Magnetic penetration depth of $(La_{1-x}Sr_x)_2CuO_4$ single crystals

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We have performed magnetization measurements on a series of high-quality, large single crystals of $(La_{1-x}Sr_x)_2CuO_4$ over a composition range of $x=0.05$–0.10, with magnetic fields parallel to the c axis. In order to avoid the large fluctuation effects near T_c in the analysis of the magnetization of these layered superconductors, a method of data analysis, based on the variational model developed by Hao and Clem, is used for the determination of the magnetic penetration depth $\lambda_{ab}(T)$ of this family. The conventional London approximation for the determination of $\lambda(T)$ from mixed-state magnetization isotherms $M(H,T)$ is also reevaluated, and found generally to overestimate $\lambda_{ab}(T)$ of $(La_{1-x}Sr_x)_2CuO_4$ by as much as 20%. Our derived values of $\lambda_{ab}(0)$ by the Hao-Clem model shows a minimum for the crystal ($x=0.077$) having the highest $T_c(=35.05\ \text{K})$. This minimum value of $\lambda_{ab}(0)$ ($=2545\pm40$ Å) is in agreement with the earlier reported value of $\lambda(0)$ (~2500 Å) for a polycrystalline sample of $(La_{1-x}Sr_x)_2CuO_4$ with $x=0.075$ obtained by using the muon-spin-relaxation technique.

I. INTRODUCTION

While the mechanism of superconductivity for high-T_c cuprates is not understood yet, an enormous amount of effort has been made to characterize their intrinsic superconducting properties. $(La_{1-x}Sr_x)_2CuO_4$ (LSCO) is one of the simplest cuprate superconductors. The measurement of the magnetic-penetration depths of LSCO with different Sr content can provide insight into the pairing mechanism. Many techniques have been utilized on LSCO polycrystalline samples, and these often lead to widely varying results due to grain boundary effects, anisotropy, and inhomogeneity.[1–3] Obviously, high-quality single crystals are most desirable for obtaining reliable data. In this paper we present the results of our measurements of $\lambda(T)$ for LSCO with various Sr contents of a series of high-quality large single crystals (a few mm along the c axis), grown by means of a traveling solvent floating-zone technique,[4] and thus free from the contamination of crucible materials.

The values of $\lambda(T)$ reported in this paper were obtained from high-field magnetization measurements on four LSCO single crystals, which are oriented such that c axis $\parallel H$. Many earlier published works[5,6] on the measurements of $\lambda(T)$ of high-T_c superconductors, based on magnetization and analyzed by the conventional London approximation,[5] did not address the strong fluctuation effects on the magnetization. It has been observed in most of high-T_c superconductors (for instance, LSCO single crystal,[7] $YBa_2Cu_3O_7$ single crystal,[8] $Bi_2Sr_2CaCu_2O_8$ single crystal,[9] and c-axis-oriented $Bi_2Sr_2Ca_2Cu_3O_{10}$ tape[10]) that large thermodynamic fluctuation effects could induce significant diamagnetic moments into the total magnetization, particularly near T_c. This makes the conventional London approximation of obtaining $\lambda(T)$ from high-field magnetization isotherms $M(H,T)$ invalid in the temperature region where fluctuation cannot be neglected, since the diamagnetic contribution induced by the fluctuation effect cannot be avoided in the total magnetization. Even in the region where the fluctuation effect is sufficiently small, the London approach tends to overestimate the value of $\lambda(T)$,[6,11,12] because the core energy of the vortices is not included in the calculation of the total free energy of the mixed state of type-II superconductors.[11,12]

Recently, a variation model has been proposed by Hao *et al.*[11,12] to describe the reversible magnetization of the mixed state of type-II superconductors for the case of magnetic fields being parallel to one of principle axes. Within this model the depression of the order parameter at the vortex core is taken into account, and thus the core energy is included in the Ginzburg-Landau free energy of the system for calculating the magnetization. A number of fundamental parameters of a superconductor, for instance, the Ginzburg-Landau parameter κ, the critical fields, and $\lambda(T)$, can be determined from a direct application of this model to experimental data. Furthermore, we have demonstrated in our earlier work[13] that this model, which is basically a three-dimensional anisotropic Ginzburg-Landau theory, is still applicable for studying the mixed-state magnetic properties of quasi-two dimensional superconductors such as $Bi_2Sr_2Ca_2Cu_3O_{10}$, at least in large magnetic fields applied perpendicular to the CuO layers. However, the model of Hao *et al.* does not take account of the thermodynamic fluctuation of the order parameters in high magnetic fields[14] so that the strong fluctuation effect could make this model invalid, particularly near T_c, as reported previously.[10,13] In order to overcome this difficulty caused by the large fluctuation effect, a data-analysis technique has been recently suggested by Li *et al.*[10] for the study of reversible-magnetic properties of superconducting

$Bi_2Sr_2Ca_2Cu_3O_{10}$. By means of this technique we obtained the value of $\lambda(T)$ for this series of LSCO single crystals, which are free of the influence of fluctuation. This technique, theoretically based on the model of Hao *et al.*, has been discussed in detail in Ref. 10, and so only a brief description is provided in Sec. III. The central part of this approach is to determine the temperature region where the fluctuation effects make negligible the contribution to the total magnetization and then apply the model of Hao *et al.* to extract $\lambda(T)$.

II. EXPERIMENTS

Each of our four LSCO single-crystal samples used in this study were cut separately from a series of large single crystals, up to 5 mm along the c axis and over a wide range of Sr content. These were grown using a traveling solvent floating-zone technique, as reported previously.[15] The Sr content of each crystal was analyzed by the inductively coupled plasma (ICP) technique. For the convenience of presentation, the four crystals that we studied are individually named as crystals A (51.2 mg, 3.20 mm along the c axis), B (29.0 mg, 2.00 mm along the c axis), C (13.85 mg, 1.4 mm along the c axis), and D (32.47 mg, 3.45 mm along the c axis). Their nominal composition and Sr contents determined by the ICP technique are given in Table I. Observation of the polished cross section of these crystals under a polarized microscope and by the x-ray back-reflection Laue technique confirmed that only one domain exists for each of the four crystals that we studied.

Low-field dc magnetization and transport measurements[15] show a rather sharp transition for each crystal. A typical result of a 2-Oe shielding measurement is shown in Fig. 1 for crystal C, where magnetic field was applied parallel to the c axis. The value of $4\pi M$ at 4.2 K is -2.995 G, which leads to a fraction of the ideal shielding volume very close to 100% after taking into account the correction for the demagnetization factor[16] along the c direction. The inset of Fig. 1 shows the method which we used to define T_c. The temperature at the intercept of a linear extrapolation of $4\pi M(T)$ to the zero-magnetization line is defined as a zero-field onset $T_c=35.05$ K, and that to the horizontal $4\pi M(T)=-2.995$ G line gives a transition width ΔT_c of 2.6 K for crystal C. T_c for the other three crystals was determined in the same fashion. As shown in Table I, we have the onset $T_c=26.2$ K for crystal A with $\Delta T_c=0.9$ K, the onset $T_c=32.4$ K for crystal B with $\Delta T_c=3.7$ K, and the onset $T_c=29.8$ K for crystal C with $\Delta T_c=1.8$ K. These sharp transitions and very close to 100% shielding signals demonstrate that a rather uniform Sr content was maintained in these large single crystals. Also, the one-to-one correspondence of T_c with Sr content[15] is found to be in good agreement with the earlier results reported by Takagi *et al.*[17] based on well-sintered LSCO polycrystalline samples.

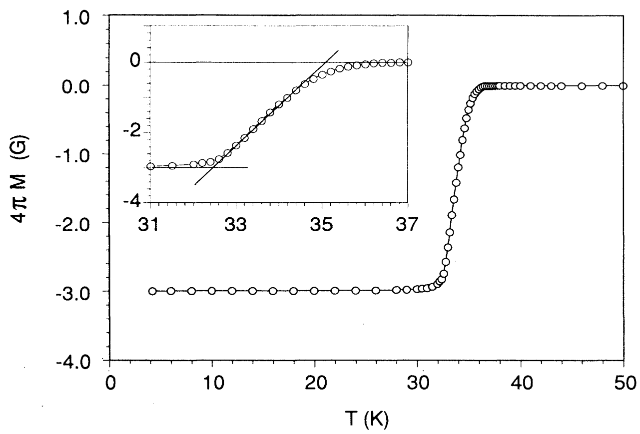

FIG. 1. Magnetic-shielding measurement of the LSCO single crystal C for a magnetic field of 2 Oe applied parallel to the c axis. The inset illustrates the method used for the determination of T_c.

All of the magnetization measurements were carried out in magnetic fields applied parallel to the c axis using a Quantum Design superconducting quantum interference device (SQUID) magnetometer with a 3-cm scan length, where the field inhomogeneity is estimated to be no greater than 0.5%. The irreversible temperature T_r for a magnetic field applied parallel to the c axis was measured first in order to determine the reversible-magnetization region within which the model of Hao *et al.* applies. The data were taken by measuring the magnetization versus temperature for each specimen at various fixed magnetic fields from T_r up to 85 K. A 10-min delay was introduced after each temperature change to stabilize the system so that the system temperature was always within

TABLE I. Composition, T_c, magnetic-penetration depth, Ginzburg-Landau parameter, and thermodynamic critical fields of $(La_{1-x}Sr_x)_2CuO_4$ single crystals.

	Sr content x		T_c (K)		$\lambda_{ab}(0)$ (Å)			
Sample	Nominal	ICP	Onset	Mean field[a]	Hao *et al.*[b]	London[c]	$H_c(0)$(Oe)	κ
A	0.05	0.046	26.2	28.20±0.55	4400±20	4920±30	1430	119
B	0.0625	0.059	32.4	32.10±0.20	3730±30	4450±70	1430	85
C	0.085	0.077	35.1	34.40±0.15	2545±40	3010±15	2510	70
D	0.10	0.090	29.8	29.80±0.10	2830±20	3135±75	2170	75

[a] Averaged value from fitting $\lambda_{ab}(T)$ derived from the model of Hao *et al.* to the BCS and empirical formulas.
[b] Determined by using the model of Hao *et al.*
[c] Determined by using the London approximation.

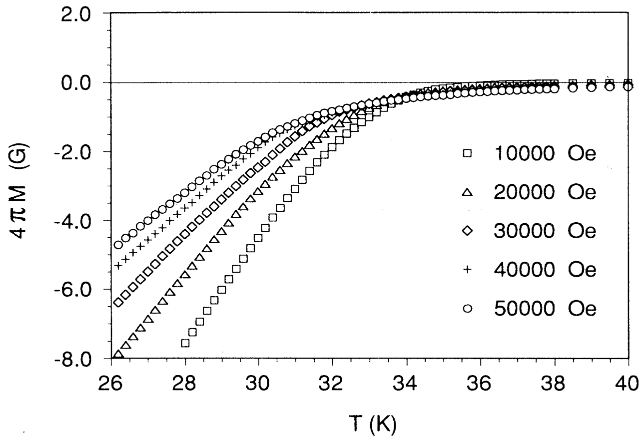

FIG. 2. Temperature dependence of the magnetization of the LSCO single crystal C measured in various magnetic fields applied parallel to the c axis.

± 0.02 K of the target temperature prior to measurement. An accuracy of better than 2×10^{-6} emu (equivalent to 2×10^{-3} G for the value of $4\pi M$ of crystal C) for magnetic moments was obtained for all the measurements. Because of the large fluctuation near T_c, background signals and normal-state magnetization were carefully subtracted by using the extrapolation of a curve fitted to the measured magnetic-moment–versus–temperature data between 60 and 85 K, which is similar to the method used earlier to study the c-axis-oriented superconducting $Bi_2Sr_2Ca_2Cu_3O_{10}$.[10,13] In this way we obtained the whole set of reversible $4\pi M(T)$-versus-T data for each superconducting LSCO specimen free of background in fields ranging from 1000 to 50 000 Oe. Shown in Fig. 2 are the plots of $4\pi M$ versus T for crystal C after subtracting the background for fields from 10 000 to 50 000 Oe. The large fluctuation effect in the vicinity of T_c is well illustrated by the crossover of various $4\pi M(T)$ curves. The induced large excessive diamagnetization was observed at temperatures up to 55 K.

III. RESULTS AND DISCUSSIONS

The large thermodynamic fluctuation near T_c for cuprate superconductors is one of the important properties intrinsic to their high transition temperature and layered structure. Fluctuation effects induce a significant amount of diamagnetic moment near T_c at high magnetic fields ($H \geq 10\,000$ Oe). As temperature is increased, or decreased away from T_c, this induced diamagnetism decreases. It was observed that, at sufficiently low temperatures, this induced diamagnetism becomes negligibly small as compared to the total magnetization.[10,13] Unfortunately, the specific way in which this induced diamagnetic moment changes as a function of temperature has not yet been established. Therefore, in order to apply any theory which does not, including thermodynamic fluctuation to study the mixed-state properties of high-T_c superconductors, the starting point naturally is to determine the temperature region where this fluctuation effect is small enough to be neglected. In Sec. III A we will demonstrate how to use the data-analysis technique, based on the variational model of Hao *et al.*, to solve this problem so as to determine $\lambda(T)$ of the superconducting LSCO system.

A. Determination of $\lambda(T)$ based on the variational model of Hao *et al.*

In our earlier study[10] on the reversible magnetization of $Bi_2Sr_2Ca_2Cu_3O_{10}$, we found that the Ginzburg-Landau parameter κ is one of the sensitive parameters, which can indicate how large the influence of the fluctuation on the magnetization of a superconductor is. According to phenomenological Ginzburg-Landau theory, κ is defined as the ratio of penetration depth λ to coherence length ξ. In terms of the magnetization measurement of an extreme type-II superconductor, the value of $1/\kappa^2$ roughly reflects the slope of magnetization versus field at fixed temperature.[18] In conventional type-II superconductors, the value of κ is nearly a constant or rather slowly decreasing with increasing temperature.[19] When the induced diamagnetism from fluctuation effects sets in near T_c, as illustrated by the data taken at 50 000 Oe in Fig. 2, the slopes of magnetization versus field at these temperatures start to decrease, which makes the value of κ appear to be increasing. Thus the temperature dependence of κ provides a good indicator of the extent to which fluctuation affects the magnetization.

The temperature dependence of κ can be obtained by utilizing the variational model of Hao *et al.* The detailed description of this method has been given in Ref. 10. In a brief summary, the general equation (20) of Ref. 11 together with $-4\pi M = H - B$ were used to fit the data of the magnetization, $4\pi M(H)$ versus H, at each fixed temperature, where the fitting parameters are κ and the thermodynamic critical fields $H_c(T)$. The experimental value of κ is determined to give the smallest deviation of $H_c(T)$. Shown in Fig. 3 are the values of κ for crystal C, obtained from the fitting of $4\pi M(H)$ data in the region of 26.2–33.2 K. κ is nearly constant at low temperatures with a value of 68.95 at 26.2 K, then slowly increases at

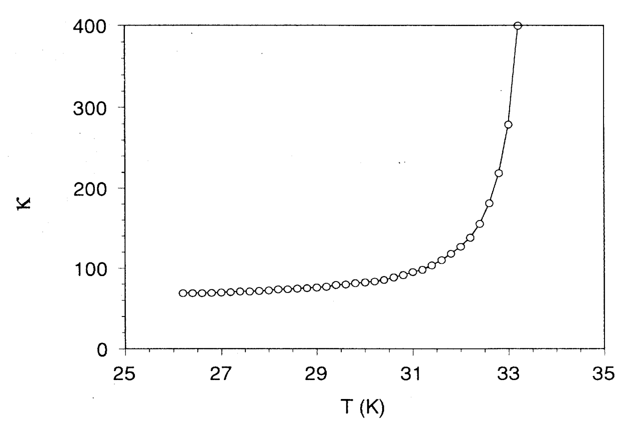

FIG. 3. Temperature dependence of κ of the LSCO single crystal C obtained by using the variational model of Hao *et al.*

temperatures above 28.2 K, and finally diverges around 33.2 K. This temperature dependence of κ shows that the fluctuation has a negligible effect on the magnetization at temperatures below 28.2 K, starts increasing as the temperature approaches T_c, and finally becomes the major contributor to the total diamagnetism at 33.2 K, which is just the temperature where all $4\pi M$-versus-T curves cross in Fig. 2.

By using the average value of κ (69.8) between 26.2 and 28.2 K, $H_c(T)$ can be obtained directly as a fitting parameter, which was in turn used to calculate $\lambda_{ab}(T)$, via $\sqrt{2}H_c=\kappa\phi_0/2\pi\lambda^2$. Such determined experimental values of $\lambda_{ab}(T)$ for crystal C are plotted as open circles in Fig. 4. To check the sensitivity of these derived values of $\lambda_{ab}(T)$ on the choices of κ in this fitting procedure, we carried out a similar fit to the same data set taken on crystal C with a different value of κ (71.8), instead of experimental value of 69.8. The result shows that such an obtained value of $\lambda_{ab}(T)$ with $\kappa=71.8$ is higher than that obtained by using the experimental value of $\kappa=69.8$ by only 1.0%. Thus we believe the small error of κ, which might come from the fitting uncertainty, does not lead to a significant change in our result of $\lambda_{ab}(T)$ reported here.

Three different formulas describing the temperature dependence of $\lambda_{ab}(T)$ are used to fit the data of $\lambda_{ab}(T)$ in Fig. 4 between 26.2 and 28.2 K. An attempt was made to fit the data by means of a two-fluid model having the form of

$$\lambda(T)/\lambda(0)=[1-(T/T_c)^4]^{-1/2} .$$

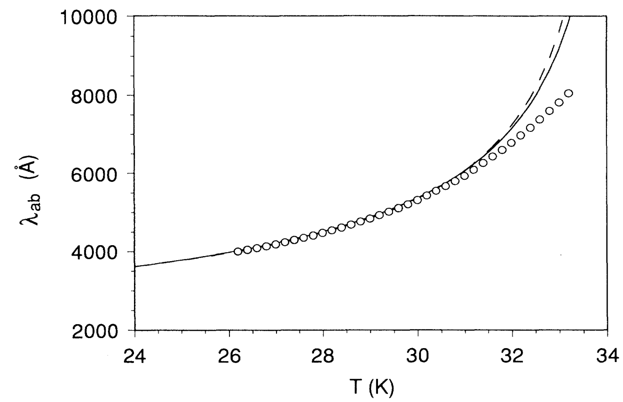

FIG. 4. Temperature dependence of the experimental data $\lambda_{ab}(T)$ (shown as open circles) of the LSCO single crystal C, obtained by using the variational model of Hao *et al.*, with a constant κ value of 69.8, where the solid line shows a BCS formula fit and the dashed line shows an empirical formula fit.

However, this form of the temperature dependence failed to reproduce the experimental data. One the other hand, a rather good fitting was achieved with the BCS formula [Eq. (1)] given by Clem,[20]

$$\frac{\lambda(T)}{\lambda(0)}=\left\{1.7367\left[1-\frac{T}{T_c}\right]\left[1-0.2730\left[1-\frac{T}{T_c}\right]-0.0949\left[1-\frac{T}{T_c}\right]^2\right]\right\}^{-1/2} , \tag{1}$$

or with the empirical formula

$$\lambda(T)/\lambda(0)=[1-(T/T_c)^2]^{-1/2} ,$$

where both $\lambda_{ab}(0)$ and T_c are chosen as free parameters. The fitting results are displayed by a solid line for the BCS formula and a dashed line for the empirical formula in Fig. 4, respectively. It is found that the fit with the BCS formula is as good as that with the empirical formula at temperatures up to 30.6 K. The fact that the experimental values of $\lambda_{ab}(T)$ at temperatures above 30.6 K are lower than that from both the fitting curves is simply due to the excessive fluctuation-induced diamagnetism near T_c which introduces the increased "apparent" condensation energy $[\propto H_c^2(T)]$ into the system and in turn gives a smaller value for the penetration depth $[\propto H_c^{-1/2}(T)]$ than the actual value. The derived value of $\lambda_{ab}(0)$ for crystal C, via fitting to the BCS formula, is 2507 ± 15 Å with $T_c=34.50\pm0.02$ K, while the value of $\lambda_{ab}(0)$, via fitting to the empirical formula, is 2583 ± 20 Å with $T_c=34.27\pm0.02$ K. The values of $\lambda_{ab}(0)$ determined from these two fitting procedures differ by only 3%, while the difference for T_c is less than 0.25 K. Thus the averaged values from these two fittings, $\lambda_{ab}(0)=2545\pm40$ Å and $T_c=34.40\pm0.14$ K, are taken as our experimental results for crystal C. Actually, this derived value of $\lambda_{ab}(0)$ of LSCO with Sr content at 0.077 is quite close to the value of $\lambda(0)$ ($\sim$2500 Å), which was estimated by Aeppli *et al.*[1] based on a muon-spin-relaxation measurement on a LSCO polycrystalline sample with Sr content of 0.075.

The magnetic-penetration depths $\lambda_{ab}(T)$ for the other three single crystals are determined in the same way as for crystal C. The temperature dependence of $\lambda_{ab}(T)$ for these cuprates was also found to fit rather well with either the BCS formula or the empirical one. It is the short reversible-magnetization temperature regions in these specimens which make it difficult to determine which model would more precisely represent the real temperature dependence of $\lambda_{ab}(T)$ for the superconducting LSCO system. Since the fluctuation effect near T_c inevitably exists, in order to perform an unambiguous temperature fit one has to obtain sufficient lower-temperature reversible-magnetization data. This means the sample must have extremely low pinning, which certainly is not the case observed in the single crystals we studied, particularly for the specimens with high Sr content. Well-annealed grain-aligned powdered samples might be possible candidates for a precise determination of the temperature dependence of $\lambda_{ab}(T)$ of this LSCO family. Nevertheless, the values of $\lambda_{ab}(0)$ and T_c obtained from the fitting of both the BCS and empirical formulas to the experimental data of $\lambda_{ab}(T)$ for each of the four crystals that we studied are rather close. In Table I are shown the average values of $\lambda_{ab}(0)$ and T_c from two fitting formulas, while the differences between them are included in the errors.

B. London approximation

As mentioned in the Introduction, the other possible way of obtaining $\lambda(T)$ from magnetization measurements is to use the London approximation.[5] London theory studies the mixed state of a type-II superconductor in the intermediate-field range, i.e., $H_{c1} \ll H_{ex} \ll H_{c2}$. In high-$T_c$ cuprates, most of magnetization measurement indeed falls into this broad field domain where the vortex cores are not overlapped. Since the coherence lengths of high-T_c cuprates are usually much smaller than the interspacing between the vortex cores under magnetic fields in most experiments, the core energy is believed to make an insignificant contribution to the total energy of a superconductor. Within this assumption the reversible magnetization $4\pi M$ in this domain has been shown to be linear versus the logarithm of the applied field.[5] In the case of a field applied parallel to the c axis, the slopes of the straight lines $4\pi M(\ln H)$ are given by the equation

$$\frac{d[4\pi M(T)]}{d(\ln H)} = \frac{\phi_0}{8\pi^2\lambda_{ab}^2} , \qquad (2)$$

where ϕ_0 is the flux quantum $hc/2e$. This general behavior of magnetization isotherms is found to be true for many high-T_c cuprates.

Typical isotherms of $4\pi M$ versus $\ln(H)$ in the reversible region for crystal C are displayed in Fig. 5. At low temperatures, for instance, at 27.0 K, a good linearity of $4\pi M$ versus $\ln(H)$ clearly exists. However, as the temperature increases, the high-field data begin to deviate away from the straight line. This is likely due to the fluctuation-induced diamagnetism, which can be easily observed from the data taken at temperatures above 31.0 K shown in Fig. 5. To determine the value of $\lambda_{ab}(T)$ in the London approximation, the slope was first obtained from the straight part of $4\pi M$ versus $\ln(H)$, as illustrated in Fig. 5. Then Eq. (2) was used to calculate $\lambda_{ab}(T)$.

London theory itself does not provide a way to distinguish the temperature region where the fluctuation has a non-negligible effect on the total magnetization. Most previously published results on the temperature dependence of $\lambda(T)$ of high-T_c cuprates, which are determined using the London approximation, are based on an overall fit of the measured $M(T,H)$ data up to T_c. When temperatures are close to T_c, the fluctuation-induced diamagnetic moment increases as the field increases, so that the slope of $4\pi M$ versus $\ln(H)$ becomes smaller than it should be without fluctuation effects. Therefore the derived value of $\lambda(T)$, obtained by applying Eq. (2), is usually higher than its real value, particularly near T_c. This overestimate of $\lambda(T)$ can be frequently found in the earlier literature.[5,6] Below, we present a comparison between the London approximation and our data-analysis technique on the determination of $\lambda(T)$.

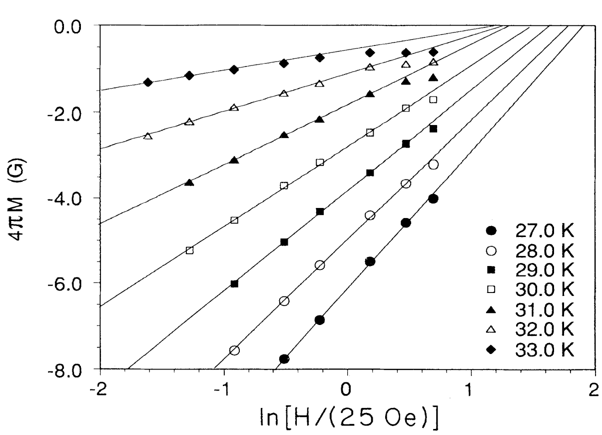

FIG. 5. Isotherms of magnetization $4\pi M$ for the LSCO crystal C plotted against $\ln(H/25\,000$ Oe).

In Fig. 6 we plotted two sets of data of $\lambda_{ab}(T)$ for crystal C determined by the two different methods. One is from the London approximation (represented by open circles), and the other is based on the model of Hao *et al.* (represented by solid circles). It was found that each value of $\lambda_{ab}(T)$ at temperatures below 28.6 K, derived from the London approximation, is higher by nearly the same amount ($\approx 20\%$) than the corresponding value of $\lambda_{ab}(T)$, derived from the model of Hao *et al.* As stated in Sec. III A, the fluctuation has negligible effects on the total magnetization only at temperatures below 28.2 K. Thus the temperature fitting using either the BCS or empirical formula to the $\lambda_{ab}(T)$ data, obtained by the London approximation, has to be restricted to temperatures below 28.2 K, just as in the case with the model of Hao *et al.* Two lines shown in Fig. 6 are the fitting curves of the BCS formula to the $\lambda_{ab}(T)$ data, where the solid line is a fit to the data obtained from the London approximation and the dotted line is a fit to the data from the model of Hao *et al.* The derived value of $\lambda_{ab}(0)$ by the London approach is 3010 ± 15 Å, which is 20% higher than that by the model of Hao *et al.*, while the value of $T_c = 34.63\pm0.08$ K, obtained by the London approximation, is almost the same as that by the model of

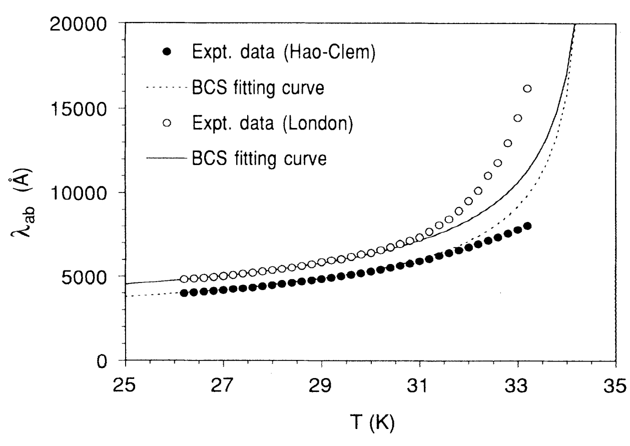

FIG. 6. Comparison of temperature dependence of $\lambda_{ab}(T)$ for the LSCO single crystal C, obtained by a method based on the variational model of Hao *et al.* (solid circles) and by the London approximation (open circles), where lines are BCS fits to the experimental data between 26.2 and 28.2 K.

Hao *et al.*(T_c =34.50±0.02 K). Therefore we can conclude that $\lambda(T)$ data obtained by the London approximation has essentially the same temperature dependence as that by the variational model of Hao *et al.*, except that the absolute value of $\lambda(T)$ is higher by a certain amount, because of the exclusion of vortex-core energy in the London approximation. This conclusion is found to be true for all four single crystals that we studied. The values of $\lambda_{ab}(0)$ and T_c determined for each of them by the London approximation are summarized in Table I. But the difference in the absolute values of $\lambda(T)$ determined by these two methods depends on how important the vortex-core energy is to the total Ginzburg-Landau free energy of the system. We found this amount to be different for each LSCO crystal. A 12% difference of the value of $\lambda(T)$ was observed for crystal A, 19.5% for crystal B, and 13.5% for crystal D. This unequal difference is presumably related to their slightly different electronic structures. The other important issue to be emphasized here is that the fluctuation effects can substantially increase the values of $\lambda(T)$ for the LSCO system at temperatures near T_c obtained from the London approximation, as demonstrated in Fig. 6. Thus the London-approximation-derived values of $\lambda(T)$ at temperatures near T_c, for instance, $T \geq 31.2$ K for crystal C, must not be used in the temperature fitting of $\lambda(T)$ for the determination of $\lambda(0)$ and the mean-field T_c of this LSCO family.

C. Sr-content dependence of $\lambda_{ab}(0)$

Figure 7 shows the data of $\lambda_{ab}(0)$ and T_c for the superconducting LSCO system plotted as a function of Sr content. For purpose of comparison, we also plot the values of $\lambda_{ab}(0)$ and T_c for one LSCO polycrystalline sample with Sr content of 0.075, determined from muon-spin-relaxation measurements, taken from Ref. 1. A minimum value of $\lambda_{ab}(0)$ was observed at the Sr content

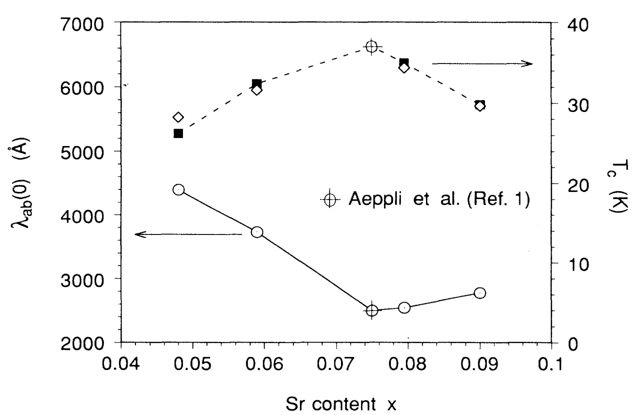

FIG. 7. Experimental data of $\lambda_{ab}(0)$ (represented by open circles) and T_c for the LSCO superconducting family are plotted as a function of Sr content, where the data points with a Sr content of 0.075 are from Ref. 1. The open diamonds represent the results of mean-field T_c from a BCS fit to the experimental data of $\lambda_{ab}(T)$, while the solid squares show the value of T_c at the onset determined from low-field shielding measurements.

giving the highest T_c. We know that the zero-temperature London penetration depth $\lambda_{ab}(0)$ is proportional to $(m_{ab}^*/n_s)^{1/2}$, where m_{ab}^* is the effective mass in the a-b plane and n_s is the superconducting carrier concentration. Therefore the behavior of $\lambda_{ab}(0)$ as a function of Sr content, displayed in Fig. 7, is equivalent to the fact that n_s/m_{ab}^* reaches the maximum value at the Sr content giving the higher T_c. Obviously, this result contradicts the earlier report by Uemura *et al.*,[21] where n_s/m_{ab}^* is found to be continuously increasing with Sr content increasing from $x=0.04$ up to 0.105. Their conclusion is drawn from the muon-spin relaxation rate measurements, made on a series of randomly oriented polycrystalline LSCO samples. Thus their results reflect an angular average over λ_{ab} and λ_c. From our magnetization measurements of LSCO single crystals with different field orientations (∥ and ⊥ to the c axis), we have found that the anisotropic ratio of $\lambda(0)$ for LSCO changes with Sr content.[22] The other factor that may have non-negligible influence on the conclusion of Uemura *et al.* is the possible nonuniformity of Sr doping, which gave a significantly broad transition of their specimen, as compared to our LSCO single crystals. Hence we believe that the relationship of $\lambda_{ab}(0)$ and T_c to the Sr content presented in this study is probably closer to the superconducting characteristics of the CuO plane in the LSCO family.

It is difficult to separately determine that either n_s or m_{ab}^* is a primary factor responsible for the behavior of $\lambda_{ab}(0)$ as a function of Sr content stated above, since there is no reliable data available on the individual measurements of n_s, m_{ab}^* for the LSCO superconducting family. Most of measurements of the carrier concentrations of LSCO are normal state. For example, Takagi *et al.*[17] measured the Sr-content dependence of the Hall coefficient R_H at 80 and 300 K, where a positive R_H is found to decrease rapidly with increasing Sr content for $x<0.15$. Chen *et al.*[23] and Fischer *et al.*[24] performed measurements on the Sr-content-dependent hole concentration of LSCO by measuring the oxygen K edge of the soft x-ray-absorption spectra. Their results also show the fact that the increase in the Sr content in LSCO monotonically raises the hole concentration of the normal state n_n. It is possible, but not necessary, that the carrier densities are the same in the normal and superconducting states. Fiory *et al.*[25] studied the normal and superconducting states of $YBa_2Cu_3O_7$, probed by an electrostatic charge-modulation technique, and they have observed that the normal excitations in this system do condense into superconducting pairs below T_c, so that the hole-carrier densities are nearly the same in both the normal and superconducting states within the experimental uncertainty (20%) for $YBa_2Cu_3O_7$. If assuming that all measured normal-state holes of LSCO are transferred into superconducting carriers for all the compositions, or at least in the same proportion, we must have a different effective mass m_{ab} in the CuO plane of LSCO for different Sr contents. In particular, after the Sr content is beyond the peak value which produces the highest T_c, an increase of effective mass in the CuO plane (m_{ab}) would be needed to explain the slow increase of the value of $\lambda_{ab}(0)$ for the overdoped compositions. On the other hand, if we assume that the phonon dressing is the same for all compositions that we studied so as to keep the effective mass m_{ab} a constant, we must have some mechanisms causing a different effectiveness of condensation of the normal excitation into the superconducting pairs for different Sr contents so that the superconducting carrier concentration n_s decreases beyond the Sr content $x=0.075$. Obviously, we cannot exclude the possibility that both m_{ab} and n_s vary with Sr content. A more detailed study on the individual relationship of m_{ab} and n_s with Sr content is certainly needed.

We also noted that the Sr-content dependence of derived $H_c(0)$ from the same data set of magnetization agrees well with that of $\lambda_{ab}(0)$. The corresponding values of $H_c(0)$ and κ with respect to each of the four LSCO crystals that we studied are listed in Table I. It was found that the composition corresponding to the highest T_c value has the highest condensation energy ($\propto H_c^2$), as well as the lowest $\lambda_{ab}(0)$.

IV. CONCLUSION

A data-analysis technique, based on the variational model of Hao *et al.*, has been demonstrated to be a powerful tool for the determination of the magnetic-penetration depth $\lambda(T)$ of layered high-T_c superconductors. By using this technique, we have obtained the temperature-dependent penetration depth of a series of LSCO single crystals over a wide range of Sr content. Both the BCS and empirical formulas are found to be quite adequate for describing the temperature dependence of $\lambda_{ab}(T)$ of the LSCO family. The derived values of $\lambda_{ab}(0)$ show a minimum at the Sr content which gives the highest T_c. In the temperature region where the fluctuation effects are insignificant, the conventional London approximation has been shown to give essentially the same temperature dependence of $\lambda_{ab}(T)$ as that determined by our technique, except for a higher absolute value of $\lambda_{ab}(T)$.

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