$\hat{c}$-Axis Electrodynamics of $YBa_2Cu_3O_{7-\delta}$

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New measurements of surface impedance in $YBa_2Cu_3O_{7-\delta}$ show that the $\hat{c}$-axis penetration depth and conductivity below T_c exhibit behavior different from that observed in the planes. The $\hat{c}$-axis penetration depth never has the linear temperature dependence seen in the *ab* plane. Instead of the conductivity peak seen in the planes, the $\hat{c}$-axis microwave conductivity falls to low values in the superconducting state, then rises slightly below 20 K. These results show that $\hat{c}$-axis transport remains incoherent below T_c, even though this is one of the least anisotropic cuprate superconductors. [S0031-9007(98)06826-4]

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The highly anisotropic nature of cuprate superconductors and the question of their dimensionality continue to play a central role in research on high temperature superconductors. Early on it was established experimentally that transport properties within the CuO_2 planes of these materials differ markedly from transport normal to the planes. The dc resistivity in the $\hat{c}$ direction can be orders of magnitude higher than it is within the planes and it often has a qualitatively different temperature dependence, exhibiting upturns with decreasing temperature [1]. The two-dimensional character that this normal state anisotropy implies has been an essential ingredient in many of the ideas that have been brought forward to explain the unusual properties and the high critical temperatures of these materials [2]. However, $YBa_2Cu_3O_{7-\delta}$, which is one of the best controlled and most studied of the high temperature superconductors, is also one of the least anisotropic members of the family. For low oxygen vacancy levels $\delta < 0.07$, the $\hat{c}$-axis resistivity shows no upturn with decreasing temperature and the resistivity anisotropy is less than a factor of 50 [3]. In this Letter we present new measurements of the $\hat{c}$-axis microwave conductivity and penetration depth which clearly show that, in the superconducting state, the interplane electrodynamics are quite different from those observed in the *ab* plane. Both quantities show that transport in the $\hat{c}$ direction is incoherent, even though the anisotropy in the normal state is not particularly large.

One of the strengths of measurements of the surface impedance $Z_s = R_s + iX_s$ is that they provide complementary information on both the superfluid and the low energy excitations out of the condensate. In the limit of local electrodynamics, the surface reactance $X_s(T) = \mu_0 \omega \lambda(T)$ provides a very direct measurement of the London penetration depth $\lambda(T)$, which in turn is related to the superfluid density $n_s(T)$ via $\lambda^{-2}(T) = \mu_0 n_s(T) e^2/m^*$. Thus, in the absence of separate information on m^*, measurements of $\lambda(T)$ give a direct measurement of $n_s(T)/m^*$, which is related to the superfluid stiffness and can be highly anisotropic. The surface resistance in the superconducting state is given by [4] $R_s = \mu_0^2 \omega^2 \lambda^3(T) \sigma_1(\omega, T)/2$, thus providing a means of observing what happens to the low frequency conductivity $\sigma_1(\omega, T)$ of the material as it is cooled below the superconducting transition.

The *ab*-plane surface impedance of $YBa_2Cu_3O_{7-\delta}$ has been extensively studied, revealing several key features of the superconducting state. Measurements of $\lambda(T)$ at low T in $YBa_2Cu_3O_{7-\delta}$ exhibit a linear temperature dependence [5], which is a strong indication of nodes in the energy gap of this material. Closer to T_c, $\lambda(T)$ has been found to vary as $[(T_c - T)/T_c]^{-1/3}$, consistent with a superconducting transition governed by 3D *XY*-like critical fluctuations [6]. The temperature dependence of the *ab*-plane surface resistance reveals an enormous peak in $\sigma_1(T)$ and is one of the measurements indicating a rapid decrease in the in-plane scattering rate below T_c [7–9].

Obtaining this kind of information for currents running in the $\hat{c}$ direction presents great technical difficulties. Most surface impedance measurements involve placing a sample in microwave magnetic fields $\vec{H}_{ac}$, where the currents induced in the surface must form closed loops. By changing the geometry or orientation of the sample one can perform measurements that contain different admixtures of *ab*-plane and $\hat{c}$-axis currents and then extract the surface impedance in different directions. This can be achieved by rotating a sample or by measuring samples cut with different orientations. Measurements that involve rotating the sample [10,11] have severe problems due to changing demagnetizing factors and changing current distributions. If one is working with thin, rectangular samples, which is the most common situation with crystals of cuprate superconductors, there is a huge change in demagnetizing factors if the sample is rotated from $\vec{H}_{ac} \parallel \hat{c}$ (planar currents only) to $\vec{H}_{ac} \perp \hat{c}$ (combination of planar and $\hat{c}$-axis currents). Even if the sample is not very thin and the demagnetizing factors can be dealt with, changes in the *ab*-plane current distribution bring poorly controlled

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uncertainties into such procedures for extracting the $\hat{c}$-axis electrodynamics.

For $La_{1.85}Sr_{0.15}CuO_4$, where large samples are available, Shibauchi *et al.* arrived at a more satisfactory solution by cutting and polishing thin slabs with different orientations [12]. This avoids the problem of changing demagnetizing factors, although it does force one to compare measurements on different samples, thus relying on two slabs being otherwise identical. Our approach to obtaining the $\hat{c}$-axis surface impedance relies on the fact that thin crystals of $YBa_2Cu_3O_{7-\delta}$ cleave very cleanly in the [100] and [010] directions. The surface resistance or penetration depth is initially measured with the microwave magnetic field lying in the plane of the thin slab, measuring with both $\vec{H}_{ac} \parallel \hat{b}$ ($\hat{a}, \hat{c}$ currents) and $\vec{H}_{ac} \parallel \hat{a}$ ($\hat{b}, \hat{c}$ currents). The contribution due to $\hat{c}$-axis currents is then increased by cleaving the slab into a set of narrow needles which is remeasured with $\vec{H}_{ac}$ lying along the axis of the needles. This technique is particularly reliable because it has no significant change in demagnetizing factors, no change in the distribution of *ab*-plane currents, and there is no need to compare different samples. With this sequence of experiments and measurements of the sample's dimensions it is straightforward to extract the surface impedance in all three directions. We have measured $\lambda(T)$ in this way in a superconducting loop-gap resonator and the results have been described elsewhere [13]. The new measurements of surface resistance in the $\hat{c}$-direction $R_{sc}(T)$ have been performed in a superconducting 22 GHz cylindrical cavity operated in the TE_{011} mode. The samples are crystals (0.7 mm^2 in area by 20 μm thickness) of $YBa_2Cu_3O_{7-\delta}$ grown in yttria-stabilized zirconia crucibles, then detwinned and annealed to set the oxygen content [14].

Figure 1 shows the temperature dependence of the penetration depth $\Delta\lambda_c(T) = \lambda_c(T) - \lambda_c(1.2\text{ K})$ extracted in the manner described above. Instead of the linear behavior seen in both directions in the *ab* plane, the temperature dependence is close to quadratic, with a power law of $\Delta\lambda(T) \propto T^{2.1}$ giving a good fit to the data up to about 40 K. These microwave results can be combined with far infrared measurements of $\lambda_c(0)$ [15,16] to produce the superfluid fractions shown in Fig. 2. A key feature of this figure is that in all three directions, the behavior near T_c is consistent with 3D *XY*-like critical fluctuations. However, at lower temperatures, the superfluid fraction in the $\hat{c}$ direction is very flat and shows no sign of the linear temperature dependence observed in the *ab* plane. Furthermore, previous work has shown that this behavior persists over a wide doping range, from underdoped ($\delta = 0.42$) to slightly overdoped ($\delta = 0.01$) [13]. This indicates that, despite the 3D *XY* critical behavior near T_c, highly doped $YBa_2Cu_3O_{7-\delta}$ does not behave as if it were a *d*-wave pairing state in an anisotropic three-dimensional metal, where one would expect $\lambda(T)$ to be linear at low temperatures in

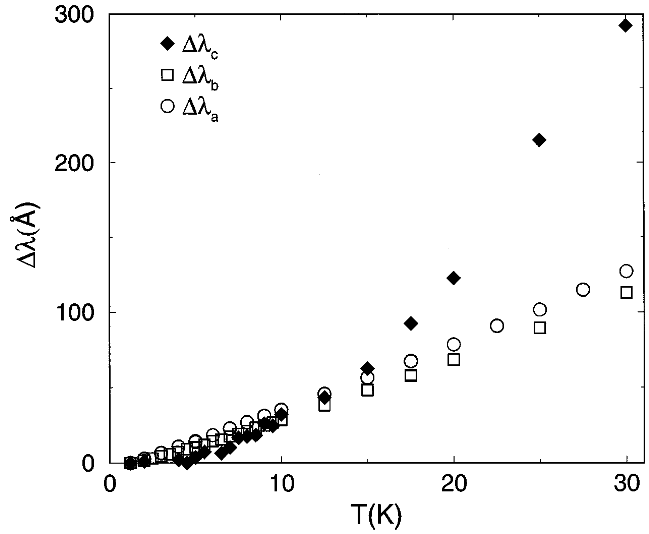

FIG. 1. The temperature dependence of the penetration depth $\Delta\lambda(T) = \lambda(T) - \lambda(1.2\text{ K})$ of $YBa_2Cu_3O_{6.95}$ is nearly quadratic in the c direction and linear in the *ab* plane.

all three directions [17,18]. Strikingly similar behavior has been reported by Shibauchi *et al.* for polished slabs of $La_{1.85}Sr_{0.15}CuO_4$ [12], by Jacobs *et al.* for cleaved crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ [19], and by Panagopoulos *et al.* for aligned powders of $HgBa_2Ca_2Cu_3O_{8+\delta}$ [20].

Figure 3 shows measurements of $R_s(T)$ at 22 GHz performed on a thin plate with $\vec{H}_{ac} \parallel \hat{a}$. This orientation produces currents running across the face of the slab in the $\hat{b}$ direction, with a small contribution from currents running down the side of the slab in the $\hat{c}$ direction. The small change seen in $R_s(T)$ after cleaving the sample into four needles is the increase in loss due to an increased $\hat{c}$-axis contribution. Except near T_c, the change is

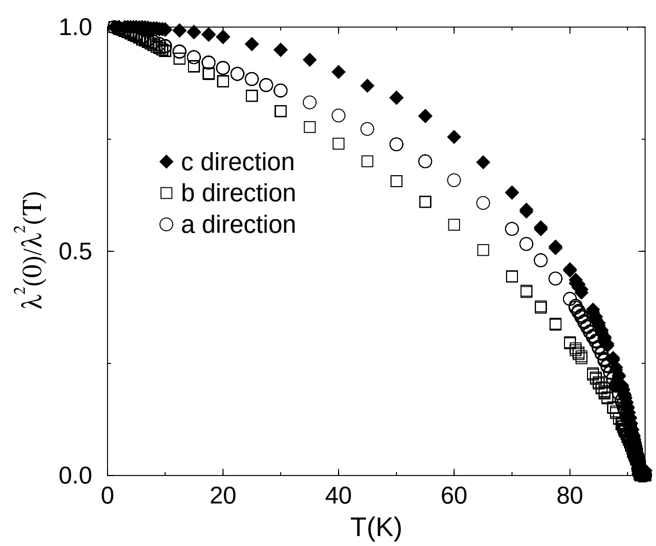

FIG. 2. The superfluid fraction in the c direction of $YBa_2Cu_3O_{6.95}$ is qualitatively different from the behavior seen in either direction in the *ab* plane.

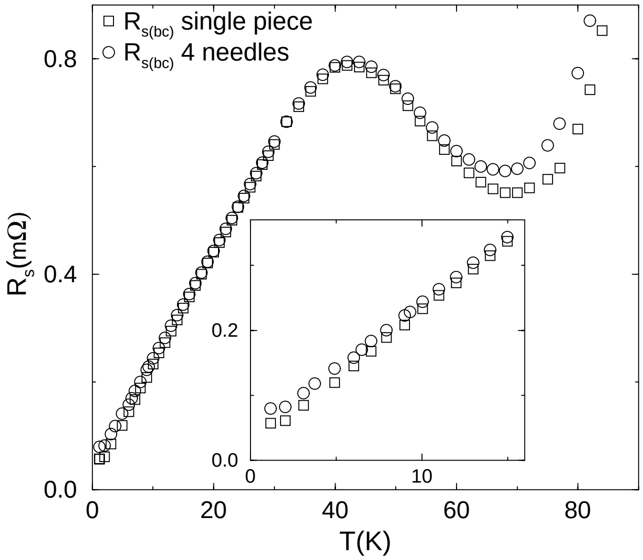

FIG. 3. The surface resistance at 22 GHz of a thin plate of $YBa_2Cu_3O_{6.95}$, before and after cleaving the plate into four needles. The small differences are used to extract the $\hat{c}$-axis surface resistance shown in Fig. 4. Inset shows increase of $\hat{c}$-axis contribution to the loss below 15 K.

extremely small which indicates that the surface resistance in the $\hat{c}$ direction $R_{sc}(T)$ is actually quite low. Since $R_s \propto \lambda^3(T)\sigma_1(\omega, T)$, we see that the increase in loss that might be expected from the much larger λ in the $\hat{c}$ direction is in fact balanced by a rather low $\hat{c}$-axis conductivity. The influence of $R_{sc}(T)$ is most clearly discernible above 60 K, and rather surprisingly there is some additional $\hat{c}$-axis loss appearing below 20 K. The small size of the effect observed here indicates that it would be difficult to unambiguously extract $R_{sc}(T)$ from the earlier techniques that involved changing the orientation of the sample [10,11], since the effect of changes in current distribution can easily be larger than the change observed in this experiment.

Figure 4 shows the surface resistance in all three directions (R_{sa}, R_{sb}, R_{sc}), extracted from the data in Fig. 3, plus a set of measurements to determine $R_{sa}(T)$. $R_{sc}(T)$ is very low and qualitatively different from that observed in either of the planar directions. In the *ab* plane, $R_s(T)$ in high purity crystals exhibits a broad peak which is caused by a very large peak in $\sigma_1(T)$ in both the $\hat{a}$ and $\hat{b}$ directions. This increase in the *ab*-plane conductivity below T_c has been attributed to a rapid increase in quasiparticle lifetime in the superconducting state, but the increase seems to be completely absent for carriers moving in the $\hat{c}$ direction. Instead, $R_{sc}(T)$ falls to very low values below T_c and then rises slightly again below 20 K.

Using the measurements of $\lambda_c(T)$, the *c*-axis conductivity $\sigma_{1c}(T)$ can be extracted from this measurement of $R_{sc}(T)$. Because $R_{sc}(T)$ is so small, and rather surprising in shape, we have repeated the entire set of measurements

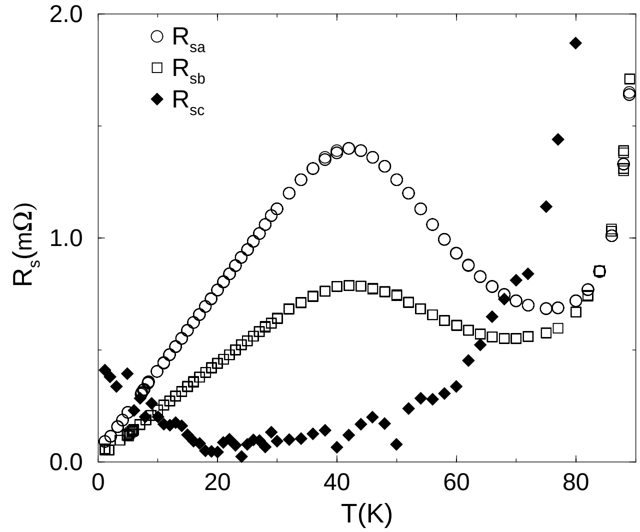

FIG. 4. The broad peak in $R_{sa}(T)$ and $R_{sb}(T)$ is due to a rapid increase in quasiparticle lifetime below T_c. The surface resistance in the $\hat{c}$ direction is different from these, showing an upturn only at low temperatures.

on a sample taken from a different crystal growth run and the conductivity from both sets of data is shown in Fig. 5. In the normal state just above T_c, the microwave conductivity of both crystals is about $6.3 \times 10^4\ \Omega^{-1}\,\mathrm{m}^{-1}$, corresponding to a dc resistivity of 1.6 mΩ cm, which is in good agreement with the range of values reported for crystals of $YBa_2Cu_3O_{7-\delta}$ in this range of oxygen doping [3]. Below T_c, $\sigma_{1c}(T)$ falls rapidly, with no sign of the peak observed in the *ab* plane, the conductivity eventually reaching a minimum value near 30 K. The

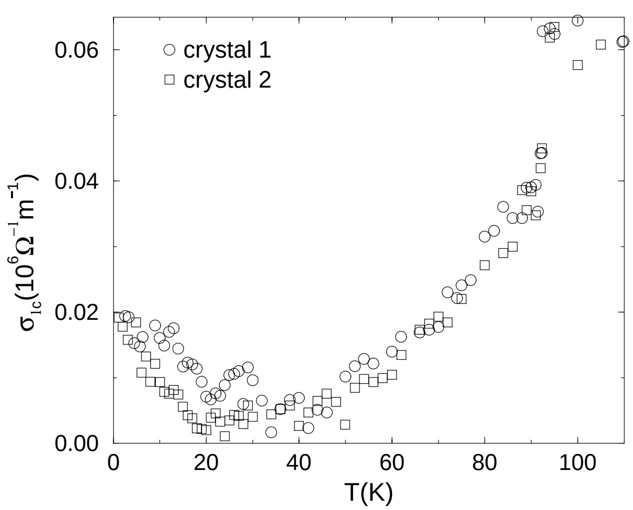

FIG. 5. Measurements of $\lambda_c(T)$ and $R_{sc}(T)$ are used to extract the $\hat{c}$-axis conductivity shown here. The $R_{sc}(T)$ measurements have been repeated on a crystal taken from a different growth run. Although the conductivity is small and difficult to measure it is clearly reproducible from run to run. Below T_c, $\sigma_{1c}(T)$ falls orders of magnitude below the *ab*-plane conductivity, then rises again slightly at low temperatures.

qualitatively different temperature dependencies in the two directions leads to an anisotropy in the conductivity of almost 10^4 by 30 K. However, $\sigma_{1c}(T)$ never falls to zero, but instead rises again at low temperatures, so the $\hat{c}$ axis never completely exhibits insulating behavior. At 10 K the value of $\sigma_{1c}(T)$ at 22 GHz is $10^4\ \Omega^{-1}\,\mathrm{m}^{-1}$, which is close to the residual conductivity of $\sigma_{1c}(T = 10\ \mathrm{K}) \approx 5 \times 10^3\ \Omega^{-1}\,\mathrm{m}^{-1}$ at $100\ \mathrm{cm}^{-1}$, the low frequency limit of far infrared $\hat{c}$-axis measurements [15].

Both the magnitude of $\sigma_{1c}(T)$ and its rapid drop in the superconducting state suggest that c-axis transport is incoherent, even below T_c in $YBa_2Cu_3O_{6.95}$. This resolves a conflict presented by earlier surface impedance measurements that showed a broad peak in $\sigma_{1c}(T)$, similar to the one observed in the *ab*-plane conductivity [10,11]. The absence of such a peak in the data presented here indicates that the $\hat{c}$-axis transport is not influenced by the development of the long transport lifetimes seen in *ab*-plane measurements below T_c, and is better approached as a case of incoherent transport. This is in accord with the conclusion that the lack of a linear temperature dependence in $\lambda_c(T)$ indicates that the $\hat{c}$-axis penetration depth is governed by incoherent processes [17,18].

A common approach to treating this incoherent transport is to model it as Josephson tunneling, where the superfluid fraction takes the form $\lambda_c^2(0)/\lambda_c^2(T) \propto \Delta(T)\tanh[\Delta(T)/2k_BT]$ [21]. We find that this expression fits the low temperature data for $YBa_2Cu_3O_{7-\delta}$ poorly. Instead, a power law close to T^2 gives a better fit from 1 to 40 K and a careful look at the published data on other systems suggests that this nearly quadratic temperature dependence is common to many materials. In fact, $\lambda_c^2(0)/\lambda_c^2(T)$ looks very similar in $YBa_2Cu_3O_{7-\delta}$ [13], $Bi_2Sr_3CaCu_2O_{8+\delta}$ [19], $La_{1.85}Sr_{0.15}CuO_4$ [12], and $HgBa_2Ca_2Cu_2O_{8+\delta}$ [20], despite substantial structural variations. This temperature dependence seems largely independent of a wide variation in the degree of anisotropy, as measured by either the normal state transport anisotropy or the wide variation in $\lambda_c(0)$ across this set of materials. This argues against models of layered superconductors, where the degree of anisotropy and structural details are correlated with the temperature dependence of the $\hat{c}$-axis penetration depth. One possible source of T^2 dependence in the c-axis superfluid stiffness (n_s/m^*) is impurity assisted hopping [17,22], but a similar power law also comes from a pair tunneling model that produces the main features seen in all three directions in $YBa_2Cu_3O_{6.95}$ [18]. Differentiating between various models comes up against the central issue of whether or not the incoherence in the $\hat{c}$ direction is an intrinsic feature of these systems, exemplified by theories involving "confinement" [23], or is a consequence of weak coupling between quasi-2D layers that nevertheless behave as Fermi liquids [17]. The very low $\hat{c}$-axis conductivity shown here for $YBa_2Cu_3O_{6.95}$ below T_c and the incoherent behavior of the $\hat{c}$-axis superfluid density in all cuprate systems studied so far provide important tests of these different points of view.

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