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

The highly anisotropic nature of cuprate superconductors and the question of their dimensionality continues 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 $c$-direction is incoherent, even though the anisotropy of this material is also one of the least anisotropic members of the family.

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 $c$-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 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 $c$-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 uncertainties into such procedures for extracting the $c$-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. 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 ob-

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**Abstract**

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

**Keywords**

$c$-Axis, Surface Impedance, YBa$_2$Cu$_3$O$_{7−δ}$, Superconductivity, Anisotropy.
measuring with both microwave magnetic field lying in the plane of the thin slab, or penetration depth is initially measured with the microwave magnetic field lying in the [100] and [010] directions. The surface resistance that thin crystals of YBa$_2$Cu$_3$O$_{7-\delta}$ containing the c-axis surface impedance relies on the fact that thin crystals of YBa$_2$Cu$_3$O$_{7-\delta}$ 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 \[1\]. 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 of YBa$_2$Cu$_3$O$_{7-\delta}$ grown in yttria-stabilized zirconia crucibles, then detwinned and annealed to set the oxygen content \[2\].

Fig. 1 shows the temperature dependence of the penetration depth $\Delta \lambda(T) = \lambda(T) - \lambda(1.2K)$ of YBa$_2$Cu$_3$O$_{6.95}$ is nearly quadratic in the \(\hat{c}\) direction and linear in the ab-plane.

with far infrared measurements of $\lambda_c(0)$ \[3\] to produce the superfluid fractions shown in Fig. 2. A key feature of this figure is that in all three directions, the behaviour 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 behaviour persists over a wide doping range, from underdoped ($\delta = 0.42$) to slightly overdoped ($\delta = 0.01$) \[1\]. This indicates that, despite the 3D XY critical behaviour near $T_c$, highly doped YBa$_2$Cu$_3$O$_{7-\delta}$ does not behave as if it were a d-wave pairing state in an anisotropic 3 dimensional metal, where one would expect the superfluid density to be linear at low temperatures in all three directions \[15\]. Strikingly similar behaviour has been reported by Shibauchi et al. for polished slabs of La$_1.85$Sr$_{0.15}$CuO$_4$ \[10\], by Jacobs et al. for cleaved crystals of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ \[17\], and by Panagopoulos et al. for aligned powders of HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ \[18\].

Fig. 2 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 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 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 $\lambda$ in...
the c-direction is in fact balanced by a rather low c-axis conductivity. The influence of \( R_{sc}(T) \) is most clearly discernable above 60 K, and rather surprisingly there is some additional 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 \([8,9]\), since the effect of changes in current distribution can easily be larger than the change observed in this experiment.

Fig. 3 shows the surface resistance in all three directions \((R_{sa}, R_{sb}, R_{sc})\), extracted from the data in Fig. 2, 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, \( R_{sa}(T) \) 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 \([3]\), 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 on a sample taken from a different crystal growth run and the conductivity from both sets of data is shown in Fig. 3. In the normal state just above \( T_c \), the microwave conductivity of both crystals is about \( 6.3 \times 10^4 \Omega^{-1}m^{-1} \), corresponding to a DC resistivity of 1.6 m\(\Omega cm\), 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 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 behaviour. At 10 K the value of \( \sigma_{1c}(T) \) at 22 GHz is \( 10^3 \Omega^{-1}m^{-1} \), which is close to the residual conductivity of \( \sigma_{1c}(T = 10K) \approx 5 \times 10^6 \Omega^{-1}m^{-1} \) at 100 \( cm^{-1} \), the low frequency limit of far infrared \( \hat{c} \)-axis measurements \([13]\).

Both the magnitude of \( \sigma_{1c}(T) \) and its rapid drop in the superconducting state suggest that \( \hat{c} \)-axis transport is incoherent, even below \( T_c \) in \( YBa_2Cu_3O_{7-\delta} \). 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 \([3,13]\). 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 superfluid density is governed by incoherent processes \([13,14]\).

A common approach to treating this incoherent transport is to model it as Josephson tunneling, where
Bisect fits the low temperature data for YBa2Cu3O6.95. In fact, temperature dependence is common to many materials. Data on other systems suggests that this nearly quadratic $\Delta(T)$ produces the main features seen in all three directions. This temperature dependence seems to be poorly. Instead, a power law, close to $\Delta(T) \propto T^2$, 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, $\Delta(T)/\Delta(0)$ looks very similar in $YBa2Cu3O7-\delta$ [11], Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ [17], La$_{1.65}$Sr$_{0.15}$CuO$_4$ [10] and $HgBa2Cu2O_{8+\delta}$ [18], despite substantial structural variations. This temperature dependence is largely independent of 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 superfluid density. One possible source of $T^2$ dependence in the $\hat{c}$-axis superfluid density is impurity assisted hopping [13,20], but a similar power law also comes from a pair tunneling model that produces the main features seen in all three directions in $YBa2Cu3O6.95$ [2]. 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” [21], or is a consequence of weak coupling between quasi-2D layers that nevertheless behave as Fermi liquids [15]. The very low $\hat{c}$-axis conductivity shown here for $YBa2Cu3O6.95$ 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.

ACKNOWLEDGMENTS

We wish to acknowledge helpful conversations with P.J. Hirschfeld, I. Affleck, C. Homes, D. Basov, and T. Timusk. This research was supported by the Natural Science and Engineering Research Council of Canada and the Canadian Institute for Advanced Research. DAB acknowledges support from the Sloan Foundation.

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 $T_c$, $\sigma_{\perp}(T)$ falls orders of magnitude below the ab-plane conductivity, then rises again slightly at low temperatures.