a-b Plane Microwave Surface Impedance of a High-Quality $Bi_2Sr_2CaCu_2O_8$ Single Crystal

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The *a-b* plane microwave surface impedance of a high-quality $Bi_2Sr_2CaCu_2O_8$ single crystal ($T_c \approx 93$ K) has been measured at 14.4, 24.6, and 34.7 GHz. The surface resistance at low temperature is the lowest yet reported, is comparable with the best $YBa_2Cu_3O_{7-\delta}$ data, and has a characteristic ω^2 frequency dependence. The change in penetration depth, $\Delta\lambda_{ab}(T)$, has a strong linear term at low temperature which is consistent with a gap with line nodes on the Fermi surface. The real part of the microwave conductivity displays a broad peak at low temperature, similar to that observed in $YBa_2Cu_3O_{7-\delta}$. [S0031-9007(96)00735-1]

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Measurements of the microwave surface impedance, $Z_s = R_s + iX_s$, have played a key role in furthering our understanding of high-T_c superconductors. A term, linear at low T, in the temperature dependence of the in-plane penetration depth, $\lambda_{ab}(T)$, first observed in $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals by Hardy *et al.* [1], opens up possibilities such as d-wave pairing [2] or an anisotropic s-wave gap [3]. The nonmonotonic T dependence of the *a-b* plane surface resistance, R_s^{ab}, observed in YBCO by Bonn *et al.* [4,5] has been interpreted in terms of an effective quasiparticle scattering time τ that increases rapidly below T_c before saturating at what is suggested to be an elastic impurity scattering limit. This qualitative picture is consistent with dominant electron-electron scattering above T_c which is rapidly suppressed below T_c as the charge carriers condense into the superfluid. Doping the YBCO crystals with small amounts of impurities such as Zn or Ni [5,6] *reduced* R_s^{ab} by *increasing* the scattering.

Assessing the applicability of these ideas to other high-T_c systems is of paramount importance. The electron doped superconductor $Nd_{1.85}Ce_{0.15}CuO_4$, for example, has strikingly different behavior from YBCO: Wu *et al.* [7] found that both R_s^{ab} and λ^{ab} are in accord with BCS s-wave theory. However, efforts to obtain meaningful surface impedance data on other cuprate superconductors have so far met with only limited success. In particular, microwave measurement [8–11] on $Bi_2Sr_2CaCu_2O_8$ (BSCCO) have yet to produce a complete picture of the surface impedance. Much of the problem has been the rather severe constraints imposed by the microwave technique [12] on sample quality: single crystals of high purity with uniform thickness, very flat surfaces, and clean, nondeformed edges are required. Whereas YBCO crystals of this quality [1,4–6,13] have been available for some time, BSCCO crystals of comparable quality are only now becoming available.

BSCCO has two CuO_2 conducting layers per unit cell like YBCO but it has no CuO chain layers. Ma *et al.* [9] have suggested that the CuO chain layers may play a significant role in the unconventional microwave response of YBCO; however, *a-b* plane R_s anisotropy measurements [13] on untwinned YBCO single crystals suggest that the CuO chain layers affect only the magnitudes of R_s and λ rather than their forms as a function of T. Various authors [14–18] have studied the consequences of $d_{x^2-y^2}$ pairing on the microwave conductivity, $\sigma = \sigma' - i\sigma''$, and find that many aspects of their results agree with the R_s and λ data on YBCO [1,4–6,13]. Alternatives to the d-wave picture such as the anisotropic s-wave scheme [3] or the approach of Klemm and Liu [19] are linked with theories which involve tunneling between adjacent CuO_2 planes or CuO chain layers. Thus surface impedance measurements of BSCCO where the CuO chain layers are absent and where the CuO_2 planes are more weakly coupled than those in YBCO should help clarify the situation.

We have made microwave measurements on BSCCO single crystals (T_c onset ≈ 93 K) of very high quality, grown by the traveling solvent floating zone method using an infrared mirror furnace [20]. This technique produces mm-size mosaics of aligned crystals. These are repeatedly cleaved to obtain thin platelets which are optically smooth on both faces. Rocking curves for these crystals generally show widths of 0.03°–0.05° for $(0, 0, 1)$ lines indicating high crystallinity [21]. A stringent test of sample quality is the variation of the mixed state, c-axis resistance as a function of the angle of an applied magnetic field. This is extremely sensitive to intercalation, cracks, bending, or other deformations because the large anisotropy ($\rho_c/\rho_{ab} \approx 10^5$) means that c-axis transport currents flow uniformly across the whole crystal. The minimum for $\vec{B} \parallel ab$ is narrower than the resolution of our goniometer stage (≈0.1°), indicating extremely high quality and flatness.

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The 24.6 and 34.7 GHz measurements reported here were made in a circular cylindrical superconducting Nb cavity maintained at 4.2 K and supporting a TE_{011} mode with Q values of, typically, 10^6–10^7, allowing high sensitivity. The 14.4 GHz R_s^{ab} data were obtained using the TE_{011} mode ($Q \approx 10^6$) of a cooled sapphire disk resonator in a Nb enclosure. In all cases, the sample is positioned at a node in the $\vec{E}$ field and at an antinode in the $\vec{H}$ field which is oriented perpendicular to the a-b plane of the single crystal sample. For an ellipsoid of revolution, this induces purely a-b plane screening currents and allows measurement of R_s^{ab} and $\Delta\lambda^{ab}$. In this orientation, the current is concentrated near the edges of the sample [12] and so it is important that they are not deformed or cracked. To the extent that the approximation of a flat, platelet crystal by an ellipsoid is not exact, it is conceivable that some c-axis currents might exist. Certainly, the consistency of our results for samples with different dimensions makes significant contributions from this effect unlikely.

The surface impedance of the sample is obtained from the cavity perturbation formula $\Delta f_B(T) - 2i\Delta f_0(T) = \Gamma(R_s + i\Delta X_s)$. $\Delta f_B(T)$ is the change in bandwidth of the transmitted resonant response when the sample is moved from the center of the cavity to outside it, and $\Delta f_0(T)$ is the resonant frequency shift with respect to the frequency at the base temperature (5 K here). Γ, a calibration constant, includes demagnetization effects and can be calculated but is more accurately determined by measuring a well characterized Nb sample cut to the same dimensions as the BSCCO crystal. The sample is situated on the end of a movable 0.5 mm diameter sapphire rod which is temperature controlled independently of the cavity. This permits determination of the empty cavity bandwidth by withdrawing the rod and sample through a hole in the top plate of the cavity while it is still cold. At 34.7 GHz, the resolution for R_s^{ab} of a 1 mm × 1 mm single crystal is $\pm 50\ \mu\Omega$. The 24.6 GHz cavity, being larger, has a corresponding resolution of $\pm 100\ \mu\Omega$. R_s^{ab} measurements at 14.4 GHz with the dielectric resonator method can achieve resolutions smaller than $\pm 50\ \mu\Omega$ by optimizing the sample position.

Measurements of $\Delta\lambda^{ab}$ are made only in the 24.6 and 34.7 GHz cylindrical cavities because the frequency shift of the sapphire disk resonance at 14.4 GHz is extremely sensitive to sample movement. It is necessary, nevertheless, to make careful checks of systematic errors caused by anomalous frequency shifts due to the thermal expansion of the sapphire rod. These effects are accounted for by measuring the detailed frequency shift in the normal state of a Nb calibration sample of identical dimensions and imposing the condition $R_s = X_s$ (expected for a normal metal). The correction term thus generated is typically $\leq 10\%$ of the total frequency shift signal and negligible below about 30 K. Frequency shifts from the thermal expansion of the BSCCO crystal itself as it is heated are also allowed for. This contribution is estimated by measurement of the dependence of the total frequency shift on sample size. If the sample is modeled as an oblate spheroid of radius a, a thermal expansion contribution will result in $(\Delta f/f)_{\mathrm{exp}} \propto a^3(\Delta a/a)$ whereas a genuine λ frequency shift gives $(\Delta f/f)_\lambda \propto a^2 g \Delta\lambda$ (g includes demagnetization effects and depends only weakly on a). At 34.6 GHz, the frequency shift, Δf_0 (30 K), for a 1.25 mm × 1.4 mm × 6 μm crystal was compared with that for a 0.45 mm × 0.5 mm × 6 μm piece cut from it. The $a^2 g$ scaling factor was determined empirically from the bandwidth data and the factor thus obtained agreed with the ratio of the two frequency shifts at 30 K to within 1%, ruling out the possibility of sample thermal expansion contaminating the frequency shift data below 30 K.

The measurements of R_s and X_s are used to extract the in-plane microwave conductivity via $Z_s = (i\mu_0\omega/\sigma)^{1/2}$ (we henceforth omit ab subscripts and superscripts as we deal exclusively with in-plane quantities). σ is widely described by a two-fluid model in the clean, local limit: $\sigma = (ne^2/m^*)[x_s/i\omega + x_n\tau/(1 + i\omega\tau)]$, where $x_s = 1 - x_n$ is the superfluid fraction, and x_n the normal fluid fraction. For $\sigma'' \gg \sigma'$ (which holds well except within a few degrees of T_c) and $\omega\tau \ll 1$, R_s and X_s reduce to $R_s = \frac{1}{2}\mu_0^2\sigma'\omega^2\lambda^3$ and $X_s = \mu_0\omega\lambda$ with x_n given by $1 - \lambda^2(0)/\lambda^2(T)$. $\lambda(0)$ is needed to calculate x_n and extract σ' from R_s. In cases where it is known that $R_s = X_s$ in the normal state, it may be estimated from the microwave data. However, in our case, the 6 μm sample thickness is comparable with the normal state skin depth (approximately 2–3 μm at 35 GHz), and therefore R_s and X_s are not expected to agree. $\lambda(0) = 2100$ Å, obtained from dc magnetization measurements on similar crystals [22], is assumed in the following analysis.

Figure 1 shows $R_s(T)$ at all three frequencies. At low T, the magnitude of R_s is comparable with that of the best YBCO crystals. We emphasize that R_s values for BSCCO at low T reported elsewhere [8,10,11] are about an order of magnitude greater than ours (when the results are extrapolated to 10 GHz assuming an ω^2 frequency dependence). For $5 < T < 80$ K, $R_s \propto \omega^2$ which is consistent with the usual expression for R_s given above if σ' is frequency independent. This in turn implies that $\omega\tau \ll 1$ for this BSCCO sample in this frequency range. It also gives confidence that the intrinsic R_s is being measured and not other extrinsic effects which would typically scale as a lower power of ω. This is an important check, not possible without multiple frequency data.

The inset of Fig. 1 presents an expanded view of R_s at low T on a linear scale. While there is no bump at around 40 K as seen in YBCO, there is a suggestion of a plateau at intermediate T and a subsequent rolloff at lower T that is reminiscent of the results obtained on YBCO crystals when doped with small amounts of impurities such as Zn or Ni. This agrees with our conclusion that $\omega\tau \ll 1$ for our samples. (In YBCO $\omega\tau \approx 1$ at 35 GHz

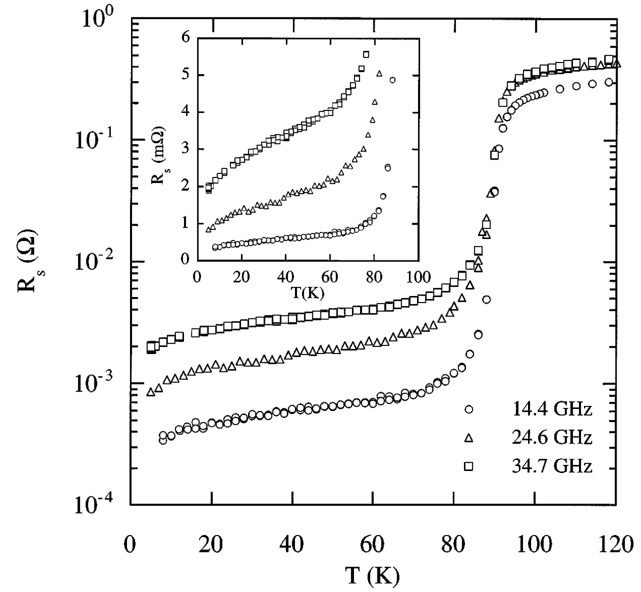

FIG. 1. The surface resistance at 14.4, 24.6, and 34.7 GHz. Inset: A closeup of the low temperature behavior of R_s.

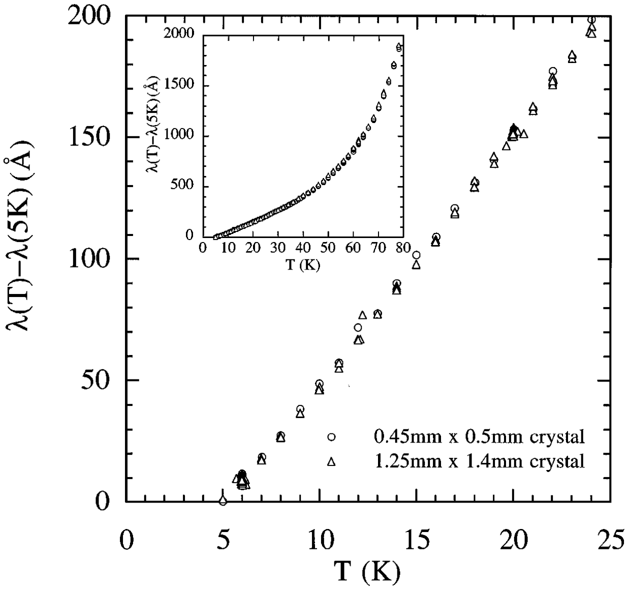

FIG. 2. The change in penetration depth with respect to λ(5 K) for $5 < T < 25$ K. Inset: $\Delta\lambda$ over a wider temperature range.

only for the purest undoped samples [5], where τ is free to increase at low T to almost an order of magnitude more than its corresponding value for doped samples.) R_s (34.6 GHz) between 20 and 60 K for our BSCCO crystal ranges from 2.7 to 4 mΩ which is about 3 to 4 times the corresponding value of 0.7 to 1.5 mΩ for a typical YBCO crystal doped with a small amount of impurities [5]. R_s $[R_s \propto x_n \tau \lambda^3/\lambda^2(0)]$ might be expected to be somewhat larger for BSCCO than for YBCO because of the larger λ. However, this factor does not account for the whole difference. A residual surface resistance, $R_s(0)$, evident at low T, is the most likely source of the discrepancy. Such a residual resistance is seen to a varying degree in all R_s measurements of high-T_c superconductors except untwinned YBCO crystals [13] and is most probably due to slight structural imperfections or impurities. However, it is clear from the ω^2 frequency dependence that it is not sensible to subtract $R_s(0)$ and use $R_s(T) - R_s(0)$ to compute σ_1 as some authors [7,8] have suggested. A more useful approach might be to assume $x_n(0) \neq 0$, i.e., a residual normal fluid at $T = 0$, which would preserve the ω^2 frequency dependence exhibited by the data.

Figure 2 presents all the 34.7 GHz $\Delta\lambda(T)$ data. These include three separate temperature sweeps for the large 1.25 mm × 1.4 mm crystal and one for the 0.45 mm × 0.5 mm piece cut from it. The agreement is excellent (the noisier 25 GHz data, not shown, also agreed well). Below about 25 K, there is a strong linear term with slope 10.2 Å/K. This value is about 2.4 times the value reported by Hardy *et al.* [1] on YBCO. Figure 3 gives the complete T dependence of x_s. Within experimental uncertainty, the data imply a linear T dependence for the normal fluid density from 30 to 5 K. The shape of this curve depends, of course, on the exact choice of $\lambda(0)$. A choice of $\lambda(0) = 2600$ Å [11] makes $x_s(T)$ more concave up but does not affect the linear T behavior below 30 K. The slight curvature apparent in $\Delta\lambda$ is not evident in $x_s(T)$ and is presumably a signature of the inaccuracy of the approximation, $x_n(T) \approx 2\Delta\lambda(T)/\lambda(0)$ which is strictly true only for very small $\Delta\lambda(T)$. For a cylindrical or spherical Fermi surface, $x_n \propto T$ is consistent with a pairing state with line nodes [2] or an anisotropic s-wave

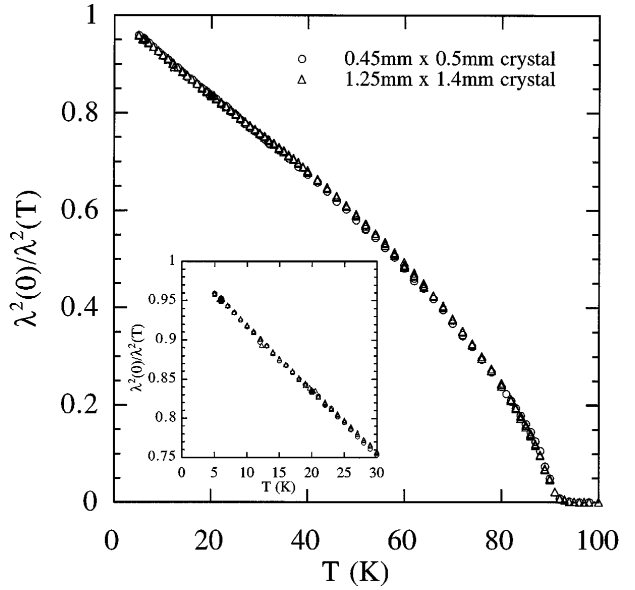

FIG. 3. The temperature dependence of the superfluid fraction, assuming $\lambda(0) = 2100$ Å. Inset: A closeup of the low temperature region.

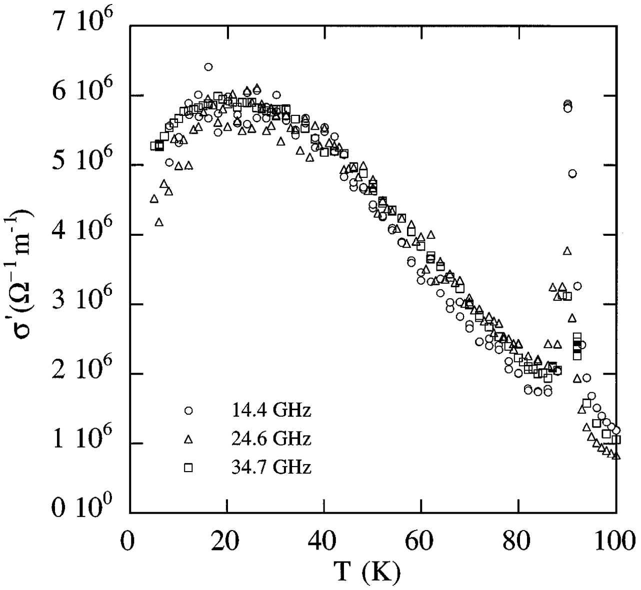

FIG. 4. The real part of the conductivity at 14.4, 24.6, and 34.7 GHz is basically frequency independent ($\omega\tau \ll 1$) and exhibits a broad peak at low temperature.

state [3,23]. These results confirm angle-resolved photoemission spectroscopy measurements [24,25] and also the λ measurements of Jacobs *et al.* [11] but contradict the conclusion that $\Delta\lambda(T) \propto T^2$ [9,10]. Disorder is known to introduce curvature into $\Delta\lambda$ and x_n for both d-wave [15] and anisotropic s-wave superconductors [23]. This was shown empirically by Bonn *et al.* [5] who shifted the low T $\Delta\lambda(T)$ in YBCO from T to T^2 by doping with small amounts of Zn. It is likely that some sort of impurity or defect was playing an analogous role in these earlier BSCCO measurements.

In Fig. 4, $\lambda(T)$ has been used to extract σ' from R_s. It exhibits a broad peak at about 20 K, symptomatic of the rise in τ below T_c being overtaken by the decrease of x_n with temperature. The finite σ' at low T is easily reconciled with the observed $R_s(0)$. The frequency dependence is weak as expected from $\omega\tau \ll 1$. The height of the peak is reduced from its value in pure YBCO crystals, and this explicitly demonstrates that $1/\tau$ in this BSCCO crystal is higher. The overall T dependence is similar to that of σ' for impurity-doped YBCO crystals [5,6] and YBCO thin films [26,27]. The shape of σ' is quite sensitive to the choice of $\lambda(0)$: as it is increased, the height of the peak is reduced and its position shifts to higher T.

We have presented what we believe to be the first complete measurements of both the intrinsic a-b plane R_s and λ of a BSCCO single crystal. They share many of the unconventional characteristics first observed in YBCO: a linear term in $\lambda(T)$ at low T and an implied broad peak in $\sigma_1(T)$. The behavior of $\lambda(T)$ is compatible with either a pairing state with line nodes or an anisotropic s-wave state. The form of $\sigma'(T)$ suggests a rapid collapse in the quasiparticle scattering rate below T_c. Its similarity to the $\sigma'(T)$ extracted from YBCO doped with impurities suggests a higher degree of scattering in this BSCCO crystal than for pure YBCO. Since BSCCO has no chain layers, our results confirm the notion [13] that the chain layers do not play an essential role in the unconventional behavior of YBCO.

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[1] W. N. Hardy *et al.*, Phys. Rev. Lett. **70**, 3999 (1993).
[2] James Annett, Nigel Goldenfeld, and S. R. Renn, Phys. Rev. B **43**, 2778 (1991).
[3] Sudip Chakravarty, Asle Sudbø, Philip W. Anderson, and Steven Strong, Science **261**, 337 (1993).
[4] D. A. Bonn, P. Dosanjh, R. Liang, and W. N. Hardy, Phys. Rev. Lett. **68**, 2390 (1992).
[5] D. A. Bonn *et al.*, Phys. Rev. B **50**, 4051 (1994).
[6] Kuan Zhang *et al.*, Appl. Phys. Lett. **62**, 3019 (1993).
[7] Dong Ho Wu *et al.*, Phys. Rev. Lett. **70**, 85 (1993).
[8] T. Shibauchi *et al.*, Physica (Amsterdam) **203C**, 315 (1992).
[9] Zhengxiang Ma *et al.*, Phys. Rev. Lett. **71**, 781 (1993).
[10] S. Oxx *et al.*, Physica (Amsterdam) **235C–240C**, 889 (1994).
[11] T. Jacobs *et al.*, Phys. Rev. Lett. **75**, 4516 (1995).
[12] C. E. Gough and N. J. Exon, Phys. Rev. B **50**, 488 (1994).
[13] Kuan Zhang *et al.*, Phys. Rev. Lett. **73**, 2484 (1994).
[14] Patrick A. Lee, Phys. Rev. Lett. **71**, 1887 (1993).
[15] Peter J. Hirschfeld and Nigel Goldenfeld, Phys. Rev. B **48**, 4219 (1993).
[16] P. J. Hirschfeld, W. O. Puttika, and D. J. Scalapino, Phys. Rev. Lett. **71**, 3705 (1993).
[17] P. J. Hirschfeld, W. O. Puttika, and D. J. Scalapino, Phys. Rev. B **50**, 10 250 (1994).
[18] T. Xiang and J. M. Wheatley, Phys. Rev. B **51**, 11 721 (1995).
[19] Richard A. Klemm and Samuel H. Liu, Phys. Rev. Lett. **74**, 2343 (1995).
[20] T. Mochiku and K. Kadowaki, Trans. Mater. Res. Soc. Jpn. **19A**, 349 (1993).
[21] K. Kadowaki and T. Mochiku, Physica (Amsterdam) **194B–196B**, 2239 (1994).
[22] K. Kadowaki *et al.* (unpublished); V. G. Kogan *et al.*, Phys. Rev. Lett. **70**, 1870 (1993).
[23] R. Fehrenbacher and M. R. Norman, Phys. Rev. B **50**, 3495 (1994).
[24] Z.-X. Shen *et al.*, Phys. Rev. Lett. **70**, 1553 (1993).
[25] H. Ding *et al.*, Phys. Rev. Lett. **74**, 2784 (1995).
[26] U. Dähne *et al.*, J. Supercond. **8**, 129 (1995).
[27] B. Avenhaus *et al.*, IEEE Trans. Appl. Supercond. **5**, 1737 (1995).