Thermally activated resistive behavior and flux motion in $La_{2-x}Sr_xCuO_4$ single-crystal thin films

Minoru Suzuki
NTT Interdisciplinary Research Laboratories, Nippon Telegraph and Telephone Corporation, 162 Tokai, Ibaraki 319-11, Japan
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Thermally activated behavior of the resistive transition under magnetic fields has been studied in $La_{2-x}Sr_xCuO_4$ ($x=0.1$, 0.15, 0.2, and 0.3) single-crystal thin films. It is found that the resistivity ρ below T_c scales as $\rho(T)=\rho_0\exp\{-U_0[1-T/T_c(H)]^n/k_BT\}$, where $n=3$ for $\mathbf{H}\|\mathbf{c}$ and $n=2.5$ for $\mathbf{H}\perp\mathbf{c}$. This behavior is explained phenomenologically as the thermal-depinning of vortices in quasi-two-dimensional superconductors having small-sized dense point pins. Numerical fitting provides values for the effective pinning potential and the mean-field upper critical field, which delineates straight H-T phase boundaries.

I. INTRODUCTION

Of the usual phenomena observed in high-T_c superconductors, the broadening of resistive transition induced by a magnetic field[1-4] is now understood to be closely related to the vortex dynamics in quasi-two-dimensional (2D) superconductors having short coherence lengths and a large Ginzburg-Landau (GL) parameter under sizable thermal fluctuations. Indeed, much effort has been directed toward the understanding of the resistive transition broadening in terms of flux creep,[3,4] or phase slip dissipation,[1] or thermally assisted flux flow (TAFF).[5] In these studies, the Arrhenius-type activation energy, or the effective pinning potential U, is dealt with as a function of a current and a magnetic field H based on the collective pinning mechanism in a temperature T region much lower than T_c. In a region near T_c, however, U exhibits strong T dependence, which has also relevance to the interesting fact that the broadening of the resistive transition occurs in the $La_{2-x}Sr_xCuO_4$ (Refs. 6 and 7) and $Nd_{2-x}Ce_xCuO_{4-\delta}$ systems[8] at much lower temperatures than in the $YBa_2Cu_3O_{7-y}$ or Bi-Sr-Ca-Cu-O systems.[2-4] Thus much remains to be understood more systematically concerning the T dependence of U.

From this point of view, this paper describes the thermally activated behavior of the field-induced resistive transition and its scaling behavior in $La_{2-x}Sr_xCuO_4$. The numerical fits based on a simple phenomenological model[8] provide values for the mean-field upper critical field H_{c2}^{MF}, which delineates straight boundaries near T_c in the H-T phase diagram in a wide T range below T_c.

II. EXPERIMENTAL RESULTS AND DISCUSSIONS

Samples measured are $La_{2-x}Sr_xCuO_4$ single-crystal thin films ($x=0.1$, 0.15, 0.2, and 0.3) epitaxially grown on $SrTiO_3$ (100) substrates. Films are 300 nm thick in average. The details of the epitaxial growth and the characterization are described in Refs. 9 and 10. Figure 1 shows the T dependence of resistivity ρ, $\ln\rho$, and the activation energy $-k_Bd\ln\rho/dT^{-1}$ below T_c for $\mathbf{H}\|c$ and $\mathbf{H}\perp c$ for a representative composition of $x=0.15$. The behavior is basically the same for the other x values. In the $La_{2-x}Sr_xCuO_4$ system, the resistive transition gradually changes from a type of the broadening to that of a parallel shift when x increases from 0.1 to 0.3 (Ref. 7). However, when the values for ρ are plotted on the semilogarithmic scale for these compositions, it is clear that there is no definite qualitative change in the resistive transition, indicating that the change of the broadening is due to the change in factors that govern the thermally activated behavior.

In Fig. 1(e) and 1(f), it is clearly seen that the activation energy is a strong function of T. Although the T dependence of $-k_Bd\ln\rho/dT^{-1}$ does not provide accurate T dependence of U, it reflects that the function is approxi-

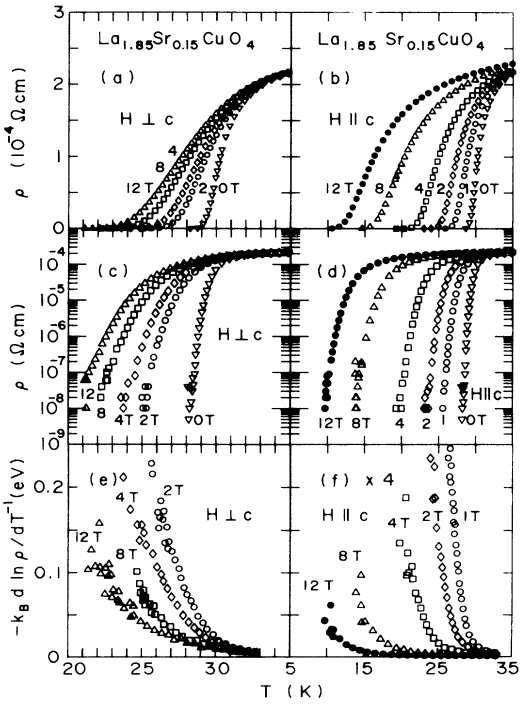

FIG. 1. (a) (b) Resistive transitions for a $La_{1.85}Sr_{0.15}CuO_4$ single-crystal thin film under magnetic fields parallel and perpendicular to the c axis. (c) (d) Resistive transitions on a semilogarithmic scale for the same film. (e) (f) Temperature dependence of $-k_Bd\ln\rho/dT^{-1}$, which roughly corresponds to the activation energy.

mately of the power-law type $(1-T/T_c)^n$. This observation has close relevance to the scaling behavior discussed in the following.

Figure 2 shows a $\ln\rho-1/T$ plots for $x=0.15$. (For other compositions, qualitatively the same behavior is seen.) The result shows at a first glance that the tail of the resistive transition is characterized by the thermally activated behavior. However, close inspection of the plots reveals that there is no region where $\ln\rho$ is linear in $1/T$ in any sample (except for $x=0.3$ at lower temperatures with $\mathbf{H}\perp c$), indicating that U is strongly T dependent.

Generally in the TAFF model,[11] $\rho(T)$ in the thermally activated region is expressed using H- and T-dependent effective pinning potential $U(H,T)$ as follows:

$$\rho(T)=\rho_0\exp[-U(H,T)/k_BT] . \quad (1)$$

The values for ρ_0 are close to the normal resistivity ρ_n. Following the argument in Ref. 8, the T dependence of $U(H,T)$ can be approximated by the following equation:

$$U(H,T)=U(H,0)(1-t)^n . \quad (2)$$

Here, n is a constant and $t=T/T_c(H)$ is the reduced temperature normalized by a mean-field transition temperature $T_c(H)=T_c^{\mathrm{MF}}(H)$. The power-law dependence in Eq. (2) is consistent with the experimental results shown in Fig. 1(e) and 1(f). Although the T dependence as expressed in Eq. (2) is also supposed for different systems, the most important and distinguishing point in Eq. (2) is that $T_c(H)$, instead of $T_c(0)$, is employed to normalize T in the presence of a field. This is a consequence of the scaling rule that the fundamental physical properties possess.

In order to determine the parameter n in Eq. (2), the data in Fig. 2 are replotted for

$$-k_BT\ln[\rho(T)/\rho_0]/U(H,0) \text{ vs } (1-t)$$

on a double-logarithmic scale, as shown in Fig. 3 for $x=0.15$. Here, the slope of the plots provides approximate values for n in both cases for $\mathbf{H}\parallel c$ and $\mathbf{H}\perp c$. (The procedure for the parameter optimization is explained in the previous work on $Nd_{2-x}Ce_xCuO_{4-\delta}$ system.[8]). In the plots, the data coalesce into two straight lines, indicating a scaling rule that the thermally activated resistive behavior exhibits near T_c. Thus, corresponding to the two straight lines, we obtain the values of $n=3$ for $\mathbf{H}\parallel c$ and $n=2.5$ for $\mathbf{H}\perp c$. (The scatter seen in a region for small $1-t$ is due to a finite transition width ranging from 1 to 2 K.) For other x values, similar plots provide the same values for n. While the value of $n=3$ for $\mathbf{H}\parallel c$ is the same as in the $Nd_{2-x}Ce_xCuO_{4-\delta}$ system, the value of $n=2.5$ for $\mathbf{H}\perp c$ is larger by 0.5, indicating somewhat different elementary pinning potential and its dependence on, probably, the anisotropy of the coherence lengths. One model to explain the present scaling rule is given in Ref. 8. Within the framework of this model, the value for n depends on ξ_c. In the extremely 2D case, e.g., in the case of $Nd_{2-x}Ce_xCuO_{4-\delta}$ system, ξ_c is replaced by a constant, leading to a value of $n=2$. In the present case, the value of $n=2.5$ is obtained by using the relation $\xi_c=\xi_c(0)(1-t)^{-1/2}$, implying that the $La_{2-x}Sr_xCuO_4$ system is less anisotropic than the $Nd_{2-x}Ce_xCuO_{4-\delta}$ system.

The solid lines in Fig. 2 are the fits to the data using the optimum values for n, $U(H,0)$, and ρ_0. The excellent fits in the range extending more than three orders of magnitude imply that the resistive behavior in the $La_{2-x}Sr_xCuO_4$ thin films is well explained by the thermally activated flux motion.

Before addressing the x dependence of $U(H,0)$, it is worthwhile mentioning its H dependence of $U(H,0)$.

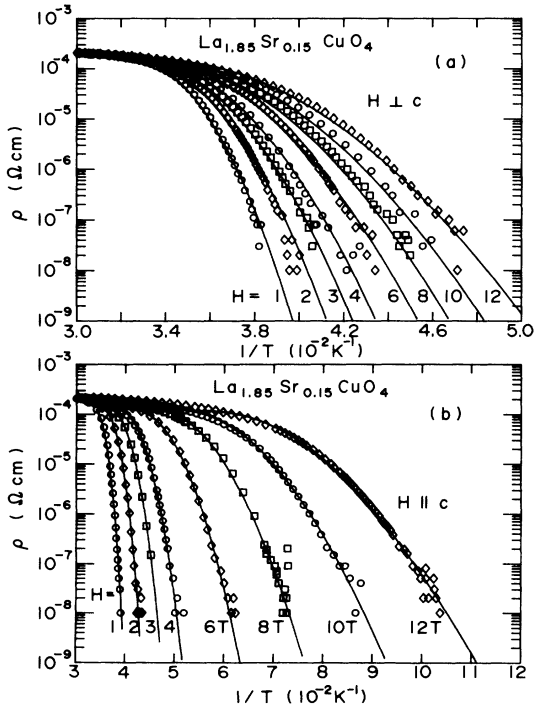

FIG. 2. Temperature dependence of ρ for $La_{1.85}Sr_{0.15}CuO_4$ in the vicinity of T_c for (a) $\mathbf{H}\perp c$ and (b) $\mathbf{H}\parallel c$. Solid lines are fit using Eqs. (1) and (2).

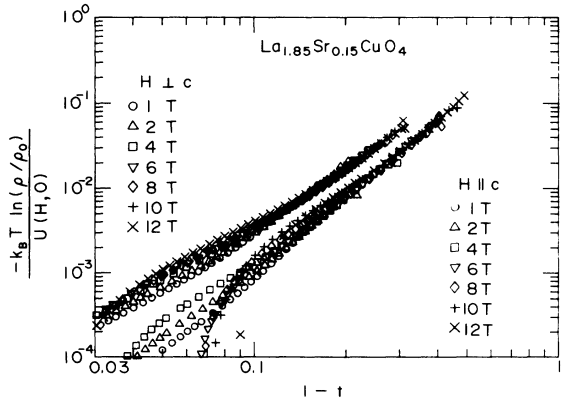

FIG. 3. Double-logarithmic plots for $[-k_BT\ln(\rho/\rho_0)/U(H,0)]$ vs $[1-T/T_c(H)]$ for the data in Fig. 2. The experimental data fall on two straight lines, showing a scaling behavior. The slopes indicate the values of $n=3\pm0.1$ and $n=2.5\pm0.1$ for $\mathbf{H}\perp c$ and $\mathbf{H}\parallel c$, respectively.

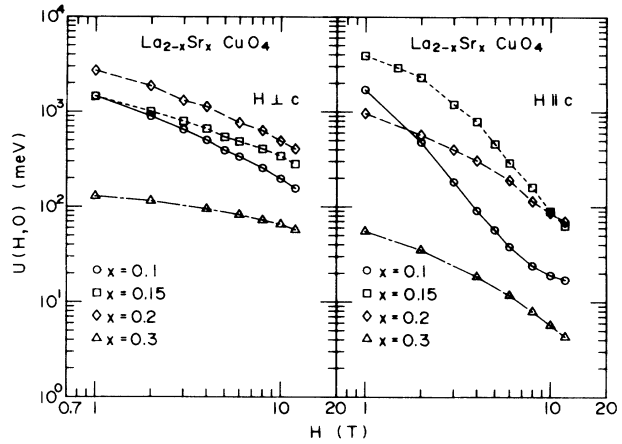

FIG. 4. Field dependence of the effective pinning potential $U(H,0)$ for the $La_{2-x}Sr_xCuO_4$ single-crystal thin films as a function of x, for $\mathbf{H}\perp c$ and $\mathbf{H}\parallel c$.

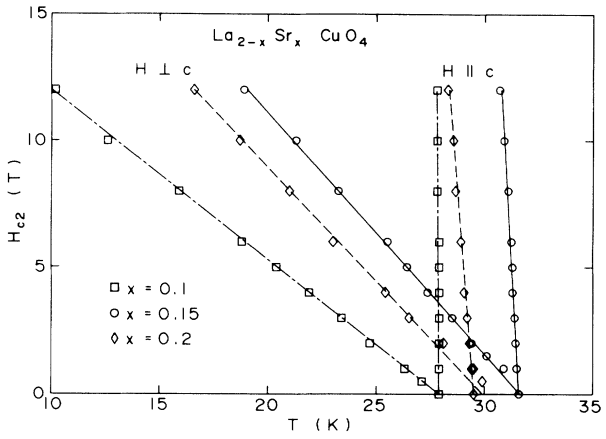

FIG. 5. Temperature dependence of the mean-field upper critical field H_{c2}^{MF} for the $La_{2-x}Sr_xCuO_4$ system, delineating straight H-T phase boundaries.

The above model addresses no reasonable explanation for the H dependence. Among other models suggested so far to explain various types of H dependence, the single vortex depinning mechanism,[12] which is roughly in line with the above model, becomes H dependent when we take into account the intervortex interaction arising from the flux lattice shear modulus. This mechanism results in linear H dependence at higher H. In the present experiment, however, there is no linear portion at least below 12 T. Thus the interpretation of the H dependence of $U(H,0)$ is yet to be clarified. Except for this H dependence, this simple model described in Ref. 8 explains the T dependence of $U(H,T)$ quite well, implying that the thermally activated flux motion over small-sized dense point pins, probably oxygen vacancies, is responsible for the resistive transition broadening of the $La_{2-x}Sr_xCuO_4$ single-crystal films under magnetic fields.

Figure 4 shows the H dependence of $U(H,0)$ for x from 0.1 to 0.3. In both cases for $\mathbf{H}\perp c$ and $\mathbf{H}\parallel c$, the effective pinning potential shows characteristic H dependence, depending on the field direction. For $\mathbf{H}\parallel c$, $U(H,0)$ shows strong H dependence and it decreases by more than one order of magnitude. Furthermore, the steepness of $U(H,0)$ decreases as x increases. When we take into account the experimental fact that the anisotropy of the $La_{2-x}Sr_xCuO_4$ system becomes quite large for smaller x (Ref. 10), the large H dependence for $x=0.1$ may be related to, if it exists, the vortex lattice melting, which is suggested to occur in the high-T_c superconductors.[13] The increase in $U(H,0)$ for $x=0.15$ and 0.2 in the intermediate H range ($2\ \mathrm{T} < H < 10\ \mathrm{T}$) may reflect a decrease in the anisotropy or an increase in $\xi_c(0)$. The significant decrease in $U(H,0)$ for $x=0.3$ may be related to the electronical inhomogeneity, which is supposed to exist in this system.[14]

From the above arguments, it is likely that $U(H,0)$ for small Sr concentration is large at low fields. This means that the Meissner fraction (fraction of ideal diamagnetism) for $x<0.15$ tends to be smaller than for $x\geq 0.15$. We believe that the observed x dependence of the Meissner fraction,[14] which peaks at $x\simeq 0.15$, is closely related to this tendency of the H dependence of $U(H,0)$ discussed here. For $\mathbf{H}\perp c$, we can observe the same behavior as in $\mathbf{H}\parallel c$, reinforcing the above argument.

The numerical fits also provide values for $T_c^{MF}(H)$, from which the mean-field upper critical field H_{c2}^{MF} is estimated. Figure 5 shows the temperature dependence of H_{c2}^{MF} thus estimated for $x=0.1$, 0.15, and 0.2. Except for a region very close to T_c, H_{c2} is linear in T, which is consistent with the mean-field theory. This is in contrast with the conventional estimates for $H_{c2}(T)$ of high-T_c superconductors, where $H_{c2}-T$ shows a positive curvature in the H-T phase diagram.

In the case of $x=0.3$, the plots of $H_{c2}-T$ results in a positive curvature, probably due to poor fits at lower temperatures. The reason for this poor fit and the positive curvature is first the electronical inhomogeneity indicated in this system,[14] as reflected in the $\ln\rho-1/T$ plots for $\mathbf{H}\perp c$. Although the effect of Anderson localization in 2D electronic system might exist, it seems difficult to ex-

TABLE I. GL coherence lengths and dH_{c2}/dT for $La_{2-x}Sr_xCuO_4$ ($x=0.1$, 0.15, and 0.2) obtained from the fits to the thermally activated resistivity data. The values in brackets for $\xi_{ab}(0)$, $\xi_c(0)$, and $\xi_{ab}(0)/\xi_c(0)$ are obtained by the fluctuation analysis.

x	T_c^{Mf} [K]	$-dH_{c2}^{\perp c}/dT\vert_{T=T_c}$ [T/K]	$-dH_{c2}^{\parallel c}/dT\vert_{T=T_c}$ [T/K]	$\xi_{ab}(0)$ [Å]	$\xi_c(0)$ [Å]	$\xi_{ab}(0)/\xi_c(0)$
0.1	27.9 [29.1]	100	0.67	42.0[31.5]	0.28[0.9]	149[35]
0.15	31.6 [31.6]	13.9	0.98	32.6[32]	2.31[2.2]	14.1[14.5]
0.2	29.5[30.4]	10.53	0.90	35.2[33]	3.01[2.4]	11.7[13.8]

plain the whole characteristics solely by this effect.

The GL coherence lengths estimated from these H_{c2} data are listed in Table I, together with those estimated by the fluctuation conductivity analysis above T_c (Ref. 10). It is seen that both estimates coincide within a factor of less than 1.1 for $x > 0.1$, while for $x = 0.1$ the present estimates for $\xi_{GL}(0)$ are larger by a factor of 1.3. As a whole, however, the present method provides a reliable way for estimating $H_{c2}(T)$. The method relying on the fluctuation analysis above T_c is applied to the evaluation of $H_{c2}(0)$ and $\xi_{GL}(0)$ but the values at finite temperatures are left unknown. The present method provides values for dH_{c2}/dT as well as $H_{c2}(0)$ and $\xi_{GL}(0)$.

III. CONCLUSIONS

It is shown that the resistive transition behavior in $La_{2-x}Sr_xCuO_4$ system scales as

$$\rho(T)=\rho_0\exp\{-U(H,0)[1-T/T_c(H)]^n\} ,$$

where $n = 2.5$ for $\mathbf{H} \perp c$ and $n = 3$ for $\mathbf{H} \| c$. It follows from this scaling law that the pins in the $La_{2-x}Sr_xCuO_4$ system are small compared with $\xi_{ab}(0)$ and densely distributed, and the most probable candidates for these pins are oxygen vacancies. The values for the elementary pinning potential of the $La_{2-x}Sr_xCuO_4$ system are estimated, showing a tendency of larger H dependence at smaller x. Based on these analyses, the values for the mean-field H_{c2} and the GL coherence lengths are estimated, which are basically consistent with the results of fluctuation analysis.

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