Strong-coupling effects on the temperature dependence of penetration depth in $YBa_2Cu_3O_{7-\delta}$ thin films near T_c

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We present accurate experimental data on the temperature dependence of the penetration depth λ in c-axis-oriented $YBa_2Cu_3O_{7-\delta}$ thin films close to T_c. The samples were grown *in situ* on $LaAlO_3$ (100) single-crystal substrates. The penetration depth measurements are performed by an inverted microstrip method, using resonators of different geometries. Near T_c we compare the three-dimensional (3D) XY critical regime and the Ginzburg-Landau (GL) behavior. Our data show that the GL approach follows the observed temperature dependence closer than the 3D XY model. The experimental results are discussed in the light of recent models describing the effect of strong coupling on the $\lambda(T)$ behavior near T_c for an s-wave and a d-wave high-temperature superconductor. [S0163-1829(97)03737-5]

Recent measurements[1] of the electromagnetic penetration depth λ in single crystals of $YBa_2Cu_3O_{7-\delta}$ for temperatures very close to T_c have shown a dependence $\lambda(T)\propto(1-T/T_c)^{-1/3}$ consistent with critical behavior of the three-dimensional (3D) XY model.[2] This result, obtained observing the frequency perturbation in a microwave cavity, seems to be in agreement with previous thermodynamic and transport studies.[3,4] However, kinetic inductance measurements performed at low frequency on $YBa_2Cu_3O_{7-\delta}$ thin films[5,6] indicate a mean-field-like exponent $[\lambda(T)\propto(1-T/T_c)^{-1/2}]$ well within the nominal critical region. It has been argued[6] that finite-size effects on the samples, if not included in the data analysis, can produce the discrepancy in the observed results.

In this report we present data on the temperature dependence of the penetration depth of $YBa_2Cu_3O_{7-\delta}$ thin films using microstrip resonators of different geometries. The results are compared with measurements performed on Nb_3Sn thin films by the same technique.

The $YBa_2Cu_3O_{7-\delta}$ thin films (thickness 3000 Å) were grown *in situ* on $LaAlO_3$ (100) single-crystal $10\times10\times0.5\ mm^3$ substrates by an inverted cylindrical magnetron sputtering (ICMS) technique. The deposition method has been discussed in detail in Ref. 7. The samples typically show zero dc resistance at 90 K, with transition widths below 1 K. Normal-state resistivities above T_c range between 40 and 50 $\mu\Omega$ cm. All the films measured are c-axis oriented and show superior structural properties, with an high degree of epitaxy.

The penetration depth measurements were performed by an inverted microstrip resonator technique, already described elsewhere.[8] Each sample is made using two films (microstrip and ground plane) grown with the same nominal deposition conditions. Resonators of different geometries have been used, meander line or annular shaped by standard photolithography. The width of the microstrip lines was between 200 and 500 μm. The dielectric layers used were sapphire or Teflon, respectively, 100 and 10 μm thick.

By this method, the quality factor Q (inversely proportional to the surface resistance R_s) and the change in the resonant frequency f_0 (proportional to $\Delta\lambda$) are simultaneously measured from 4.2 K up to values very close to the critical temperature of the films. However, the low signal-to-noise ratio near T_c makes very difficult and unreliable the determination of the Q values with the standard 3-dB-bandwidth method, allowing only the measurement of the maximum in the frequency resonance curve up to the temperature value in correspondance of which the signal disappears. This temperature in the best measurements corresponds to $0.995T_c$, whose value is estimated, as discussed below, fitting the $f_0(T)$ curve. The critical temperature values found using the rf technique are about 1 K lower than using a four-point dc resistivity method. In the following, we will refer our analysis to the rf estimated T_c.

A resonator based on Nb_3Sn films (5000 Å thick), grown on single-crystal sapphire by a dc magnetron sputtering technique, was also tested for comparison.

The microstrip resonant technique allows to measure with extreme accuracy the variations in the penetration depth, using the phase velocity expression for a lossless transmission line:

$$v_p=\frac{c/\sqrt{\varepsilon_{\rm eff}}}{\sqrt{1+(2\lambda/h)\coth(t/\lambda)+g_c{\rm csch}(t/\lambda)}},\qquad(1)$$

valid for aspect ratio $w/h\geqslant1$ (Ref. 9) (w is the microstrip width). In relation (1), c is the speed of light in vacuum, $\varepsilon_{\rm eff}$ the effective dielectric constant, and h and t are the dielectric and film thickness respectively, while the factor g_c takes into account contributions from field fringing. As shown in detail in Ref. 9, for $w/h\gg1$ (as always verified in our measurements), this last term can be neglected.

The phase velocity v_p is related to the measured quantity, the resonant frequency f_0, through the relation

$$f_0=\frac{v_p}{D},\qquad(2)$$

where D is the effective length of the resonator. In our measurements the first resonant mode ranges between 1.5 and 3.5 GHz.

All the samples have been also measured at low temperatures. In our $YBa_2Cu_3O_{7-\delta}$ films, λ increases quadratically with temperature.[10] The behavior of Nb_3Sn is instead well described in the framework of the usual BCS formalism,[11] with standard strong-coupling corrections.

Near the critical temperature, however, relation (1) should be used with some caution.

First of all, the transmission line cannot be considered anymore lossless, and the possible ''pulling down'' of the resonance frequency due to damping oscillations should be taken into account. The fractional change in f_0 due to losses has been evaluated to be[12] $\Delta f_{\rm loss}/f_0 \approx -1/4Q^2$. This value must be compared with the sensitivity limit of the resonance curve method, which in our case is estimated to be $\Delta f/f_0 \approx (4\times 10^{-2})/Q$. Also, very close to T_c (minimum Q values of about 20), the measurement resolution in λ is about 5 times lower than the maximum systematic error introduced by ''damping.''

In a microstrip configuration, because of the quasi-two-dimensional field distribution, electromagnetic fields are not entirely confined to the dielectric between the strip and ground plane films. Moreover, for $T \geqslant 0.95T_c$ the penetration depth exceeds the thickness of the $YBa_2Cu_3O_{7-\delta}$ superconducting films. Thus the effective dielectric constant will depend on the temperature-dependent relative dielectric constants of both the dielectric layer and the substrates much more than it will do at low temperatures. A simple calculation shows that in the worst case[13] $(1/\varepsilon_r)\Delta\varepsilon_r/\Delta T$ should be less than 10^{-4} K^{-1} to have no influence on the determination of the penetration depth. Recent measurements[14] indicate that the permittivities of $LaAlO_3$, sapphire, and Teflon are pratically constant at low temperatures, with fractional dielectric temperature variations lower than 10^{-5} K^{-1}. Other effects due to thermal variations of transmission line dimensions are discussed in detail in Ref. 12 and shown to be neglectable.

Finally, finite-size effects have been found[6] to affect the critical behavior in measurements of complex ac conductance. This is because near T_c the film impedance variations will change the current distributions and ultimately the temperature dependence of the response signal. An accurate analysis of this contribution is not simple because the current density in the microstrip depends on the kinetic inductance of the superconducting films, which is, in turn, dependent on the penetration depth.[15] However, analysis of Nb and Nb_3Sn samples, shaped with the same size and geometry of the $YBa_2Cu_3O_{7-\delta}$ samples, rules out the influence of boundary effects on the behavior of the penetration depth near T_c. These microstrips fully satisfy the Ginzburg-Landau (GL) predictions from T_c down to about $0.8T_c$. The absence of finite-size effects in the resonator inductance is likely related to the increase in the uniformity of the current distribution in the microstrip line,[16] since very close to T_c the penetration depth exceeds the film thickness.

Near T_c, we compare for YBCO the three-dimensional (3D) XY critical regime and the GL behavior, using the expression

$$\lambda(T) = \lambda^*(1 - T/T_c)^{-n}, \qquad (3)$$

where $n = 1/3$ and 1/2, respectively. Fixing n and fitting the experimental data close to the transition through relations (1) and (2), one can yield the quantities λ^* and T_c for each of the two exponents n. The only assumption one has to make is $f_0(4.2\ \mathrm{K}) \approx f_0(0)$, in order to estimate independently the value of $\varepsilon_{\rm eff}$.[17]

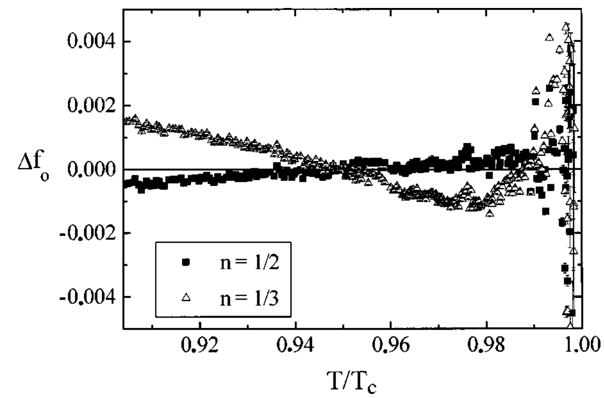

FIG. 1. Deviation Δf_0 of the fitting curves from the experimental resonant frequencies, using relation (3) and $n = 1/2$ or 1/3, respectively, for one of the $YBa_2Cu_3O_{7-\delta}$ samples as a function of temperature near T_c.

The results of the two different expressions for one of the c-axis $YBa_2Cu_3O_{7-\delta}$ sample (Y130) are shown in Fig. 1 in terms of the quantity Δf_0. This represents the deviation of the fitting curves, using relation (3) from $0.9T_c$ up to the critical temperature. One can see that the fit using the GL expression shows a better agreement with the experimental results. The scattering of the points observed in the figure approaching T_c is due to the larger indetermination affecting the experimental data near the critical temperature. The estimated critical temperatures are very close to each other: $T_c = 88.53 \pm 0.04$ K for $n = 1/2$ and $T_c = 88.38 \pm 0.05$ K for $n = 1/3$. On the contrary, the values of the coefficient λ^* are quite different: $\lambda^* = 1060 \pm 20$ Å for the GL theory and $\lambda^* = 2570 \pm 50$ Å for the 3D XY model.

It is worth noting that only a deviation plot method and very accurate data can help to discern the correct power law. In fact, if one plots as a function of temperature T, using the corresponding values of λ^* and critical temperature, the quantity $[\lambda^*/\lambda(T)]^2$ for the GL law and the quantity $[\lambda^*/\lambda(T)]^3$ for the 3D XY law, close to T_c a clear linear behavior is observed in both cases.

Our experimental data show that the GL approach explains the observed behavior better than the 3D XY model does. However, without any assumption on the temperature dependence of the penetration depth, the microstrip technique is not suitable to give absolute values of λ in the overall temperature range.

Since the microscopic model for the electromagnetic response of superconducting $YBa_2Cu_3O_{7-\delta}$ is still a matter of debate, to estimate independently the zero-temperature magnetic screening penetration depth in our samples we used the simple two-fluid model through the phenomenological relation $\lambda(T) = \lambda^{2\mathrm{fl}}(0)[1 - (T/T_c)^4]^{-1/2}$, which is considered to hold well for London superconductors. More precisely, fitting the experimental data with the two-fluid expression throughout all the temperature region (from 4.2 K to T_c) should give a reasonable estimation of the zero-temperature London penetration depth $\lambda_L(0)$, that is, $\lambda^{2\mathrm{fl}}(0) \approx \lambda_L(0)$.

From the experimental $f_0(T)$ curves, values of $\lambda_L(0)$

TABLE I. Fit results for the $YBa_2Cu_3O_{7-\delta}$ and Nb_3Sn samples. $\lambda_L(0)$ and T_c for the $YBa_2Cu_3O_{7-\delta}$ films are obtained fitting the overall $f_0(T)$ curve within the two-fluid model, while for Nb_3Sn they are estimated using the complete BCS expression (Ref. 11). λ^* is extracted from the data near T_c using relation (3) with $n=1/2$ (see text).

Sample	$\lambda_L(0)$ (Å)	T_c (K)	$[\lambda_L(0)/\lambda^*]^2$
Y32	2200±100	89.5 ±0.1	4.4±0.4
Y105	3500±300	89.7 ±0.1	3.5±0.6
Y130	2100±100	88.5 ±0.1	4.2±0.4
Nb_3Sn	8500±300	15.97±0.05	3.2±0.2

ranging between 2000 and 3500 Å are extracted (see Table I). This is in reasonable agreement with other microwave,[18] mutual inductance,[19] and far-infrared[20] measurements of $YBa_2Cu_3O_{7-\delta}$ thin films.

Strong coupling increases the screening of the external magnetic field inside a superconductor and therefore affects the temperature slope of the penetration depth. This is particularly evident near T_c. The coupling strength can be evaluated from the quantity[21,22]

$$T_c\left|\frac{d}{dT}\left[\frac{\lambda_L(0)}{\lambda_L(T)}\right]^2\right|_{T=T_c}=F(\alpha), \tag{4}$$

where $\lambda_L(T)$ is the temperature dependence of the penetration depth in the London regime, while F is a function of the ratio $\alpha=T_c/\Omega$ and its explicit form depends on the symmetry of the order parameter in the superconductor. Ω represents a characteristic energy scale involved in the pairing mechanism, which can be otherwise left unspecified. Using Eqs. (3) and (4) one can relate the function F to the experimentally evaluated quantities $\lambda_L(0)$ and λ^* (from the GL model),

$$F(\alpha)^{1/2}=\frac{\lambda_L(0)}{\lambda^*}, \tag{5}$$

since in the London regime the equality $\lambda(T)=\lambda_L(T)$ holds.

For the case of $YBa_2Cu_3O_{7-\delta}$, the ratios $[\lambda_L(0)/\lambda^*]^2$ for the different samples measured are summarized in Table I. The values found are similar to that reported for single crystals in previous measurements in the ab plane by Mao *et al.*[23] The data for the Nb_3Sn, which is also a London superconductor, are shown for comparison.

In the framework of the BCS theory, a study on strong-coupling effects near T_c was carried out by Kresin and Litovchenko.[21] They found analytical expressions describing $\lambda(T)$ in strong-coupled superconductors, but the analysis was limited for $T_c \ll \Omega$. Semiphenomenological formulas involving the single parameter $\alpha=T_c/\Omega$ and valid for $\alpha \leq 0.25$ were then derived by Marsiglio *et al.*[22] with the aim of providing simple useful equations for strong-coupling corrections. For T near T_c and for a London, strong-coupling, isotropic s-wave superconductor in the clean limit, one has

$$F(\alpha)=\frac{2}{1-2\alpha+11\alpha^2\ln(4.5\alpha)}. \tag{6}$$

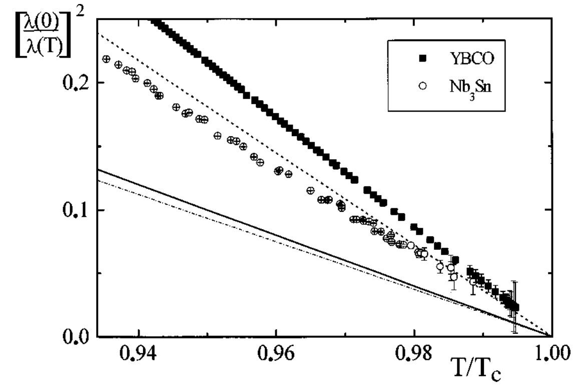

FIG. 2. $[\lambda(0)/\lambda(T)]^2$ vs T for an epitaxial c-axis $YBa_2Cu_3O_{7-\delta}$ sample and for Nb_3Sn. The solid line represents the BCS limit ($\alpha=0$), while the dotted and dashed lines are the expected behavior for an s-wave and a d-wave superconductor, respectively, in the strong-coupling theory using $\alpha=0.2$.

It is worth noting that in the weak-coupling limit the BCS result $F(\alpha)=2$ is recovered.[24]

One can use relations (5) and (6) to estimate for Nb_3Sn the value of α from the slope $[\lambda_L(0)/\lambda_L(T)]^2$ at $T/T_c=1$. We obtain $\alpha=0.15\pm0.02$, in agreement with previous results.[25]

For a d-wave superconductor, the function F will depend not only on the quantity α, but also on the d wave considered. Chi and Carbotte[26] evaluated F considering a $k_x^2-k_y^2$ superconductor and a spherical Fermi surface. Assuming a magnetic field perpendicular to the symmetry axis of the order parameter, they found

$$F(\alpha)\approx\frac{1.2}{1+\pi^2\alpha^2[8/3+2.5\ln(1.13\alpha)]}. \tag{7}$$

Relation (7) shows that in the weak-coupling limit of a $k_x^2-k_y^2$ d-wave superconductor the slope of the penetration depth curve near T_c is much lower than in the corresponding s-wave isotropic case. Besides that, numerical calculations[27] have shown that in d-wave superconductors strong-coupling corrections initially move the curve away from BCS in the direction indicated by relation (7), but this trend very quickly saturates and then reverses itself. According to the previous formula, the maximum in the function F occurs around $\alpha \approx 0.2$.

In Fig. 2 the temperature dependence $[\lambda_L(0)/\lambda(T)]^2$ close to T_c for Nb_3Sn and one of the $YBa_2Cu_3O_{7-\delta}$ samples (Y130) is shown. On the same graph the BCS result (solid line) and the s-wave (dotted line) and d-wave (dashed line) expectations for $\alpha=0.2$, as evaluated from Eqs. (6) and (7), respectively, are plotted. One can see that the steep rise of the superfluid density for all the $YBa_2Cu_3O_{7-\delta}$ films is in remarkable contrast to what predicted by the d-wave calculation. The results are instead fully compatible with a strong-coupling s-wave behavior.

Our data, however, should not be interpreted as a definite argument against d-wave theories. Rather, they only point out that a simple $k_x^2-k_y^2$ model, even with strong coupling, cannot be used to achieve a good fit with experiments.

On the other side, the agreement with the standard s-wave strong-coupling model has to be taken with some caution.

Relation (6) surely oversimplifies the description of an anisotropic, high-temperature superconductor like $YBa_2Cu_3O_{7-\delta}$, where more complex models,[28,29] taking into account the relevant role played by the CuO_2 planes and CuO chains in the description of electrodynamic and screening properties, should be applied.

In summary, our experimental data using YBCO microstrip resonators show that near T_c the temperature dependence of the penetration depth can be consistently described using a mean-field exponent, in agreement with the Ginzburg-Landau theory. From the comparison of simple s-wave and d-wave models, we draw to the conclusion that a $k_x^2-k_y^2$ symmetry is not able to account for the large slope observed in the penetration depth at $T \sim T_c$, which is instead compatible with a strong-coupling s-wave behavior.

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