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Optical anisotropy of $Bi_2Sr_2CaCu_2O_8$

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The optical anisotropy of $Bi_2Sr_2CaCu_2O_8$ in the 0.08–0.5 eV region is investigated by polarized reflectance measurements on single crystals. A very large anisotropy is found in this spectral region. The in-plane reflectance exhibits metallic behavior, while the c-axis reflectance exhibits insulatorlike behavior. This result is consistent with the large anisotropy found in the resistivity of $Bi_2Sr_2CaCu_2O_8$. Our spectroscopic data suggest that $Bi_2Sr_2CaCu_2O_8$ is a quasi-two-dimensional metal similar to $La_{2-x}Sr_xCuO_4$.

It is well known that all the high-T_c superconducting cuprates are quite anisotropic in their electronic properties, as indeed expected from their layered crystal structures. The anisotropy or even quasi-two-dimensionality may prove to be a key feature for obtaining high-T_c superconductivity, as is suggested by many theoretical models. With that motivation, numerous attempts have been made to directly measure the anisotropy of various electronic properties, such as dc conductivity, Hall tensor, magnetic penetration depth, H_{c2}, thermal conductivity, etc.[1–11] However, these measurements can be severely affected by stacking faults, microcracks, voids, and inhomogeneous oxygen concentration, all of which are known to occur extensively in routinely prepared high-T_c samples. This fact is likely the origin of substantial discrepancies concerning the qualitative character of the c-axis conductivity in $YBa_2Cu_3O_{7-\delta}$; it has remained controversial even whether it is insulating or metallic in that direction. On the other hand, high-frequency measurements, like infrared spectroscopy, are less sensitive to such defects (because charge displacements are rather small) and they can reliably probe the intrinsic properties. Hence, infrared spectroscopy with polarized light on single-crystal specimens should faithfully represent the electronic anisotropy of high-T_c compounds.

So far, the optical anisotropy of $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_{7-\delta}$ has been studied.[12–14] The results are somewhat diverging. $La_{2-x}Sr_xCuO_4$ seems to show quasi-two-dimensional characteristics, i.e., metal-like behavior if the electric field is parallel to the CuO_2 planes (**E**‖**a**-**b**) and insulatorlike behavior for the perpendicular polarization (**E**‖**c**). Similar anisotropy was observed earlier in La_2NiO_4,[15] a compound isostructural with La_2CuO_4 (for anisotropy study of La_2CuO_4, see Refs. 16 and 17). $YBa_2Cu_3O_{7-\delta}$, on the other hand, seems to exhibit different behavior—it looks metallic, both in the ab plane and along the c axis, with $\tilde{\omega}_p^{\parallel} \approx 1.4$ eV and $\tilde{\omega}_p^{\perp} \approx 0.3$ eV.[14,18] Therefore, it is of great interest to extend these studies to other high-T_c superconductors, in particular, to the more anisotropic materials like $Bi_2Sr_2CaCu_2O_8$.

Single crystals of $Bi_2Sr_2CaCu_2O_8$ were prepared as described in Ref. 19 using a directional solidification technique. After extracting crystals from the melt, they were pressure annealed in 12 atm of oxygen at 540 °C for 18 h and then quenched to room temperature. A large Meissner signal was observed with an onset at 77 K and a transition width of approximately 2 K in a 0.5 Oe applied field (note that the measurement of the magnetic transition width is a far more rigorous test of sample quality than that of the resistive transition width). X-ray diffraction data indicated lattice constants of $a_0=5.408(2)$, $b_0=5.413(2)$, and $c_0=30.81(1)$ with an incommensurate modulation $(4.8b_0)$ along the b axis. Wavelength-dispersive microprobe analysis yielded a cation composition $Bi_{2.1}Sr_{1.9}Ca_{0.9}Cu_{2.1}O_y$ for these crystals. Samples of typical width of ~3 mm were then cast vertically in a stycast epoxy into a disk and then polished on both sides to optical quality in order to provide two *ac* planes of the $Bi_2Sr_2CaCu_2O_8$ crystals. The thickness of the disk was ~1 mm.

Our mid-infrared polarized reflectance measurements were made with a Bio-Rad FTS-40 Fourier-transform infrared (FTIR) spectrometer coupled to a Spectra-Tech IR-PLAN microscope. The microscope was equipped with a dedicated HgCdTe detector (cooled with liquid nitrogen) and provided spatial resolution of 100 μm with which small domains of single crystals were isolated for measurement. The polarization was changed by rotating the sample. The spectra were taken at room temperature.

The reflection due to light scattered from the polarizer and the aperture was less than 2% of the reflection due to the sample and was subtracted from both the sample spectra and the reference (gold mirror) spectra.

The reflectance spectra of a single crystal of $Bi_2Sr_2CaCu_2O_8$, with the light beam incident normal to ac or bc faces, for both **E**‖**a-b** and **E**‖**c** polarizations, are presented in Fig. 1. For comparison, a reflectance spectrum of a similar crystal, with the light beam incident normal to the **a-b** face (the large platelet face), for **E**‖**a-b** is also presented showing an almost identical spectrum to the **E**‖**a-b** spectrum taken from the narrow platelet side.

A large anisotropy is clearly seen. [The real anisotropy should be even larger; our measured $R_\perp$ in reality contained some small admixture—say 5–10%—of $R_\parallel$, because of imperfect orientation, some diffuse reflectance which arises from surface imperfections, and because the beam was slightly convergent.] Notice the rise of $R_\parallel$ to high metallic reflectance at lower frequencies. In contrast, $R_\perp$ has no such feature; it is rather resemblant of an insulator. The experimental results suggest that $Bi_2Sr_2CaCu_2O_8$ is a quasi-two-dimensional metal; certainly, the effective mass of the holes must be much larger in

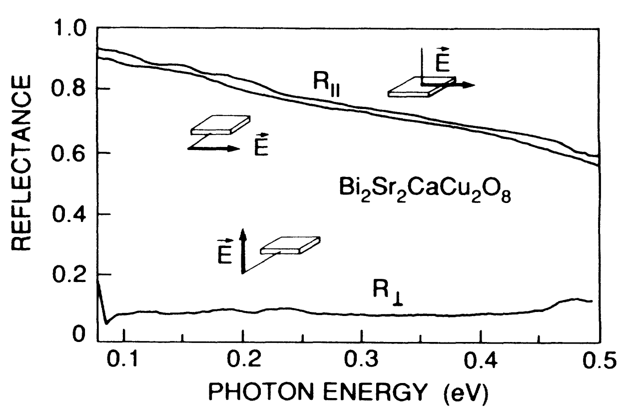

FIG. 1. The polarized mid-infrared reflectance spectra of single crystals of $Bi_2Sr_2CaCu_2O_8$. See text.

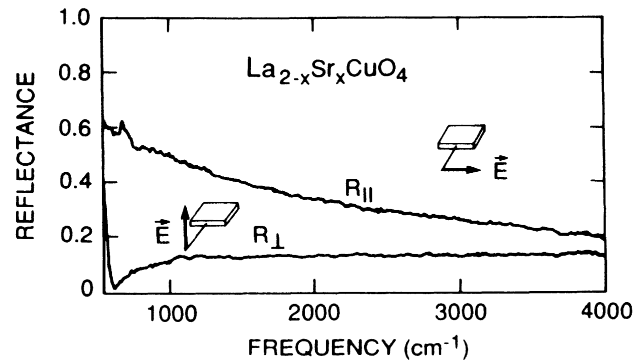

FIG. 2. The polarized mid-infrared reflectance spectra of a single crystal of $La_{2-x}Sr_xCuO_4$ (from Ref. 13). The original data actually extend through the far-infrared region, which is not considered in our work.

the c-axis direction than along the a- or b-axis direction. This is consistent with the large anisotropy[5] in resistivity of $Bi_2Sr_2CaCu_2O_8$ $(\rho_\perp/\rho_\parallel \approx 10^5)$; furthermore, $\rho_\parallel$ shows a metallic temperature dependence in contrast to the fast increase of $\rho_\perp$ when the temperature is decreased. In this respect, $Bi_2Sr_2CaCu_2O_8$ is similar to $La_{2-x}Sr_xCuO_4$ (Fig. 2) while it is apparently different from $YBa_2Cu_3O_{7-\delta}$ (Fig. 3).

According to Ref. 11, $YBa_2Cu_3O_{7-\delta}$ is metallic along the c axis; if that is indeed true then $YBa_2Cu_3O_{7-\delta}$ is rather exceptional in view of the insulatorlike characteristics of $La_{2-x}Sr_xCuO_4$ and $Bi_2Sr_2CaCu_2O_8$ along the c axis. Either the dimensionality is irrelevant to high-T_c superconductivity or $YBa_2Cu_3O_{7-\delta}$ is showing some inessential, special features. One possible way out of the paradox is that $YBa_2Cu_3O_{7-\delta}$ might have two types of carriers or relevant states. One set of states may be related to CuO_2 planes, which are similar to the in-plane states in $La_{2-x}Sr_xCuO_4$ and $Bi_2Sr_2CaCu_2O_8$; it should be essentially quasi-two-dimensional. The other set of states may

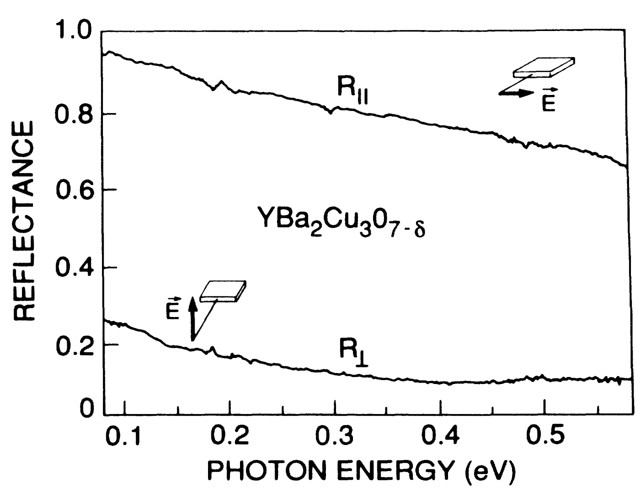

FIG. 3. The polarized mid-infrared reflectance spectra of a single crystal of $YBa_2Cu_3O_{7-\delta}$, with the light beam incident normal to *ab* or *bc* faces, for both **E**‖**a-b** and **E**‖**c** polarizations (from Ref. 14).

be possibly related to CuO chains and hence responsible for the observed metallic *c*-axis reflectance and also for the relatively high *c*-axis conductivity in the normal state.

It may be relevant to note that the distance between CuO_2 layers in $La_{2-x}Sr_xCuO_4$ is about 7 Å and that the distance between CuO_2-Ca-CuO_2 slabs in $Bi_2Sr_2CaCu_2O_8$ is about 12.5 Å. In $YBa_2Cu_3O_{7-\delta}$, however, there are CuO chains inserted halfway between CuO_2-Y-CuO_2 slabs and the distance between a CuO chain and a CuO_2-Y-CuO_2 slab is about 4 Å. These CuO chains might serve as "bridges" to support metallic transport along the direction normal to the *a*-*b* plane, which would account for the metallic *c*-axis reflectance.

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