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Josephson Plasma Resonance in $Bi_2Sr_2CaCu_2O_{8+y}$ Crystals with Macroscopic Inhomogeneities

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The Josephson plasma resonance (JPR) is studied in $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) crystals with macroscopic inhomogeneities, which are introduced by two methods; fabricating the crystal in the form having arrays of mesa structures (20x20 μm^2 ~ 100x100 μm^2) or by irradiating heavy-ions in half of the crystal. The JPR in BSCCO with mesa array shows an additional resonance peak indicating that the length scale where phase coherence is averaged is smaller than the size of the mesas. On the other hand, the resonance fields in the half-irradiated BSCCO and those after cutting the crystal into two are different, suggesting the presence of some kind of interference between regions which have different macroscopically averaged phase coherence properties.

1. INTRODUCTION

The JPR in layered high temperature superconductors has now been accepted as a powerful tool to study vortex states[1-4]. This is due to the fact that the plasma frequency, which is determined by the gauge-invariant phase difference between neighboring superconducting layers, is modified by the presence of vortices[5]. The decoupling nature of the vortex lattice melting has recently been revealed in a convincing manner using this technique[4]. In a homogeneous superconductor, we have only one JPR as a function of field, since the locally random phase difference is averaged out in a semi-macroscopic length scale of the order of 1 μm[6]. This is also true for heavy-ion irradiated crystals, which have inhomogeneity in sub-micron scale, except for the region of the field-induced recoupling transition[3,7]. Estimation of the phase coherence length is related to the mechanism of JPR and is still to be determined experimentally. In contrast to the theoretical prediction, a suggestion was made by JPR in $Bi_2(Sr,La)_2CuO_{6+y}$ that the resonance frequency is determined by the averaged field over the sample size[8]. In order to clarify this problem we intentionally introduce inhomogeneity in the crystal and measure resulting JPR. One way for the introduction of the inhomogeneity is to make an array of mesa structures on top of a single crystal. Inhomogeneity of the phase coherence can be introduced either by the variation of oxygen content near the processed region or by the size/boundary effect on the vortex matter. Another way to introduce inhomogeneity is to irradiate heavy-ions into a part of the crystal. By doing this, the phase coherence of the irradiated part is largely enhanced compared with that in the unirradiated part. JPR of the half-irradiated crystal and after cutting the crystal into two are compared.

2. EXPERIMENTAL

The crystals used in the present study are grown using the floating zone method[9]. Crystals with an array of mesa structures are fabricated by using Ar ion-milling. Two-dimensional arrays of mesa structures with dimensions of 20×20 μm^2 (20-BSCCO), 50×50 μm^2 (50-BSCCO), and 100×100 μm^2 (100-BSCCO) with a separation of about 20 μm between the mesas are prepared. The thickness of the crystals is in the range of 12 to 20 μm, and the height of the mesa is about half of the original crystal thickness (6 to 10 μm)

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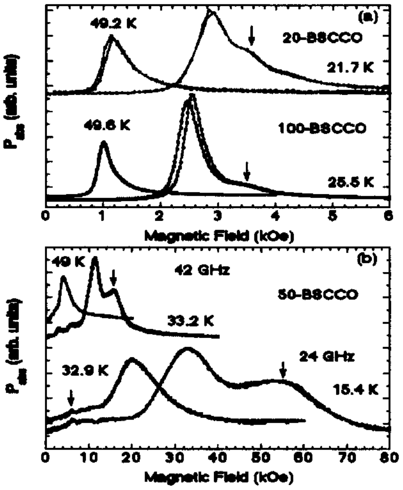

Figure 1. (a) $P_{abs}(H)$ at 42 GHz for 20-BSCCO (21.7 and 49.2 K) and 100-BSCCO (25.5 and 49.6 K). (b) $P_{abs}(H)$ at 24 GHz (15.4 and 32.9 K) and 42 GHz (33.2 and 49 K) for 50-BSCCO. Arrows indicate the new resonance peaks.

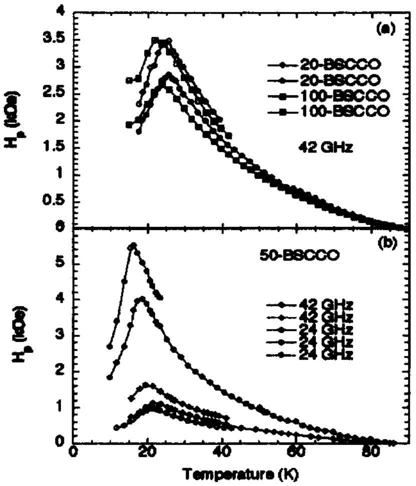

Figure 2. (a) $H_p(T)$ at 42 GHz for 20-BSCCO and 100-BSCCO. (b) $H_p(T)$ at 24 and 42 GHz for 50-BSCCO. Solid and open symbols show the main and the new peaks, respectively.

so that the volumes of mesa array and the substrate crystal are comparable. The same fabrication process is utilized to make small crystals for the study of the size effect on the vortex matter and will be reported separately[10].

To minimize possible variation of the oxygen content induced by Ar milling, crystals are annealed at 350 °C for 24 hours in 0.1% O_2 atmosphere after milling. All the measured crystals are optimally doped and T_c is in the range between 89 and 91 K with $\Delta T_c \sim 1$ K. For the inhomogeneous introduction of columnar defects, half of the crystal ($700\times400\times20$ μm^3) is covered by 100 μm thick gold sheet during the irradiation of 6 GeV Pb ions with matching field of 20 kG. Enhancement of the in-plane critical current density only in the irradiated part is confirmed by observing the critical state field profile using the magneto-optical technique. After measuring JPR in the half-irradiated crystal (HI-BSCCO), it is carefully cut into two pieces using wire-saw so that two pieces are pristine (HI-BSCCO-p) and 100 percent irradiated (HI-BSCCO-i) crystals. Finally, JPR in each piece is measured. JPR is measured by the cavity perturbation method at 24 and 42 GHz[4]. The crystal is set in a cavity so that microwave electric field is applied parallel to the c-axis. The external magnetic field is also applied parallel to the c-axis.

3. RESULTS AND DISCUSSION

Figure 1(a) shows microwave absorption as a function of field, $P_{abs}(H)$, for 20-BSCCO and 100-BSCCO at around 25 K and 50 K. At lower temperatures, there appears a new resonance peak at a field higher than the main resonance peak. The intensity of the new peak is higher at lower temperatures and it becomes lower and difficult to resolve at higher temperatures. The presence of the additional peak is especially ev-

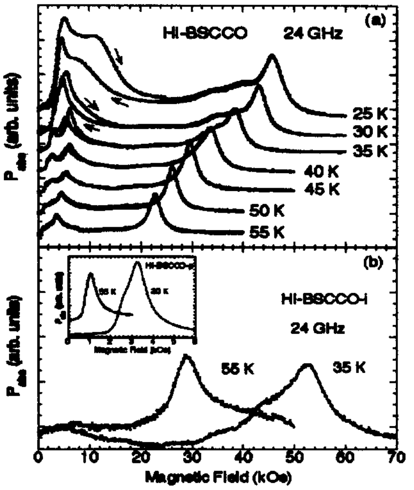

Figure 3. (a) $P_{abs}(H)$ at 24 GHz between 25 and 55 K for HI-BSCCO. Two resonances are observed at higher temperatures, while three resonances are observed at lower temperatures. Arrows indicate the direction of field sweep. (b) $P_{abs}(H)$ at 24 GHz and at 35 K and 55 K for HI-BSCCO-i. Inset shows $P_{abs}(H)$ for HI-BSCCO-p at 30 and 55K.

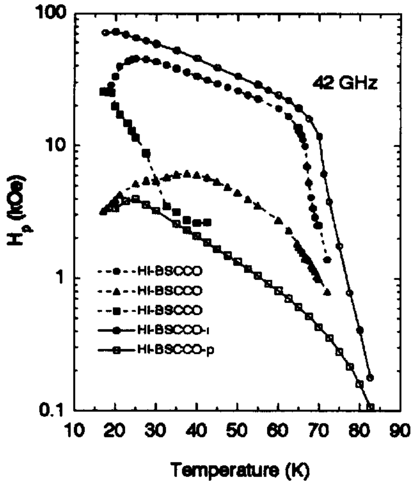

Figure 4. (c) $H_p(T)$ for HI-BSCCO, HI-BSCCO-i, and HI-BSCCO-p. Note that $H_p(T)$ in HI-BSCCO-i is higher than the highest $H_p(T)$ in HI-BSCCO which is believed to come from the irradiated part.

ident in 50-BSCCO as shown in Fig. 1(b). In addition to the two resonances, one more resonance at a lower field appears at 24 GHz. We have measured more than six samples and all of them show additional resonance peaks at fields $20 \sim 30$ % higher than the main peaks after the fabrication process.

Temperature dependence of the resonance field, $H_p(T)$, are plotted in Fig. 2(a) for 20-BSCCO and 100-BSCCO. $H_p(T)$ does not sensitively depend on the size of the mesas. $H_p(T)$ for 50-BSCCO at 24 and 42 GHz are shown in Fig. 2(b). All the resonance peaks at high temperatures show the temperature dependence which is characteristic of the decoupled vortex liquid state[1,2,4,11]. If the resonance field at a fixed temperature is fitted by $\omega_p^2 \propto H^{-\mu}$, μ is close to one. This is another strong indication that vortices in a region responsible for the JPR are almost decoupled. The ratio and the magnitude of the main and the new resonances weakly depend on the doping level.

Now let us discuss the origin of the two resonances. One of the possible origins is the inhomogeneity of the oxygen content. Oxygen is reported to be mobile even at room temperature and could diffuse in and out of the crystal through sample edges. Since the mesa part has larger surface area, the oxygen content in this region could be slightly higher compared with unprocessed substrate part, giving higher resonance field due to the decrease in the anisotropy parameter. Another possibility is that the vortex states in different regions of the crystal are different and the additional resonance occurs from the minor region having higher phase coherence. The region could be edges of the mesa and the crystal edges. JPR frequency is determined by the following formula, $\omega_p^2 \propto \langle \cos\phi_{n,n+1} \rangle$, where $\phi_{n,n+1}$ is the gauge-invariant phase difference between the neighboring layers and $\langle\ \rangle$ indicates the thermal and disorder average over phase coherent volume. The fact that we observe two separate resonance peaks in the crystal with mesa array shows that the average is not taken over the entire crystal. Theoretically, the phase coherence length is calculated by balancing the typical kinetic energy of supercurrents with the typical fluctuation of Josephson energy, and is estimated as $L_\phi = \lambda_J^2/a$, where λ_J is the Josephson length and a is inter-vortex distance[6]. At 1 T, L_ϕ is estimated as about 2 μm with $\gamma = 200$. Hence, the presence of the two resonance peaks is consistent with the theoretical estimate of the phase coherence length.

Figure 3(a) shows examples of $P_{abs}(H)$ in HI-BSCCO. At higher temperatures, two resonances are observed, while one more resonance becomes prominent at low temperatures. In a heavy-ion irradiated crystals at low temperatures, two resonance are reported as a function of field due to the nonmonotonic field dependence of the c-axis critical current[12]. Hence the presence of three resonance peak is naturally interpreted in a way that two of them coming from irradiated part and the remaining one comes from the pristine part. Figure 3(b) shows $P_{abs}(H)$ after cutting the crystal into two pieces. The pristine part, HI-BSCCO-p, shows only one resonance typical of pristine crystals, while irradiated part, HI-BSCCO-i, shows much higher resonance field. Temperature dependence of H_p is summarized in Fig. 4 in a logarithmic scale. Astonishingly the resonance field in HI-BSCCO-i is higher than the highest peak in HI-BSCCO before cutting. Also the resonance field in HI-BSCCO-p is lower than the lowest peak in HI-BSCCO. All these trend is understood by assuming that the resonance in each part of HI-BSCCO is somehow affected by the neighboring region having quite different phase coherence in a macroscopic scale.

Evidently the results in both sets of experiments contradicts to each other and we may need to reconsider the mechanism of averaging the phase coherence in JPR.

4. CONCLUSION

JPR in BSCCO having macroscopic inhomogeneity in the form of mesa array or nonuniform introduction of columnar defects are studied. In samples with mesa array, a weaker resonance is detected in addition to the main resonance. The additional resonance is possibly originated from the different regions having different vortex states in a macroscopic scale. The presence of the additional resonance suggests that the phase coherence is not averaged over the entire sample but is averaged in a scale smaller than the size of mesas. On the other hand, JPR in the half-irradiated BSCCO occurs at fields different from that in the separated pristine and irradiated parts. This indicates that there is an interference of the phase coherence in a length scale much larger than the estimated phase correlation length.

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