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Infrared Reflectivity Spectra of Underdoped and Optimally Doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ Thin Films

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We investigated the ab-plane reflectivity spectra of an optimally doped and a strongly underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) thin film as a function of the temperature. The far-infrared (FIR, ω<1000 cm^{-1}) spectra exhibit strong doping dependencies. When the temperature decreases, both samples show a reflectivity upturn at ω~800 cm^{-1}. This feature starts to develop at T_C for the optimally doped film, whereas it is already observed at T~6T_C for the underdoped film. Below T_C, the FIR reflectivity keeps increasing for the optimally doped film, whereas it is temperature independent for the underdoped sample. The structure of these FIR spectra is analysed, taking into account the measured substrate response. The opening of a pseudo-gap is discussed.

Bi-2212 infrared data, in underdoped crystals, show a pseudo-gap behaviour not clearly seen in optimally doped samples. Bi-2212 thin films can achieve much higher levels of underdoping while keeping an optically adequate surface. In this paper, we present the infrared reflectivity R of a close to optimally doped (OD, T_C=80K) and a strongly underdoped (SUD, T_C=32K) Bi-2212 thin film for temperatures between 10K and 300K. The c-axis oriented films (5000Å thick) were epitaxially grown by r.f. magnetron sputtering on an $SrTiO_3$ substrate [1]. T_C is defined as the temperature at which the resistivity drops to zero.

The spectra were obtained by Fourier transform spectroscopy (FTS) using a Bruker IFS66v/S spectrometer in the 50-7000 cm^{-1} range. The noise in our measurements is lower than 0.5%, and the accuracy in the absolute reflectivity is better than 1%. To minimise the effects of temperature drifts, the sample and the reference were alternately measured at the same temperature.

To ensure that our analysis is not biased by the temperature-dependent dielectric function of the substrate, we measured the reflectivity of $SrTiO_3$ in the 10-300K range. Using numerical simulations in multilayer systems, we verified that the temperature variations of the reflectivity in the relevant spectral ranges can be assigned to the Bi-2212 film.

The FIR (100-800 cm^{-1}) ab-plane normalised frequency-dependent reflectivities $[R_T(\omega)/R_{300K}(\omega)]$ of the two films are shown in Fig. 1. For both films, we observe an upturn at ω~800 cm^{-1}, a frequency scale in agreement with previous reports in Bi-2212 single crystals [2, 3]. The magnitude of this upturn increases as the temperature decreases, and is larger for the SUD film. The various dips (appearing with the normalisation) are due to either phonon resonances from the substrate (90, 180 and 525 cm^{-1}) [4], or to phonon resonances in both the substrate and the film (475 cm^{-1}) [2, 4], or to the film alone (630 cm^{-1}) [2]. We suggest the same latter assignment for the dips at 300 and 360 cm^{-1}, because the substrate has no phonon structure in this region. Furthermore, numerical simulations of the reflectivity spectra require these two oscillators in this range.

Figure 2 shows the temperature dependence of the normalised reflectivity of the two studied films for different frequencies. For the SUD film, an increase in the reflectivity can be seen at 190K (~6T$_C$) for frequencies below 400 cm^{-1}. Resistivity measurements in this film show a departure from linearity below the same temperature, suggesting the opening of a pseudo-gap as pointed out in [5]. Below T_C the reflectivity remains constant in temperature. In contrast, earlier

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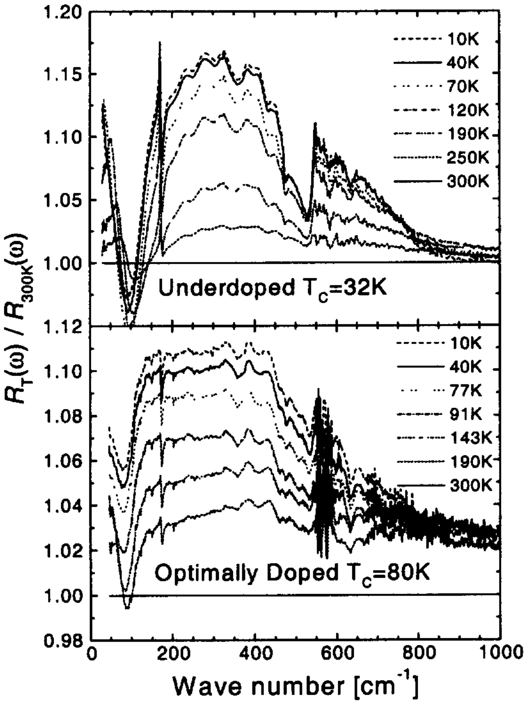

Figure 1. Ratio R_T/R_{300K} of the reflectivity spectra of SUD (upper panel) and OD (lower panel) Bi-2212 thin films at 10K<T<300K. Noise in the 550-600 cm^{-1} range is due to a poor overlap in the transmittance of the beam-splitters. Vertical scales in the upper and lower panels are different.

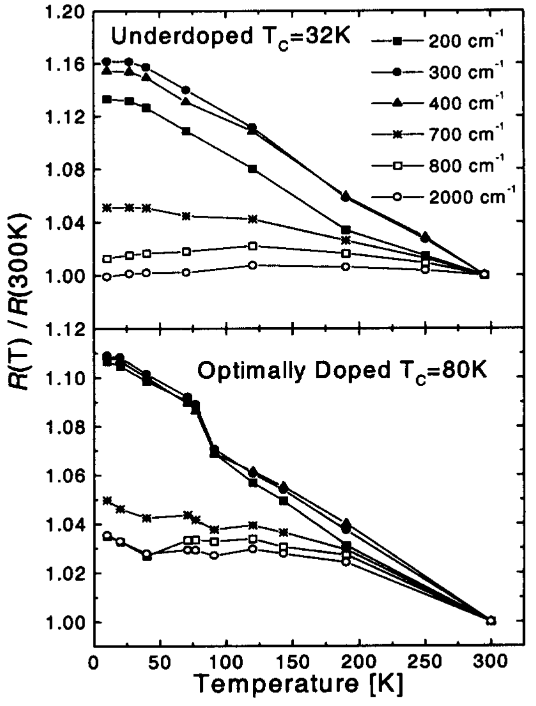

Figure 2. Temperature dependence of the ratio R_T/R_{300K} for different wave numbers. Films are the same as in Fig. 1. Each point is an 11 data-points average around a given frequency. Error bars are smaller than the symbols size. Vertical scales in the upper and lower panels are different.

reports in moderately underdoped (T_C=67K) Bi-2212 single crystals show a noticeable (~1%) change of the reflectivity when crossing T_C, associated with a small extra loss of spectral weight in the corresponding optical conductivity [3].

For the OD film (Fig. 2, lower panel), the reflectivity exhibits a jump at $T=T_C$, and keeps increasing below T_C, which we associate to the condensation of quasi-particles. We therefore infer that in the SUD sample there is a vanishing small loss of spectral weight below T_C.

In summary, below 800 cm^{-1}, the SUD film shows enhanced reflectivity below T~$6T_C$, which we assign to the pseudo-gap opening, whereas a similar behaviour occurs only below T_C in the OD sample. The reflectivity saturates at T_C in the SUD film while it keeps increasing in the OD sample.

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