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The *ab*-plane optical conductivity of high-T_c superconductors

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There is anisotropy in the *ab*-plane optical properties of the high-temperature superconductors, both in the normal state and in the superconducting state. In both states, two components appear in the optical conductivity: a free carrier part and a "midinfrared" component. Below T_c, the free carriers form the superconducting condensate. In $YBa_2Cu_3O_{7-\delta}$, the anisotropy of the penetration depth shows that the chains contribute strongly to this superfluid. In $Bi_2Sr_2CaCu_2O_8$, where chains are absent, there is still *ab* plane anisotropy. Below T_c a finite absorption parallel *b* remains at frequencies as small as 20 meV. This anisotropy could be due to anisotropy either of the superconducting gap or the midinfrared component.

KEY WORDS: Superconductors, optical properties, High-T_c

1. INTRODUCTION

Despite intense effort over the past eight years, open questions remain about the infrared response of high-T_c superconductors, particularly in the superconducting state.[1,2] There is no convincing evidence of superconducting gap absorption in most spectra. Instead, the data suggest two components to the optical conductivity: a free carrier part and a "midinfrared" component. Below T_c, the free carriers form the superconducting condensate, with most of the spectral weight associated with the free carriers residing in the delta function response of the superfluid and with the midinfrared component masking any excitations of the condensate. The weight of the delta function can be measured through its contribution to the superconducting screening, either as a $-\omega_{ps}^2/\omega^2$ contribution to the dielectric function[3] or, equivalently, in terms of a generalized penetration depth.[4]

In this paper, we compare the *ab*-plane anisotropy in the far-infrared for three materials: $Bi_2Sr_2CaCu_2O_8$, $YBa_2Cu_3O_{7-\delta}$, and $YBa_2Cu_4O_8$. These materials have similar T_c's, resistivities, and square-planar CuO_2 bilayers. The principal difference amongst them is the presence in the Y-based materials of CuO chains, giving them rather more structural anisotropy. In $Bi_2Sr_2CaCu_2O_8$ chains are absent, but there is still *ab* plane anisotropy in the far-infrared spectra and in the dc transport properties.[5] Previous infrared measurements of *ab*-plane anisotropy have been reported for $YBa_2Cu_3O_{7-\delta}$[4,6–10] and $Bi_2Sr_2CaCu_2O_8$.[11–14]

Infrared spectroscopy is sensitive only to certain types of anisotropy, both in normal and superconducting states. To observe a difference in infrared reflectance or conductivity, quantities like $|\Delta|^2$, the gap, must have only a twofold axis of symmetry in the *ab* plane (*i.e.*, orthorhombic symmetry). Then, the *a* and *b* components of the dielectric tensor will differ. If the *ab* plane has a fourfold axis, then the optical properties will be isotropic. Thus, although the optical conductivity is affected by the anisotropic order parameter of an unconventional superconductor,[15] in not every case does the anisotropy of the order parameter lead to an anisotropic *ab*-plane opti-

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cal conductivity. As a pertinent example, the optical conductivity for pure $d_{x^2-y^2}$ pairing is isotropic in the *ab* plane (although the spectrum *is* different from the case of *s*-wave pairing). In contrast, a *p*-wave component, a d_{xz} pairing, or a combination of *s*- and *d*- symmetries can give anisotropic *ab*-plane optical conductivities.

2. EXPERIMENTAL

The crystal growth procedures have been described previously.[16–18] We measured the polarized reflectance of single-domain single crystals using a Bruker IFS 113v interferometric spectrometer over 50–5000 cm^{-1} (0.006–0.6 eV) and using Perkin-Elmer 16U spectrometer over 1000–30000 cm^{-1} (0.12–3.7 eV).[14] The light was polarized using wire-grid polarizers in the far- and mid-infrared regions and dichroic polarizers in the near-infrared–near-ultraviolet regions. For our measurements we used the natural crystal surface unmodified by polishing or any other treatment. The reflectance was measured relative to an Al reference mirror and corrected for the known reflectance of Al. After measurements, the surface of our crystal was coated with Al and the reflectance of the coated sample measured, in order to determine accurately the sample area and to estimate the diffuse scattering due to any imperfections in the surface. A continuous-flow cryostat was used to cool the sample to a base temperature of 12 K.

The accuracy in absolute reflectance, estimated from reproducibility found in measurements of three different samples, is ± 1%. However, the accuracy of the anisotropy of the reflectance (*i.e.*, the difference between *a* and *b* results on the same sample at the same temperature) is better than ± 0.25%.

The reflectance data were analyzed by Kramers-Kronig techniques[19] to estimate the phase shift on reflectance. From the reflectance and phase shift, any of the optical functions (refractive index, dielectric function, conductivity, penetration depth, *etc.*) may be calculated.

3. RESULTS

Both $Bi_2Sr_2CaCu_2O_8$ and $YBa_2Cu_3O_{7-\delta}$ display *ab*-plane anisotropy in their infrared spectra. The anisotropy in $YBa_2Cu_3O_{7-\delta}$ is expected, on account of the structural anisotropy from the chains. That $Bi_2Sr_2CaCu_2O_8$ is anisotropic is less expected; the only structural anisotropy is the weak superlattice along *b*, which primarily affects the Bi-O layers.[20–22] In fact, because the Cu-O bond is rotated 45° with respect to the Bi-O bond in $Bi_2Sr_2CaCu_2O_8$, the superlattice does not affect the Cu-O *distance* at all. In the following, we will discuss $Bi_2Sr_2CaCu_2O_8$ first, then $YBa_2Cu_3O_{7-\delta}$.

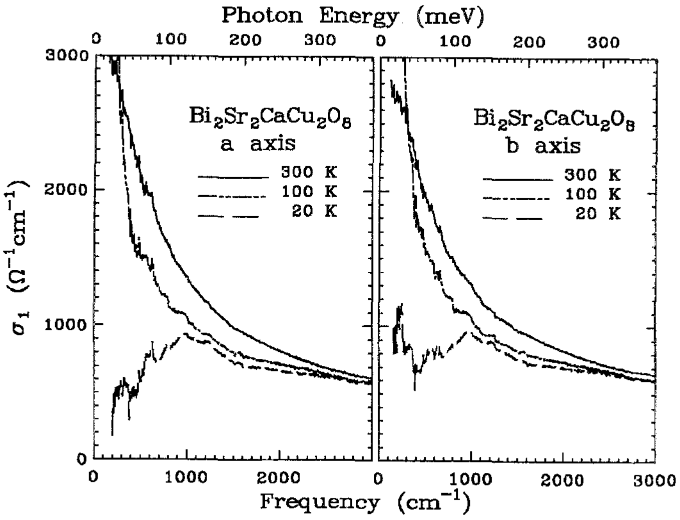

Fig. 1. Optical conductivity of $Bi_2Sr_2CaCu_2O_8$ at three temperatures. The left panel shows the results for the *a* axis, the right for the *b* axis.

Figure 1 shows the optical conductivity of $Bi_2Sr_2CaCu_2O_8$ at three temperatures. In the normal state, there is a free-carrier component dominating at low frequencies, with a broad, nearly temperature independent midinfrared contribution at higher frequencies. Below T_c, a substantial amount of spectral weight has been removed from $\sigma_1(\omega)$ and appears in the zero-frequency delta function of the superconductor. There is anisotropy in the *ab*-plane conductivity: about 10% in the normal state and nearly a factor of two in the low-frequency far-infrared conductivity below T_c.

Figure 2 shows the optical conductivity of $YBa_2Cu_3O_{7-\delta}$ at three temperatures. In the normal state, there is a free-carrier component dominating at low frequencies, with a broad, nearly temperature independent midinfrared contribution at higher frequencies. Below T_c, a substantial amount of spectral weight has been removed from $\sigma_1(\omega)$ and appears in the delta function. There is anisotropy in the *ab*-plane conductivity: about a factor of 2 in the normal state and nearly a factor of four in the low-frequency far-infrared conductivity below T_c.

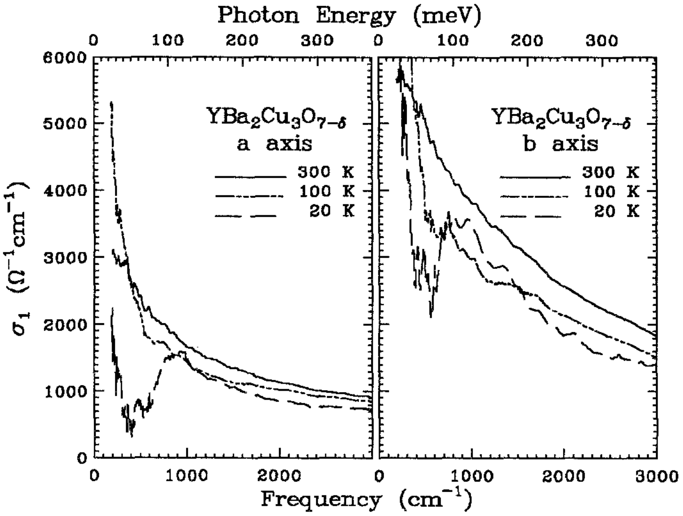

Fig. 2. Optical conductivity of YBa$_2$Cu$_3$O$_{7-\delta}$ at three temperatures. The left panel shows the results for the *a* axis, the right for the *b* axis.

Figure 3 shows a generalized penetration depth for three materials at the lowest temperatures. This quantity is $\lambda_L(\omega) = c/\omega_{ps} = c/\sqrt{4\pi\omega\sigma_2(\omega)}$, where σ_2 is the imaginary part of the optical conductivity, c is lightspeed, and ω_{ps} is the superfluid "plasma frequency." The latter quantity is related to the superfluid density, n_s through $\omega_{ps} = \sqrt{4\pi n_s e^2/m^*}$. Results are shown for Bi$_2$Sr$_2$CaCu$_2$O$_8$, YBa$_2$Cu$_3$O$_{7-\delta}$, and YBa$_2$Cu$_4$O$_8$. To the extent that these curves are flat, the substance obeys London electrodynamics, with $\sigma(\omega) = \omega_{ps}^2\delta(\omega)/8 + i\omega_{ps}^2/4\pi\omega$. The difference between the *a* and *b* directions is striking, being about 10% for Bi$_2$Sr$_2$CaCu$_2$O$_8$, 35% for YBa$_2$Cu$_3$O$_{7-\delta}$, and more than a factor of two for YBa$_2$Cu$_4$O$_8$.

4. DISCUSSION

That there is anisotropy in the optical properties of these materials is consistent with their orthorhombic crystal structure. The anisotropy in the superconducting state is however a little surprising. Generally one tends to view these systems as having square-planar, quasi-two-dimensional, CuO$_2$ planes, with a fourfold axis of symmetry about the copper site, and with the other structural elements less important for the superconducting state. This should be particularly true for Bi$_2$Sr$_2$CaCu$_2$O$_8$, where the only states at the Fermi level are from the CuO$_2$ sites. Then, the differences between the *a* and the *b* directions in the superconducting state shown in Fig. 1 can arise in one of two ways. If there is only one component to the infrared conductivity, as in a marginal Fermi liquid,[23] nested Fermi liquid,[24] or other models,[25] then the anisotropy reflects a two-fold symmetry to the superconducting gap absorption. (There is no other low-lying absorption band in these pictures.) As mentioned above, this anisotropy would be inconsistent with a purely $d_{x^2-y^2}$ gap symmetry. The second possibility is that there is a second component to the optical conductivity, so that the anisotropy could be attributed to this second component. (This "mid-infrared" absorption must exist in order to assign the observed anisotropy to it.)

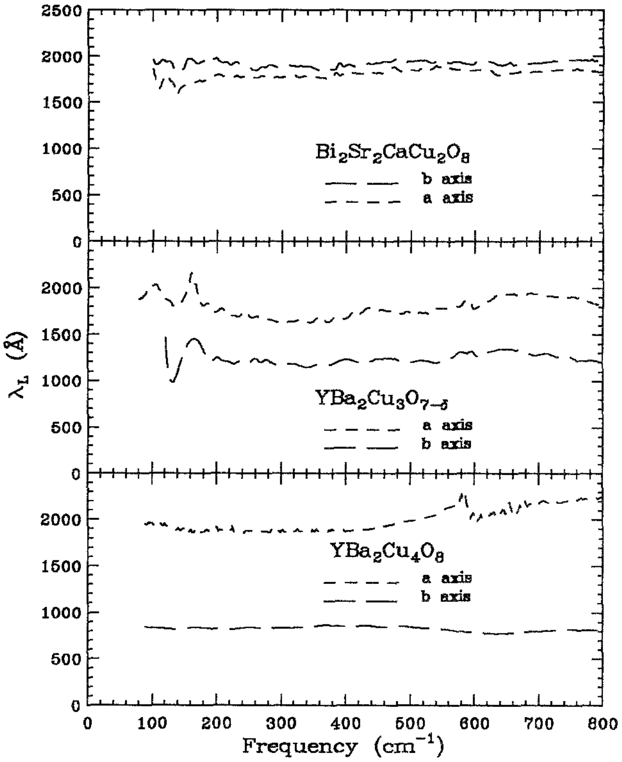

Fig. 3. The penetration depth for electric field directions in the *a* and *b* directions for three high-temperature superconductors. Data are at 20 K for Bi$_2$Sr$_2$CaCu$_2$O$_8$ and YBa$_2$Cu$_3$O$_{7-\delta}$ and at 10 K for YBa$_2$Cu$_4$O$_8$.

The results in Fig. 3 reveal that the superconducting penetration depth in Bi$_2$Sr$_2$CaCu$_2$O$_8$ is anisotropic, with the *b* direction having the larger λ_L and therefore the smaller superfluid density. The free carrier (Drude) density is also anisotropic (by a slightly smaller amount). In YBa$_2$Cu$_3$O$_{7-\delta}$ and YBa$_2$Cu$_4$O$_8$, the penetration depth is smaller in the chain direction than it is normal to the chains; therefore, a large portion of the free carrier density that can be attributed to the chains in the normal state condenses below T_c. These results indicate that superconductivity, at least in these compounds, is not confined to the planes but extends to the chains as well.

Finally, taken together, these results, *ab*-plane anisotropy in the chain-free $Bi_2Sr_2CaCu_2O_8$ and larger superfluid density in the *b* direction in $YBa_2Cu_3O_{7-\delta}$ and $YBa_2Cu_4O_8$, suggest that the common practice of separating *ab*-plane response into parallel chain and plane contributions in the chain-containing materials may not be justified.

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