Physica C 235-240 (1994) 1145-1146
North-Holland

PHYSICA C

# Damping Mechanism of the Strongly Renormalized $c$-Axis Plasma Frequency in High-$T_c$ Cuprates

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We study the charge dynamics of high-$T_c$ superconductors with the electric field perpendicular to the planes, using polarized oblique-incidence reflectometry for thin films of $Tl_2Ba_2Ca_2Cu_3O_{10}$ and normal incidence reflectometry for single crystals of $La_{1.85}Sr_{0.15}CuO_4$. In $Tl_2Ba_2Ca_2Cu_3O_{10}$ we observe no $c$-axis optical plasmon either above or below $T_c$. For $E//c$ in $La_{2-x}Sr_xCuO_4$, no plasmon is observed in the normal state, but as soon as $T$ drops below $T_c$, a plasma edge in the reflectivity occurs, which moves up to about $2k_BT_c$ for $T \rightarrow 0$. The electronic contribution to $\sigma(\omega) \approx 7\ \Omega^{-1}\text{cm}^{-1}$ is independent of frequency up to several hundred $\text{cm}^{-1}$, which implies that the optical scattering rate ($\tau_c^{-1}$) is large compared to the $c$-axis plasma frequency ($\omega_{pc}$). We prove experimentally that $\hbar/\tau_c > \hbar\omega_{pc} \gg 3.5k_BT_c$, hence the $c$-axis response is in a universality class different from the dirty (Mattis-Bardeen) limit, and the absence of a plasma edge in the normal state is due to overdamping. Recent experimental data of various groups show that this is a generic feature of high-$T_c$ cuprates. There is no need to assume a large many-body reduction of the *ab initio* LDA-RPA plasma frequency along the $c$-axis. Yet the overdamping of the plasmon could be a many-body effect. The 'confinement' to the planes as was proposed by Anderson is therefore due to a strong scattering in the $c$-direction. In the dirty limit only the relatively small amount of oscillator strength in the below-gap region is transferred to the pair-response (the $\delta$-function at zero frequency). As a result the plasma edge in the superconducting state occurs at about $3.4(k_BT_c\hbar/\gamma)^{0.5}\omega_{pc} \ll 3.5k_BT_c \ll \hbar\omega_{pc}$.

## 1. $c$-AXIS INFRARED RESPONSE OF $Tl_2Ba_2Ca_2Cu_3O_{10}$

We have developed a new technique which allows for an accurate determination of the loss function along the optical axis of a uniaxial medium (whose optical axis is perpendicular to its face) through oblique-incidence polarized reflectivity measurements [1]. This method has been applied to $c$-axis-oriented $Tl_2Ba_2Ca_2Cu_3O_{10}$ films of $T_c \approx 123$ K. In Figure 1 we present the $c$-axis loss function of $Tl_2Ba_2Ca_2Cu_3O_{10}$ at various temperatures. The peaks in the $c$-axis loss function centered at 400 and 620 $\text{cm}^{-1}$ corresponds to longitudinal optical (LO) $c$-axis phonons. The more or less flat electronic background suggests that the optical plasmon along the $c$-axis is either absent or very small in energy (below 200 $\text{cm}^{-1}$). A recent report by Tajima *et al.* [2] on the $c$-axis infrared response of $Bi_2Sr_2CaCu_2O_8$ indicated that the optical plasmon along the $c$-axis is either absent or very low in energy. Both compounds are characterized by extremely large anisotropy.

## 2. $c$-AXIS INFRARED RESPONSE OF $La_{1.85}Sr_{0.15}CuO_4$

We also performed normal-incidence polarized reflectivity measurements on $La_{1.85}Sr_{0.15}CuO_4$ crystals (with the $ac$-plane on the face) of $T_c \approx 31$ K. In Figure 2 we present the $c$-axis reflectivity of $La_{1.85}Sr_{0.15}CuO_4$ at various temperatures. The normal-state spectrum is characteristic of an insulator with infrared active phonons dom-

0921-4534/94/$07.00 
SSDI 0921-4534(94)01136-2

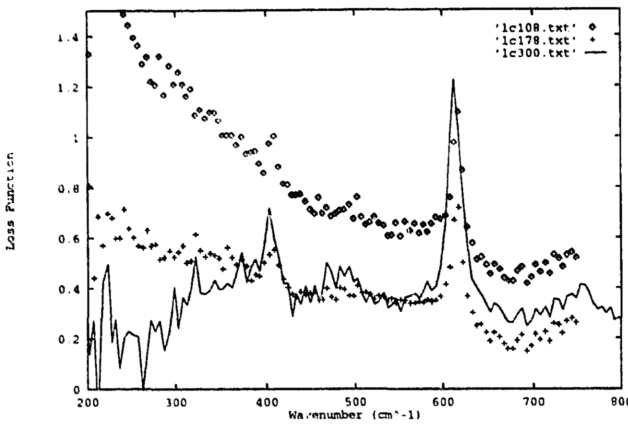


Figure 1. The $c$-axis loss function of $Tl_2Ba_2Ca_2Cu_3O_{10}$. The temperatures are 108 K (diamonds), 178 K (crosses), and 300 K (solid line).

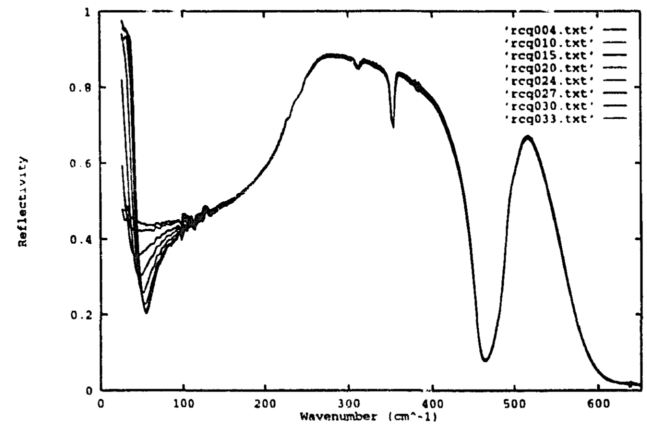


Figure 2. The $c$-axis reflectivity of $La_{1.85}Sr_{0.15}CuO_4$ at various temperatures. The curves correspond to 8, 10, 15, 20, 24, 27, 30, 33, and 300 K (from bottom to top).

inating the far-infrared (FIR) range. However, the superconducting-state spectra exhibit a dramatic development of a reflectivity edge due to an optical plasmon [3]. The reflectivity edge shifts to about $2k_BT_c$ as $T \rightarrow 0$. The electronic background of the $c$-axis conductivity is rather flat, indicating that the scattering rate, $\gamma$, is much larger than $\omega_{pc}$, the $c$-axis plasma frequency, which in turn is much larger than $3.5k_BT_c$. The superconducting-state $c$-axis reflectivity below 650 $cm^{-1}$ can be fitted reasonably well if we assume the two-fluid model:

$$\epsilon(\omega) = \epsilon_{LF} - \frac{(1-f_n)\omega_{pc}^2}{\omega(\omega + i0^+)} - \frac{f_n\omega_{pc}^2}{\omega(\omega + i\gamma)} + \text{phonons} \quad (1)$$

where $\epsilon_{LF}$ is the low-frequency dielectric constant, $f_n$ is the normal fraction, and $\gamma$ is the scattering rate of the normal fluid. The best-fit parameters at 4 K are given by $\epsilon_{LF} = 29$, $f_n = 0.95$, $\omega_{pc} = 960$ $cm^{-1}$, and $\gamma = 4800$ $cm^{-1}$. Hence the $c$-axis infrared response of $La_{1.85}Sr_{0.15}CuO_4$ is in the dirty limit for $3.5k_BT_c \ll \gamma$, but is different from what is expected in the usual dirty limit (in the Mattis-Bardeen sense) where $\gamma \ll \omega_{pc}$. The absence of a plasma edge in the normal state is due to overdamping. It is not necessary to assume a large reduction of the *ab initio* LDA-RPA plasma frequency along the $c$ axis. The overdamping of the plasmon could be due to a many-body effect. In the dirty limit, only the relatively small amount of the oscillator strength in the below-gap region is transferred to the $\delta$-function and the plasma edge occurs at $\omega_{pc} \times 3.4\sqrt{k_BT_c/\hbar\gamma}$.

## REFERENCES

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