Phenomenological model for the c-axis resistive dissipation in $La_{2-x}Sr_xCuO_4$ as a function of temperature, magnetic field, and its orientation

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The measurement of c-axis resistance in $La_{2-x}Sr_xCuO_4$ at different temperatures for fields at any orientation shows that the observed dissipation is not dominated by any Lorentz-force-dependent mechanism. To explain the experimental findings, a phenomenological model is developed for c-axis resistance as a function of temperature T, field B, and angle θ between B and ab plane. Excellent agreement between calculated and experimental curves in a wide transition region (5 decades) gives a strong support to the present approach. © *1995 American Institute of Physics.*

I. INTRODUCTION

Energy dissipation in high-T_c superconductors (HTSCs) continues as a subject of both considerable interest and controversy. Previous attempts by the Lorentz-force-driven vortex motion gave no explanation of the dissipation observed for $B\|I\|c$ in HTSCs. To explain the dissipation for $B\|I\|c$, the models including one-dimensional phase slippage,[1] interlayer Josephson coupling,[2] critical fluctuations,[3] etc, have been advanced. As shown in the recent work,[4,5] however, they could not quantitatively explain the dissipation for $B\|I\|c$ if a wider transition region is accounted for. Quite recently a virtual extension of the phase slippage model developed by Ambegaokar and Halperin (AH)[6] has been made[7–9] by accounting for the intrinsic layered structures in HTSCs and introducing the effective energy. The analytical expression developed on this basis has been proven[8,9] to be able to quantitatively account for the observed dissipation for $B\|I\|c$ in various HTSCs in almost the whole transition region.

In the present work, the c-axis resistance $R(T,B,\theta)$ of $La_{2-x}Sr_xCuO_4$ is experimentally studied as a function of temperature T, magnetic-field strength B, and field angle θ with respect to the ab plane. It is shown that the observed dissipation is not dominated by any Lorentz-force-dependent mechanism. To explain the experimental findings, a phenomenological model of c-axis resistance for fields at any orientation is developed, which quantitatively accounts for the observed dissipation as a function of T, B, and θ in the selected transition region (5 decades).

II. EXPERIMENTS AND RESULTS

A crystal of $La_{2-x}Sr_xCuO_4$ ($x=0.14$) is used in the present study, which is the same as that used in the previous work.[5] The c-axis resistance was measured by directly flowing the currents along the c axis in terms of the standard four-probe method. Details for the measurement of c-axis resistance as a function of T, B, and θ are described elsewhere.[10] Figure 1 displays the c-axis resistance of the sample at $T=31.28$ K as a function of B and θ. It can be found that the minimum resistance corresponds to the case of fields parallel to the basal plane (i.e., $\theta=0$). Because the transport current is oriented normal to the plane in the present study, the experimental behaviors are contrary to that expected within the framework of a Lorentz force driven vortex motion scenario. In the latter case, the macroscopic driving force of a uniform current with density J on a flux-line lattice with vortex density B is given by $\mathbf{F}_d=\mathbf{J}\times\mathbf{B}$, therefore, one would expect F_d to vary like $\cos\theta$, and $R\propto\cos\theta$, implying the minimum resistance occurring at $\theta=90°$. This contrariety argues against the importance of any force-driven vortex motion as the origin of the observed phenomena.

III. PHENOMENOLOGICAL MODEL

To explain the experimental findings we try to make an attempt to develop a phenomenological model for c-axis resistance as a function of T, B, and θ. The basic features are summarized as follows:

(a) The observed dissipation is dominated by the phase slippages across Josephson junctions, similar to that in the AH model.[6] However, in the present case the Josephson junctions originate from the intrinsic layered structures, which contain the superconducting Cu-O layers separated by some nonsuperconducting materials. Therefore, even in a perfect single crystal the amplitude of the order parameter should vary strongly between the layers, leading to the idea, that the c-axis conduction could be viewed as a series of weakly coupled Josephson junctions along the c axis.

(b) The irreversibility line is assumed to be the demarcation between a vortex glass and a vortex liquid phase. Below the line the vortices are in the glass state. No dissipation is observed since the vortices are strongly pinned in the glass state, but above the line energy dissipation is expected to occur due to the thermal motion of vortices. Consequently, it

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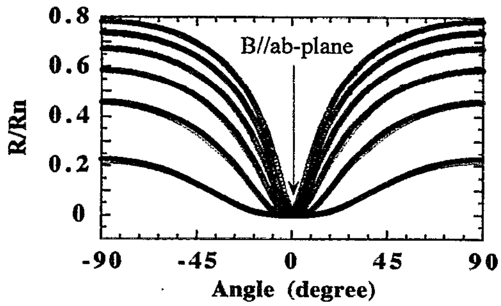

FIG. 1. The angular dependence of c-axis normalized resistance in $La_{1.86}Sr_{0.14}CuO_4$ at $T=31.28$ K for fields of $B=6$, 5, 4, 3, 2, and 1 (from top to bottom): (O) the experimental data and (dotted lines) the calculated results on the basis of Eq. (6) by using $C_0=130$.

is suggested that the thermal energy k_BT in the AH model[6] should be replaced by the effective thermal energy, $k_BT(1-T_{irr}/T)=k_B(T-T_{irr})$. The term of $(1-T_{irr}/T)$ reflects the effective contribution to the thermal energy. To address this, the field dependence of magnetization for $B\|c$ at different temperatures was measured for the present sample. As an example, the M-B curve at $T=14.26$ K is shown in Fig. 2(a). Similar to the discussion in Ref. 11, the irreversible magnetization $M_{irr}(B)$ could be obtained from the measured magnetization, i.e.,

$$M_{irr}(T,B)=[M(T,B^-)-M(T,B^+)]/2,$$

where $M(T,B^-)$ and $M(T,B^+)$ are the measured magnetizations corresponding to the decreasing and increasing applied fields, respectively. The irreversibility temperature $T_{irr}(B)$ is then determined from $M_{irr}(T,B)=0$. Clearly, the thus-determined $T_{irr}(B)$ value depends on the experimental criterion of $M_{irr}(T,B)=0$. For the present sample the maximum irreversible magnetization at 4.2 K is experimentally shown to be

$$M_{irr,max}(4.2\ \text{K},0\ \text{T})=7\times10^5\ \text{A/m}.$$

We then use

$$M_{irr}(T,B)/M_{irr,max}(4.2\ \text{K},0\ \text{T})=10^{-6}$$

as a criterion of $M_{irr}(T,B)=0$. The thus-determined T_{irr} values for different fields parallel to the c axis are shown in Fig. 2(b) (open circles). In this figure we also plot the B-T curves extracted from the R/R_n-T curves for $B\|c$, where different resistive criterions are used. The latter was reported elsewhere.[5] It can be found that with decreasing the resistivity level the B-T curve determined by the resistive transition tends to the irreversibility line determined by the magnetization. Especially if $R=10^{-6}R_n$ is used as a criterion of $R=0$ the determined $T_{c,R=0}-B$ curves are close to the $T_{irr}(B)$ curves. This is evidence that a true superconducting state of $R=0$ is realized at $T\leqslant T_{irr}$, not at $T=0$ K as that in the AH model.[6]

(c) Similar to the argument given in Ref. 7, the maximum Josephson coupling current density in magnetic fields is given approximately by

$$J_c(T,\mathbf{B})\simeq J_{c0}(T)(\gamma_0/\gamma)^2, \tag{1}$$

where $J_{c0}(T)$ is the maximum Josephson coupling current density in zero field, γ_0 and γ are the anisotropic parameters in zero field and in fields, respectively. Here, the effect of a magnetic field on $J_c(T,\mathbf{B})$ is accounted for by introducing γ. Assuming the effective junction area to be A_0 and $J_{c0}(T)$ to follow $J_{c0}(T)=J_{c0}(0)(1-T/T_c)$, the Josephson coupling energy $E_j(T,\mathbf{B})[\equiv hA_0J_c(T,\mathbf{B})/2\pi e]$ is then expressed by

$$E_j(T,\mathbf{B})=[hJ_{c0}(0)A_0/2\pi e](1-T/T_c)(\gamma_0/\gamma)^2. \tag{2}$$

Replacing E_j/k_BT in the AH model[6] with $E_j(T,\mathbf{B})/k_B(T-T_{irr})$, the c-axis resistance in the limit of zero measuring current is given approximately by

$$R=R_nI_0^{-2}\{C_0(1-T/T_c)(\gamma_0/\gamma)^2/[T-T_{irr}(\mathbf{B})]\}, \tag{3}$$

where R_n is the c-axis normal resistance, $C_0=hJ_{c0}(0)A_0/4\pi ek_B$ is a T- and $\mathbf{B}$-independent constant, and I_0 is the modified Bessel function.

(d) Within the framework of the usual effective mass model, various scaling rules for magnetic fields, thermodynamic quantities, and transport properties have been developed by Hao and Clem[12] as well as by Blatter, Geshkenbein, and Larkin[13], independently. Applying to the case of resistance as a function of B and θ, the scaling theory gives

$$R(T,B,\theta)=R(T,h), \tag{4}$$

where $h=B(\sin^2\theta+\cos^2\theta/\gamma^2)^{1/2}$ is the so-called reduced field. Equation (4) implies that at each given temperature resistance as a function B and θ should map onto a simple curve by the reduced field h. As shown in the recent work,[10] however, γ for a system similar to that used in the present

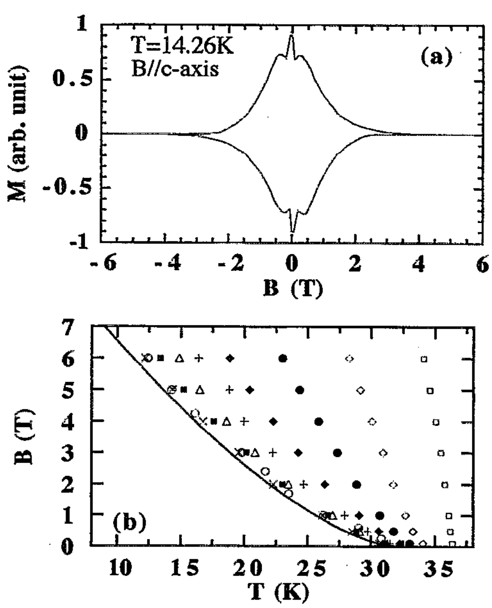

FIG. 2. For single-crystalline $La_{1.86}Sr_{0.14}CuO_4$: (a) M-B curve at $T=14.26$ K for $B\|c$; and (b) B-T curves for $B\|c$ extracted from magnetization (O) with $M_{irr}(T,B)=10^{-6}M_{irr,max}(4.2$ K, 0 T) as a criterion of $M_{irr}=0$, and resistive transitions with different resistivity levels of $R/R_n=0.9$ (□), 0.5 (◇), 10^{-1} (●), 10^{-2} (◆), 10^{-3}(+), 10^{-4}(△), 10^{-5} (■) and 10^{-6}(×), respectively. The solid curve in (b) follows $T_{irr}=31.9[1-(B/11.5)^{2/3}]$ (K) (B in T).

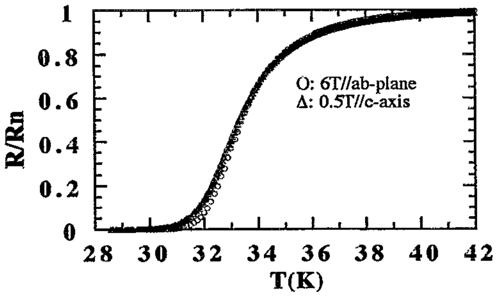

FIG. 3. The c-axis resistive transitions of single-crystalline $La_{1.86}Sr_{0.14}CuO_4$ for fields of $6T \| ab$(O) and $0.5\ T \| c$(Δ).

study strongly depends on T and becomes substantially large as T is reduced toward T_{irr}. Furthermore, it has been given approximately by[10]

$$\gamma = \gamma_0[(T_c - T_{irr})/(T - T_{irr})]^{1/3}. \tag{5}$$

Note that Eq. (5) is not expected by the usual effective mass theory for anisotropic type-II superconductors. According to this theory, γ should be a T-independent quantity. This suggests that the usual theory may be inappropriate for HTSCs. As is known, the effective-mass model is based on the conventional Abrikosov vortex dynamic picture with a modification for the anisotropic materials.[14] In the case of HTSCs there is a problem concerning the validity of the usual vortex dynamic picture. In the extreme case, the two-dimensional (2D) vortex picture has been introduced[15] for highly anisotropic HTSCs. This picture is based on the idea that physical properties at any field orientation are only determined by $B \sin \theta$, the c-axis component of the field. As shown in recent work,[10] however, it is inappropriate for a real high-T_c material in the temperature range of $T > T_{irr}$, since the observed resistance as a function of B and θ could not be scaled by $B \sin \theta$. A plausible picture of vortex dynamics in HTSCs is based on the vortex glass-liquid transition theory.[16] It is assumed that the irreversibility line is the demarcation between a glass and a liquid phase. Above it the vortices are in the liquid state. Because of the thermal motion of the vortices, the usual Abrikosov vortex dynamics is no longer held. Differing from the 2D pancake picture,[15] in the present case the vortices are still considered as the set of flux lines, so that a successful approach to the problem could be achieved with the help of the conventional effective-mass model. However, the conventional concept of a regular vortex lattice breaks down to the thermal motion of the vortices. Taking this effect into account, γ is expected to be a T-dependent quantity. As T is decreased toward T_{irr}, the glass-liquid transition[16] occurs at $T = T_{irr}$. For $T < T_{irr}$, the set of vortices could be viewed as a true glass, in which the flux lines are strongly pinned, suggesting that γ diverges at $T = T_{irr}$. The details are discussed elsewhere.[10]

Inserting Eq. (5) into Eq. (3), the T-dependence c-axis resistance of the present sample for fields at any orientation is finally written as

$$R = R_n I_0^{-2}\{C_0(1 - T/T_c)[(T - T_{irr})/(T_c - T_{irr})]^{2/3}/(T - T_{irr})\}. \tag{6}$$

IV. COMPARISON WITH EXPERIMENTAL RESULTS

To show the advantages of the above model, in this section we compare the calculated curves by means of Eq. (6) with the experimental results obtained in $La_{1.86}Sr_{0.14}CuO_4$. Note that Eq. (6) is a fitting equation having only one adjustable parameter, i.e., C_0, since the remaining parameters can be extracted in experiments, as follows.

(i) Both T_c and R_n could be directly determined to be $T_c = 35.7$ K and

$$R_n = 2.732 + 0.446 \exp(53.3/T)(\Omega),$$

respectively. The latter is extracted from the T-dependent c-axis normal state resistance at $T > 40$ K.

(ii) In order to estimate γ_0 of the sample, two selected c-axis transition curves are displayed in Fig. 3 for fields of $6T \| ab$ and $0.5T \| c$. It can be found that near T_c the R-T curve measured for $6T \| ab$ is almost the same as that for $0.5T \| c$. From this fact γ_0 of the sample is estimated to be about 12.

(iii) Based on the experimental data shown in Fig. 2(b), the $T_{irr}(B \| c)$ is given approximately by

$$T_{irr}(B \| c) = 31.9[1 - (B/11.5)^{2/3}](\mathrm{K}),$$

with B in T. Using the scaling rule, $T_{irr}(B, \theta) = T_{irr}(h)$, one then has

$$T_{irr}(B, \theta) = 31.9[1 - (h/11.5)^{2/3}]\ (\mathrm{K}),$$

where $h = B(\sin^2 \theta + \cos^2 \theta/\gamma^2)^{1/2}$. It should be noted that γ as a function of T and T_{irr} is hidden in the expression of h. Therefore, the B- and θ-dependent T_{irr} cannot be given in the form of an analytic function. To the first order $T_{irr}(B, \theta)$ can be calculated by the following process:

(1) h is first calculated by approximate $\gamma_0(=12)$ as γ according to

$$h \equiv B(\sin^2 \theta + \cos^2 \theta/\gamma_0^2)^{1/2}$$

and $T_{irr}(h)$ is then obtained according to

$$T_{irr}(h) \equiv 31.9[1 - (h/11.5)^{2/3}];$$

(2) by inserting the thus-obtained $T_{irr}(h)$ into Eq. (5), γ is calculated as a function of T, B, and θ and then h is recalculated following $h \equiv B(\sin^2 \theta + \cos^2 \theta/\gamma^2)^{1/2}$;

(3) using the thus-obtained h, $T_{irr}(B, \theta)$ is finally given approximately by

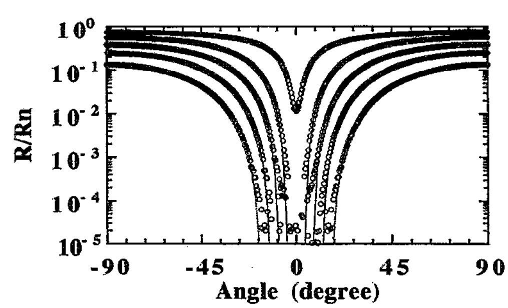

FIG. 4. Semilog plots for the angular dependence of c-axis normalized resistance in $La_{1.86}Sr_{0.14}CuO_4$ for a field of 5 T at $T = 31.28$, 29.314, 27.827, 26.337, and 24.84 K (from top to bottom): (O) the experimental data and (dotted lines) the calculated curves in terms of Eq. (6) by using $C_0 = 130$.

$$T_{irr}(B,\theta)=31.9[1-(h/11.5)^{2/3}].$$

Once the above parameters are determined, the experimental c-axis resistance of the present sample is expected to be reproduced as a function of T, B, and θ by means of Eq. (6). The calculated c-axis resistance as a function of B and θ at $T=31.28$ K is added in Fig. 1 (dotted lines), where $C_0=130$ is used. It can be seen that the experimental data at $T=31.28$ K can be nicely reyielded by the present model. To further confirm the model, we use the same parameters to calculate the c-axis resistance for a field of 5 T as a function of T and θ by means of Eq. (6). The calculated curves are displayed in Fig. 4 (dotted lines) for semilog plots together with the corresponding experimental data (open circles). Clearly the experimental data can be satisfactorily explained by the present model in 5 decades.

V. SUMMARY

In summary, we show that the c-axis resistance observed in single-crystalline $La_{2-x}Sr_xCuO_4$ as a function of T, B, and θ is not dominated by the Lorentz-force-driven vortex motion. To explain the experimental findings, a phenomenological model is developed, which quantitatively accounts for the c-axis resistance of the present sample as a function of T, B, and θ in the selected region (5 decades).

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