Josephson Plasma Resonance in Solid and Glass Phases of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

Itsuhiro Kakeya $^{ab}$, Ryo Nakamura $^a$, Tomoyuki Wada $^a$, and Kazuo Kadowaki $^{ab}$

$^a$Institute of Materials Science, University of Tsukuba, 1-1-1 Ten-nodai, Tsukuba, Ibaraki 305-8573, Japan

$^b$CREST, Japan Science and Technology Cooperation

Vortex matter phases and phase transitions are investigated by means of Josephson plasma resonance in under-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals in a microwave frequency range between 19 and 70 GHz. Accompanied by the vortex lattice melting transition, a jump of the interlayer phase coherence extracted from the field dependence of the plasma frequency was observed. In the solid phase, the interlayer coherence little depends on field at a temperature region well below $T_c$ while it gradually decreases as field increases toward the melting line up to just below $T_c$. As a result, the magnitude of the jump decreases with increasing temperature and is gradually lost in the vicinity of $T_c$. This indicates that the vortex lines formed in the vortex solid phase are thermally meandering and the phase transition becomes weak especially just below $T_c$.

**KEYWORDS:** Josephson plasma, vortex state, interlayer coherence

Studies of the mixed state in high-$T_c$ superconductors have brought about deeper understandings of the vortex matter in this decade. Most significant notion here is in the existence of the first order vortex lattice melting phenomenon occurring at $H_M$ as shown in Fig. 1 schematically. In high-$T_c$ superconductors, this lies well below the upper critical field $H_{c2}$ expected from the mean field approximation. This drastic change of the phase diagram has led much interest especially in the vortex liquid state existing above the first order vortex lattice melting transition (and the irreversibility line) below $H_{c2}$ line. Since the macroscopic superconducting phase coherence is lost there, the vortex liquid state has been considered as a non-superconducting state having only the short range coherence. In Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO), the vortex lattice melting transition occurs in temperatures and magnetic fields being easily accessible experimentally. The first order character of the phase transition continues up to the critical point, at which it changes the character to the second order phase transition and continues to the irreversibility line and the horizontal line so called the second magnetization peak as shown schematically in Fig. 1. So far, most of the Josephson plasma resonance (JPR) have been done in the vortex liquid phase except little study in the other vortex phases. JPR can provide quantitative information on the interlayer coherence between adjacent superconducting CuO$_2$ layers in highly anisotropic superconductor such as BSCCO. The Josephson plasma frequency in a finite field and a temperature is expressed as

$$\omega_p^2(H,T) = \omega_p^2(T)\langle \cos \varphi_{n,n+1}\rangle(H,T),$$  \hspace{1cm} (1)
axis correlations of pancakes, it is of considerable interest in studying the different vortex states discriminated by the various phase transition lines by means of JPR 6,7,8.

In Ref. 6,8, abrupt jump of the plasma frequency accompanied with the melting transition is reported. Their result indicates that the clear jump of the phase coherence continues up to $T_c$ and the jump suddenly disappears at $T_c$. According to Blatter et al., the first order melting transition is weaken near $T_c$ and the symptoms have been found experimentally 10. Quite recently, Koshelev and Bulaevskii also pointed out that the interlayer coherence does not change considerably at the melting transition in low fields (in the vicinity of $T_c$) because of strong meandering of the vortex lines 11.

In this paper, we discuss the melting transition quantitatively and the vortex state especially for the vortex solid phase below the melting transition in terms of the interlayer coherence extracted from JPR measurements as functions of microwave frequency, temperature, and magnetic field. As consequences, the change of interlayer coherence at the transition is quite small especially in the vicinity of $T_c$, where the vortex lines are not straight but meandering strongly even in the vortex solid state.

JPR measurements were performed in a microwave frequency range between 19 and 70 GHz in an under-doped BSCCO single crystal with $T_c$ of 72.4 K. Frequency-stabilized microwave was generated by a signal swept generator or Gunn oscillators and the resonance was detected either by sweeping external magnetic field at a fixed temperature or by sweeping temperature at a fixed field. Details of the experimental setup are described in Ref. 12.

Figure 2(a) represents typical resonance curves obtained by sweeping magnetic field. The resonance appears from 25 K in a finite field, the resonance field shows maximum around 30 K, and it disappears above 59 K, where the zero field plasma frequency $\omega_p(T)$ coincides with the incidental microwave frequency of 52.4 GHz. At all frequencies below 64 GHz, we observed similar feature of the resonance: the resonance field increase and decrease as temperature increases, and the resonance disappears below $T_c$. It is noted that the resonance becomes hysteretic and quickly moves towards low field as temperature is decreased below 30 K, and it is no longer observable below 20 K. As clearly seen in Fig. 2(a), it is also noticeable that the resonance line width which becomes larger quickly below the temperature at which the resonance field is maximum. By sweeping temperature on the contrary, a sharp resonance is observed below 68 Oe as shown in Fig. 2(b).

In Fig. 3, temperature dependences of the resonance field $H_{res}$ at 12 frequencies between 18 and 64 GHz together with temperature dependence of the vortex lattice melting field ($H_M$) obtained by the magnetization measurements by a SQUID magnetometer in the same crystal are plotted. $H_{res}$ at a given temperature decreases with increasing frequency, and the resonance is observed not only in the vortex liquid state but also in the vortex solid state below $H_M$. The temperature dependence of $H_{res}$ below $H_M$ is similar to the one in the liquid state: a broad maximum around 30 K and $H_{res}$ decrease toward $T_c$. Below 30 K, $H_{res}$ decreases toward low temperature at all frequencies even below $H_M$. As shown in the inset of Fig. 2(b), the resonance positions obtained by sweeping both magnetic field and temperature coincide above the maximum. This means that the thermal equilibrium state of vortices is realized even in the solid phase above the maximum by sweeping magnetic field, whereas it is not below the maximum. In previous studies, this inequilibrium state has been explained due to a pinning effect in the vortex glass state because the maximum of $H_{res}$ almost coincides with $H_{irr}$ shown in Fig. 1. Although this explanation may be valid for the resonance above $H_M$, the behaviors of the resonance in the solid phase implies that there is also a phase boundary similar to $H_{irr}$ line even below $H_M$ indicated as a dotted line in Fig. 1.

In our previous publication 13, the temperature dependence of JPR in zero magnetic field $\omega_p(T)$ was explained by the two fluid model very well as

$$\omega_p^2(T) = \frac{\omega_p^2(0)}{2}\left[1-\tilde{\tau}^{-2} + \sqrt{(1+\tilde{\tau}^{-2})^2 - 4\tilde{\tau}^{-2}(T/T_c)^2}\right],$$  \(2\)
where \( \tilde{\tau} = \tau \omega_p(0) \) is the reduced scattering rate. Using Eq. (1) and Eq. (2), we can derive the interlayer coherence without ambiguity. The normalized field dependence of the interlayer phase coherence \( \omega_p^2(H, T)/\omega_c^2(T) \) at \( H_M \) is plotted as a function of field in Fig. 4. It is clearly observed that the interlayer phase coherence abruptly jumps in the vicinity of \( H_M \) with decreasing magnetic field at low temperatures below 55 K. This jump can be attributed to the first order phase transition from liquid to solid as reported previously [5]. Although the magnitude of this jump is clearly noticeable, it amounts only to 0.65 at most and becomes even smaller at higher temperatures. Such a relatively small jump of the phase coherence at \( H_M \) is partly caused by the precursor reduction of the phase coherence already beginning well below \( H_M \), indicating that the thermal phase fluctuations dominate in wide temperature region below \( T_c \). The interlayer coherence continues to survive even above \( H_M \) and seems to follow the \( 1/H \) dependence very well in good accordance with the theoretical prediction [4].

The magnitude of the jump of the interlayer coherence decreases as temperature increases, the sharp jump gradually disappears and turns to a broad increase above 65 K. In terms of the interlayer coherence, this result is interpreted that the vortex lattice melting transition becomes weaker as temperature increases and finally loses one of the characteristics of the first order phase transition in temperatures considerably below \( T_c \) (5–7 K). This is in contrast to the results in Ref. [3], where the change of interlayer coherence accompanied by the first order transition seems not to depend on temperature. Koshelev and Bulaevskii have derived a relation between plasma frequencies and the vortex wandering length \( r_w \) defined as mean deviation of two pancake vortices of a vortex line at neighboring layers, which does not depend on the wandering mechanism of vortex lines [11]. They conclude that in the low field region of \( B < 20 \) G the wandering length of the vortex lines is comparable with the Josephson length \( \lambda_J \) and the interlayer coherence does not change considerably at the melting transition. Here, \( \lambda_J \) is given by the anisotropy parameter \( \gamma \) and the interlayer spacing \( s \) as \( \lambda_J \equiv \gamma s \). This suggestion is consistent with our experimental results in a sense that the abrupt jump at \( T_M \) in the vicinity of \( T_c \) is hardly visible due perhaps to the weakening of the melting transition caused by the strong vortex fluctuations even in the vortex solid state.

Finally, we mention about the line-shape of the resonance in the solid phase. As shown in Fig. 3, the resonance line observed in the liquid state (between 35 and 46 K) is sharp and has a slight tail at higher field side, whereas the line in the glass and the solid phases is relatively broad and has a tail at lower field side. The line-shape in the liquid state has been explained by the dispersion relation of the longitudinal Josephson plasma mode [15]. On the contrary to this, non-uniform field distribution—interlayer phase difference \( \varphi_{n,n+1} \) over a layer may be generated in the solid and the glass phases, since pancake vortices are localized because of formation of the vortex lines. As a result, \( \varphi_{n,n+1} \) has relatively large inhomogenity over a layer, from which the low field tail and broadening of the line could be explained.

In summary, the vortex lattice melting transition is studied quantitatively in terms of interlayer coherence by the Josephson plasma resonance. The transition becomes weaker at higher temperatures and the jump of the interlayer coherence remarkably diminishes near \( T_c \). This result suggest that the fluctuations of the vortices even in the vortex solid phase is considerably strong and the melting transition may turn from the first to the second order.

This work is partly supported by the REIMEI Research Resources of Japan Atomic Energy Research Institute.

REFERENCES
1. E. Zeldov et al., Nature (London) 375, 373 (1995)
2. B. Khaykovich et al., Phys. Rev. Lett. 76, 2555 (1996).
3. L. N. Bulaevskii et al., Phys. Rev. Lett. 74, 801 (1995).
4. Y. Matsuda et al., Phys. Rev. Lett. 75, 4512 (1995).
5. T. Hanaguri et al., Phys. Rev. Lett. 78, 3177 (1997).
6. I. Kakeya et al., Physica B 244-8, 881 (2000).
7. T. Shibauchi et al., Phys. Rev. Lett. 83, 1010 (1999).
8. M. B. Gaifullin et al., Phys. Rev. Lett. 84, 2945 (2000).
9. G. Blatter et al., Phys. Rev. B 54, 72 (1996).
10. e.g., K. Kadowaki and K. Kimura, Phys. Rev. B 57, 11 674 (1998).
11. A. E. Koshelev and L. N. Bulaevskii, cond-mat/0002196.
12. I. Kakeya et al., Phys. Rev. B 57, 3110 (1998).
13. K. Kadowaki et al., Int. J. Mod. Phys. B. 14 547 (2000).
14. A. E. Koshelev, Phys. Rev. Lett. 77, 3961 (1996).
15. K. Kadowaki et al., Phys. Rev. B 56, 5617 (1997).

Figure 1. Schematic vortex phase diagram in high-$T_c$ superconductors with weak pinning in fields parallel to the $c$ axis.

Figure 2. A set of JPR lines observed at 52.4 GHz at various temperatures obtained by sweeping field (a) and at various fields by sweeping temperature (b). In the inset of (b), the resonance positions obtained by sweeping field and temperature are plotted as solid and open symbols, respectively. These agree well except for temperatures below 35 K. It denotes that these curves in (a) and (b) were obtained in increasing $H$ and $T$, and no hysteresis due to sweeping $H$ and $T$ was found except when field was swept below 30 K.
Figure 3. Temperature dependence of the resonance field $H_{res}$ for frequencies between 18.85 and 63.5 GHz. Small symbols indicate observed resonance fields and large open circle indicates the vortex lattice melting transition observed by a SQUID magnetometer.

Figure 4. The interlayer coherence $\langle \cos \varphi_{n,n+1}(H,T) \rangle$ plotted as a function of magnetic field normalized by $H_M$. Magnitude of the jump of $\langle \cos \varphi_{n,n+1}(H,T) \rangle$ at the vortex lattice melting transition is larger at lower temperatures. Thick line follows $\langle \cos \varphi_{n,n+1}(H,T) \rangle \propto H^{-1}$. The inset shows the temperature dependence of the zero field plasma frequency. Solid symbols indicate experimental results and solid lines were obtained by fitting Eq. (2) to experimental results. The agreement between experiment and the model is very good.