Nonlinear Conductivity in the Slightly Hole-Doped $Sr_{14-x}Ca_xCu_{24}O_{41}$ Ladder Compounds

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Abstract

We studied the nonlinear dc conductivity of the slightly hole-doped spin-ladder compounds, $Sr_{14-x}Ca_xCu_{24}O_{41}$ (x=0 and 1), as a function of electric field. In both the ladder (c-axis) and the rung (a-axis) directions, we observed a definite nonlinear conduction (NLC) below 160 K, although the nature of NLC was quite different between both directions. Detailed studies suggest that only the c-axis NLC for the x=0 material was attributed to the sliding motion of the charge ordered state, which was already suggested by the observation of the sharp resonance in the microwave region. We also suggest that the sliding motion was strongly one-dimensional and easily destroyed by the carrier doping on the ladder, which may be characteristic of this new collective mode in strongly correlated systems.

Key words: collective mode; charge order; sliding motion; $Sr_{14-x}Ca_xCu_{24}O_{41}$

The study of $Sr_{14-x}Ca_xCu_{24}O_{41}$ compounds with the two-leg spin ladders is one of the most important issues which may be related to the mechanism of high-T_c superconductivity [1]. In particular, the charge dynamics of the slightly doped holes on the Cu_2O_3 ladders are quite interesting, because a sharp resonance was observed in the frequency dependence of the microwave and millimeter wave conductivity along the ladder direction, suggesting that a collective excitation of some charge ordered state such as charge-/spin-density wave (CDW/SDW) contributes to the charge dynamics in the ladder direction [2]. In this paper, to clarify the details of such a collective mode, we studied the dc nonlinear conduction (NLC) of $Sr_{14-x}Ca_xCu_{24}O_{41}$ (x=0 and 1) both along the ladder (c-axis) and rung (a-axis) directions, as a function of electric field.

Single crystals of $Sr_{14-x}Ca_xCu_{24}O_{41}$ (x=0 and 1) were grown by the traveling-solvent-floating-zone (TSFZ) method [3]. Small pieces were cut into rectangular shapes with the longest dimension in the c-or a-axis direction. The conductivity as a function of electric field was measured by four-probe dc method. In order to check the Joule-heating effect, short pulses were applied to the sample, and the response was measured by a boxcar averager or a digital oscilloscope. More details of the experimental technique were decribed elsewhere [4].

Figures 1(a) and 1(b) show the differential conductivity $\sigma'(\equiv dj/dE)$ along the c-axis and a-axis of the x=0 material as a function of electric filed, respectively. The data at each temperature were normalized by the low-field ohmic conductivity, σ_0. In both directions, we observed a clear nonlinearity in σ' as a function of elctric field. However, as described below, the nature of the NLC was quite different between both directions, suggesting that the mechanism of the NLC was quite different from each other.

First, the amount of the c-axis conductivity increase is much smaller ($\sim$5 % of σ_0 at 5 V/cm) than that of the a-axis conductivity increase (more than 20 % of σ_0 at 5 V/cm). Because the resonance mode in the microwave region also has a strongly reduced spectral weight [2], both features seem to be closely related to each other. Second, although it is hard to define a def-

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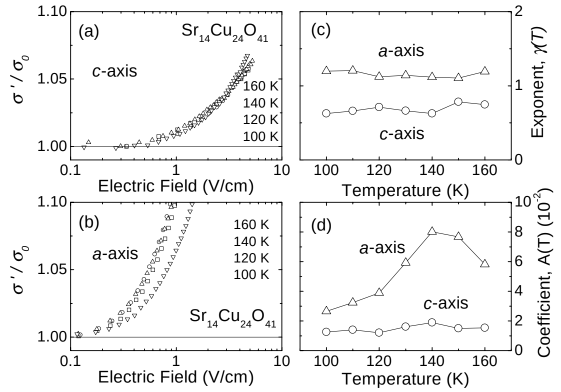

Fig. 1. (a)The c-axis differential conductivity σ' of the x=0 material as a function of electric field at various temperatures. All data were normalized by the low-filed conductivity, σ_0. Holizontal straight line is a guide for eyes. (b)The a-axis differential conductivity of x=0 material at the corresponding temperatures. (c)Fitting results of exponents appeared in eq. 1. (d)Fitting results of coefficients appeared in eq. 1.

inite threshold field for the onset of NLC, the c-axis nonlinearity seems to start around 0.5 V/cm, as shown in Fig. 1(a). On the other hand, for the a-axis conductivity, a characteristic field for the onset of NLC seems to be absent, as shown in Fig. 1(b). Thirdly, we found that the dependence on electric field of $\sigma'(E)/\sigma_0$ along the c-axis was almost independent of temperature below 160 K, while $\sigma'(E)/\sigma_0$ along the a-axis seemed to be strongly dependent on temperature.

In order to discuss the final point more quantitatively, we empirically express the data of $\sigma'(E)/\sigma_0$ by using power laws as follows,

$$\frac{\sigma'(E,T)}{\sigma_0(T)} - 1 = A(T)\xi(E)^{\gamma(T)}, \quad (1)$$

where $\xi(E)$ is $E/E_0^{(c)} - 1$ for the c-axis and $E/E_0^{(c)}$ for the a-axis, respectively. $E_0^{(c)}$ is the c-axis characteristic field for the onset of the NLC, which was found not to depend on T very much [4]. $A(T)$ and $\gamma(T)$ are a coefficient and an exponent of power laws, respectively. By fitting the data of $\sigma'(E,T)/\sigma_0(T)$ to eq. (1), we obtained the T dependence of $\gamma(T)$ and $A(T)$ for both directions, as shown in Figs. 1(c) and 1(d), respectively.

We found that the T dependence of $\gamma(T)$ and $A(T)$ for the c-axis was very weak between 100 K and 160 K. This is quite remarkable because $\sigma_0(T)$ showed a strong T dependence which corresponded to an activation energy of $\sim$1400 K [3,4]. This feature suggests that there is a scaling relation between the excess conductivity, $\Delta\sigma'(\equiv \sigma' - \sigma_0)$, due to an applied electric field and the low-field conductivity, σ_0. On the other hand, the T dependence of $A(T)$ for the a-axis was rather strong, while that of $\gamma(T)$ for the a-axis remained to be weak. Therefore, the scaling relation between $\Delta\sigma'$ and σ_0 seems to hold only for the ladder direction. For the quasi-one dimensional CDW system, it has been known that there was a scaling relation between the excess conductivity due to the collective motion and the uncondensed quasiparticle conductivity [5,6], which was very similar to the observed scaling relation between $\Delta\sigma'$ and σ_0.

Thus, all features associated with the c-axis NLC are quite reminiscent of a sliding motion of some charge ordered state. On the other hand, as for the a-axis charge dynamics, no observation of the microwave resonance mode [2], the absence of the characteristic field for the onset of NLC and the strongly temperature-dependent behavior of NLC suggest that the a-axis NLC is due to the hopping conduction of uncondensed quasiparticles across ladders. This also suggests a strongly one-dimensional nature of the observed sliding charge ordered state.

For the x=1 material, we found that the NLC along the c-axis was qualitatively similar to the a-axis NLC of the x=0 material [4]. Therefore, the sliding motion of the charge ordered state seems to vanish with increasing amount of holes on the ladders.

In conclusion, we investigated the nonlinear conduction of the slightly hole-doped $Sr_{14-x}Ca_xCu_{24}O_{41}$ (x=0 and 1) both along the ladder and rung directions. The detailed studies suggest that the NLC in the ladder direction was probably due to the sliding motion of the charge ordered state responsible for the sharp resonance in the microwave region. We also suggest that the sliding motion was strongly one-dimensional and easily destroyed by carrier doping, which may be characteristic of this new collective mode.

Acknowledgements

This work was partially supported by Grant-in-Aid for Scientific Research (12046222, 13750005) from the Ministry of the Science, Sports and Culture of Japan.

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