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Josephson plasma resonance in a single-layered cuprate $Bi_2(Sr,La)_2CuO_y$

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Microwave absorption was measured in the mixed state of (Bi or Tl)$_2$(Sr or Ba)$_2$Ca$_{n-1}$Cu$_n$O$_y$. In a La-substituted $Bi_2Sr_2CuO_y$ (Bi-2201), a sharp resonant structure was found in the absorption as a function of magnetic field only when the microwave current flowed across the CuO_2 planes, as well as in $Bi_2Sr_2CaCu_2O_y$ (Bi-2212). Together with the frequency-dependence data, the resonant structure in the absorption in Bi-2201 is considered to be the Josephson plasma resonance. The anisotropy ratio $\gamma \equiv (m_c/m_{ab})^{1/2}$ was tentatively estimated to be ~ 750. A striking difference was found in the temperature dependence of the resonance field between Bi-2201 and Bi-2212. We argue that this comes from the difference in the dimensionality of the vortex systems. In $Tl_2Ba_2CaCu_2O_y$, no such resonance was found in the microwave region, which is probably due to a smaller anisotropy in this material. [S0163-1829(96)51622-X]

The ac response of the mixed state is one of the most interesting issues in the physics of high-T_c superconductors. We can discuss either pinning properties or quasiparticle dynamics in the vortex core, depending on frequency, temperature, and magnetic field.[1] Reflecting the quasi-two-dimensional character, a large number of peculiar phenomena have been reported. In particular, recently, much attention has been paid to a sharp resonance in the magneticfield dependence of the microwave absorption in the mixed state of $Bi_2Sr_2CaCu_2O_y$ (Bi-2212).[2] The absorption-peak magnetic field B_p was found to decrease with increasing frequency of the microwave field. The temperature dependence of B_p also showed a cusp around the irreversibility temperature. A subsequent study[3] clarified that the phenomenon was a resonance of the collective plasma oscillation of the supercurrent across the intrinsic Josephson junction between the CuO_2 planes (Josephson plasma oscillation).

Prior to the microwave experiments, the appearance of the sharp *c*-axis plasma edge in the superconducting state discovered in $(La,Sr)_2CuO_4$ (LSCO) (Ref. 4) was interpreted in terms of the Josephson plasma mode.[5] Thus, the Josephson plasma oscillation is a common feature of the cuprate superconductors. The details on this collective excitation, however, have not been known yet. In particular, the experimental observations in Bi-2212,[2] described above, have not been understood yet completely. Therefore, it is quite important to question which aspects of the observed peculiar features (temperature- and frequency dependence of the plasma frequency, etc.) in Bi-2212 are universal to other cuprates. We have performed a microwave absorption study of the mixed state in materials which have similar, but slightly different crystal structures; namely in $Tl_2Ba_2CaCu_2O_y$ (Tl-2212) and $Bi_2(La,Sr)_2CuO_y$ (Bi-2201), as well as in Bi-2212. Although in Tl-2212, no such resonance was observed, in Bi-2201 there was a resonancelike structure, which is observed only for the microwave electric field perpendicular to the CuO_2 plane, as was the case in Bi-2212.[3] However, several differences were remarkable. In particular, the most striking difference was found in the temperature dependence of B_p. We argue that this comes from the difference in the dimensionality of the vortex systems.

Single crystals were prepared by a flux technique using gold capsules for Tl-2212 at ISSP (Ref. 6) and the floating zone technique for Bi-2212 at Tokyo[7] and Bi-2201 at Tsukuba.[8] In the case of Bi-2201, Sr was partially substituted by La to achieve T_c which is close to the optimum value. T_c's of the crystals used in this study are 113 K (Tl-2212), 89 K (Bi-2212) and 26 K (Bi-2201). In terms of "the hole concentration vs the T_c map," the Tl-2212 crystals are almost optimally doped, whereas the Bi-2212 crystals are slightly overdoped, and Bi-2201 crystals are slightly underdoped.

Microwave absorption was measured by a bolometric technique.[2,3] The microwave electromagnetic field was generated by a HP-8350B sweeper. To control microwave fields (or currents), cylindrical cavities with a TM_{011} mode and a TE_{011} mode were used. A platelike sample, with a typical dimension of $0.5\times0.5\times0.02$ mm^3, was put at the bottom for the TM_{011} cavity, and at the center for the TE_{011} cavity. In the former configuration, microwave current $I_{\rm rf}$ is perpendicular to the CuO_2 plane. On the other hand, in the latter case, $I_{\rm rf}$ exists only within the CuO_2 plane. The Q values of these cavities were found to be $600\sim3000$. In all experiments, the dc magnetic field was applied perpendicular to the

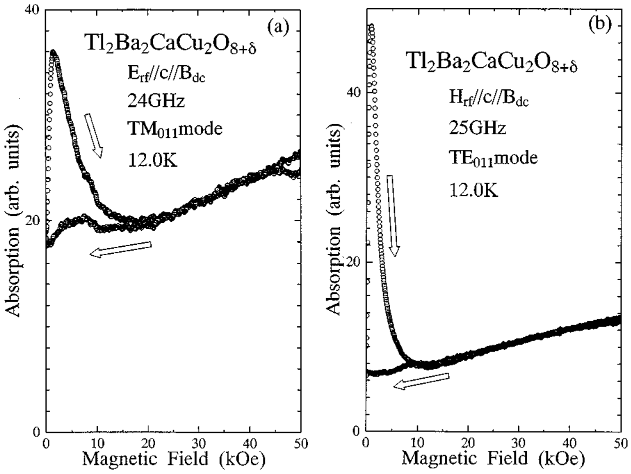

FIG. 1. Microwave absorption as a function of magnetic field in a Tl-2212 crystal at 12 K. Arrows indicate the direction of the field sweep. (a) For the configuration where $I_{rf} \perp CuO_2$ at 24 GHz. (b) For the configuration where I_{rf} is only in the plane at 25 GHz.

CuO_2 plane. For experiments where the detailed frequency dependence was needed, the sample was placed in a waveguide, as in Ref. 2, and the absorption was measured for microwave fields with various frequencies.

Figure 1 shows the microwave absorption as a function of magnetic field in a Tl-2212 crystal. Although a large peak can be seen, it is observed only for the initial sweep after zero-field cooling. It is not considered to be the Josephson-plasma resonance as reported in Bi-2212, for the following reasons: (1) the peak was observable in both configurations ($I_{rf} \perp CuO_2$ and $I_{rf} \| CuO_2$), and (2) the peak field depends on frequency very weakly, increasing slightly with increasing frequency.

Figure 2 shows the microwave absorption in a Bi-2201 crystal, taken in the two different cavities. In the configuration where the microwave electric field E_{rf} is perpendicular to the CuO_2 plane, a definite peak was observed in the magnetic field dependence of the absorption [Fig. 2 (a)]. Because of the pinning in the sample, and also because of the residual fields of the superconducting magnet, hysteresis was observed. On the other hand, in the configuration where I_{rf} exists only in the CuO_2 plane, a gradual increase of the absorption (sublinear in B) can be seen without any peak structure [Fig. 2 (b)]. We also performed the same measurements in a different TM_{011} cavity operating at 16 GHz. In this case, although the resonance structure was obtained, when compared at the same temperature, B_p is larger for 16 GHz than for 24 GHz. All of these are similar to the resonance observed in Bi-2212.[2,3] This strongly suggests that the resonancelike structure in Bi-2201 has the same origin as in Bi-2212; Josephson-plasma resonance.

There are, however, several remarkable differences in the details of the resonance. First, the peak field is 1~2 orders of magnitude smaller than that in Bi-2212. As will be discussed later, this is related to the rather large anisotropy in Bi-2201. The data up to 8 kOe was shown in the inset of Fig. 2(a). After the resonance in the lower field region, the absorption decreases monotonically up to the highest field measured. Thus, the line shape of the resonance in Bi-2201 is highly asymmetric which is quite different from the data in Bi-2212.

The most striking difference was found in the temperature dependence of B_p. Figure 3(a) shows B_p of Bi-2201 as a function of temperature measured at two frequencies, together with an irreversibility line for dc magnetization measured by a superconducting quantum interference device magnetometer. With decreasing temperature, it shows a broad maximum at around the irreversibility line. With further decreasing of the temperature, however, there was another cusp at some temperature T^* (for example, 3.8 K for 16 GHz). Below T^*, a difference in B_p for increasing field and decreasing field increases rapidly, which suggests that the nature of the vortex pinning changes suddenly below T^*. This behavior is distinctly different from that in Bi-2212, shown in Fig. 3(b). Our data in Bi-2212 are essentially the same as was reported in Refs. 2 and 3. B_p shows a relatively sharp maximum at some temperature, which almost coincides with the irreversibility temperature.

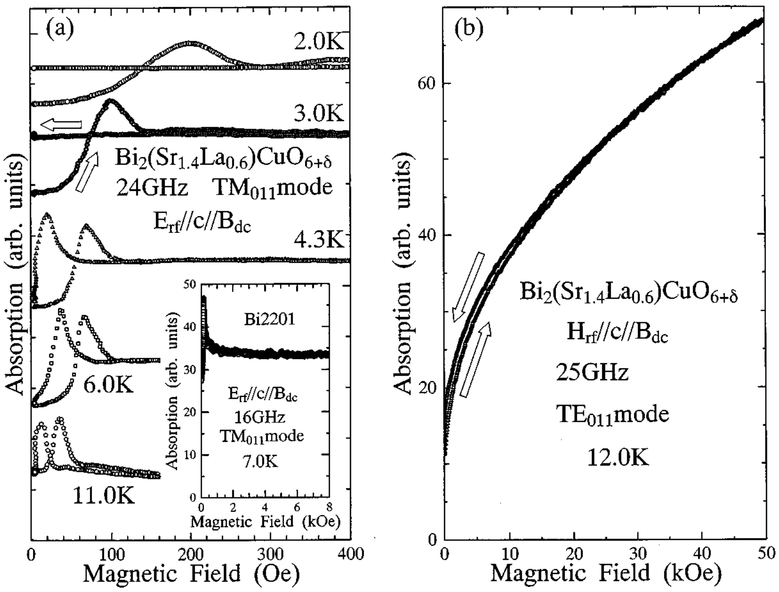

FIG. 2. Microwave absorption as a function of magnetic field in a Bi-2201 crystal, measured in the cavities. (a) For the configuration where $I_{rf} \perp CuO_2$ at 24 GHz. The inset shows the microwave absorption up to 8 kOe as a function of magnetic field in the same crystal, measured in the *TM* 011 cavities at 16 GHz, where $I_{rf} \perp CuO_2$. Origins for absorption were shifted. (b) For the configuration where I_{rf} is only in the plane at 25 GHz.

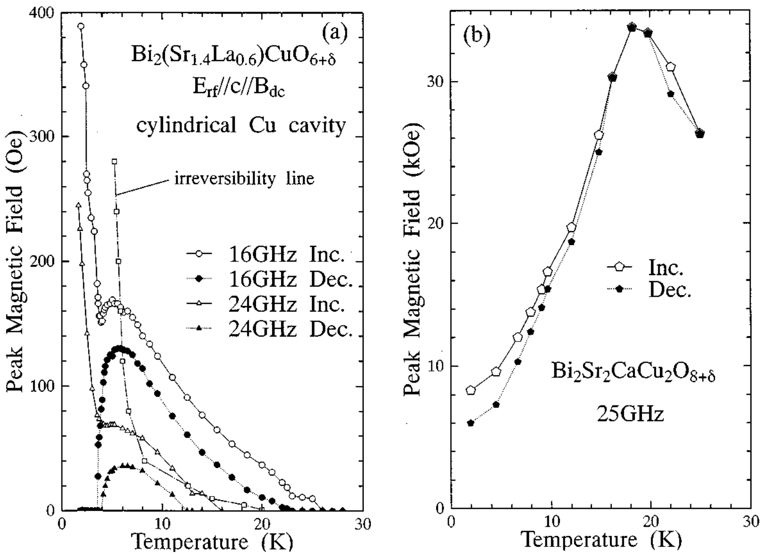

FIG. 3. The temperature dependence of the peak field B_p. Open and closed marks are for the data with increasing and decreasing field, respectively. Solid and dotted curves for the data points are guides for the eye. (a) For Bi-2201. Open squares are the irreversibility line of the dc magnetization. The dashed-solid curve is a guide for the eye. (b) For Bi-2212.

To obtain the detailed frequency dependence of B_p, we also measured the absorption of the same sample in a waveguide, without using cavities. In this case, however, many peaks appeared at different fields. Some of them agree with the peak which is observed in the cavity experiments. At present, we do not understand the process through which many peaks appear. The peak field as a function of frequency at 4.5 K is shown in Fig. 4. B_p was found to vary as $\omega^{-\nu}$ where ν is 3.8 for the two series appearing in the highest field region, and 1.5 for the remaining two series. A sudden decrease of B_p around 30 GHz suggests that the zero-field Josephson plasma frequency at 4.5 K is ~30 GHz.

In the above, we have shown that the Josephson plasma resonance exists in Bi-2201. However, there are several remarkable differences as has already been pointed out. First, B_p is 1~2 orders of magnitude smaller than that in Bi-2212. In terms of a theoretical model,[5,9] the Josephson plasma frequency, ω_p, as a function of dc magnetic field B is given by

$$\omega_p^2(B)=J_s\frac{8\pi^2cs}{\epsilon\Phi_0}\langle\cos\phi_{n,n+1}\rangle\equiv J_s^c(B)\frac{8\pi^2cs}{\epsilon\Phi_0}, \qquad (1)$$

where, $J_s=c\Phi_0/8\pi^2\lambda_c^2 s$ is the Josephson critical current density, s is the interlayer spacing, λ_c is the c-axis penetration depth, $\phi_{n,n+1}$ is the phase difference between adjacent layers, ϵ is the dielectric constant in the high frequency limit, Φ_0 is the flux quantum, and $\langle\ \rangle$ represents an average value. The field dependence is contained in the $\langle\cos\rangle$ factor. With increasing B, ω_p naturally decreases because $J_s^c(B)$ decreases. As for the difference among materials, the most important factor is the interplane penetration depth λ_c. Thus, the difference of B_p between Bi-2212 and Bi-2201 should be attributed to the difference in λ_c in the measured samples. Although a detailed quantitative comparison is impossible since the temperature dependence of B_p is quite different in the two materials, we will discuss the order of magnitude. The difference in λ_c roughly corresponds to the difference in the anisotropy of the effective mass. In terms of this picture, the anisotropy parameter $\gamma\equiv(m_c/m_{ab})^{1/2}$ can roughly be estimated as ~750 for Bi-2201.[10] This is consistent with the anisotropy ratio estimated from the dc resistivity $[\rho_c/\rho_{ab}\sim 10^5$ (Ref. 8) leading to $\gamma\sim 300]$. On the other hand, γ of a Bi-2212 crystal from the same batch was $\sim(5\times 10^3)^{1/2}\simeq 70$.[11] Thus, the ratio of the γ's is ~10. This explains the difference in B_p qualitatively. For more quantitative understanding, the detailed data of $J_s^c(B)$ should be taken into account.

The absence of a resonance in the microwave region in Tl-2212 is understood from the same standpoint. The anisotropy of the resistivity just above T_c was reported to be 250,[12] leading to $\gamma\sim 16$. The anisotropy of the coherence length was reported to be 33,[6] which corresponds to $\gamma\sim 33$, assuming the anisotropic Ginzburg-Landau (GL) theory.[13] These suggest that the anisotropy in Tl-2212 is smaller than that in Bi-2212. To be more quantitative, if we take $\gamma=16$, assuming a similar temperature dependence as shown in Fig. 3(b) and a relationship $B_p\propto\omega^{-1.5}$ as shown in Fig. 4, a magnetic field of 180 kOe is necessary to observe the resonance at 25 Hz at 12 K. This is consistent with the fact that the Josephson plasma resonance was not found in the microwave windows in the measurement up to 50 kOe.

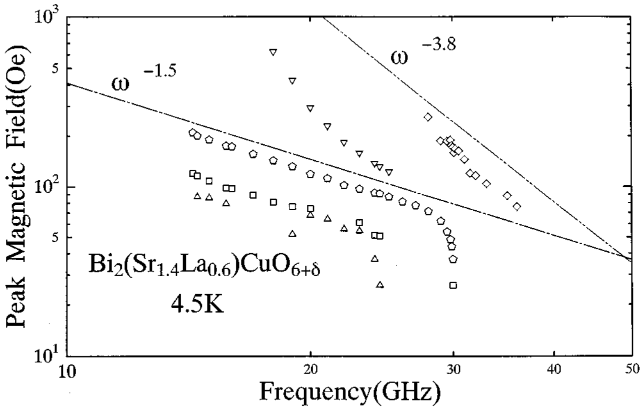

FIG. 4. B_p as a function of frequency at 4.5 K. The data were taken in the waveguide with increasing field after zero-field cooling. Two dashed-solid lines represent a $\omega^{-3.8}$ law and a $\omega^{-1.5}$ law, respectively.

The second striking difference is the line shape of the resonance. As was seen in Fig. 2, the line shape of Bi-2201 is highly asymmetric, which is in sharp contrast to that in Bi-2212. According to a recent theoretical calculation, the line shape of the resonance is determined by the dispersion of the plasma mode and the magnetic-field dependence of the complex conductivity.[14] At present, however, we do not understand the meaning of the highly asymmetric line shape of Bi-2201 in terms of this theory at all. Further studies are necessary.

The most striking difference is the behavior of B_p at the lowest temperatures. B_p of Bi-2201 (measured with increasing field) increases with decreasing temperature in the lowest temperature region. This is in sharp contrast to the $B_p(T)$ in Bi-2212, where it decreases with decreasing temperature below the irreversibility temperature, which has been interpreted as follows.[3] In the higher temperature region, the decrease of B_p with increasing temperature corresponds to the decrease of the interplane correlation $\langle \cos\phi_{n,n+1} \rangle$ with increasing thermal fluctuation. When the temperature is decreased, $\langle \cos\phi_{n,n+1} \rangle$ is considered to be reduced because the pinning strength by randomly distributed centers increases, which makes vortices more two-dimensional pancakelike. In terms of the same picture, the low-temperature increase of B_p in Bi-2201 means the recovery of the interplane correlation at the lowest temperatures. Very recently, Machida and Tachiki performed a numerical simulation based on the time-dependent GL equation,[15] and obtained a temperature dependence of $\langle \cos\phi_{n,n+1} \rangle$, which is very similar to that of B_p measured with increasing field shown in Fig. 3(a). According to them, a nonmonotonic temperature dependence was obtained by introducing pinning. Even in that case, however, $\langle \cos\phi_{n,n+1} \rangle$ increases with decreasing temperature at the lowest temperatures. Thus, why B_p decreases so rapidly at low temperatures in Bi-2212 remains a difficult question. As for the data of Bi-2201, the exact correspondence to the simulation cannot be made, since it was performed in an equilibrium state and does not correspond to the field swept experiment. However, the above mentioned similarity is interesting.

Although the origin of the difference of $B_p(T)$ between Bi-2201 and Bi-2212 is not clear at present, we consider that the difference in the magnitude of B_p is important. The increase of B_p at lowest temperatures means that the elastic force of the vortex exceeds the pinning force. In other words, vortices are three dimensional rather than two dimensional. The dimensional crossover in the vortex systems has been characterized by a crossover field $B_{\rm cr} = \Phi_0/\gamma^2 s^2$, where Φ_0 is the flux quantum, γ is the anisotropy parameter, and s is the distance between layers.[16] If we use γ's of 70 and 750 for Bi-2212 and Bi-2201, respectively, $B_{\rm cr}$'s are found to be 0.15 T for Bi-2212 and 25 G for Bi-2201. The data in Fig. 3(a) means that $B_p \sim B_{\rm cr}$ for Bi-2201, whereas for Bi-2212, $B_p \gg B_{\rm cr}$. Thus, the quantitative estimate was found to support the above picture. In fact, our tentative $B_p(T)$ measurement of Bi-2201 in the waveguide, where several series of resonance were observed simultaneously, showed that for the series in the higher field region, the temperature dependence of B_p becomes more similar to that in Bi-2212.

In conclusion, microwave absorption was measured in the mixed state of (Bi or Tl)$_2$(Sr or Ba)$_2$Ca$_{n-1}$Cu$_n$O$_y$. In Tl-2212, there was no Josephson plasma resonance in the microwave window. On the other hand, in Bi-2201, a sharp resonant structure was found in the absorption as a function of magnetic field only when the microwave current flows across the CuO$_2$ planes, as observed in Bi-2212. Together with the frequency dependence data, this shows that the absorption in Bi-2201 is the Josephson plasma resonance. The small peak field results from the large anisotropy of this material (the tentatively estimated anisotropy ratio is $\sim$750). The absence of the resonance in the microwave region in Tl-2212 was also understood in terms of the smaller anisotropy in this material. The most striking difference was found in the temperature dependence of the resonance field, which is thought to result from the difference in the dimensionality of the vortex system. A further systematic study in samples with various magnitudes of anisotropy is in progress.

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[10] In Fig. 3(a), B_p's are zero at 24 and 14 K for 16 and 24 GHz, respectively. From these, we interpret the zero-field plasma frequency as 16 GHz at 24 K and 24 GHz at 14 K. With the aid of the $\lambda_{ab}(T)$ data in Ref. 8 and the equation $\omega_p = c/\sqrt{\epsilon}\gamma\lambda_{ab}$, λ_c was estimated to be 600 μm (24 K) and 400 μm (14 K), which leads to $\gamma \sim 750$ at both temperatures, assuming $\epsilon \sim 25$.

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