Microwave Penetration Depth Measurements on $Bi_2Sr_2CaCu_2O_8$ Single Crystals and $YBa_2Cu_3O_{7-\delta}$ Thin Films

Zhengxiang Ma,[1] R. C. Taber,[2] L. W. Lombardo,[1] A. Kapitulnik,[1] M. R. Beasley,[1] P. Merchant,[2] C. B. Eom,[3] S. Y. Hou,[3] and Julia M. Phillips[3]

[1]*Department of Applied Physics, Stanford University, Stanford, California 94305*
[2]*Hewlett-Packard Laboratories, 3500 Deer Creek Road, Palo Alto, California 94304-1392*
[3]*AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974*
(Received 14 May 1993)

The temperature dependence of the magnetic penetration depth of $Bi_2Sr_2CaCu_2O_8$ single crystals and $YBa_2Cu_3O_{7-\delta}$ thin films has been measured with a parallel plate resonator technique at microwave frequencies. Both materials show a T^2 temperature dependence between 10 and 25 K, and systematic deviations towards a flatter temperature dependence below 10 K. We have also calculated the real part of the complex conductivity of $YBa_2Cu_3O_{7-\delta}$ thin films from our penetration depth and surface resistance data and compare them with those of $YBa_2Cu_3O_{7-\delta}$ single crystals.

PACS numbers: 74.25.Nf, 74.72.Bk, 74.72.Hs, 74.76.Bz

The zero-field magnetic penetration depth $\lambda(T)$ is a direct measure of the superfluid density of a superconductor. Its temperature dependence as $T \rightarrow 0$ reflects the low-lying single-particle excitations of a superconductor and therefore yields information regarding the pairing state in the material. Various pairing states have been proposed for the high-T_c materials [1]. In some cases the expected low-lying excitations have been explicitly discussed [2-6]. A major characteristic that differentiates these theories is whether or not there are nodes in the gap function. For any pairing state for which there is a finite excitation energy, the change in λ at low temperatures is $\Delta\lambda(T) \propto \exp(-\Delta/k_B T)$, where Δ is the minimum value of the energy gap over the Fermi surface. For pairing states with line nodes on the Fermi surface, $\Delta\lambda(T) \propto T^p$ [7], where $p=1$ for the simplest form of gap with d-wave symmetry. It has also been pointed out that for a d-wave superconductor impurity scattering could change the linear T dependence to T^2 [8,9]. Recently, it has even been argued that a low density of strong scatterers can lead to the formation of a gap in the single-particle excitation spectrum of a d-wave superconductor [10]. In any event it is clear that the limiting temperature dependence of $\lambda(T)$ as $T \rightarrow 0$ is an important diagnostic for exotic superconductivity.

There exist a large number of measurements of the penetration depth of the high-T_c cuprate superconductors, some of which have been used to draw conclusions about the nature of the pairing of these remarkable materials [11]. A high sensitivity approach was adopted by the Stanford-Hewlett-Packard group and is based on measurements of the resonant frequency of microstrip and parallel plate resonators formed from high-T_c $YBa_2Cu_3O_{7-\delta}$ (YBCO) superconducting thin films [12-15]. More recently high sensitivity has also been achieved by Hardy *et al.* [16] for single crystals using a cavity perturbation approach in a microcavity made from conventional superconductors. Both groups have studied YBCO. The results are significantly different.

The initial thin film resonator experiments were interpreted by Anlage *et al.* [15] to show evidence for a finite minimum energy gap. Bonn and co-workers [17] emphasized that the data from these films were also consistent with a T^2 temperature dependence. Subsequently Hardy *et al.* [16] reported a linear T dependence down to 12 K for YBCO single crystals, which they interpret as evidence for d-wave pairing. They argue that the difference between the data on YBCO thin films and single crystals results from the more disordered nature of thin films compared with single crystals. In addition, a group at the University of Maryland has reported a BCS-like temperature dependence of the penetration depth for the n-type cuprate superconductor NdCeCuO over the temperature range from a T_c of 22 K down to 4 K [18]. Clearly it is important to clarify the intrinsic temperature dependence of the penetration depth in the high-T_c cuprate superconductors and how it is affected by disorder.

In this paper we report measurements of the temperature dependence of the penetration depth at low temperatures on high-quality single crystals of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) using the parallel plate resonator technique. We also report improved measurements on a variety of YBCO thin films with a range of T_c's made using both *in situ* and postannealed techniques. Systematic differences between these films exist. However, both the BSCCO single crystals and the YBCO thin films exhibit a T^2 temperature dependence that rolls over to a weaker temperature dependence at the lowest temperatures. No evidence for a linear T dependence was observed in either case.

The details of the parallel plate resonator technique we employed are described elsewhere [12,13]. With this technique we obtain high resolution data with little scatter, especially at low temperatures. The data analysis is straightforward. Measurements are all carried out in the weakly coupled limit with low microwave power and in a partial vacuum with a small amount of helium exchange gas. The resonators are made by sandwiching a

0031-9007/93/71(5)/781(4)$06.00

thin dielectric between two YBCO thin films or two pieces of a freshly cleaved single crystal of BSCCO.

There is a simple relationship between the penetration depth and the resonant frequency of the parallel plate resonator, assuming open circuit boundary conditions,

$$f(T)=\frac{2c}{L\varepsilon_{\rm eff}^{1/2}\{1+[2\lambda(T)/d]\coth[t/\lambda(T)]\}^{1/2}},$$

where c is the speed of light, L is the length of the sample for the mode in question, $\varepsilon_{\rm eff}$ is the effective dielectric constant of the resonator, $\lambda(T)$ is the penetration depth of the sample, d is the thickness of the dielectric, and t is the thickness of the sample. Because of uncertainties in L and $\varepsilon_{\rm eff}$, we cannot directly invert this relationship and extract $\lambda(T)$. However, at low temperatures, where changes of penetration depth are small relative to $\lambda(0)$, we can expand this relation to obtain

$$\Delta\lambda=\lambda(T)-\lambda(T_0)=d_{\rm eff}\{[f(T_0)/f(T)]^2-1\},$$

where

$$d_{\rm eff}=\frac{d}{2}\Big/\frac{\coth[t/\lambda(0)]+t/\lambda(0)}{sh^2[t/\lambda(0)]}.$$

This provides a simple and clean way to determine the temperature dependence of the penetration depth at low temperatures independent of uncertain cavity parameters. The quality factor of the resonator yields a value for the surface resistance. The contributions of dielectric loss and radiation loss are negligible in the case of our thin film resonators.

To confirm the correctness of our measurement approach, we measured a pair of Nb thin films of thickness 2000 Å. Both the penetration depth data and surface resistance data at 10 GHz (corrected for the residual loss of about 3 $\mu\Omega$ at $T=0$) showed an exponential temperature dependence as $T\to 0$. Moreover they yielded $2\Delta=4.0$–$4.5k_BT_c$, slightly larger but consistent with previous work [19]. The lowest surface resistance measured in the Nb films is 4.4 $\mu\Omega$. This sets an upper limit for extrinsic contributions such as dielectric loss and radiation loss of the resonator.

Large area (5 by 3 mm) high-quality BSCCO single crystals were grown as reported elsewhere [20]. Their high degree of homogeneity and purity is shown by their narrow transition width (0.3 K) in magnetization measurements [20], extremely small pinning in the vortex state [21], and low temperature specific heat measurements [22]. An angular resolved photoemission study has also been reported recently on these single crystals [23]. To perform rf measurements on BSCCO single crystals, we sandwiched a piece of thin sapphire dielectric between two thin sheets of cleaved single crystals to form a parallel plate resonator. The Q's of the resonator are dominated by extrinsic factors due to the nonideal geometry, but the analysis of frequency shift data should remain meaningful.

The YBCO films we have studied come from three different sources. We present here the results on six pairs of films that we believe are representative. Among them are four pairs of *in situ* off-axis sputtered films, two on sapphire substrates with CeO_2 buffer layers from HP Labs [24] and two on $LaAlO_3$ substrates from AT&T Bell Labs [25]. The other two pairs are BaF_2 postannealed films on $LaAlO_3$ from AT&T [26]. The dielectric used is 13 μm thick Teflon in all measurements except for one pair of postannealed films, in which case 36 μm thick sapphire was used.

The penetration depth data for the BSCCO single crystals are shown in Fig. 1. In the figure we plot $\Delta\lambda(T)$ vs T^2 for temperatures below 23 K. The three sets of measurements, done on resonators obtained from three different crystals and with different dielectric thicknesses, are virtually identical. The data follow a T^2 law very closely except for a small deviation (see lowest curve) at the low temperature end. This result is in marked con-

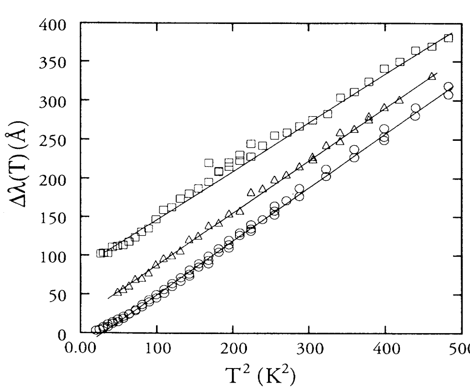

FIG. 1. $\Delta\lambda$ vs T^2 for three pairs of BSCCO single crystals. Curves are offset for clarity. The straight lines are T^2 fits to the data.

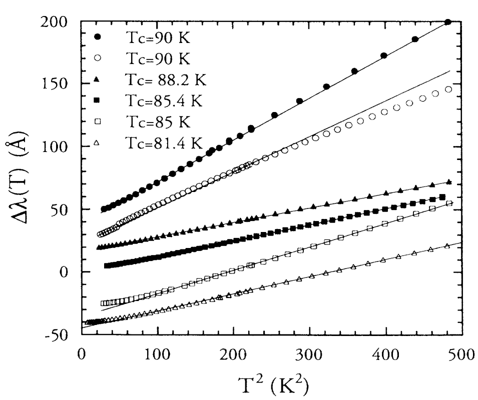

FIG. 2. $\Delta\lambda$ vs T^2 for six pairs of YBCO thin films. Data are offset from each other and ordered by their T_c's. The top two are for postannealed films. The straight lines are T^2 fits to the data.

trast with the linear temperature dependence on YBCO single crystals reported by Hardy *et al.* [16].

The penetration depth data for the YBCO thin films are shown in Fig. 2. It is quite evident that the temperature dependence is T^2 for all the samples, except at the lowest temperatures, where there is a deviation towards a flatter temperature dependence. There is considerable consistency among *in situ* films, with one exception. On the other hand, it is clear that curves for the postannealed films have higher slopes than those of the *in situ* films. They also show a larger power dependence at high rf power. Close inspection suggests that the deviation from T^2 observed at low temperatures may be correlated with the T_c of the sample. As the T_c increases, the observed deviations become smaller. Quantitative analysis shows that these deviations can be viewed either as a crossover to a higher order power law or to an activated behavior with a very small gap. For example, for the lowest T_c sample shown in Fig. 2, a power law fit to the data yields an exponent of about 5, and an exponential fit yields a gap 2Δ of about $0.56k_BT_c$.

The surface resistances of the YBCO films determined from Q measurements are shown in Fig. 3. They are clearly sample dependent. We note that the surface resistance data are not corrected for different film thicknesses. Nonetheless, the surface resistance of the postannealed films is clearly higher and has a plateau from 30 to 60 K, whereas the surface resistance of *in situ* films is generally lower and decreases continuously below T_c. The surface resistances approach their zero temperature values with a temperature dependence between T and T^2. No flattening of $R_s(T)$ as $T \rightarrow 0$ was observed.

In the thick film limit, $R_s(T) \propto \lambda(T)^3\sigma_1(T)$. Hence, the presence of a plateau in R_s and its absence in $\Delta\lambda$ implies a strong temperature dependence of $\sigma_1(T)$ as first emphasized by Nuss *et al.* [27] and Bonn *et al.* [17]. A peak in $\sigma_1(T)$ has also been independently predicted by Littlewood and Varma [6] based on a marginal Fermi liquid model. From our measurements we have both $R_s(T)$ and $\Delta\lambda(T)$. We only need to make a reasonable assumption for $\lambda(0)$ to obtain σ_1. We find that there indeed is an anomalous peak in σ_1 below T_c. This striking qualitative feature of the data is insensitive to the specific $\lambda(0)$ value used. The data are shown in Fig. 4 assuming $\lambda(0) = 1900$ Å, along with the single crystal data reported by Bonn *et al.* [17].

In light of the different temperature dependences of $\lambda(T)$ reported for the high-T_c cuprate superconductors, one must scrutinize possible extrinsic effects to deduce the intrinsic behavior. Laderman *et al.* [28] have shown previously that high densities of grain boundaries (i.e., planar defects) acting as weak links can dominate the surface resistance of YBCO thin films. No comparably detailed study of $\lambda(T)$ (i.e, the surface inductance) has been carried out. In this case, it is hard to argue that the weak link behavior would dominate in the entire range of samples and materials we have studied. Moreover, it is extremely unlikely that weak link effects would produce a flattening of $\lambda(T)$ at low temperatures. It has been suggested that YBCO films have sufficiently large scattering to change the intrinsic linear T dependence into T^2. In view of the fact that the same behavior is also observed in high-quality $Bi_2Sr_2CaCu_2O_8$ single crystals, we believe such an argument about the effects of scattering cannot be regarded as definitive. Possibly one has to consider the influence of the copper-oxygen chains on the electrodynamic response of YBCO.

Surface resistance measurements reported by Klein *et al.* [29] indicate that oxygen content and disordering strongly affect the temperature dependence of R_s, especially at low temperatures. Our R_s data for YBCO thin films show a significant sample dependence even within samples from the same process. Thus it is not possible to deduce the intrinsic temperature dependence of R_s from those data. Nonetheless, as shown in Fig. 4, there appears to be a systematic progression in $\sigma_1(T)$ from YBCO thin films to YBCO single crystals. In assessing

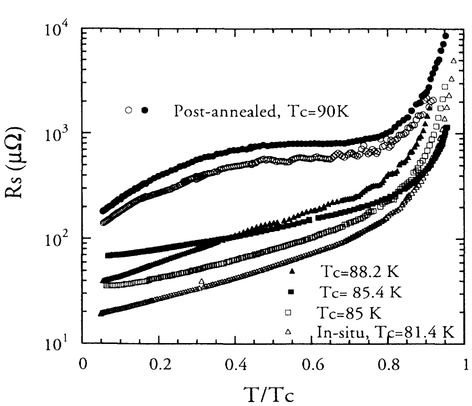

FIG. 3. R_s at 10 GHz vs T/T_c for six pairs of YBCO thin films.

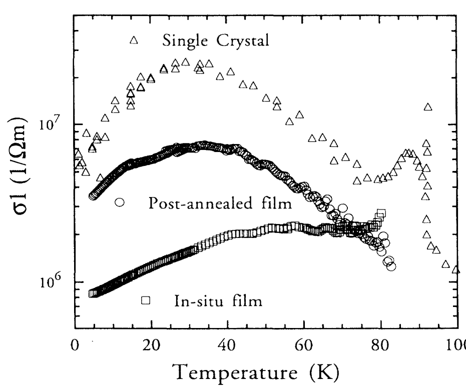

FIG. 4. σ_1 vs T for a single crystal YBCO at 2.0 GHz taken from Ref. [17], a pair of postannealed YBCO thin films and a pair of *in situ* YBCO thin films at about 10 GHz. All the curves were determined using an assumed $\lambda(0)$.

$R_s(T)$ data it is important to note that even in conventional superconductors (e.g., our Nb thin film parallel plate resonators), the temperature dependence of the penetration depth is less susceptible to extrinsic factors, for example, residual loss mechanisms, than is R_s.

In conclusion, we find in our work that the temperature dependence of magnetic penetration depth for both BSCCO single crystals and YBCO thin films is T^2 at low temperatures with a rolling over to a flatter temperature dependence at the lowest temperatures. The correlation between T_c and the microwave properties appears to suggest that disorder is playing an important role in the behavior of these films. A more thorough experimental study with better characterization of the disorder in the films is necessary to establish quantitative relations.

We would like to thank S. Doniach, R. Laughlin, J. Halbritter, D. Scalapino, and W. Hardy for helpful discussions. This work was supported by the NSF Grant No. ECS-92 14592 and the AFOSR.

[1] For a good discussion on this subject, please see P. W. Anderson and R. Schrieffer, Phys. Today **44**, No. 6, 54 (1991).
[2] R. B. Laughlin, Phys. Rev. Lett. **60**, 2677 (1988); (private communication).
[3] S. Chakravarty, A. Sudbø, P. W. Anderson, and S. Strong (to be published).
[4] D. J. Scalapino, E. Loh, Jr., and J. E. Hirsch, Phys. Rev. B **34**, 8190 (1986).
[5] P. Monthoux, A. V. Balasky, and D. Pines, Phys. Rev. Lett. **67**, 3448 (1991).
[6] P. B. Littlewood and C. M. Varma, Phys. Rev. B **46**, 405 (1992).
[7] J. F. Annett, N. Goldenfeld, and S. R. Renn, Phys. Rev. B **43**, 2778 (1991).
[8] F. Gross *et al.*, Z. Phys. B **64**, 175 (1986).
[9] M. Prohammer and J. P. Carbotte, Phys. Rev. B **43**, 5370 (1991).
[10] Patrick Lee (to be published).
[11] For a good review, please see B. Batlogg, Phys. Today **44**, No. 6, 44 (1991).
[12] R. C. Taber, Rev. Sci. Instrum. **61**, 2200–2206 (1990).
[13] R. C. Taber *et al.*, J. Supercond. **5**, 371 (1992).
[14] B. W. Langley *et al.*, Rev. Sci. Instrum. **62**, 1801 (1991).
[15] S. Anlage *et al.*, Phys. Rev. B **44**, 9764–9767 (1991).
[16] W. N. Hardy *et al.*, Phys. Rev. Lett. **70**, 3999 (1993).
[17] D. A. Bonn *et al.*, Phys. Rev. B **47**, 11314 (1993).
[18] D. H. Wu *et al.*, Phys. Rev. Lett. **70**, 85 (1993).
[19] J. P. Carbotte, Rev. Mod. Phys. **62**, 1027 (1990).
[20] L. W. Lombardo and A. Kapitulnik, J. Cryst. Growth **118**, 483 (1992).
[21] L. W. Lombardo, D. B. Mitzi, and A. Kapitulnik, Phys. Rev. B **46**, 5615 (1992), and references therein.
[22] J. S. Urbach *et al.*, Phys. Rev. B **39**, 12391 (1989).
[23] Z. X. Shen *et al.*, Phys. Rev. Lett. **70**, 1553 (1993).
[24] P. Merchant *et al.*, Appl. Phys. Lett. **60**, 763 (1992).
[25] C. B. Eom *et al.*, Appl. Phys. Lett. **55**, 595 (1989).
[26] M. P. Siegal *et al.*, J. Appl. Phys. **70**, 4982 (1991).
[27] M. C. Nuss *et al.*, Phys. Rev. Lett. **66**, 3305 (1991).
[28] S. S. Laderman *et al.*, Phys. Rev. B **43**, 2922 (1991).
[29] N. Klein *et al.* (to be published).