Recoupling of Decoupled Vortex Liquid by Columnar Defects in $Bi_2Sr_2CaCu_2O_{8+y}$

M. Sato,[1] T. Shibauchi,[1] S. Ooi,[1] T. Tamegai,[1] and M. Konczykowski[2]
[1]*Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113, Japan*
[2]*Laboratoire des Solides Irradiés, CNRS URA-1380, École Polytéchnique, 91128 Palaiseau, France*
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We report on the effect of columnar defects on the interlayer phase coherence in $Bi_2Sr_2CaCu_2O_{8+y}$ using Josephson plasma resonance as a probe. In the vortex liquid phase close to T_c, the resonance field (H_p) shows a characteristic exponential temperature dependence similar to that of the irreversibility line. A drastic increase in H_p occurs at a frequency-dependent temperature in the vortex liquid phase. We interpret this change as a manifestation of field-induced recoupling of decoupled vortex liquid by columnar defects. The double resonance peaks observed in this temperature range indicate the coexistence of coupled and decoupled vortex regions. [S0031-9007(97)04419-0]

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In high temperature superconductors, large thermal fluctuations and the small pinning potential suppress the critical current density J_c. This makes the irreversibility line, which separates the region with vanishing J_c from that with a finite J_c, well below the mean field upper critical field. The introduction of artificial pinning centers by chemical modification [1] or by high energy particles [2,3] is an effective way to shift the irreversibility line to the practically useful range. Columnar defects (CDs) introduced by the heavy-ion irradiation are reported to be effective to increase J_c and shift the irreversibility line towards higher temperatures in $YBa_2Cu_3O_7$ [2,3]. In the case of $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) having much larger anisotropy, the effect is more dramatic [4] compared with $YBa_2Cu_3O_7$.

Accumulated experimental evidence shows that the vortices in a pristine BSCCO are decoupled at least well above the vortex lattice melting line [5,6]. An important question one may ask is whether CDs are effective in pinning decoupled two-dimensional vortices, i.e., pancake vortices. Vortices in superconductors with CDs can be mapped onto the problem of Bose particles in a random two-dimensional short range potential [7]. In this framework, CDs are predicted to suppress the thermal decoupling of vortices by inducing strong localization of vortices on them [8]. Experimentally, the presence of directional pinning due to CDs is suggested by the angular dependence of the irreversibility line [9,10]. Flux-transformer-type experiments in the heavy-ion irradiated BSCCO also show the correlation of the vortices along the *c* axis in the vortex liquid phase [11,12]. Despite these theoretical and experimental works, the detailed nature of vortices and the phase diagram in this system remains to be clarified.

The plasma with its polarization along the *c* axis in high temperature superconductors has peculiar characteristics. Its energy is much smaller than the superconducting gap [13], which makes this plasma long lived since it barely suffers from Landau damping [14]. The plasma resonance occurs when the incident electromagnetic wave frequency coincides with the plasma frequency. The resonance frequency is strongly modified by the presence of vortices [15]. The magnetoabsorption in a Josephson-coupled layered superconductor BSCCO discovered by Tsui *et al.* [16] was confirmed to be due to Josephson plasma resonance (JPR) [17]. It is also reported that the JPR field (H_p) shows a characteristic temperature dependence with a sharp cusp at the irreversibility line [16,17]. All these findings indicate that JPR can be a new powerful tool for the investigation of a vortex system, especially the coherence along the *c* axis.

In this Letter we report on the effect of CDs on the interlayer phase coherence of vortices using JPR as a probe. A sharp increase in the phase coherence along the *c* axis was found in the vortex liquid phase. We interpret this change as a manifestation of the recoupling of vortices by CDs. The coherence sets in as a crossoverlike change at a weakly temperature dependent magnetic field.

BSCCO crystals used in this experiment were grown by the floating zone method. A large piece of the crystal was cut into several pieces with approximate dimensions of $1 \times 0.5 \times 0.01$ mm^3 and irradiated with 5.8 GeV Pb ions at the heavy-ion irradiation facility, GANIL (Caen, France). Samples we used for JPR experiments have dose-equivalent fields (matching field B_Φ) of 0.5, 2.0, and 10 kG, whose superconducting transition temperatures T_c are 87.0, 87.1, and 83.0 K, respectively. We also measured an unirradiated sample with T_c of 87.7 K as a reference. The cavity perturbation method was used to detect dissipation due to JPR. This method has advantages over the bolometric method used by other groups [16–18] because we can minimize the microwave power and also measure the frequency shift, which could give additional information on the plasma resonance. We used three cylindrical cavities of 24, 41, and 56 GHz. The sample was placed at the position so that the maximum ac electric field is applied perpendicular to the CuO_2 planes. A dc magnetic field up to 90 kOe was also applied perpendicular to the CuO_2 planes. Irreversibility lines were determined by dc magnetization hysteresis loops measured by a superconducting quantum interference device (SQUID) magnetometer (MPMS-XL5, Quantum Design) in the reciprocating sample mode. The sample was oscillated at a frequency of 4 Hz with a travel of 0.5 cm. We defined the irreversibility field (H_{irr}) by the criterion of $J_c = 20\ \mathrm{A/cm^2}$. We also used ac-susceptibility measurements and got consistent results by the SQUID measurements. Detailed discussion on H_{irr} determined by both methods will be published in a separate paper [19].

Figure 1 shows temperature dependence of H_{irr} determined by SQUID measurements. The heavy-ion irradiation makes H_{irr} higher below dose-dependent characteristic temperatures, which is consistent with previous reports [9,10]. With increasing B_Φ, the upward shift of H_{irr} becomes larger and sharper. The steep rise of H_{irr} terminates at a field close to B_Φ. The inset in Fig. 1 shows the same data in a logarithmic scale. This plot indicates that there are two temperature regions in which $H_{\mathrm{irr}}(T)$ shows exponential temperature dependence; $H_{\mathrm{irr}}(T) \propto \exp(-T/T_0)$. Two values of T_0 for higher and lower temperature regions are 4.8 and 33 K, respectively.

Temperature dependence of the JPR field (H_p) measured at 24 GHz for irradiated and unirradiated BSCCO is shown in Fig. 2(a). It should be noted that JPR at high temperatures occurs above the irreversibility line, namely, in the vortex liquid phase. There are two remarkable points. The first is the upward shift of H_p compared with that of the unirradiated sample. The shift becomes larger and sharper with increasing B_Φ as in the case of H_{irr}. According to Bulaevskii *et al.* [15], the resonance frequency ω_p is related to $\phi_{n,n+1}$ as $\omega_p^2 \propto \langle\cos\phi_{n,n+1}\rangle$, where $\phi_{n,n+1}$ is a gauge invariant phase difference between nth and $n+1$th layers and $\langle\ \rangle$ denotes thermal and disorder average. When the interlayer coherence $\langle\cos\phi_{n,n+1}\rangle$ increases, the resonance field H_p measured at fixed frequency should increase. Thus, the increase in H_p is a direct proof of the enhanced interlayer phase coherence, namely, the alignment of vortices by CDs. Second, in the intermediate temperature region, $H_p(T)$ changes from convex to concave. For example in BSCCO with $B_\Phi = 10$ kG, $H_p(T)$ is concave from 20 to 50 K, whereas it is convex from 50 to 75 K. The change in the temperature dependence of H_p can be attributed to the presence of two kinds of vortices in the system, line vortices and decoupled (pancake) vortices. In the low temperature high field region, there are many vortices which are not trapped in CDs since the number of vortices surmounts the number of CDs. These vortices can be decoupled and make $H_p(T)$ concave as in the case of the vortex liquid phase in the unirradiated sample [16,17,20]. On the other hand, when the vortices aligned by CDs are dominant as in the range of $50 \lesssim T \lesssim 75$ K, $H_p(T)$ is convex. This is just like the situation in the vortex solid phase in the unirradiated sample, where vortices are well coupled and $H_p(T)$ is convex [21].

Figure 2(b) shows $H_p(T)$ at three frequencies together with H_{irr} for BSCCO with $B_\Phi = 10$ kG. As we have seen above, $H_p(T)$ at 24 GHz show both convex and concave. With increasing the frequency, $H_p(T)$ decreases and its temperature dependence in the intermediate temperature range becomes weaker. This is because at fields close to or lower than B_Φ, most of the vortices are trapped in CDs and $H_p(T)$ is mainly determined by the line vortices.

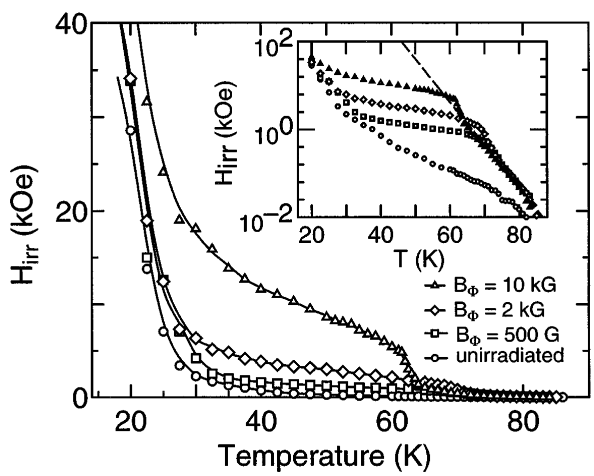

FIG. 1. Temperature dependence of H_{irr} determined by a SQUID magnetometer for irradiated and unirradiated BSCCO crystals. The inset shows logarithmic plots. The broken line shows a universal temperature dependence of H_{irr} for samples with CDs close to T_c.

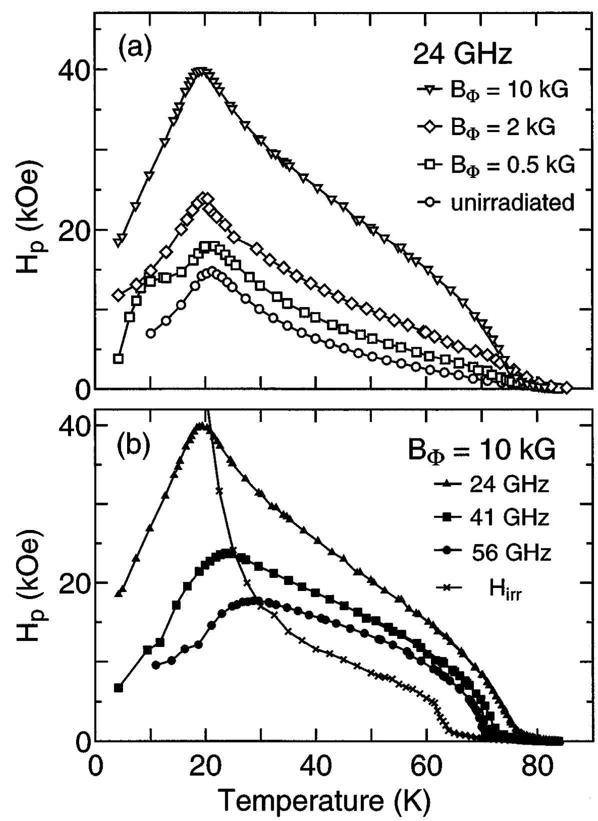

FIG. 2. (a) Temperature dependence of H_p at 24 GHz for irradiated and unirradiated BSCCO. (b) Temperature dependence of H_p at 24, 41, and 56 GHz and irreversibility line for irradiated BSCCO with $B_\Phi = 10$ kG.

Here, we comment on the location of the maximum in $H_p(T)$ with respect to $H_{\mathrm{irr}}(T)$. As is clear from Fig. 2(b), the maximum of H_p occurs close to $H_{\mathrm{irr}}(T)$ but at a slightly lower temperature. Previous reports [16,17] showed that the peak in H_p locates on $H_{\mathrm{irr}}(T)$. This difference originates from the criterion to estimate H_{irr}. We used a lower criterion of $J_c = 20\ \mathrm{A/cm^2}$ to determine H_{irr}. The decrease in $H_p(T)$ at low temperatures is a result of disorder-induced wandering of vortices which reduces the phase coherence [21]. The wandering of vortices is also a measure of J_c. So, in order to have an appreciable reduction of $H_p(T)$, we need to have a certain amount of J_c by going to a lower temperature. J_c at the maximum of $H_p(T)$ is of the order of $10^4\ \mathrm{A/cm^2}$. This value is quite consistent with the result of JPR in an organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ [22]. In this superconductor with a small $J_c < 1 \times 10^4\ \mathrm{A/cm^2}$, $H_p(T)$ does not show a peak structure.

Now we focus on the detailed temperature dependence of JPR near the sharp increase in H_p. Figure 3(a) shows the magnetic field dependence of the inverse of quality factor (Q), which is related to the dissipation, for BSCCO with $B_\Phi = 10$ kG in this temperature range. From 66.0 to 68.1 K, another small peak appears at about 2 kOe in addition to the sharp resonance peak which continues from lower temperatures. It should be noted that the field dependence of $1/Q$ is reversible with the sweep rate of about 2 kOe/min. At higher temperatures, the magnitude of the higher field peak is diminished whereas the temperature dependent peak at lower field remains up to T_c. These two peaks are plotted in Fig. 3(b), which clearly shows that peak at lower fields has weak temperature and frequency dependence. The existence of these two peaks may be explained by the fluctuation of the density of CDs. The fluctuation of the defect density divides the sample into two regions, one with lower CDs density dominated by decoupled vortices and the other with higher CDs density dominated by line vortices. At lower temperatures, vortices in the former region satisfy the resonance condition at a lower field, whereas vortices in the majority of the sample are aligned by CDs giving a larger resonance field. As the ratio of decoupled vortices becomes higher with increasing temperature by thermal fluctuations, the peak at higher field disappears. The reason why H_p for the second resonance peak is nearly temperature independent is not clear at the present stage.

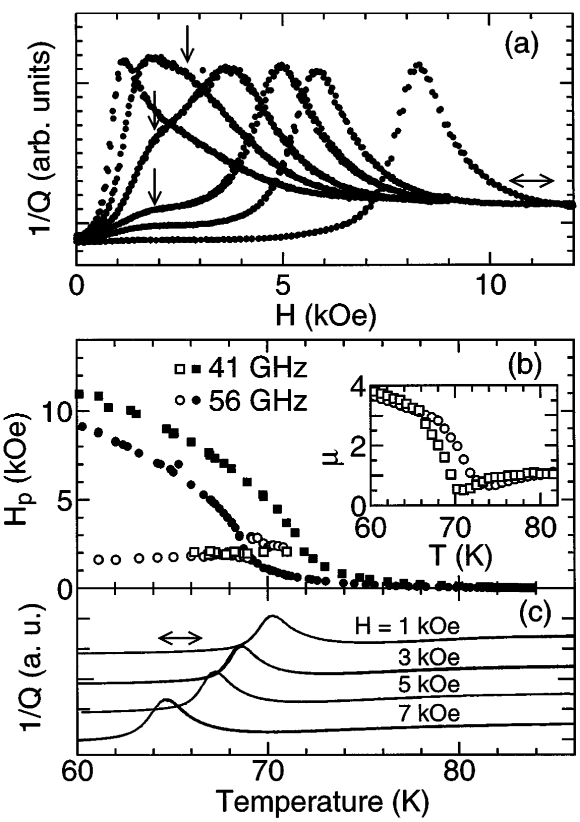

FIG. 3. (a) Magnetic field dependence of $1/Q$ for BSCCO with $B_\Phi = 10$ kG at 56 GHz at 62.0, 66.0, 67.0, 68.1, 68.9, and 69.8 K. Arrows indicate small resonance peaks which appear only after irradiation. (b) Temperature dependences of H_p and the additional peak. Inset shows the temperature dependence of the exponent μ using data at 24 and 41 GHz (open circles) and 41 and 56 GHz (open squares). (c) Temperature sweep measurements of $1/Q$.

In the decoupled vortex liquid state, H_p is related to ω as $H_p^{-\mu} \propto \omega^2$ [20], where μ represents the strength of disorder in the sample [15]. While it is predicted that $\mu = 1$ for a completely decoupled vortex system [20], it is about 0.8 and 0.7 for BSCCO [17] and κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ [22], respectively. We calculate μ using data at two frequencies out of three after appropriate interpolation as shown in the inset in Fig. 3(b). However, there is no reason to guarantee the above power-law frequency dependence of H_p once we have CDs. Actually, the disagreement of the two μ-T curves around 70 K shows that the above formula is not good in this temperature range. Below about 70 K, μ increases to a large value reflecting a small frequency dependence of H_p. In this temperature range, the contribution from vortices trapped in CDs giving constant contribution to the phase difference dominates.

Figure 4(a) shows a logarithmic plot of $H_p(T)$ as functions of normalized temperature for BSCCO with $B_\Phi = 10$ kG and the unirradiated sample at three frequencies. Although $H_p(T)$ in the irradiated samples shown in Fig. 2(a) seems to overlap to that of the unirradiated sample close to T_c, it is clear that both of them have different temperature dependence. $H_p(T)$ in the irradiated sample shows an exponential temperature dependence with weakly frequency dependent $T_0 \sim 3.3$ K (56 GHz) which is similar to $H_{\mathrm{irr}}(T)$ shown in the inset in Fig. 1. Since $H_p(T)$ in the unirradiated sample is well fitted by the formula for decoupled vortices [20], the separation of two $H_p(T)$ curves strongly supports that vortices in the irradiated sample are not completely decoupled. With lowering temperature, H_p shows a sharp increase at *frequency dependent* temperature and continues to

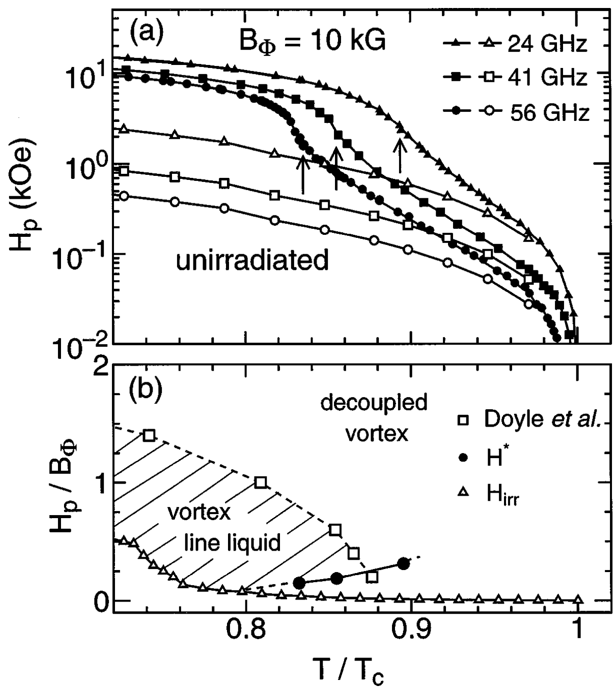

FIG. 4. (a) Semilogarithmic plot of H_p as a function of normalized temperature at three frequencies for BSCCO with $B_\Phi = 10$ kG and the unirradiated BSCCO. Arrows indicate H^*, above which a sharp increase in $H_p(T)$ occurs. (b) $H^*(T)$, $H_{\rm irr}(T)$, and the result of flux-transformer measurements [12] normalized by T_c and B_Φ.

the lower temperature curve smoothly. This frequency dependence clearly indicates that the increase in H_p is not probing a change at the so-called depinning temperature which should be frequency independent [8]. We define the field H^* at the point where $H_p(T)$ deviates from the exponential temperature dependence. $H^*(T)$ is of the order of a few hundred oersteds and weakly frequency dependent. When H_p reaches $H^*(T)$, nearly decoupled vortices start to be recoupled by CDs even in the vortex liquid phase.

Recent flux-transformer (FT) measurements at fixed magnetic fields also show that there is a temperature range where the top and the bottom voltage coincide indicating the alignment of pancake vortices in the vortex liquid phase. It must be noted, however, that the length scales which JPR and the FT measurements probe are different. JPR probes phase coherence between the neighboring layers, whereas the FT measurement reflects the coherence between the top and the bottom faces of the sample. $H^*(T)$, $H_{\rm irr}(T)$ for the sample with $B_\Phi = 10$ kG, and the points taken from FT measurements ($B_\Phi = 5$ kG) [12] normalized by B_Φ are plotted in Fig. 4(b) as functions of normalized temperature [23]. In the regime which is surrounded by three lines, vortices are in the form of line liquid. Below $H^*(T)$ and above $H_{\rm irr}(T)$, decoupled vortices affected by CDs are dominant.

Finally, we comment on the nature of the sharp increase in H_p. The sharp increase in H_p and the double peak structure shown in Fig. 3(a) may suggest a first order phase transition from decoupled vortices to vortex line liquid in this temperature range. However, there are several points which are not in favor of this scenario. (i) As we have shown in Fig. 3(a), there are no magnetic field hystereses in the resonance curves. (ii) Careful temperature sweep measurements with a rate of 0.2 K/min shown in Fig. 3(c) also show no temperature hystereses. (iii) The deviation of H_p from the exponential temperature dependence at higher temperature shown in Fig. 4(a) is rather gradual, so we interpret that the change in $H_p(T)$ at H^* is a crossover from the decoupled vortices dominated region to the vortex line liquid dominated region.

In conclusion, we found clear evidence of enhancement of the interlayer phase coherence in BSCCO with CDs using JPR. We interpret this phenomenon as a manifestation of recoupling of decoupled vortex liquid by CDs. This recoupling occurs with a sharp increase in $H_p(T)$ above a characteristic field which is weakly frequency dependent. $H_p(T)$ below this characteristic field shows an exponential temperature dependence similar to $H_{\rm irr}$. In the temperature range of the drastic change in H_p, double resonance peaks are present, which is probably due to the coexistence of coupled and decoupled vortex regions.

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[23] $H_p(T)$ and the data from [12] are determined by different criteria of the phase coherence. The line from [12] will be shifted toward higher fields when we draw this line with the same criterion as that for $H_p(T)$.