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Far-infrared ellipsometry of electrons and phonons in $\text{La}_{1.87}\text{Sr}_{0.13}\text{CuO}_4$

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We measured the complex dielectric function from 30 to 680 cm^{-1} along the c axis of a large, high quality single crystal of $\text{La}_{1.87}\text{Sr}_{0.13}\text{CuO}_4$ at temperatures between 6 and 300 K with a far-infrared Fourier-ellipsometer. We obtain the complex dielectric function directly, without Kramers-Kronig analysis. In agreement with findings of Tamasaku *et al.* [PRL 69, 1455 (1989)], our data indicate an almost complete blockade of c axis single-particle transport. We present accurate optical phonon data and discuss upper limits of the low temperature far-infrared c axis ac conductivity. We find an anomalously large strength of the 235 cm^{-1} optical phonon and discuss its possible origin.

Recent infrared reflectivity studies of the c axis optical response of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ [1] indicate severely suppressed low frequency conductivity $\tilde{\sigma}^c(\omega)$ in the normal state and a sudden restoration of the coherent charge transport in the superconducting state. Such a confinement of normal-state carriers plays also an important role in the Luttinger liquid model [2] of high T_c superconductivity.

We present direct measurements of the dielectric function of $\text{La}_{1.87}\text{Sr}_{0.13}\text{CuO}_4$ along c at frequencies between 30 and 680 cm^{-1} . Using ellipsometry we obtain both, amplitude and phase information. Neither errors introduced by Kramers-Kronig calculations nor the reference problem, both ubiquitous in far-infrared reflectivity measurements, influence our result.

We investigated a single crystal grown by the traveling-solvent-floating-zone method [3]. SQUID magnetization measurements (fc and zfc) showed a sharp superconducting transition at 31 K. The crystal was a long rod with 7 mm diameter and (100) growth direction. In order to get a (100) surface large enough for our experiment we cut 5 slices. We aligned the c axes of the pieces using Raman and Laue measurements and glued the mosaic onto a Cu plate. Finally we polished the surface of the sample constructed this way. The useful area of our sample was $8 \times 8 \text{ mm}^2$.

By rotating analyzer ellipsometry with an ellipsometer attached to a Fourier transform IR spectrometer [4] we obtained the complex reflectance ratio $\tilde{\rho} = \frac{\tilde{r}_p}{\tilde{r}_s}$ [5]. The angle of incidence was 80° (beam divergence $\pm 1.2^\circ$).

Since the sample is anisotropic, the pseudodielectric function (i.e. the dielectric function calculated from the complex reflectance ratio assuming an isotropic, clean and homogeneous sample/ambient interface) contains contributions from all dielectric tensor elements. By fitting the Fresnel equations for a uniaxial material to two experimental spectra of $\tilde{\rho}$ (c axis parallel and perpendicular to the plane of incidence) [5] we obtained the dielectric tensor components $\tilde{\epsilon}^a$ and $\tilde{\epsilon}^c$. The fit confirmed the conjecture, that the pseudodielectric function is a good approximation for the dielectric tensor element along the line of intersection between the plane of incidence and the sample surface. $\tilde{\epsilon}^c$ also proved to be rather insensitive to simulated changes in $\tilde{\epsilon}^a$.

The real and imaginary parts of the dielectric function, $\epsilon_1^c(\omega)$ and $\epsilon_2^c(\omega)$ are shown in Figs. 1 and 2. We have modelled $\epsilon_2^c(\omega)$ by a sum of 5 Lorentzians, representing the contribution of optical phonons. The agreement between the fit and the $\epsilon_2^c(\omega)$ data is excellent, except for the low-frequency electronic contribution, where various models (Drude, diffusive etc.) have been

Figure 1. $\epsilon_1^c(\omega)$ of $\text{La}_{1.87}\text{Sr}_{0.13}\text{CuO}_4$ between 30–680 cm^{-1} at RT and at 5K. The insert shows temperature dependent values for the "missing area" in $\sigma_1(\omega)$ ($\int_{30\text{cm}^{-1}}^{100\text{cm}^{-1}} \sigma_1^c(\omega) d\omega$) and the plasma frequency ω_p obtained from ϵ_1^c .

tried without much success. In particular, in our data, down to 30 cm^{-1} we do not see any up-turn of $\epsilon_2^c(\omega)$ characteristic for metallic conductivity. The Lorentz model parameters also allow perfect representation of the real part of the dielectric function, pointing at Kramers-Kronig consistency of our spectra. The values of the fit parameters at 5K are shown in Table 1. They are in good agreement with previous measurements of ceramic materials, indicating a dominant contribution of the c axis response in these spectra. Between 300 and 600 cm^{-1} the spectral weight of the phonon oscillators contributes, within the fit accuracy, 100% of the measured conductivity. Therefore, our data indicate that in this spectral range there is a vanishingly small electronic contribution along the c axis. The lowest TO phonon at 235 cm^{-1} has an anomalously large oscillator strength $S_1 \approx 14.5$. Standard shell-model calculations, which assume

Table 1

Lorentz parameters for the modelling of $\tilde{\epsilon}^c$ at 5K with the energy position ω_i , the width γ_i and the oscillator strength S_i

	Oscillator				
	1	2	3	4	5
ω_i [cm^{-1}]	234.9	250.5	312	353	491.5
γ_i [cm^{-1}]	28	12	5	4	18
S_i	14.5	3.5	0.02	0.05	0.25

Figure 2. The imaginary part of the c axis dielectric function of $\text{La}_{1.87}\text{Sr}_{0.13}\text{CuO}_4$. The insert shows the low-energy conductivity $\sigma_1(\omega)$ as a function of temperature, between 6 and 100K.

formal ionic charges, yield values almost 7 times lower. Such a discrepancy, also observed in other high T_c materials [6], indicates a charge-transfer mechanism.

Below T_c at low frequencies, $\omega \leq 100 \text{ cm}^{-1}$, both $\epsilon_1^c(\omega)$ and $\epsilon_2^c(\omega)$ show characteristic signatures of superconductivity. In the insert in Fig. 1 we display the "missing area" in $\sigma_1(\omega)$ as a function of T as well as the condensate "plasma frequency" obtained from $\epsilon_1^c(\omega)$. Both are consistent in the sense that the carriers missing in the imaginary part show up in the real part of $\tilde{\epsilon}^c(\omega)$.

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