . \tag{3}$$

Since the lower critical field H_{c1} of the film is much smaller than the magnetic field used in the study, in the remainder of this paper we will not differentiate B, the flux density in the sample, from H, the applied magnetic field, as in Eq. (3).

Using the expression of Eq. (2) we expect that the effective activation energy U in the high-current limit should have the form, $U(H,I,T) = U_0(H,T)(1 - I/I_0)$, where U_0 is the nominal activation energy with magnetic field and temperature dependence only. This current dependence of U has been observed in $YBa_2Cu_3O_{7-\delta}$ epitaxial films.[2] Zeldov *et al.*, however, reported the logarithmic current dependence of U at high-current densities used in their sample[3] as

$$U(T,H,I) = U_0(T,H) \ln(I/I_0) \ , \tag{4}$$

instead of being linear in current. They speculated that, if the forced unidirectional hopping rate of the flux bundles becomes much larger than the random thermal equilibrium motion in high-current regime, the strongly correlated collective motion of the flux bundles may lead to the deviation from the linear-in-current behavior into the logarithmic behavior, by possible deformation of the pinning energies, the volumes of the bundles, or the distance of hopping.

As to $U_0(T,H)$, Yeshurun and Malozemoff by a scaling argument suggested the functional dependence of the form,[4]

$$U_0(T,H) \sim H_c^2 \xi \phi_0 / H = A g(T)/H \ , \tag{5}$$

where H_c is the thermodynamic critical field, ξ the Ginzberg-Landau coherence length, ϕ_0 the flux quantum $hc/2e$. In the latter expression in Eq. (5), $g(T)$ is the temperature function resulting from the temperature dependences of H_c and ξ, although there has been a report of temperature-independent activation energy in $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ single crystals.[5] Since $H_c(t) \sim 1 - t^2$ and $\xi(t) \sim [(1+t^2)/(1-t^2)]^{1/2}$, we get $g(T)$ as[1–3,6]

$$g(T) = (1-t^2)(1-t^4)^{1/2} \ , \tag{6}$$

where $t = T/T_{c0}$, the reduced temperature.

If we generalize the field dependence of U_0 in Eq. (5) as[3]

$$U_0(T,H) \sim A g(t) H^{-\beta} \tag{7}$$

with the value of β close to 1, we can recast the dissipation due to thermally activated flux creep with field, current, and temperature as follows:

$$R = R_0 \left[\frac{I}{I_0} \right]^{-AH^{-\beta} g(T)/k_B T} \tag{8}$$

an empirical formula for the thermally activated dissipation.[3] We will interpret all our data in terms of Eq. (8) in the remainder of this paper.

II. SAMPLE PREPARATION AND EXPERIMENT

The high-quality epitaxial $YBa_2Cu_3O_{7-\delta}$ thin film of thickness 5000 Å was grown by laser ablation using a 248-nm KrF excimer laser onto $SrTiO_3$ (100) substrate held at 600 °C. Extensive characterization of the film using x-ray diffraction showed highly well-aligned c-axis growth of the film perpendicular to the plane of the substrate and lack of development of any discernible grain boundary. Also the scanning tunneling micrographs of the film revealed extremely smooth surface morphology.

A standard dc four-probe technique with remote-controlled data acquisition scheme for signal averaging was used to measure the resistive transition of the film. The film was patterned into 1.0-mm-wide strip using a mechanical mask. 4000-Å-thick silver contact pads were evaporated upon the film, providing low resistance (less than 0.1Ω) contacts. The distance between voltage contacts was 2.7 mm. Electrical wires were attached to the pads using indium press. The magnetic field was applied parallel to the c axis of the film (perpendicular to the plane of the substrate) using a superconducting magnet and the current parallel to the ab plane. The temperature was measured with a calibrated carbon glass sensor, with the sensitivity better than 10 mK in the temperature range of measurements.

III. EXPERIMENTAL RESULTS AND ANALYSIS

The zero-field current-voltage (IV) characteristics of the sample are given in Fig. 1, which show the power-law

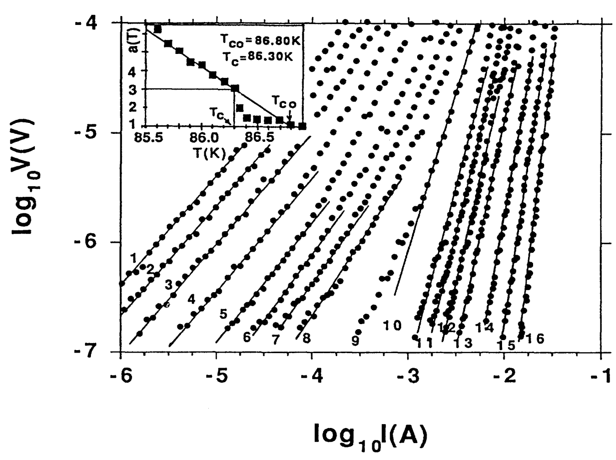

FIG. 1. Current-voltage characteristics of the $YBa_2Cu_3O_{7-\delta}$ film in zero magnetic field. The temperature for each isotherm is as follows: 1; 87.10 K, 2; 87.00 K, 3; 86.90 K, 4; 86.80 K, 5; 86.70 K, 6; 86.60 K, 7; 86.50 K, 8; 86.40 K, 9; 86.35 K, 10; 86.30 K, 11; 86.20 K, 12; 86.10 K, 13; 86.00 K, 14; 85.80 K, 15; 85.60 K, 16; 85.40 K. The solid lines are guides to the eye. The inset shows the exponent $a(T)$ of the current-voltage characteristics as a function of temperature, giving $T_c = 86.30$ and $T_{c0} = 86.80$ K.

dependence of the voltage with current at temperatures below 86.35 K, at temperatures above which the *IV* characteristics are linear at low-current levels with exponentially increasing resistance with temperature. The power-law behavior of the *IV* characteristics at low temperatures satisfies the relation $V \sim I^{a(T)}$. We plot, in the inset, the temperature variation of the exponent $a(T)$, which displays a discontinuity in value from 1 to 3 as 86.3 K is approached from below. This is the typical Kosterlitz-Thouless (KT) transition behavior[7] arising from the intrinsic two-dimensional nature of the conductivity in the Cu-O planes of $YBa_2Cu_3O_{7-\delta}$ films. The existence of the well-defined typical KT behavior in the sample is an indirect confirmation of the high homogeneity of the sample. We determine the KT transition temperature $T_c = 86.30$ K from the value of temperature which gives $a(T_c) = 3$. We also obtain the mean-field superconducting transition temperature $T_{c0} = 86.80$ K, to be used for fittings below, by extrapolating the linear region outside the critical temperature range below T_c, down to $a(T_{c0}) = 1$.[8]

In Fig. 2 we show the resistive transition taken with current $I = 10$ mA ($J = 2000$ Å/cm^2) in zero field and in various magnetic fields applied up to 6 T parallel to the *c* axis of the film. The figure exhibits a continuous broadening of the transition with increasing field. Tinkham,[6] in analogy with the dissipation mechanism due to phase slip in a heavily damped current-driven single Josephson junction,[9] predicted that the broadening, $T_{c0} - T$, in any resistance level should vary as

$$T_{c0} - T \sim H^{2/3} . \tag{9}$$

The power-law dependence of the broadening on a magnetic field for the various resistance level in this sample is evident from the inset of Fig. 2. The exponent determined from the inset is 0.86, quite close to the expectation 2/3, considering the simplicity of the model given by Tinkham in relation with Eq. (9) as well as the possible error introduced by the high-current level used for our measurements. In addition, since the thermally activated flux creep is dominant only in the resistive tail, as evident from Fig. 3 for resistance range near 0.3 Ω, extracting the value of the exponent mostly from the data in the high resistivity range near the transition may have been the source of the deviation. Oh also obtained the similar value, 0.85 ± 0.005, with the polycrystalline epitaxial $YBa_2Cu_3O_{7-\delta}$ films.[10] We speculate that we may get a prediction for the value of the exponent closer to the ones observed experimentally if we take into account the hierarchical distribution of the activation energy existing in the $YBa_2Cu_3O_{7-\delta}$ superconducting systems.[11]

In Fig. 3 we replot the resistive transition in various magnetic fields as a function of $g(T)/T$, showing a clear thermal-activation behavior of resistance in accordance with Eq. (8). The activation energy obtained from the linear least-squares fit to the slope of the resistance tail in Fig. 3 is shown in the inset, where we extract the value of the exponent β defined in Eq. (7). β determined in this way turns out to be -0.73 ± 0.02, deviating a little from the value -1 that can be expected from the expression given in Eq. (5). In Fig. 4 we plot, as a function of field, the resistance prefactor R_0 obtained from the intercept at $g(T)/T = 0$ of the extrapolation of the linear resistance tail in Fig. 3. It shows that R_0 varies linearly with field, the result in consistence with the field dependence of R_0 in Eq. (1), but in clear contradiction to the field-independent behavior of the prefactor observed by Palstra *et al.*[5] in $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ single crystals in the low-current limit.

Since the exponent β and especially R_0 are very sensitive to the choice of T_{c0}, in the fitting above, we assumed, as a measure of care, that the mean-field transition temperature T_{c0} is suppressed by the application of the field satisfying the Ginzburg-Landau relation[1]

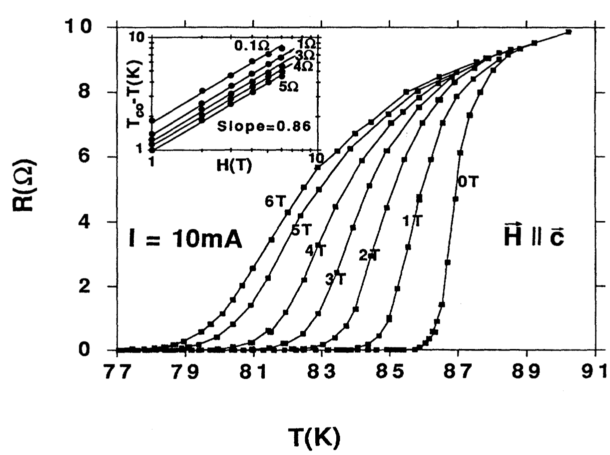

FIG. 2. Temperature dependence of the resistance in various magnetic fields up to 6 T, applied parallel to the *c* axis of the film. Inset: the broadening of the transition $T_{c0} - T$ in different resistance levels, all showing power-law behavior with the same value of exponent, 0.86.

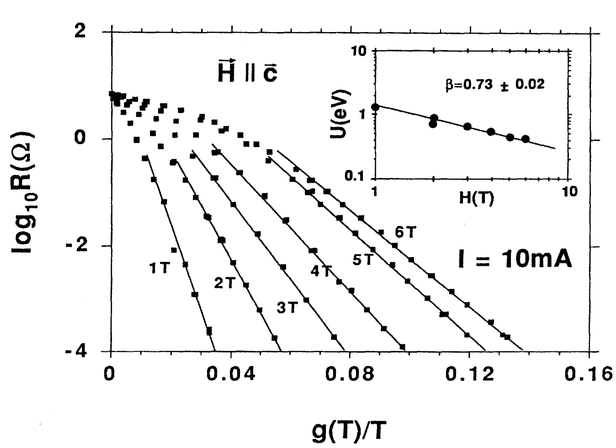

FIG. 3. A replot of the resistance in Fig. 2 as a function of $g(T)/T$, with $g(T)$ a temperature function defined in the text. The activation energy obtained from the slope of the linear tail is plotted in the inset as a function of magnetic field.

$$T_{c0}(H)=T_{c0}(H=0)\left[\frac{1-H/H_{c2}(T=0)}{1+H/H_{c2}(T=0)}\right]^{1/2} . \quad (10)$$

We used $H_{c2}(T=0)=200$ T (Ref. 12) and adopted $T_{c0}(H=0)=86.80$ K, the value determined from the *IV* characteristics given in Fig. 1. We found that the resistive transition still showed a thermal-activation behavior with $\beta=0.80$ even with the field-independent T_{c0}, 86.80 K. In this case, however, R_0 is extremely sensitive to the field so that $R_0(H=6\ \text{T}) \sim 350\ R_0(H=1\ \text{T})$, which appears quite unreasonable in light of the expression in Eq. (1) or (2).

Figures 5(a) and 5(b) show the current dependence of the resistive transition in fields of 1 and 2 T, respectively, plotted again as a function of $g(T)/T$. In the inset we plot the effective activation energy obtained from the figures as a function of current, which confirms well the logarithmic current dependence of the activation energy in Eq. (4), but is in contradiction to the results by Hettinger *et al.*[2] The ratio of the slopes of the lines 1.56 itself is quite close to the expectation $2^{\beta}=1.66$ with $\beta=0.73$, the value determined from the field dependence of the activation energy. We observed, in this sample, that the resistive transition became current independent at currents below 0.1 mA ($J=20$ A/cm^2) in a field of 1 T.

Now Fig. 6 shows the magnetoresistances at various temperatures below T_{c0}. In order to investigate the behavior in terms of the flux-creep picture, we replot it as a function of $H^{-\beta}g(T)/T$ in Fig. 7. Note that $g(T)$ is weakly dependent on magnetic field through the relation in Eq. (10). The fact that all the data fall into straight lines with the same slope confirms the validity of Eq. (8) with the correct temperature and field dependence of the activation energy given in Eq. (7). In addition, it also implies that A is temperature independent. Figure 7, corresponding to Fig. 3 of Ref. 5, shows that the resistance prefactor R_0 is varying with temperature, which contradicts to the results in the reference. We also note that this magnetic field dependence is quite distinctive from

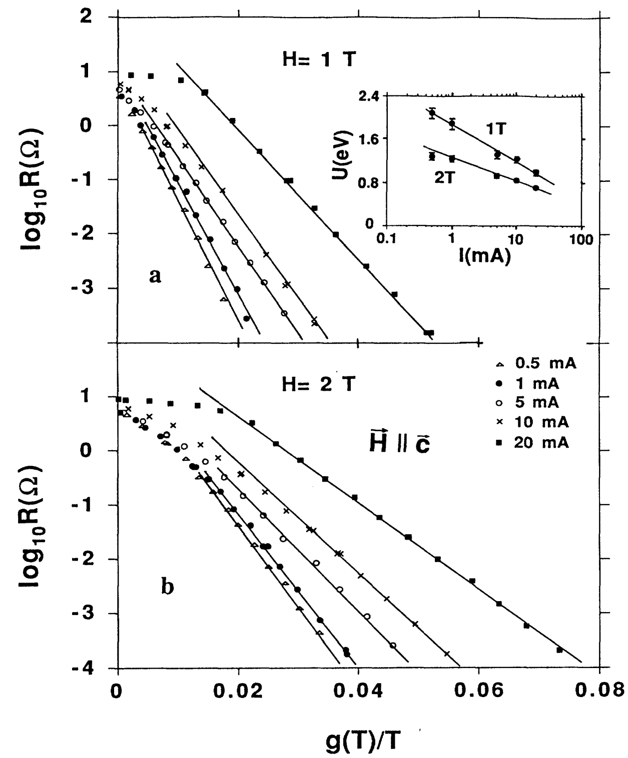

FIG. 5. Current dependence of the thermal activation in magnetic field of 1 T (a) and 2 T (b). Inset: the activation energy in the two fields as a function of current.

the thermally activated flux-flow behavior observed in the thin ($d<300$ Å) In/InO_x superconducting films.[13]

IV. DISCUSSION

The threshold current I_0 for our sample film estimated from the inset of Fig. 5, the intercept of the lines at the current axis, is about 700 mA, corresponding to 1.6×10^5

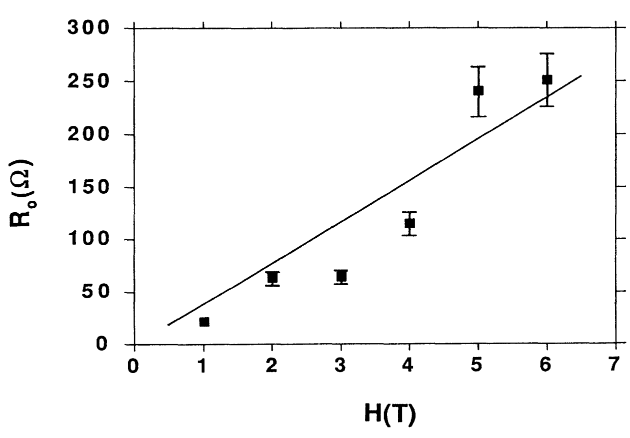

FIG. 4. The prefactor R_0 determined from the intercepts at $g(T)/T=0$ in Fig. 3, showing that R_0 scales linearly with applied magnetic field H. The solid line is to guide the eye.

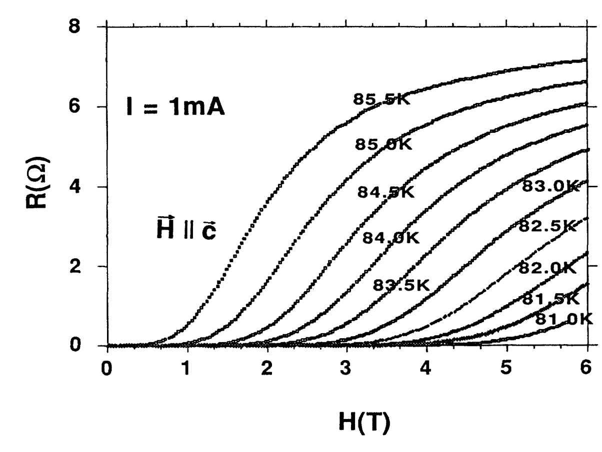

FIG. 6. The magnetoresistance at various temperatures below T_{c0}.

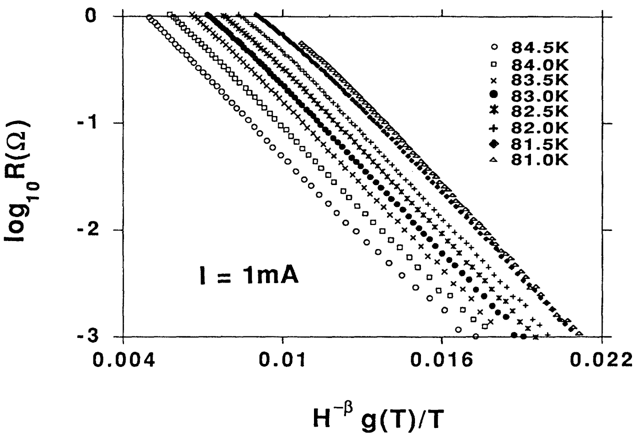

FIG. 7. A replot of Fig. 6 as a function of $H^{-\beta}g(T)/T$, with $\beta=0.73$. The linearity of the data in this plot with the same slope confirms the validity of Eq. (8).

A/cm^2. This value is a little smaller than the values 4×10^5 and 3×10^6 A/cm^2 obtained by Hettinger *et al.*[2] and by Zeldov *et al.*,[3] respectively, using epitaxial $YBa_2Cu_3O_{7-\delta}$ thin films. In the lower level of the current range used in the study, $100\sim4000$ A/cm^2, the argument of the sinh function in Eq. (1) or (2) is smaller than 1, yet the data look to support the replacement of the sinh function by the exponential function.

Although the current density we used is quite smaller than the threshold current density J_0, the dissipation is well described by the logarithmic current dependence of Eq. (4),[3] but in apparent disagreement with the linear-in-current dependence reported with much larger current density than ours, $\sim(0.5-2.5)\times10^5$ A/cm^2. This fact itself raises a question about the mechanism of generating the logarithmic current dependence of the activation energy, since it has been argued that the strong collective motion of the flux bundles in the high-current regime would be a possible cause of the logarithmic dependence.[3] Recently, however, Zeldov *et al.* have proposed that the thermally activated flux creep in a logarithmically shaped flux line potential can lead to the logarithmic current dependence of the activation energy.[14,15] On the other hand, Griessen[16] has claimed that the apparent logarithmic current dependence of the activation energy is a mere consequence of the log-normal[17] distribution of the activation energies.

At various temperatures close to the zero-field transition temperature, we have also obtained IV characteristics for this sample in magnetic fields in the range of $\sim1-6$ T, which shows power-law behavior without any evidence for a transition to the behavior of the negative curvature in the log-log IV plot as the temperature is lowered. This result is in apparent contradiction to the exponential IV characteristics as observed and claimed by Koch *et al.*[18] as an evidence for the vortex-glass behavior,[19] i.e., $V\sim\exp[-(I_c/I)^{\mu}]$ with the exponent $0<\mu<1$. Since both behaviors of flux motion have been observed in the similar range of magnetic field without much differences in the resulting average distance $l\sim(\phi_0/\pi H)^{1/2}$ between the flux lines, we assume that sample-dependent differences in the flux correlation length ξ may give rise to the contradictory characteristics in the flux behavior.

In conclusion, the magnetic field and the current dependence of the resistance of an epitaxial $YBa_2Cu_3O_{7-\delta}$ sample well support the thermally activated creep picture of flux motion. In addition, the resistive transition as a function of field and current reveals the functional dependence of the activation energy of the form $H^{-\beta}\ln(I/I_0)g(T)$ which is in turn consistent with the observed magnetoresistance as a function of temperature. We found that the suppression of the mean-field transition temperature T_{c0} in a magnetic field should be taken into account to obtain a better fit in explaining the field dependence of the resistance prefactor R_0. Although the interpretation of the present study in terms of the logarithmic current dependence of the activation energy U is all self-consistent, the mechanism of the electrical current dependence of U, linear or logarithmic, is yet to be clarified.

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