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Josephson plasma frequencies in overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Far-infrared sphere resonance in $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples with various oxygen concentrations is measured down to 5 cm^{-1}. Although no peaks are observed in this frequency range for the optimumly doped sample, the Josephson plasma peak is observed at 5 cm^{-1} for a 1-atm-O_2-annealed sample. The peak shifts to higher frequencies as the doping increases, and is observed at 11 cm^{-1} for a 150-atm-O_2-annealed sample. The c-axis penetration depth λ_c obtained from the peak frequencies is determined to be 77 to 35 μm. These large λ_c values are larger than the value estimated from the Josephson-coupled layer model, while the doping dependence is qualitatively explained by the model. [S0163-1829(99)50718-2]

It is believed that the electronic state of the high-T_c cuprates in the superconducting state is two dimensional. Many cuprates, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$, exhibit dc and ac intrinsic Josephson effects, which reveals that the Josephson-coupled layer model along the c axis is applicable to the high-T_c cuprates.[1] In the model, the plasma of condensed carriers observed in the far-infrared region is considered to be the Josephson plasma.[2] The plasma has been observed in most of the high-T_c cuprates, such as $La_{2-x}Sr_xCuO_4$ (T phase), $YBa_2Cu_3O_{6+\delta}$, $Nd_2CuO_{4-x}F_x$ (T' phase), $La_{2-x}Ca_{1+x}Cu_2O_{6+\delta}$, $Tl_2Ba_2CuO_6$, $Bi_{1.85}Pb_{0.35}Sr_2Ca_2Cu_{3.1}O_y$ (Bi2223), and $SmLa_{1-x}Sr_xCuO_{4-\delta}$ (T^* phase).[3–10] However, there are no reports of its observation in $Bi_2Sr_2CaCu_2O_{8+\delta}$ in a zero magnetic field. In an earlier report by Tajima *et al.*, the plasma was not observed down to 30 cm^{-1}.[11] We have also shown that the plasma does not exist down to 7.5 cm^{-1} for optimumly doped $Bi_2Sr_2CaCu_2O_{8+\delta}$.[3]

Contrary to these optical measurements, many microwave measurements have shown an absorption peak of $Bi_2Sr_2CaCu_2O_{8+\delta}$ under a magnetic field when microwave electric fields are applied parallel to the c axis.[12–15] The peak has also been identified as the Josephson plasma.[16] However, recently Sonin claimed the peak is from the vortex vibration mode.[17] While the peak disappears in a zero magnetic field based on the latter interpretation, there have been some estimations of the plasma frequency in a zero magnetic field based on the former. Tsu, Ong, and Peterson estimated the zero field plasma frequency to be 5.3 cm^{-1} from the angular and magnetic field dependence of the plasma.[13] Walkenhorst *et al.* estimated it to be from 105 to 220 GHz (3.5 to 7.3 cm^{-1}) from a mixing experiment with a bias current.[14] Ichiguchi estimated it to be 107 GHz (3.6 cm^{-1}) from magnetic field dependence of the plasma.[15] Observation of the plasma in a zero magnetic field in the above frequency range will strongly support the validity of the interpretation of the Josephson plasma, as well as provide useful information, such as the c axis penetration depth.

In this paper, we report the Josephson plasma frequencies of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with various oxygen concentrations in a zero magnetic field. Although the plasma was not observed for the optimumly doped sample due to the low-frequency limitation of the measurement, the plasma was found at 5 cm^{-1} for a 1-atm-O_2-annealed sample, 8 cm^{-1} for a 9-atm-O_2-annealed sample, and 11 cm^{-1} for a 150-atm-O_2-annealed sample. The c-axis penetration depth λ_c is estimated from the peak frequencies, and is discussed based on the Josephson-coupled layer model.

In the experiment, the sphere resonance method was adopted to find the Josephson plasma.[3,4,10,18,19] The method is easier than the conventional reflectivity measurement of single crystals; it uses only powder samples and requires no growth of thick single crystals. One may think that the method cannot determine the plasma along the c axis, since the spectra of the powder sample may include both the c-axis and the in-plane response in a complex manner. However, as shown in the following, the spectra is dominated by the c-axis response in the far-infrared region.[3] The only assumption is that the in-plane spectra is metal-like with a plasma frequency of around 1 eV, which has been commonly observed for all the high-T_c cuprates. In the sphere resonance, the effective dielectric constant of the medium, $\epsilon^{av}(\omega)$ is calculated according to the relation

$$\frac{\epsilon^{av}(\omega)-\epsilon_m}{\epsilon^{av}(\omega)+2\epsilon_m}=\frac{f}{3}\sum_i\frac{\epsilon_i(\omega)-\epsilon_m}{\epsilon_i(\omega)+2\epsilon_m}, \tag{1}$$

where $\epsilon_i(\omega)$ and ϵ_m are the dielectric constants of a single crystal along the i-th crystal axis and polyethylene, and f is the volume fraction of the particles.[18,19] Since $\epsilon_{a,b}(\omega)$ is strongly negative in the far-infrared region due to the metal-like property in these directions, $\epsilon_{a,b}(\omega)$ are canceled in Eq. (1) and the effective dielectric constant becomes

$$\epsilon^{av}(\omega)=\epsilon_m\frac{(1+2f)\epsilon_c(\omega)+2(1+f)\epsilon_m}{(1-f)\epsilon_c(\omega)+(2-f)\epsilon_m}. \tag{2}$$

Equation (2) shows that the resonance peak appears at $\epsilon_{1c}(\omega)\approx-2\epsilon_m$ and the ab-plane resonance peak around 1 eV has no effect in the far-infrared region. The usefulness of this method has also been confirmed by many experiments: the sphere resonance of many cuprates, such as $La_{2-x}Sr_xCuO_4$, $YBa_2Cu_3O_{6+x}$, $La_{2-x}Ca_{1+x}Cu_2O_{6+\delta}$, and $Nd_2CuO_{4-x}F_x$, are consistently in agreement with the c-axis reflectivity data on single crystals.[3,8]

$Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals were grown by the conventional self-flux method in alumina crucibles. The samples

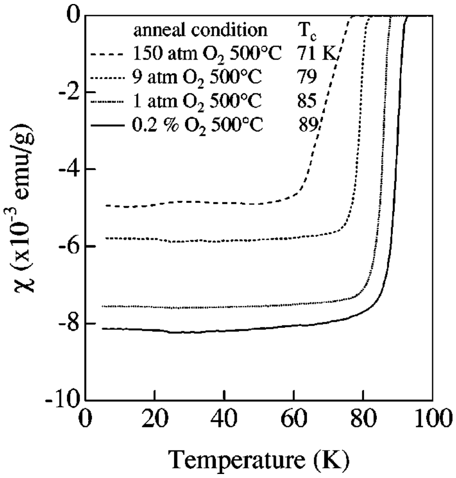

FIG. 1. Meissner signals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with various oxygen annealing conditions. The measurements were performed under a magnetic field of 2 G without correction for demagnetization.

were oxidized at 500 °C for 100 h in various oxygen atmospheres and quenched to room temperature. For the high-oxygen-pressure annealing, a furnace for hot isostatic pressing (HIP) was used. The Meissner signals of these samples are summarized in Fig. 1, which shows that T_c decreases from 89 to 71 K as the doping increases from optimum to slightly overdoped. The crystals were ground into fine particles about ~ 2 μm in diameter, mixed with polyethylene powder in a volume fraction $f \approx 0.5\%$, and pressed into pellets about 2.5-mm thick. Transmission spectra of the pellets were measured between 5 and 35 cm^{-1} using a Fourier transform spectrometer combined with a Si Bolometer operated at 1.5 K. Details of the measurement have been described in a previous paper.[3]

Figure 2 shows the difference in the absorption coefficients between $\alpha(T)$ and $\alpha(T>T_c)$ for $Bi_2Sr_2CaCu_2O_{8+\delta}$ particles in polyethylene with various doping levels. No peaks appear for the optimumly doped samples. However, a peak appears at 5 cm^{-1} for the 1-atm-O_2-annealed sample, and it shifts to 8 cm^{-1} for the 9-atm-O_2-annealed sample. The frequency further increases to 11 cm^{-1} for the 150-atm-O_2-annealed sample. All the peaks shift to smaller frequencies and weaken as the temperature approaches T_c, and no peaks are observed in the normal state. These changes are common in the other high-T_c cuprates and confirm that the peaks are the plasma of condensed carriers along the c axis.[3] In the figure, it is striking that the side of the peak decreases as the temperature decreases below T_c for all doping levels. These changes have also been observed for the other high-T_c cuprates, and are explained by the realization of the sum rule of carriers between the normal and the superconducting states.[4] For the optimumly doped sample, the decrease of the absorption in this frequency region suggests that the plasma peak exists below 5 cm^{-1}.

In the two-fluid model, the low-frequency dielectric function of the superconductor can be written as $\epsilon_c(\omega) = \epsilon_\infty - \omega_{ps}^2/\omega^2 - \omega_{pn}^2/\omega(\omega + i\gamma)$, where ϵ_∞, ω_{ps}, ω_{pn}, and γ are the high-frequency dielectric constant, plasma frequency of the condensed carrier, plasma frequency of the normal component, and the normal component's scattering rate. In this

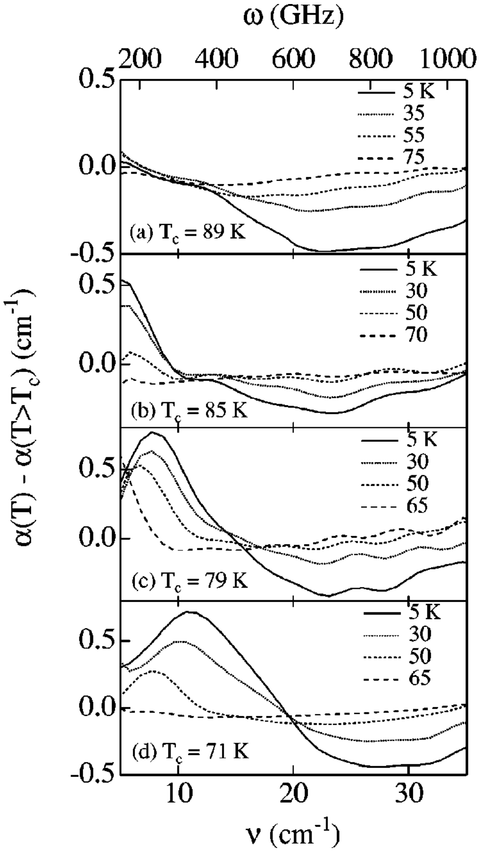

FIG. 2. Difference in α in the superconducting and normal states for $Bi_2Sr_2CaCu_2O_{8+\delta}$ with (a) optimumly annealed with $T_c = 89$ K, (b) 1-atm-O_2-annealed with $T_c = 85$ K, (c) 9-atm-O_2-annealed with $T_c = 79$ K, and (d) 150-atm-O_2-annealed with $T_c = 71$ K

equation, the Drude formula temporarily expresses the residual conductivity within the superconducting gap region. Since the $Bi_2Sr_2CaCu_2O_{8+\delta}$ is optimumly doped to slightly overdoped in this experiment, the normal component seems to be overdamped, and the effect is negligible for determining the resonance peak frequency ω_{peak}, which satisfies $\epsilon_{1c}(\omega_{peak}) = -2\epsilon_m$. In this case, the London penetration depth λ_c can be obtained from the peak frequency ω_{peak} and ϵ_∞ by the formula

$$\lambda_c = \frac{c}{\omega_{ps}} = \frac{c}{\sqrt{\epsilon_\infty + 2\epsilon_m}\,\omega_{peak}}. \qquad (3)$$

If we use $\epsilon_\infty = 12$ from the single crystal value of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Ref. 11), $\lambda_c = 77{,}48$, and 35 μm for the 1-atm, 9-atm, and 150-atm-O_2-annealed samples, respectively. These values are much larger than the in-plane penetration depth λ_{ab} obtained from the torque measurement,[20] which changes from 2200 to 2000 Å as the doping increases. Although the anisotropic parameter $\gamma = \lambda_c/\lambda_{ab}$ decreases from 350 to 175 as the doping increases, the large γ indicates the strong two dimensionality of the system even in the overdoped region.

It has been revealed that the Josephson-coupled layer model along the c axis can well explain the λ_c value of many high-T_c cuprates, such as $La_{2-x}Sr_xCuO_4$, $YBa_2Cu_4O_8$ and $Nd_2CuO_{4-x}F_x$.[3,7] In the model, λ_c is determined by the Josephson current density J_c as $\lambda_c = \sqrt{\hbar c^2/8\pi d e J_c}$, where d is the distance between the CuO_2 planes. Since J_c is determined by the normal state tunneling resistance $R_n = \rho_c d$ and the superconducting gap value Δ as $J_c = [\pi\Delta(T)/2eR_n]\tanh[\Delta(T)/2kT]$ in the BCS model,

$$\lambda_c = \sqrt{\frac{\hbar c^2 \rho_c}{4\pi^2 \Delta}}. \tag{4}$$

In this case, however, the model seems not to be consistent with the above λ_c value, if we use the ρ_c value obtained from the transport measurement of bulk samples. For the 1-atm-O_2-annealed sample, the value of ρ_c just above T_c is about 3Ω cm.[21] Using this value and assuming $2\Delta = 50$ meV obtained from a tunneling junction experiment,[22] we deduce that $\lambda_c \approx 14$ μm, which is much shorter than the observed value of 77 μm. The discrepancy is very large and cannot be explained by the error of assuming 2Δ. There seems to be two possible explanations for this discrepancy. One is the overuse of the above J_c formula. It has been reported that the $I_c R_N$ product, obtained from dc intrinsic Josephson junction experiments, is much smaller than that expected from the above J_c formula.[23] In the case of the d-wave superconductivity, the above J_c formula will be modified and this may explain the discrepancy. The other possibility is our lower estimation of ρ_c in Eq. (4). Recently, Suzuki, Karimoto, and Namekawa found that the ρ_c obtained in the small mesas for the intrinsic Josephson junction experiment is more than ten times larger than that obtained by the conventional transport measurements of bulk samples, and explained the difference by electrical shorts due to stacking-fault defects in the bulk samples.[22] This can explain the discrepancy.

Although the model cannot quantitatively explain the λ_c value, it can qualitatively explain their doping dependence. In the weak coupling BCS limit, Eq. (4) becomes $\lambda_c \propto \sqrt{\rho_c/T_c}$. Since the ρ_c just above T_c changes from 3 to 1 Ω cm as the doping increases from 1- to 150-atm-O_2-annealed sample,[21] the ratio of $\lambda_c(150\ \text{atm})/\lambda_c(1\ \text{atm})$ is estimated to be 0.6, which is almost consistent to the observed value 35 μm/77 μm$\approx$0.5. Basov *et al.* showed that the λ_c values on many cuprates are mainly determined by the values of ρ_c, which change very large compared to the change of T_c.[7] Our result of $Bi_2Sr_2CaCu_2O_{8+\delta}$ in the slightly overdoped region also seems to qualitatively support the relation.

The observed anisotropy in the effective mass $m_c/m_{ab} = (\lambda_c/\lambda_{ab})^2$ change from 1.2×10^5 to 3×10^4 as the doping increases from 1- to 150-atm-O_2-annealed sample. These values are comparable to the resistivity anisotropy just above T_c obtained from the transport measurement,[21] which changes from 4×10^4 to 1.6×10^4. This may indicates that the interlayer Josephson coupling is determined by the temperature-dependent normal state interlayer coupling just above T_c. The coincidence between $(\lambda_c/\lambda_{ab})^2$ and ρ_c/ρ_{ab} just above T_c has been also observed in $La_{2-x}Sr_xCuO_4$.[5]

In summary, we have measured the sphere resonance of $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples with various oxygen concentrations down to 5 cm^{-1} and found the Josephson plasma peaks at 5,8,11 cm^{-1} for the 1-, 9-, 150-atm-O_2-annealed sample, respectively. No peaks are observed in this frequency range for the optimumly doped sample, which suggests that the plasma exists below 5 cm^{-1}. The λ_c's of 77 (1 atm), 48 (9 atm), 35 μm (150 atm) were obtained from the peak frequencies. Although these λ_c's are much larger than the value estimated from the Josephson-coupled layer model, the doping dependence is qualitatively explained by the model.

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