In-Plane and \( \hat{c} \)-Axis Microwave Penetration Depth of \( \text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+\delta} \) Crystals

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The complete temperature dependences of the in-plane and \( \hat{c} \)-axis microwave (10 GHz) penetration depth \( \lambda(T) \) and the surface resistance \( R_s(T) \) of high quality \( \text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+\delta} \) crystals are reported. In contrast to earlier measurements, a leading \( \lambda_{ab} \propto T \) dependence is observed at low temperatures, consistent with nodes in the in-plane gap. The overall behavior of \( \lambda_{ab}(T) \) and \( R_s(T) \) is similar to that of \( \text{YBa}_2\text{Cu}_3\text{O}_y \) at low \( T \), but differs at temperatures near \( T_c \). The \( \hat{c} \)-axis penetration depth \( \lambda_c(T) \) is shown to best agree with a model of weakly coupled superconducting layers with nodes in the gap.

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An important issue concerning the high \( T_c \) superconductors is the nature of the superconducting state, particularly the issue of \( s \)-wave vs \( d \)-wave order parameters [1]. Microwave measurements on superconductors can yield important information regarding this issue. At low temperatures, the microwave penetration depth of \( \text{YBa}_2\text{Cu}_3\text{O}_y \) (YBCO) crystals has been shown to obey a \( \lambda(T) \propto T \) dependence suggestive of a superconducting state with nodes in the gap [2]. However, \( \text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+\delta} \) (BSCCO) crystals have shown a strongly anisotropic in-plane gap [2,9–11], except for scale factors. This strongly suggests a common energy dependence of the density of states in BSCCO and YBCO and resolves the possible controversy raised by previous measurements of BSCCO [3,4]. The surface resistance \( R_{sab} \) also has a linear temperature dependence over a wide range of \( T \) from 4.2 to 45 K. The large anisotropy in BSCCO leads to some remarkable properties of \( R_s \) and \( \lambda \). We find that when microwave currents flow along the \( \hat{c} \) axis, the \( \hat{c} \)-axis penetration depth \( \lambda_c(T) \) is in quantitative agreement with a model of tunneling between \( d \)-wave superconducting layers.

The high quality BSCCO crystals were grown by the traveling solvent floating-zone method [12]. In contrast to flux growth methods, which have \( \text{CuO} \) impurities and other phases, the present crystals appear to be pure. This is confirmed by x-ray diffraction, electron-probe microanalysis, standard resistivity, and susceptibility measurements, in addition to the microwave measurements reported here. The \( T_c \) of these crystals is 91 K, one of the highest reported. The dc resistivity \( \rho_d(100 \, \text{K}) = 77 \, \mu \Omega \, \text{cm} \) for these crystals is lower than those typically reported in the literature for other “high quality” crystals. The susceptibility shows a very sharp transition and apparently 100% flux exclusion in the magnetic shielding measurement [13].

The microwave measurements of \( R_s(T) \) and \( \lambda(T) \) were carried out in a Nb cavity using a “hot finger” technique originally introduced by one of us [14]. The concept introduced there of utilizing a heated sample in a cold (4.2 K) cavity is at the heart of all high sensitivity measurements of crystals reported nowadays. An important feature of our measurements is that the anisotropy of the microwave properties can be measured. When the sample is oriented with \( H_{rf} \parallel \hat{c} \), currents only flow in the \( ab \) plane, and we measure \( \lambda_{ab} \) and \( R_{sab} \). When \( H_{rf} \parallel \hat{a} \), currents flow both in the plane and along the \( \hat{c} \) axis. The \( \hat{c} \)-axis properties \( \lambda_c \) and \( R_{sc} \) are extracted from the combined measurements.

\( ab \)-plane behavior. — The results for \( R_{sab} \) and \( X_{sab} \) are shown in Fig. 1. The normal state \( \hat{a} \)-\( \hat{b} \)-plane behavior is well described by \( R_{nab} = X_{nab} = \sqrt{\omega \mu_0 (\rho_{ab} + \gamma T)/2} \).
and a skin-depth limited response. In these very clean crystals the normal-state scattering times are about $1.3 \times 10^{14}$ sec$^{-1}$ at 130 K, comparable to that of untwinned LuBa$_2$Cu$_3$O$_y$ $(1.6 \times 10^{14}$ sec$^{-1}$ at 130 K).

The penetration depth $\lambda_{ab}(T)$ has a low temperature linear behavior, as shown in Fig. 2, followed by a faster rise at higher temperature. This is distinctly different from our own previous measurements [4] and that of Ma et al. [3], both of whom found a $T^2$ behavior at low temperature.

To gain a perspective on our results we compare our data with the simplest BCS theory of anisotropic superconductivity. For a cylindrical Fermi surface

$$\frac{\lambda^2_{ab}(0)}{\lambda^2_{ab}(T)} = 1 + 2 \int_0^\infty d\epsilon \frac{\partial f}{\partial E_k},$$  

(1)

where $\langle \cdots \rangle = \int_0^{2\pi} d\phi / 2\pi$, $E_k = \sqrt{\epsilon^2 + \Delta^2_k}$, and $\Delta_k = \Delta(T, \phi) = \Delta_d(T) \cos(2\phi)$ and $\Delta_d(0) = 2.16kT_c$. It should be noted that an anisotropic $s$-wave state with a $\cos(2\phi)$ angular dependence cannot be distinguished from a $d_\sigma$ state, since the penetration depth measurements are insensitive to the phase. We calculate the isotropic $s$-wave behavior with $\Delta(T, \phi) = \Delta_s(T)$ and $\Delta_s(0) = 1.77kT_c$. Mean-field $T$ dependences were used for $\Delta_d(T)$ and $\Delta_s(T)$.

A comparison to the theory requires a knowledge of $\lambda_{ab}(0)$. An absolute value of $X_{s,ab}(0) = \mu_o\omega \lambda_{ab}(0)$ can be estimated by making the assumption $R_{n,ab} = X_{n,ab}$, consistent with the observed normal-state skin depth response (see Fig. 1). This limits $\lambda_{ab}(0)$ to values between 1500 and 3000 Å, well within the range of available estimates [15,16]. We stress that relative measurements $\Delta_{ab}(T)$ have far higher accuracy with errors smaller than 1 Å, as is evident from the quality of the data presented. A possibly more accurate value of $\lambda_{ab}(0)$ follows from the low temperature slope of the penetration depth. The low $T$ region with $\lambda_{ab}(T) \approx T$ is consistent with a gap with nodes in the plane [17], such as for $d$-wave or anisotropic $s$-wave order parameters. For a $d_\sigma$ order parameter, the low temperature slope $d[\Delta_{ab}(T)]/dT$ is expected to be $\lambda_{ab}(0) \ln(2)/\Delta_d(0)$ [18]. The measured slope $d[\Delta_{ab}(T)]/dT \sim 10 \, \text{Å/K}$ leads to $\lambda_{ab}(0) = 2600 \, \text{Å}$ assuming the weak-coupling gap. This value is well within our previous limits, and we will use it for further analysis of our data.

Numerical calculations using the above value of $\lambda_{ab}(0)$ are shown in Fig. 2 for both $d_\sigma$ and isotropic $s$-wave gaps. The impossibility of fitting the $s$-wave result with any choice of parameters at low $T$ is obvious. The clean limit $d_\sigma$ calculation fits the low $T$ linear part very well, but is inadequate at higher $T$.

The complete temperature dependence of the penetration depth $\lambda_{ab}(T) = \lambda_{ab}(0) + \Delta_{ab}(T)$ is shown in Fig. 3 as a plot of $\lambda^2_{ab}(0)/\lambda^2_{ab}(t)$ vs $t = T/T_c$ using $\lambda_{ab}(0) = 2600 \, \text{Å}$ and $T_c = 91.0 \, \text{K}$. The low temperature behavior agrees with the clean limit weak-coupling $d$-wave calculation. In order to understand the deviations from the clean limit calculation at higher $T$, more complete calculations are required, such as we have previously carried out for YBCO [10], which include the effects of (i) strong coupling to incorporate larger gap values [7,8], (ii) the $T$ dependence of scattering, and (iii) fluctuations that appear to persist far from $T_c$.

The present measurements compare almost exactly with data on YBCO crystals [2] at low temperature [see inset to Fig. 3 (bottom)], except for scale factors. We show in Fig. 3 (bottom) the $a$-axis response of untwinned YBCO [11] in a $\lambda_{ab}(0)/\lambda_{ab}(t)$ representation. With $\lambda_{ab}(0) = 3000 \, \text{Å}$ and $T_c = 87.5 \, \text{K}$ (3.5 K lower than $T_c$ measured via magnetization [13]), the BSCCO and YBCO single crystals behave identically over a wide range of $0 \leq T/T_c \leq 0.97$, far more than expected from the clean limit $d_\sigma$ calculation. The representation with $\lambda_{ab}(0) = 2600 \, \text{Å}$ and $T_c = 91.0 \, \text{K}$ is also shown for comparison.

Near $T_c$ qualitative differences between BSCCO and YBCO are obvious and can be ascribed to the different nature of the fluctuations arising from the differing crystal
FIG. 3. Top: $\lambda_{ab}^2(0)/\lambda_{ab}^2(T)$ using $\lambda_{ab}(0) = 2600$ Å and $T_c = 91.0$ K with comparison to clean limit $s$- and $d$-wave calculations. Inset: Transition region. The arrow marks magnetization measurements. Bottom: $[\lambda_{ab}(0)/\lambda_{ab}(T)]^2$ using (a) $\lambda_{ab}(0) = 2600$ Å, $T_c = 91.0$ K and (b) $\lambda_{ab}(0) = 3000$ Å, $T_c = 87.5$ K for comparison with the YBa$_2$Cu$_3$O$_y$ $a$-axis data of Ref. [11]. Inset: Low temperature behavior of BSCCO ($\times 1$) and YBa$_2$Cu$_3$O$_y$ ($\times 2$).

A linear $T$ dependence of $R_s$ has not yet been explained by available theories of $d$-wave response at microwave frequencies. Since one expects a nonzero normal conductivity $\sigma_{00}$ for a clean $d$-wave superconductor [24], $\sigma_1 \rightarrow \sigma_{00} + aT^2$ and in a 2-fluid model $R_s \propto \lambda_{ab}^2(0)\sigma_1$, at sufficiently low temperature one expects that $R_s \rightarrow R_s(0) + bT^2$.

The residual conductivity $\sigma_{00}$ deduced from the measured residual resistance $R_s(0)$ and $\lambda_{ab}(0)$ appears to be much larger than would be expected from estimates of $\sigma_{00}$. While an extrinsic origin cannot be ruled out, the nature of the residual scattering and the role of impurities in affecting the conductivity of BSCCO crystals are important questions that need to be addressed. However, these effects are not expected to affect the low $T$ penetration depth results, which are dominated by the density of states.

$\hat{c}$-axis behavior.—A remarkable feature of BSCCO is the extremely large anisotropy between in-plane and $\hat{c}$-axis transport for $H_{rf} \parallel \hat{a}\hat{b}$. Even for thin samples like the ones used in this study the $\hat{c}$-axis component of the current can dominate. The $\hat{c}$-axis surface impedance $Z_{sc}$ was extracted from the measured $Z_{sa\hat{b}c} = H_{rf} \parallel \hat{a}\hat{b}$ and $Z_{sa\hat{b}} = Z_{sc} = [Z_{sa\hat{b}c}(l_a + l_c) - Z_{sa\hat{b}c}l_a]/l_c$. We have carefully checked our results for consistency: (i) A sample was cut into 4 pieces and re-measured, in which case the $ab$ contribution is unchanged but the $\hat{c}$-axis contribution is 4 times greater, as confirmed by the measurement. (ii) One sample was cleaved repeatedly and measured, and the results were found to be proportional to thickness, which can only happen if the $\hat{c}$-axis contribution dominates. Near $T_c$ the $\hat{c}$-axis penetration depth becomes comparable to the sample width. The above extraction does not apply where this is the case. In the normal state the size effect plays a crucial role and limits our ability to extract meaningful results. Nevertheless, an overall semiconducting behavior can be inferred for the conductivity in a 20 K region above $T_c$. For $T < 0.9T_c$ we are sure that size effects need not be taken into account, but our results for $\lambda_c(T)\parallel \hat{c}$ are less reliable.

The penetration depth $\Delta \lambda_c(T) = \lambda_c(T) - \lambda_c(4.2)$ K at low $T$ is shown in Fig. 4. The variation of $\lambda_c$ from 4.2 K to $T_c$ of at least 170 µm is much larger than the variation of $\lambda_{ab}$ of only 3.7 µm. This large variation suggests that the $\hat{c}$-axis transport is characteristic of weak superconductivity, and is consistent with experiments that suggest a tunneling mechanism for $\hat{c}$-axis transport [16,25].

In view of the layered structure of BSCCO, and the large anisotropy between $\lambda_{ab}$ and $\lambda_c$, a natural picture that emerges is of strongly superconducting CuO$_2$ layers weakly coupled along the $\hat{c}$ axis. Recently there have been several calculations [21,26–28] of $\lambda_{ab}(T)$ and $\lambda_c(T)$ for layered superconductors such as the cuprates. In particular, Ref. [21] points out the importance of measuring both $\lambda_{ab}(T)$ and $\lambda_c(T)$ for conclusions regarding the order parameter. Although the details of the temperature
was adjusted. Three data sets are shown, along with the inset: Field configuration with dashed line and s-wave (dash-dotted line) calculations. Top inset: Field configuration with $H_{\text{ef}} \parallel ab$. Bottom inset: Low $T$ behavior on a linear scale. The prediction for the microwave response and our data are almost indistinguishable.

dependence vary with the model used, the general low $T$ behavior is as expected; viz. an exponential dependence if the in-plane order parameter is $s$ wave and a linear dependence if it is $d$ wave. For illustrative purposes, we use the model of Ref. [26] which finds for direct tunneling

$$\lambda_c^2(0)/\lambda_c^2(T) = \left(\int_{-\infty}^{\infty} d\varepsilon (\Delta_{\varepsilon}^2/E_k^2) \times \left[\tanh(E_k/2k_BT)/2E_k + \partial f/\partial E_k\right]\right),$$

which is coincidentally identical with Eq. (1). The comparisons are shown in Fig. 4 for the isotropic $s$ wave and the $d_{x^2-y^2}$ order parameters. The agreement with the $d$-wave model over a wide range of temperature from 4 to 70 K is evident, as is the clear disagreement with the isotropic $s$-wave model. The only adjustable parameter in the fit is the vertical scale from which we get $\lambda_c(0) = 40 \mu m$. Conclusions at high temperature are vitiated by the size effects noted above, and could well be responsible for the deviations above $0.9T_c$.

The key point to be made here is that the low $T$ behavior of $\lambda_c(T)$ again reflects an in-plane superconducting order parameter with nodes in the gap. The rather striking agreement over such a wide range of temperature with the tunneling result is to some extent fortuitous, since the deviations of $\lambda_{ab}(T)$ from the clean limit weak-coupling result observed in Fig. 2 would be expected to appear in the comparison of Fig. 4 also.

By measuring the complete $T$ dependences of $\lambda_{ab}(T)$ and $\lambda_c(T)$, we have demonstrated important phenomenological aspects of microwave transport in BSCCO crystals. Some striking similarities with YBCO are evident, particularly as regards the low temperature properties, strongly suggesting a common energy dependence of the density of states for both these cuprate superconductors. However, there are some differences as well, which can be attributed to differences in anisotropy, and fluctuations near $T_c$. The role of scattering and of O content needs to be studied further in both materials in order to understand the dissipation represented by $R_{\text{D}}(T)$ and $\lambda(T)$. The experimental phenomenology reported in this paper is important for a successful theoretical description of superconductivity in the high $T_c$ cuprates.

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