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c-axis microwave conductivity of $YBa_2Cu_3O_{7-\delta}$ in the superconducting state

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We measured the surface impedance of $YBa_2Cu_3O_{7-\delta}$ single crystals at 10 GHz in two kinds of magnetic-field configurations ($H_\omega \| c, H_\omega \perp c$). We investigated the temperature dependence of the c-axis microwave conductivity σ_1^c in the superconducting state for a fully oxygenated sample ($T_c = 93$ K) and two oxygen-reduced samples ($T_c = 65$ K, 63 K). In the fully oxygenated sample, $\sigma_1^c(T)$ shows a broad peak similar to that of $\sigma_1^{ab}(T)$, while in the oxygen-reduced samples $\sigma_1^c(T)$ shows quite different dependence on temperature from $\sigma_1^{ab}(T)$. Namely, $\sigma_1^c(T)$ in the superconducting state strongly depends on the oxygen content in $YBa_2Cu_3O_{7-\delta}$. The result suggests that the dynamics of the quasiparticles in the oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ keeps a strong two-dimensional nature in the superconducting state.

High-T_c cuprates have the layered structure of CuO_2 planes. The charge dynamics in the CuO_2 planes (a-b planes) has been extensively investigated, while the nature of c-axis ($\perp$ CuO_2 plane) charge dynamics has not been studied enough. In the normal state, dc-resistivity[1] and optical[2] measurements have revealed that the c-axis charge dynamics is "metallic" in $YBa_2Cu_3O_7$ ($T_c \sim$ 90 K) but "semiconductive" in $YBa_2Cu_3O_{7-\delta}$ ($T_c \sim$ 60 K). In the superconducting state, a recent optical measurement[3] has reported that the c-axis optical conductivity in oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ is different from that in fully oxygenated $YBa_2Cu_3O_7$ at the lower frequency region. Information on the charge dynamics at energies below the optical region is obtained from microwave surface impedance measurements, which are more suitable for obtaining the temperature dependence of the penetration depth, ac conductivity, and quasiparticle scattering rate.[4,5] However, experiments on the surface impedance measurement have been concentrated on the properties in the CuO_2 planes,[4,5] except for a recent investigation of the anisotropic penetration depth in large $La_{2-x}Sr_xCuO_4$ crystals.[6]

In this paper, we present the temperature dependence of the c-axis microwave conductivity σ_1^c as well as the in-plane conductivity σ_1^{ab} on a fully oxygenated sample and two oxygen-reduced samples of $YBa_2Cu_3O_{7-\delta}$. We find that the behavior of $\sigma_1^{ab}(T)$ is basically similar among samples with different oxygen content. On the other hand, $\sigma_1^c(T)$ is found to change dramatically with the oxygen content. We report the systematic change of $\sigma_1^c(T)$ in the microwave region as a function of the hole concentration. Our results suggest that the dynamics of the quasiparticles in the oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ keeps a strong two-dimensional nature even in the superconducting state.

Single crystals of $YBa_2Cu_3O_{7-\delta}$, which are thick enough to measure the anisotropy of the surface impedance, were grown using techniques described elsewhere.[7] The dimensions and superconducting properties of the three measured samples are listed in Table I. The fully oxygenated sample (sample A) shows low resistivity ($\rho^{ab} \simeq$ 40 $\mu\Omega$ cm just above T_c).[7] Two oxygen-reduced samples (samples B and C) are obtained from the usual quenching technique.[8] The values of T_c (see Table I) and c-axis lattice parameters (11.72 and 11.73 Å for samples B and C, respectively) indicate that the oxygen content in sample C is smaller than that of sample B.

The surface impedance ($Z_s = R_s + iX_s$) was measured at 10 GHz using a superconducting Pb cavity resonator[5] with a heated sapphire rod inside. High quality factor Q ($\sim 1 \times 10^6$) of the cavity enables stable resonance ($\delta f / f < 10^{-8}$). The microwave magnetic field H_ω is parallel

TABLE I. The dimensions and superconducting properties of the measured samples. The dimensions are described as a-b plane × c axis. The values of R_s and λ are those just above T_c and at the lowest temperatures, respectively. Sample C was used only in the configuration $H_\omega \perp c$, because of its platelike shape.

Sample	Dimensions (mm^3)	T_c (K)	R_s^{ab} (Ω)	R_s^c (Ω)	λ^{ab} (μm)	λ^c (μm)
A	2.0×1.2×0.8	93	0.12	1.8	0.14	0.9
B	0.9×0.8×0.9	65	0.17	14	0.28	12
C	1.2×0.3×0.4	63		17		17

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to the axis of the rod on which the sample is mounted. Then the screening current flows around the four faces of the sample which are parallel to H_ω, in the region with the thickness of the classical skin depth δ_{cl} above T_c or the penetration depth λ below T_c from the sample surface. In the cavity perturbation technique, the surface resistance R_s is obtained from the formula $R_s = G_1(Q^{-1} - Q_{\text{blank}}^{-1})$, and the change in the surface reactance ΔX_s is obtained from $\Delta X_s = -G_2 \Delta f/f$, where G_1 and G_2 are the geometrical factors determined experimentally by using a reference sample. Q_{blank} is the Q of the cavity without a sample, and ΔX_s is the change of X_s. The absolute value of X_s is determined by the relation $R_s = X_s = \sqrt{\mu_0 \omega \rho /2}$, which is valid in the normal state in the microwave region.[9]

In order to investigate the anisotropy of Z_s, the measurements were performed for each sample in two kinds of magnetic-field configurations ($H_\omega \| c, H_\omega \perp c$). In the configuration of $H_\omega \| c$, the screening current flows only in the CuO_2 planes, and the surface impedance obtained from this configuration is Z_s^{ab}, namely,

$$Z_s^{H_\omega \| c} = Z_s^{ab}. \tag{1}$$

The superscript (ab or c) of Z_s expresses the direction of the screening current. We neglected the anisotropy in the CuO_2 plane because we used twinned crystals. On the other hand, in the configuration of $H_\omega \perp c$, $Z_s^{H_\omega \perp c}$ is described as the geometrical mean value of Z_s^{ab} and Z_s^c by

$$Z_s^{H_\omega \perp c} = \frac{S^{ab} Z_s^{ab} + S^c Z_s^c}{S^{ab} + S^c}. \tag{2}$$

S^{ab} and S^c are the areas of the faces where the screening current flows in the CuO_2 plane and along the c direction, respectively. In this approximation, we neglect the bending effect of the electromagnetic field at the edges of a sample, but the experimental results show that the application of Eq. (2) is valid in this system, as described below. From the measured Z_s in the configurations of $H_\omega \| c$ and $H_\omega \perp c$, we can obtain Z_s^c using Eq. (1) as

$$Z_s^c = (1 + L^{ab}/L^c) Z_s^{H_\omega \perp c} - (L^{ab}/L^c) Z_s^{H_\omega \| c}, \tag{3}$$

where L^c and L^{ab} are the sample dimensions in the c direction and the a-b direction, respectively (see the inset of Fig. 1).

The microwave complex conductivity ($\sigma = \sigma_1 - i\sigma_2$) is related to the surface impedance by the formula[10]

$$Z_s = \sqrt{i \mu_0 \omega / \sigma}, \tag{4}$$

in the local electrodynamics regime.[11]

Figure 1 shows the temperature dependence of the surface impedance for sample A ($T_c = 93$ K) and sample B ($T_c = 65$ K). In the normal state, we can estimate the values of the resistivity ρ from the surface resistance ($\rho = 2R_s^2/\mu_0 \omega$). The estimation just above T_c is $\rho^{ab} = 38$ $\mu\Omega$ cm and $\rho^c = 9$ mΩ cm for sample A, consistent with the published values of fully oxygenated crystals.[7] In the superconducting state, the penetration depth λ is obtained from the surface reactance ($\lambda = X_s/\mu_0 \omega$). The values of the penetration depth at the lowest temperature in the fully oxygenated sample are 0.14 μm for λ^{ab}, 0.9 μm for λ^c, which are also consistent with the published values.[12] Therefore, the obtained values of both R_s above T_c and λ below T_c guarantee the accuracy of the extracted values of Z_s^c using Eq. (3). For the oxygen-reduced samples (B and C), larger anisotropy of Z_s is observed (see Fig. 1 and Table I). In sample C, the contribution of Z_s^{ab} to $Z_s^{H_\omega \perp c}$ is negligible because of the large anisotropy.

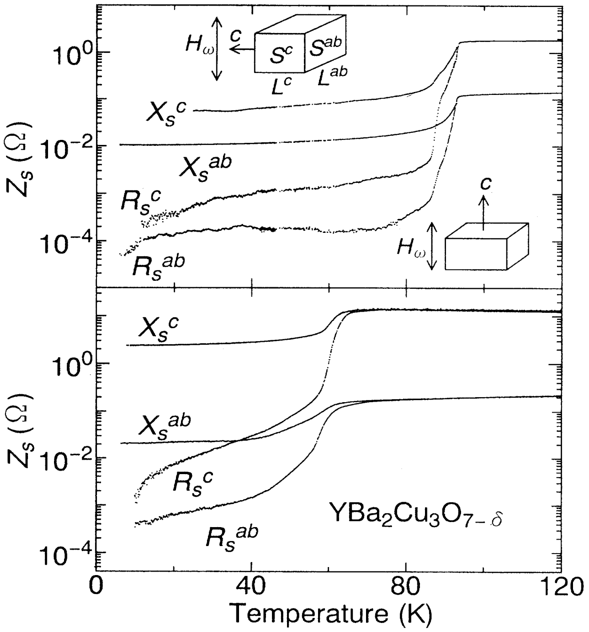

FIG. 1. Temperature dependence of anisotropic surface impedance ($Z_s = R_s + iX_s$) in $YBa_2Cu_3O_{7-\delta}$ crystals. Upper panel: sample A ($T_c = 93$ K). Lower panel: sample B ($T_c = 65$ K). Z_s^j is extracted from the measurements of the two magnetic-field configuration (inset), where the superscript j denotes the direction of the screening current.

In Fig. 2, we show the temperature dependence of the microwave conductivity σ_1 normalized to the value at T_c, which is obtained from Z_s using Eq. (4). The narrow peak visible near T_c in Figs. 2(a) and 2(b) may be regarded as an artificial peak arising from the width of the superconducting transition,[5,13] although another interpretation for the origin of this peak exists.[14] In any case we are interested here in the temperature dependence of the conductivity away from T_c, and the existence of this narrow peak does not affect our conclusions in this paper.

First, for $\sigma_1^{ab}(T)$, we can find a common structure in the temperature dependence of σ_1^{ab} as in Fig. 2(b). Both $\sigma_1^{ab}(T)$ of samples A and B show a similar broad peak at low temperatures as that reported in Refs. 4, 5, and 15. The origin of this structure is interpreted as the suppression of the inelastic scattering of quasiparticles in the CuO_2 planes.[4,5,15] The appearance of the broad peak structure in all *in-plane* conductivities of fully oxygenated, oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_{8+y}$ (Ref. 5) clearly indicates that the suppression of the quasiparticle damping in the superconducting state is a common feature in the CuO_2 planes of high-T_c cuprates. To see more carefully, the height and the

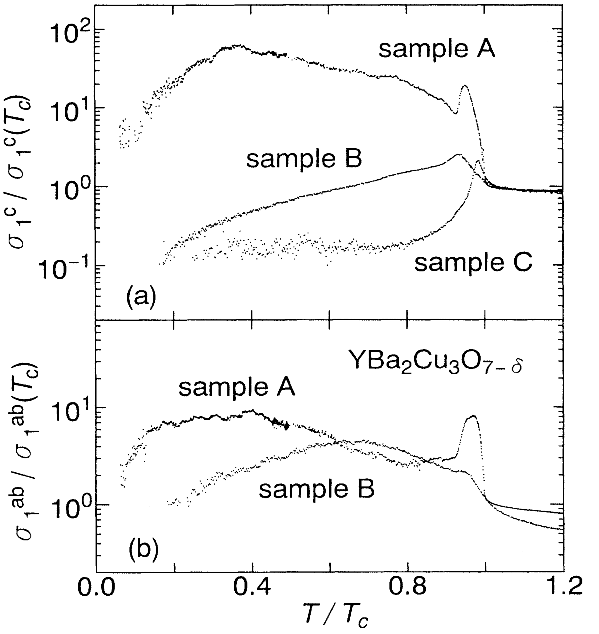

FIG. 2. Temperature dependence of the microwave conductivity normalized to the values at T_c. (a) c-axis conductivity σ_1^c. (b) The conductivity σ_1^{ab} in the CuO_2 plane.

position of the broad peak are different among three samples. This difference may be due to the slight difference in the temperature dependence of the scattering rate below T_c between these samples, which will be discussed in a future publication.[17]

In contrast to $\sigma_1^{ab}(T)$, a drastic difference was found in $\sigma_1^c(T)$ among samples A, B, and C, as shown in Fig. 2(a). $\sigma_1^c(T)$ of sample A rapidly increases below T_c and has a broad peak structure at lower temperatures. The maximum value, near $0.4T_c$, is about 70 times as large as $\sigma_1^c(T_c)$. In sample A the magnitudes of σ_1^c and σ_1^{ab} are anisotropic (factor of 100 at T_c), but the temperature dependences are similar. It should be noted again that the temperature dependence of the c-axis dc conductivity in the normal state is exceptionally high and metallic in fully oxygenated $YBa_2Cu_3O_7$.[1] The fact that $\sigma_1^c(T)$ of sample A also shows a broad peak suggests that the inelastic scattering of quasiparticles is suppressed along the c direction as well as in the CuO_2 plane in the superconducting state, as discussed below. On the other hand, $\sigma_1^c(T)$ of samples B and C does not show such a rapid increase, and still remains at the low level below T_c [see Fig. 2(a)]. In particular, $\sigma_1^c(T)$ in sample C decreases rather rapidly below T_c, which is in sharp contrast to $\sigma_1^c(T)$ in the fully oxygenated sample. Thus, it is found that the temperature dependence of $\sigma_1^c(T)$ strongly depends on the content of oxygen in $YBa_2Cu_3O_{7-\delta}$.

The strong dependence of the quasiparticle dynamics along the c direction on the oxygen content in $YBa_2Cu_3O_7$ is also seen in the recent optical conductivity measurements[3,16] in the superconducting state. Schützmann *et al.*[16] recently observed a Drude-like structure in the optical $\sigma_1^c(\omega)$ of a fully oxygenated $YBa_2Cu_3O_7$ crystal. On the other hand, Homes *et al.*[3] have reported that the optical conductivity $\sigma_1^c(\omega)$ at 10 K in an oxygen-reduced sample of $YBa_2Cu_3O_{6.70}$ has small values down to the lowest frequency. These reports of the c-axis optical conductivity are qualitatively consistent with our microwave result of $\sigma_1^c(T)$ in $YBa_2Cu_3O_{7-\delta}$. The low c-axis conductivity below T_c in the oxygen-deficient samples demonstrates that the quasiparticles are nearly confined in the CuO_2 planes in those samples.

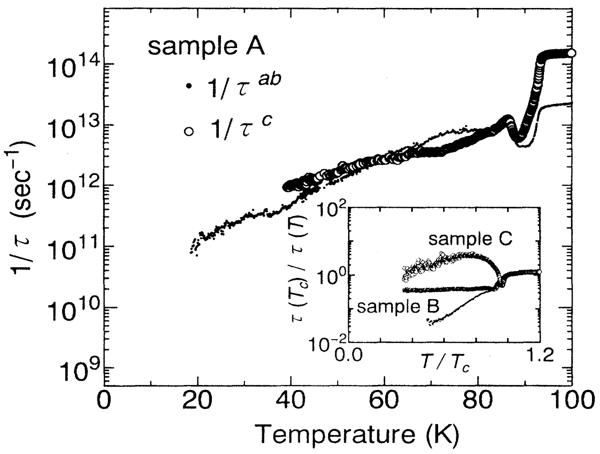

FIG. 3. The quasiparticle damping $1/\tau(T)$ in sample A in the superconducting state, obtained from the generalized two-fluid analysis. The inset shows the quasiparticle scattering rates normalized to the values at T_c in samples B and C, which are formally obtained by using the same analysis. From the bottom to the top of the inset, $1/\tau^{ab}$, $1/\tau^c$ in sample B, $1/\tau^c$ in sample C. See text for applicability of this method.

We extracted the quasiparticle damping $1/\tau(T)$ from $\sigma_1(T)$ by applying the generalized two-fluid model analysis,[5,13] as in Fig. 3. $1/\tau(T)$ of the fully oxygenated sample rapidly decreases below T_c along the c direction as well as in the CuO_2 plane. Note that $1/\tau(T)$ is drawn in a log scale in Fig. 3. At the lowest temperature, $1/\tau^{ab}(T)$ decreases by nearly two orders of magnitude, and the magnitude and the temperature dependence of $1/\tau^{ab}(T)$ correspond well to the result in Ref. 13. We find that $1/\tau^c(T)$ has the same order of magnitude as $1/\tau^{ab}(T)$ at low temperatures. This result implies that the inelastic scattering of quasiparticles in fully oxygenated $YBa_2Cu_3O_7$ becomes isotropic in the superconducting state.

The situation is, however, quite different in the oxygen-deficient samples. As in the inset of Fig. 3, $1/\tau^{ab}(T)$ of sample B shows a similar rapid decrease as that of sample A. On the other hand, $1/\tau^c(T)$ of sample B only decreases by one-fourth of the value at T_c at the lowest temperature, and a rapid *increase* is observed in $1/\tau^c(T)$ of sample C. This striking behavior of $1/\tau^c(T)$ in samples B and C results from the application of the generalized two-fluid analysis. In the generalized two-fluid model, the normal fluid conductivity is described by Drude theory.[5,13] In this picture the quasiparticles in the low-energy region are itinerant, which was shown to be incorrect by optical and by the present microwave experiments. In order to extract true $1/\tau^c(T)$ in the oxygen-reduced samples, we need a more careful analysis.

The recent systematic investigation of the anisotropic penetration depth λ in $La_{2-x}Sr_xCuO_4$ claimed that the response of the superfluid can be regarded two-dimensional in the superconducting state,[6] and concluded that λ^c is determined by the intrinsic Josephson current across the CuO_2 planes. The observed large anisotropy of the penetration depth in oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ (see Table I) implies that the supercurrent along the c axis in this system is also characterized by a Josephson-like coupling mechanism.[17] In other words, λ^c in the oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ may be determined by Josephson current flowing between the CuO_2 bilayers. Therefore, together with the above presented results on the c-axis conductivity, we conclude that the charge dynamics of both superfluids and quasiparticles in the oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ has a strong two-dimensional nature in the superconducting state. The strong two-dimensional nature in the oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ is also observed in the resistivity[1] and optical conductivity[2] measurements in the normal state. Then, one can say that the large anisotropy in the charge dynamics (or the strong confinement of charges in CuO_2 layers) in the normal state remains valid even in the superconducting state.

For the fully oxygenated $YBa_2Cu_3O_{7-\delta}$, we have observed exceptionally high σ_1^c below T_c. One possible explanation is the effect of the insertion of the CuO conducting chain into the superconducting layers. It has been pointed out that the CuO chains inserted between CuO_2 planes contribute to the normal-state conduction along the c direction.[1,2] However, the present results may also come from the intrinsic change in the high-T_c superconductivity as a function of the hole concentration. More detailed investigation is needed for other optimal- and over-doped materials.

In conclusion, we have measured the microwave conductivity perpendicular to the CuO_2 planes as a function of temperature in the fully oxygenated and oxygen-reduced crystals of $YBa_2Cu_3O_{7-\delta}$. The c-axis $\sigma_1(T)$ in the fully oxygenated sample shows a broad peak similar to the in-plane $\sigma_1(T)$, suggesting exceptionally isotropic scattering in the superconducting state. In contrast, for the oxygen-reduced samples $\sigma_1^c(T)$ remains at low level and shows no drastic enhancement below T_c. The results imply the quasi-two-dimensional nature of the CuO_2 planes even in the superconducting state.

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