Terahertz conductivity in the underdoped Pb$_{1-2y}$Sr$_2$Y$_{1-x}$Ca$_x$Cu$_{2+y}$O$_{7+\delta}$ epitaxial film

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Abstract

We measured the complex conductivity from 0.2 THz to 1.0 THz in an underdoped Pb$_{1-2y}$Sr$_2$Y$_{1-x}$Ca$_x$Cu$_{2+y}$O$_{7+\delta}$ (Pb1212) epitaxial film with terahertz time-domain spectrosocopy. By analyzing temperature and frequency dependence of the complex conductivity, the superconducting fluctuation persists up to 12 K above $T_{c,\text{onset}}$ in the sample. Compared with previous reports, the superconducting fluctuation in Pb1212 is observed shorter temperature range than Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ and La$_{2-2y}$Sr$_y$CuO$_4$. This is ascribed to the lower anisotropy of Pb1212.

1. Introduction

Fundamental physical properties in high-$T_c$ superconductors (HTSCs) have been intensively investigated to elucidate the mechanism of high temperature superconductivity. Among unique properties of HTSCs, superconducting fluctuation is fascinating because the quasi-two-dimensional crystal structure and the low superfluid density make the phase fluctuation significant in HTSCs in contrast to conventional superconductors [1]. The strong superconducting fluctuation results in rich variety of vortex states in HTSCs [2, 3, 4]. In addition, the phase fluctuation is a candidate for the nature of the pseudogap [5], which generally opens in the underdoped region at a temperature $T^*$ [6]. Whether the pseudogap is originated in superconducting fluctuation or not is the key to clarify the mechanism of high-$T_c$ superconductivity [7].

In this paper, we focus on Pb$_{1-2y}$Sr$_2$Y$_{1-x}$Ca$_x$Cu$_{2+y}$O$_{7+\delta}$ (Pb1212) which has single block layers and double CuO$_2$ layers similar to YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO). We have succeeded in growing Pb1212 epitaxial films and clarified that Pb1212 is a low anisotropic cuprate superconductor ($\gamma \sim 10$ [8]). Here we report the complex conductivity, $\sigma(\omega, T) = \sigma_1(\omega, T) - i\sigma_2(\omega, T)$, in an underdoped Pb1212 epitaxial film measured by terahertz time-domain spectrosocopy (THz-TDS), and discuss the superconducting fluctuation in Pb1212.

2. Experiments

Pb1212 epitaxial film was grown on LaAlO$_3$(100) substrate by a two-step method [8]. The temperature dependence of the resistivity has shown that $T_{c,\text{onset}}$ is 48 K and $T_{c,\text{onset}}=0$ is 36 K. The sample is in the underdoped region ($T_{c,\text{onset}} = 110$ K was reported in bulk Pb1212 [9]). The thickness of the film has been determined as 40 nm by cross-sectional scanning electronic microscopy.

The complex conductivity data of the sample was obtained by home-built THz-TDS system. We measured two time-domain waveforms transmitted substrates with and without the sample. The measurements were performed under the purge with dry nitrogen gas to eliminate the effect of absorption by water vapor. We calculated the transmission coefficient, $T(\omega, T)$, and the phase difference, $\Delta\phi(\omega, T)$, by performing Fourier transformation to each waveform. Among the measurement methods of high-frequency properties, THz-TDS is particularly powerful because we directly obtain THz complex conductivity without the Kramers-Kronig analysis.

According to the two-fluid model, $\sigma(\omega, T)$ in the superconducting state is given by

$$\sigma_1(\omega, T) = \frac{\pi n_n e^2}{2m} \delta(\omega) + \frac{n_n e^2 \tau_n}{m}, \quad (1)$$

$$\sigma_2(\omega, T) = \frac{n_n e^2}{m\omega}, \quad (2)$$

where $e$ is the elementary charge, $m$ is the mass of electron, $\tau_n$ is the relaxation time of normal electrons, $n_n$ is the density of normal electrons, and $n_s$ is the superfluid density. On the other hand, $\sigma(\omega, T)$ in the normal state is given by the Drude model as

$$\sigma_1(\omega, T) = \frac{\sigma_{dc}}{1 + (\tau_n\omega)^2}, \quad (3)$$

$$\sigma_2(\omega, T) = \frac{\tau_n \omega}{1 + (\tau_n\omega)^2} \sigma_{dc}. \quad (4)$$
3. Results and discussion

Figure 1(a) shows frequency dependence of $\sigma_1$ from 10 to 280 K. At 280 K, $\sigma_1(\omega)$ is almost constant from 0.2 to 1.0 THz, which is predicted by the Drude model under the condition of $\tau_n, \omega \ll 1$. Figure 1(b) shows temperature dependence of $\sigma_1$ at various frequencies. The maximum of $\sigma_1(T)$ around $T_c$, which is supposed to be caused by superconducting fluctuation [10], shifts to higher temperature with increasing frequency. This is interpreted that higher frequency component of the superconducting fluctuation survives up to higher temperatures.

Figure 1(c) shows frequency dependence of $\sigma_2$ from 10 to 280 K. It is shown that $\sigma_2(\omega)$ is proportional to $\omega^{-1}$ and $\omega$ below and above $T_c$, respectively. These are consistent with both the two-fluid and Drude models. Figure 1(d) shows temperature dependence of $\sigma_2$ at various frequencies. The broad maximum of $\sigma_2(T)$ is seen slightly above $T_{c,\text{onset}}$. Since the frequency dependence of $\sigma_2(\omega)$ is approximately explained by the Drude model above $T_{c,\text{onset}}$, this anomalous peak is considered to be mainly caused by the contribution of normal electrons.

The appearance of the peak around $T_c$ in $\sigma_1(T)$, however, suggests that superconducting fluctuation also make a contribution to $\sigma_2(\omega, T)$ above $T_{c,\text{onset}}$. In order to confirm the existence of superconducting fluctuation, we calculated the relaxation time of superconducting fluctuation, $\tau_n(T)$, at each temperature by fitting $\sigma_2(\omega)$ to the Drude model. The temperature dependence of $\sigma_2(T)$ qualitatively agrees with that of $\tau_n(T)$ (not shown) excluding the contribution of superconducting fluctuation. $\tau_n$ is the order of $10^{-14}$ s slightly above $T_c$ and this is consistent with previous reports about YBCO [11, 12]. In contrast to $\sigma_2(T)$, $\tau_n(T)$ decreases monotonically with increasing temperature. This is the evidence that not only normal electrons but also superconducting fluctuation contributes to $\sigma_2(\omega, T)$. We conclude that the superconducting fluctuation persists up to 60 K (12 K above $T_{c,\text{onset}}$) where $\tau_n(T)$ changes discontinuously and the temperature dependence of the peak of $\sigma_1(T)$ is altered. This means that superconducting fluctuation disappears at much lower temperature than $T^*$. 

4. Summary

We measured terahertz conductivity $\sigma(\omega, T)$ in the underdoped Pb1212 epitaxial film. Temperature and frequency dependence of the complex conductivity is explained by the two-fluid model and by the Drude model below and above $T_c$, respectively. The behavior of $\sigma_1(\omega, T)$ and $\sigma_2(\omega, T)$ show that the superconducting fluctuation persists up to 12 K above $T_{c,\text{onset}}$. The narrower temperature range of the superconducting fluctuation than Bi2212 and LSCO in the underdoped region is attributed to the lower anisotropy of Pb1212.

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