Anisotropic Penetration Depth in $La_{2-x}Sr_xCuO_4$

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The surface impedance at 10 GHz was measured systematically in single-crystal $La_{2-x}Sr_xCuO_4$ for carrier concentrations $0.09 \le x \le 0.19$, from which the penetration depth λ was determined. The anisotropy and the dependences on x and temperature T of λ are extensively studied for the first time. The anisotropy of $\lambda(T=0)$ decreases with increasing x, and still remains larger than 10 for $x = 0.19$. The out-of-plane penetration depth (λ_c) has a different temperature dependence from the in-plane one (λ_{ab}). These results suggest that the electrodynamic properties in the superconducting state along the c axis can be explained by a Josephson-coupled layer model.

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A large number of experimental results have revealed that high-T_c superconductivity occurs in the CuO_2 planes. There are many theoretical models reflecting its two dimensionality. It is still unknown, however, how we can describe the coupling between the layers in the superconducting state. In other words, it should be clarified whether the electronic properties of the superconducting state are essentially two or three dimensional. So far many anisotropic superconducting properties [1,2] have been analyzed in terms of a so-called "effective-mass model," where the anisotropy of various parameters is ascribed to the anisotropic effective masses in the Ginzburg-Landau (GL) theory. This model can be applied only when the electrodynamic properties are essentially three dimensional.

Recent studies have shown the anomalous properties of high-T_c cuprates across the CuO_2 planes [3–5]. In particular, the c-axis resistivity in the normal state shows nonmetallic behavior, suggesting the two-dimensional nature of high-T_c superconductors [3]. However, less investigated are the out-of-plane electromagnetic properties in the superconducting state, which are suitable for a crucial test of the dimensionality of the superfluid. It is well known that the measurement of the penetration depth λ provides quantitative information on the mass anisotropy. The London penetration depth is given by

$$\lambda_L = \left(\frac{m^* c^2}{4\pi n_s e^2}\right)^{1/2}, \tag{1}$$

where n_s and m^* are the density and the effective mass of the superconducting carriers, respectively [6]. In high-T_c superconductors, the experimental studies of the penetration depth have been performed mainly on λ_{ab} with the screening current flowing in the CuO_2 planes (a-b planes) [7]. The c-axis penetration depth λ_c has received much less attention, partly because high-T_c crystals are not thick enough in the c direction.

In this Letter, we report the magnitude and the temperature dependence of the anisotropic penetration depth in large high-quality single crystals of $La_{2-x}Sr_xCuO_4$ at five compositions ($x = 0.09, 0.12, 0.15, 0.18, 0.19$). As far as we know, this is the first determination of λ_c/λ_{ab} as a function of x and T over a wide range of the carrier concentrations in this system. $La_{2-x}Sr_xCuO_4$ has the simplest crystal structure with only one CuO_2 plane per primitive cell, and is appropriate for a critical test of the theoretical models. We find that the magnitude and temperature dependence of λ_c are consistent with a Josephson-coupled layer model.

Single crystals of $La_{2-x}Sr_xCuO_4$ were grown by a traveling-solvent-floating-zone method, as described elsewhere [8]. Note that the crystals are large (up to 5 mm along the c axis) enough for various anisotropy measurements. The crystals were thoroughly characterized over a wide range of x, using the inductively coupled plasma emission spectroscopy, resistivity anisotropy, and susceptibility measurements [8]. These measurements show that the crystals are of high quality.

The surface impedance was measured at 10 GHz using a superconducting Pb cavity resonator with the sample on the heated rod [9,10]. The quality factor Q of the cavity is typically 1×10^6 and we achieved stable resonant frequency ($\delta f/f < 10^{-8}$) at 4.2 K. One can obtain the surface resistance R_s and the surface reactance X_s from the Q value and the resonant frequency f by the formula $R_s = G_1\left(Q^{-1} - Q^{-1}_{\text{blank}}\right)$ and $\Delta X_s = -G_2 \Delta f$, where G_1 and G_2 are geometrical factors. Q_{blank} is the Q of the cavity without a sample, and ΔX_s is the change of X_s. The geometrical factors were determined experimentally by using Pb as a reference sample. $La_{2-x}Sr_xCuO_4$ crystals were cut into the

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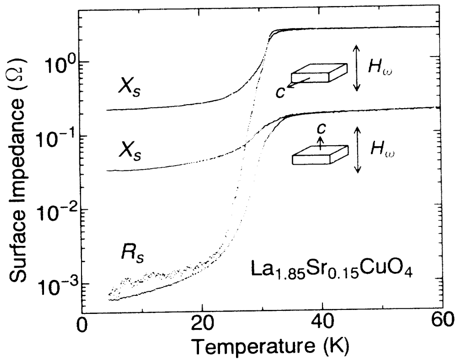

FIG. 1. Temperature dependence of the surface resistance R_s and the surface reactance X_s in $La_{1.85}Sr_{0.15}CuO_4$ crystals with microwave field parallel and perpendicular to the CuO_2 planes.

specimens of typically $1 \times 1 \times 0.2$ mm^3, having two types of crystal orientations, large faces parallel and perpendicular to the a-b planes. The weak microwave magnetic field H_ω is applied perpendicular to the large faces for the two types of crystals (see Fig. 1) [11]. The small size of the sample ensures the cavity perturbation method.

In the superconducting state, the surface reactance is proportional to the penetration depth λ by [12]

$$X_s = \mu_0 \omega \lambda, \tag{2}$$

where μ_0 is the permeability of free space and $\omega = 2\pi f$. In the normal state, we can show the equation

$$R_s = X_s = \tfrac{1}{2}\mu_0 \omega \delta_{\rm cl} \tag{3}$$

in the normal skin effect regime (mean free path $l \ll \delta_{\rm cl}$), where $\delta_{\rm cl} = (2/\mu_0\omega\sigma_1)^{1/2}$ is the classical skin depth and σ_1 the real part of the conductivity [13]. Since we measured R_s and ΔX_s simultaneously, the magnitude of X_s and hence the magnitude of λ can be determined from Eqs. (2) and (3) [10]. This method is supported by the excellent agreement between μSR measurements and our estimations of $\lambda_{ab}(0)$ for $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$ [10]. It should be emphasized that in our method no special theoretical forms of the temperature dependence of λ are required for the determination of $\lambda(0)$. This shows clear contrast to other measurements, such as magnetic susceptibility measurements [2] and usual frequency shift measurements in the rf region [14].

Figure 1 shows the temperature dependence of the surface resistance and the surface reactance for the $x = 0.15$ samples. A large anisotropy in the surface impedance is clearly seen in both the normal and the superconducting states. Similar temperature dependence of the anisotropic surface impedance was observed for all the compositions except for $x = 0.09$ with $H_\omega \perp c$ [15]. In the configuration of $H_\omega \parallel c$, the screening current flows in the CuO_2 planes in the region with the length $\lambda_{ab}(= X_s^{ab}/\mu_0\omega)$ from the edge below T_c. In contrast,

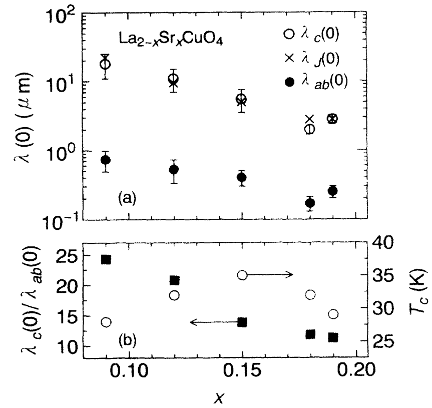

FIG. 2. (a) Magnitude of the in-plane penetration depth $\lambda_{ab}(0)$ and the c-axis penetration depth $\lambda_c(0)$ for the wide range of x. Estimations for $\lambda_c(0)$ in the Josephson-coupled layer model are also shown ($\times$). (b) Compositional dependence of $\lambda_c(0)/\lambda_{ab}(0)$ and T_c determined by the onset in $Z_s(T)$.

when H_ω is perpendicular to the c axis, the current flows both in and across the CuO_2 planes. Thus, the penetration depth $\lambda_c(= X_s^c/\mu_0\omega)$ with the current flowing across the CuO_2 planes can be estimated using the formula $X_s \propto A\lambda_{ab} + C\lambda_c$, where A and C are the appropriate dimensions ($A \sim C \sim 1$ mm) of the sample perpendicular to H_ω [16].

In Fig. 2(a), we show the magnitude of $\lambda_{ab}(0)$ and $\lambda_c(0)$ for the wide range of the compositions. Both $\lambda_{ab}(0)$ and $\lambda_c(0)$ become shorter as the composition x increases. The orders of magnitude of $\lambda_{ab}(0)$ (~ 0.4 μm) and $\lambda_c(0)$ (~ 5.5 μm) for $x = 0.15$ are consistent with the μSR measurements for polycrystalline samples [17] [$\lambda_{ab}(0) \sim 0.3$ μm] and an estimation of $\lambda_c(0)$ (~ 5 μm) from optical measurements [4], respectively. The anisotropy $\lambda_c(0)/\lambda_{ab}(0)$ becomes small with increasing x [Fig. 2(b)], but still remains larger than 10 for $x = 0.19$.

First, let us show that the three-dimensional (3D) approach cannot easily explain the c-axis electrodynamics. If this system can be regarded as an anisotropic 3D metal (this assumption is not good at all as will be discussed below), the anisotropy of the surface reactance X_s^c/X_s^{ab} in the normal state is equal to the square root of anisotropy of the conductivity according to Eq. (3). In this picture, the band mass anisotropy can be estimated through the simple Drude model where $\sigma_1 = ne^2\tau/m^*$. Recent infrared measurements [4,18] show that the anisotropy of the low-frequency scattering time τ is about 1.7 for optimum concentrations. Thus, in this model we estimate the band mass anisotropy to be 530 just above T_c for $x = 0.15$ (see the inset of Fig. 3). In the anisotropic GL theory below T_c, $(\lambda_c/\lambda_{ab})^2$ [$= (X_s^c/X_s^{ab})^2 \sim 200$ for $x = 0.15$] should be equal to the band mass anisotropy in the normal state, when the superconducting gap is isotropic [19]. The estimated mass anisotropy in the normal state is considerably larger than that in the super-

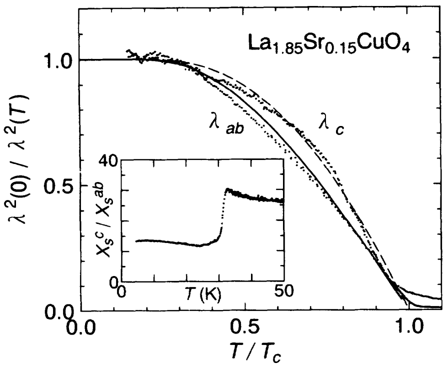

FIG. 3. $\lambda_{ab}^2(0)/\lambda_{ab}^2(T)$ and $\lambda_c^2(0)/\lambda_c^2(T)$ as functions of reduced temperature T/T_c. Solid curve represents the temperature dependence of λ_L predicted by the BCS theory, while the dashed curve is calculated according to Eq. (4). The inset shows the temperature dependence of the anisotropy of the surface reactance X_s^c/X_s^{ab}.

conducting state. Therefore, such a 3D approach cannot explain the magnitude of the anisotropy factor λ_c/λ_{ab} and the steplike feature in the temperature dependence of X_s^c/X_s^{ab} demonstrated in the inset of Fig. 3. Similar steplike features are observed for all the samples, suggesting that the 3D analysis within the effective-mass model is not appropriate for this system.

It is claimed by some papers that the 3D analysis is inconsistent with the normal-state behavior, such as the nonmetallic nature of the c-axis conductivity [3,4]. Next we shall show that whether or not we start from 3D in the normal state, anisotropic 3D treatment is inappropriate in the superconducting state. In the BCS theory [6], the determined penetration depth is described by the expression $\lambda(T) = \lambda_L(T)\{1+\xi_0/J_0(T)l\}^{1/2}$, where ξ_0 is the coherence length, l the mean free path, and $J_0(T)$ the BCS range function with a value $J_0(0) = 1$. In the hole-doped high-T_c superconductors, the in-plane penetration depth is given by the local clean-limit approximation ($\xi_0/l \ll 1$) [17], and λ_{ab} is nearly equal to the London value.

Figure 3 shows the temperature dependence of $\lambda^2(0)/\lambda^2(T)$ for the $x = 0.15$ crystals. The temperature dependence of λ_{ab} is roughly explained by the local, clean-limit BCS theory [20], which resembles the case of $YBa_2Cu_3O_7$ film [21]. In contrast, $\lambda_c(T)$ clearly deviates from this formula, and is rather consistent with the expression

$$\frac{\lambda^2(0)}{\lambda^2(T)} = \frac{\Delta(T)}{\Delta(0)} \tanh \frac{\Delta(T)}{2k_BT}, \tag{4}$$

where $\Delta(T)$ is the BCS-type temperature dependence of the superconducting gap. This result indicates that the electrodynamics along the c axis is clearly different from the in-plane dynamics in the superconducting state. The above expression [Eq. (4)] is predicted by the Josephson-coupled layer model, which will be discussed later, as well as by the dirty-limit approximation ($\xi_0/l \gg 1$).

If the dirty-limit approximation were a true picture, the mean free path of the superfluid at low temperatures should be much smaller than the c-axis coherence length (~ 3 Å [22]). This means that the superfluid is nearly confined in the CuO_2 planes. In such a situation, the mean free path in the c direction is quite meaningless, and the three-dimensional effective-mass approach cannot be applied. Thus, the dirty-limit picture is not good and a two-dimensional approach should be examined for the out-of-plane electrodynamics.

Now we show that a better description is the Josephson-coupled layer model of two-dimensional superconductors, which was originally suggested by Lawrence and Doniach [23]. In this model, the superconducting order parameter in adjacent layers is coupled by Josephson tunneling. If we apply this model to $La_{2-x}Sr_xCuO_4$, the c-axis penetration depth is dominated by the Josephson penetration depth [24,25]

$$\lambda_J = \left(\frac{c\phi_0}{8\pi^2 s J_s}\right)^{1/2}, \tag{5}$$

where s is the distance between the CuO_2 planes ($\sim$ 6.6 Å), and J_s the Josephson tunneling current density. In the BCS theory [26], J_s is related to the tunneling resistance per unit area in the normal state R_n by

$$J_s(T) = \frac{\pi\Delta(T)}{2eR_n} \tanh \frac{\Delta(T)}{2k_BT}. \tag{6}$$

When we adopt the BCS gap value of $\Delta(0) \sim 1.76k_BT_c$ [27] and assume $R_n = \rho_c s$ [28], we can calculate $\lambda_J(0)$ by

$$\lambda_J(0)\ (\mathrm{cm}) \sim 1.1\times 10^{-2} \times \sqrt{\frac{\rho_c\ (\Omega\,\mathrm{cm})}{T_c\ (\mathrm{K})}},$$

where ρ_c is the c-axis resistivity in the normal state and T_c is shown in Fig. 2(b). In this study we use the values of ρ_c just above T_c which are determined by the resistivity measurements, and the results are shown in Fig. 2(a). These estimations show excellent agreement with the experimental data of $\lambda_c(0)$. The ambiguity of estimation of ρ_c is not so serious in the scale of Fig. 2(a). These results strongly suggest that this model is an appropriate picture; i.e., $La_{2-x}Sr_xCuO_4$ can be described as an array of Josephson-coupled superconducting layers along the c axis.

Next we turn to the temperature dependence of λ_c. In the Josephson-coupled layer model, when we substitute Eq. (5) into Eq. (6), we obtain Eq. (4) as the temperature dependence of the Josephson penetration depth λ_J. This temperature dependence is quite consistent with the data of $\lambda_c(T)$ (see Fig. 3). Thus, the observed temperature dependence of λ_c can be interpreted as another evidence for the intrinsic Josephson coupling between CuO_2 planes.

Recently, Kleiner *et al.* [5] have suggested the intrinsic Josephson coupling in $Bi_2Sr_2CaCu_2O_8$ from the *I-V* characteristics measurements. Their result in $Bi_2Sr_2CaCu_2O_8$ is consistent with our penetration depth measurements in $La_{2-x}Sr_xCuO_4$, suggesting that these features are common to these two superconductors.

In summary, we have measured, for the first time, the magnitude and the temperature dependence of the anisotropic penetration depth λ_{ab} and λ_c in high-quality $La_{2-x}Sr_xCuO_4$ single crystals. The anisotropy $\lambda_c(0)/\lambda_{ab}(0)$ decreases with increasing x, and is larger than 10 even in the $x = 0.19$ crystals. The magnitude of $\lambda_c(0)$ shows excellent agreement with the Josephson-coupled layer model over a wide range of the compositions. We have also found that the temperature dependence of λ_c is different from the local-limit BCS formula, and that it is consistent with the Josephson-coupled layer model. These results imply that the electronic states of $La_{2-x}Sr_xCuO_4$ ($0.09 \leq x \leq 0.19$) can be regarded as two dimensional in the superconducting state, and that the interlayer coupling is characterized by Josephson-like interaction.

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