c-Axis Infrared Properties of Sm$_{2-x}$Ce$_x$CuO$_{4-\delta}$

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We have measured the grazing-incidence $p$-polarized far-infrared reflectivity of Sm$_{2-x}$Ce$_x$CuO$_{4-\delta}$ 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 $E \parallel c$ 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$_2$Ba$_2$CuO$_4$ and Bi$_2$Sr$_2$CuO$_4$, 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$_x$CuO$_{4-\delta}$ single crystals ($ab$-plane face) with $T_c = 15$ K [6], and performed grazing-incidence ($\theta \approx 80^\circ$) $p$-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$_2$CuO$_4$ [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
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$_x$CuO$_{4-\delta}$ 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$_x$CuO$_{4-\delta}$ ($T_c = 15$ 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 $3-4k_B T_c$ 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.

REFERENCES