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c-Axis Infrared Properties of $Sm_{2-x}Ce_xCuO_{4-\delta}$

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We have measured the grazing-incidence p-polarized far-infrared reflectivity of $Sm_{2-x}Ce_xCuO_{4-\delta}$ crystals ($T_c = 15$ K). C-axis longitudinal-optical phonon features are clearly visible at 430, 570, and 600 cm^{-1}. The phonon frequencies do not shift with temperature, which indicates that the electronic component of the dielectric function remains almost unaltered above the energy scale of 3-4k_BT_c across the superconducting transition. Below T_c the absorptivity (measured down to 30 cm^{-1}) does not show a signature of a threshold at around 3.5k_BT_c characteristic of BCS superconductivity. Based on our observations with $\vec{E} \parallel \vec{c}$ an upper limit of 30 cm^{-1} can be placed on the energy of the screened Josephson plasmon for temperatures down to 4 K.

The c-axis infrared properties of high-T_c superconductors attracted much attention recently, especially in connection with the Josephson plasmon [1,2]. For most flux-grown single crystals, however, the dimension along the c axis is not large enough to permit the standard normal-incidence reflectivity measurement. It is nevertheless possible to utilize such single crystals for the study of their c-axis infrared properties by employing grazing-incidence p-polarized reflectivity measurements [3,4]. For example, this technique has been applied to probe the presence of a c-axis Josephson plasmon in $Tl_2Ba_2CuO_6$ and $Bi_2Sr_2CuO_6$, none of which exhibited any related feature in the infrared region [4]. These results were taken as an evidence both against the prediction based on the BCS theory with an isotropic s wave gap, and against that based on more exotic interlayer tunneling theory [5].

In order to extend this investigation to electron-doped cuprate superconductors, we have synthesized $Sm_{2-x}Ce_xCuO_{4-\delta}$ single crystals (ab-plane face) with $T_c = 15$ K [6], and performed grazing-incidence ($\theta \approx 80°$) p-polarized reflectivity measurements in which a substantial portion of the electric field lies along the c axis, probing the otherwise inaccessible c-axis infrared response. The samples were mounted on a Cu cone in a cryostat and later coated with Au *in situ* for acquisition of absolute reflectivity.

Figure 1 presents the p-polarized reflectivity spectra (R_p) at temperatures of 4, 20, and 40 K, and Figure 2 presents the generalized absorptivity $A_p/2(2-A_p)$ with $A_p = 1-R_p$, the peaks of which correspond to the c-axis longitudinal excitations in the present case [4]. C-axis longitudinal-optical (LO) phonon features are clearly visible at 430, 570, 600 cm^{-1}, and (somewhat less clearly) 150 cm^{-1}. We can identify these A_{2u} modes rather easily based on previous studies on Nd_2CuO_4 [7]. The 150 cm^{-1} mode is most likely due to the vibration of Cu against Sm/Ce atoms, and the 430 cm^{-1} mode can be attributed to the in-phase vibration of all O atoms against Sm/Ce atoms. The 570 cm^{-1} and 600 cm^{-1} modes are assigned to the vibration of in-plane O atoms against Cu and out-of-plane O atoms. Although group-theoretical considerations require only three c-axis LO modes, the change in the local environment of the out-of-plane O atoms, due to partial replacement of Sm by Ce atoms, can lead to the

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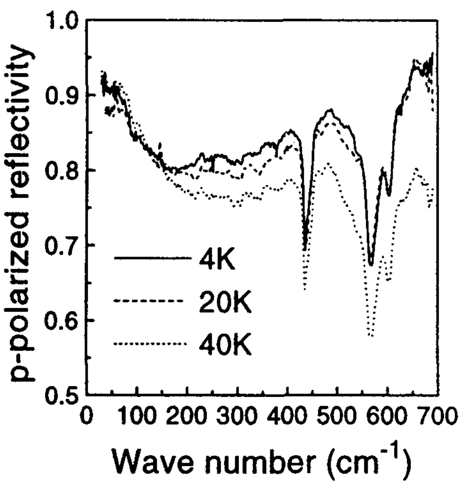

Figure 1. Grazing-incidence p-polarized reflectivity R_p of a superconducting $Sm_{2-x}Ce_xCuO_{4-\delta}$ crystal at 4, 20, and 40 K.

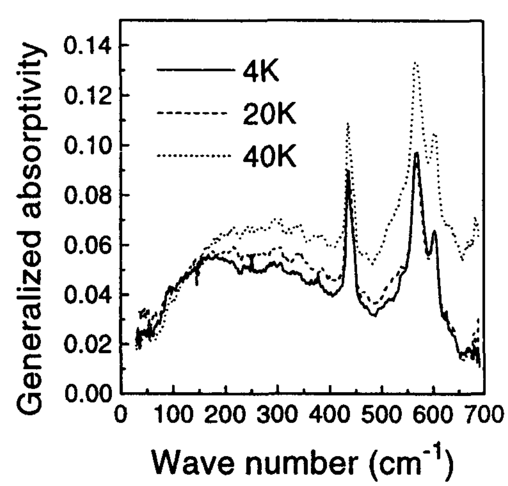

Figure 2. Generalized absorptivity calulated from R_p of $Sm_{2-x}Ce_xCuO_{4-\delta}$ at 4, 20, and 40 K.

splitting of the highest phonon mode.

The observed phonon modes do not shift with temperature, and there is no indication of an additional c-axis LO mode below T_c down to 4 K. Such a mode, absent in our $Sm_{2-x}Ce_xCuO_{4-\delta}$ crystals down to 30 cm^{-1}, would have been due to the presence of a Josephson plasmon, which could arise from the conductivity sum-rule requirement in the dirty-limit picture within BCS theory, or from the relation between the interlayer coupling energy and the superfluid plasma frequency within the interlayer-tunneling theory [5]. The latter scenario, quite distinct from the former, predicts the screened superfluid plasma frequency of 110 cm^{-1} for $Sm_{2-x}Ce_xCuO_{4-\delta}$ (T_c = 15 K, a=3.95 Å, d=6.05 Å where a and d are respectively the in-plane lattice parameter and the inter-CuO_2 layer spacing). This in turn would have altered the electronic component of the c-axis dielectric function, leading to a substantial up-shift of the c-axis LO phonons. Hence the electronic part remains almost unaltered above the energy scale of 3-4k_BT_c across T_c and we can assign an upper limit of 30 cm^{-1} on the energy of the screened Josephson plasmon for temperatures down to 4 K.

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