Coherent-to-Incoherent Crossover in Optical Conductivity of Bad-Metallic $La_{2-x}Sr_xCuO_4$

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Abstract

The in-plane charge dynamics of $La_{1.92}Sr_{0.08}CuO_4$ are examined. The in-plane resistivity $\rho_{ab}(T)$ is metallic up to 1000 K without saturation at the Mott criterion, whereas the in-plane optical conductivity $\sigma_{ab}(\omega)$ shows a Drude peak only below a certain temperature $T^{*}\sim$300 K. Above T^{*} the Drude peak shifts to finite energy. The relation between the shift of the Drude peak and the Mott Criterion indicates the "dynamical" localization of the carriers.

Key words: cuprate; bad metal; superconductivity; optical conductivity

In a wide range of strongly correlated metals, the dc resistivity can increase to far higher values than the Mott Criterion $\rho_{\rm Mott}$ corresponding to a mean free path l comparable to the Fermi wavelength $\lambda_{\rm F}=2\pi/k_{\rm F}$ [1]. This contradicts the general assumption of ordinary metals, $l>\lambda_{\rm F}$. Materials with this unusual characteristic are generically called *bad metals* [2], in contrast with ordinary metals showing resistivity saturation near $\rho_{\rm Mott}$ at high temperatures [3]. In order to get insight into the bad-metallic transport, we have studied the charge "dynamics" of a typical bad metal, lightly doped $La_{2-x}Sr_xCuO_4$ (LSCO, x=0.06−0.10), based on the optical spectra up to 500 K.

Single crystals of LSCO were grown by a traveling-solvent-floating-zone method. The in-plane resistivity $\rho_{ab}(T)$ was measured using a four-probe method. Near-normal incident in-plane ($\mathbf{E}\perp c$) reflectivity $R_{ab}(\omega)$ was measured using a Fourier-type interferometer (0.004−1.6 eV) and a grating spectrometer (0.8−6.6 eV). The in-plane optical conductivity $\sigma_{ab}(\omega)$ was deduced from $R_{ab}(\omega)$ via a Kramers-Kronig transformation. We made the extrapolation in the low energy using Hagen-Rubens reflectivity. We measured R_{ab} at each temperature T below 3.2 eV, and above 3.2 eV we assumed the room-T data. $\rho_{ab}(T)$ for x=0.06−0.10 is metallic ($d\rho/dT>0$) up to 1000 K without saturation at $\rho_{\rm Mott}$=1.5−1.7 mΩcm (Inset of Fig. 1). The details of the experiments were described elsewhere [4].

$\sigma_{ab}(\omega)$ for x=0.08 (Fig. 1) consists of two components, a broad mid-infrared (mid-IR) band (0.2−1 eV) and a lower-energy intraband mode (0−0.2 eV) associated with the conducting carriers [e.g., data at 500 K]. The mid-IR band is almost T-independent, whereas the intraband mode changes drastically with T. At low T, a Drude-like peak at ω=0 is observed. However, it decays more slowly ($\propto\omega^{-1}$) than a simple-Drude response ($\propto\omega^{-2}$). This quasi-Drude response is observed only below a certain temperature T^{*}, which is about room temperature for x=0.08. Above T^{*}, the peak shifts to finite energy and σ_{ab} even *increases* as a function of ω in the far-IR limit. It is not clear whether the qualitative form of $\sigma_{ab}(\omega)$ actually changes or the peak shifts to frequencies below the observed range. However, $\sigma_{\rm dc}$ estimated from ρ_{ab} is higher (lower) than σ_{ab} at the lowest energy 4 meV below 150 K (above 295 K), which may support the former case. If the finite-energy (FE) peak appeared below 4 meV below 150 K, the shape of $\sigma_{ab}(\omega)$ became distorted unnaturally.

As doping proceeds, the intraband mode grows and the center of the mid-IR band shifts to lower energies (Fig. 2). For x=0.10, the two-component structure is

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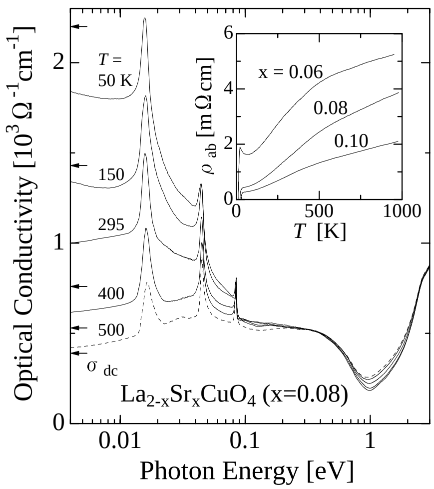

Fig. 1. In-plane optical conductivity of $La_{1.92}Sr_{0.08}CuO_4$. Dashed line represents spectrum at 500 K. Arrows represent dc conductivity estimated from ρ_{ab}. Inset shows in-plane resistivity $\rho_{ab}(T)$ of $La_{2-x}Sr_xCuO_4$ (x=0.06−0.10).

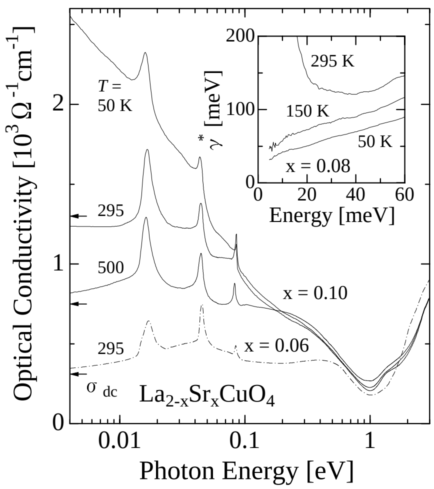

Fig. 2. In-plane optical conductivity of $La_{2-x}Sr_xCuO_4$ (x=0.06 and 0.01). Arrows represent dc conductivity estimated from ρ_{ab}. Inset shows frequency-dependent (renormalized) scattering rate γ^* for x=0.08 (ω_p=11,000 cm^{-1}; ε_∞=2).

no longer clear. The overall ω- and x-dependence of σ_{ab} at room T is consistent with previous data [5]. $\sigma_{ab}(\omega)$ is characterized by a FE peak at 295 K for x=0.06 and at 500 K for x=0.10. For all values of x, the Drude-like response seems to appear only below a certain temperature T^*, which increases as the doping proceeds.

The FE peak above T^* cannot be explained by a simple-Drude picture; the simple-Drude conductivity only asymptotically approaches the ω-independent (flat) function and still peaks at ω=0, no matter how strong the scattering becomes. The peculiarity is exposed more clearly by an extended-Drude analysis. Below 150 K, the ω-dependent scattering rate γ^* (Inset of Fig. 2) monotonically increases with ω, which is typical of correlated metals such as highly doped cuprates [6]. In contrast, at 295 K γ^* turns upward at low ω. This non-monotonic behavior is unusual and seems to be beyond even the ω-dependent scattering description of the coherent motion. The tail of the broad mid-IR band cannot be the origin of the FE peak because the FE peak is higher than the mid-IR band and the two-component structure becomes obvious at high temperatures.

It is well-known that the FE peak is a characteristic of the hopping conduction. The shift of the Drude peak indicates the continuous change from low-T coherent (Drude) to high-T incoherent transport. One of the most important implications is a relation to the Mott criterion in σ_{dc}. For x=0.08, σ_{dc} at $T^*\sim$300 K is close to $\sigma_{Mott}=\rho_{Mott}^{-1}$. For x=0.06 and 0.10, $\sigma_{ab}(\omega)$ appears to exhibit the quasi-Drude peak only when $\sigma_{dc}>\sigma_{Mott}$. The relation to σ_{Mott} suggests that the present FE peak is due to some scattering process. However, it is distinct from the Anderson localization because it appears at *high* temperatures where inelastic scattering is strong. The FE peak is an indication of "dynamical" localization. The shift of the Drude peak is also observed for other bad metals, $SrRuO_3$ [7] and $La_{1-x}Sr_xMnO_3$ [8].

Recently Ando *et al.* [9] reported that ρ_{ab} is metallic for all values of x at moderate temperatures and μ at 300 K changes only by a factor of 3 between x=0.01 and 0.17. Based on their results, the authors claim that the charge transport is governed by essentially the same mechanism in the range x=0.01 to 0.17, suggesting the relation to formation of the charged stripes. The relation between the formation of the stripes and the shift of the Drude peak is an interesting future issue.

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