Visualization of Interacting Crossing Vortex Lattices in the Presence of Quenched Disorder

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We have imaged *interacting* crossing pancake vortex (PV) and Josephson vortex (JV) lattices in highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals under tilted magnetic fields. The dependence of vortex structures on in-plane field is in good *quantitative* agreement with theoretical predictions, yielding an almost *temperature-independent* anisotropy parameter of $\gamma = 640 \pm 25$. We *directly* confirm that the PV/JV attraction arises from small PV displacements in the presence of JV supercurrents and demonstrate how the existence of quenched disorder leads to *indirect* JV pinning and *dynamic* vortex fragmentation.

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The prediction of a novel composite state of vortex matter in highly anisotropic high temperature superconductors (HTS) under tilted magnetic fields has recently stimulated intense research in the area. Superconductivity in HTS resides in weakly coupled CuO_2 layers lying parallel to the *a-b* plane. Under *c*-axis magnetic fields, vortices are formally viewed as stacks of 2D pancake vortices (PVs) whose supercurrents flow within the CuO_2 planes [1,2] and which order into an hexagonal Abrikosov lattice [3]. With the field in the *a-b* plane, Josephson vortices (JVs) [2] form whose "cores" reside in the spaces between CuO_2 planes and which order into a greatly stretched rhombic lattice. In extremely anisotropic HTS, uniformly tilted vortices are expected to be unstable with respect to the formation of perpendicular hexagonal PV and rhombic JV lattices [4]. Furthermore, small PV displacements driven by the underlying JV supercurrents have been predicted to lead to an attractive interaction between these two "crossing" lattices [5]. A number of earlier experiments on highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) crystals in tilted magnetic fields are consistent with the crossing lattices ground state including the observation of a composite lattice of PV chains in a hexagonal "matrix" by Bitter decoration [6–8] and Lorentz microscopy [9] as well as the linear dependence of the vortex solid melting transition on in-plane field [10–12]. *To our knowledge, however, there has been no unambiguous experimental verification of interacting crossing lattices in such materials and this is the first important objective of this Letter.*

Scanning Hall probe microscopy (SHPM) [13] has been used to directly observe discrete PVs in BSCCO single crystals under *independently* applied $H_{\vec{c}}$ and $H_{\|}$ fields. Magnetic images are generated parallel to the *a-b* surface of freshly cleaved crystals with a lateral resolution of ~500 nm. The Hall probe is capable of resolving a single pancake vortex at the sample surface but typically detects the top 300 PVs in a stack [14]. The location of stacks of JVs is inferred from the fact that they become "decorated" by PVs due to their mutual attraction, in strong analogy with the Bitter decoration technique.

The left-hand inset of Fig. 1 shows an SHPM image of the magnetic induction just above the *a-b* face of an as-grown BSCCO single crystal ($T_c = 90$ K) at 81 K with the magnetic field at an angle of 89° to the *c* axis ($H_{\vec{c}} = 0.7$ Oe, $H_{\|} = 49.5$ Oe). This scan illustrates the formation of well-separated chains of PV stacks along the direction of the in-plane field component, which were reported in Refs. [15,16]. Assuming that these chains correspond to the "decoration" of the underlying JV lattice by PV stacks in the interacting crossing lattices ground state, we expect that the chain spacing will be independent of $H_{\vec{c}}$ (if $H_{\vec{c}}$ is small) and will directly mirror the in-plane JV lattice spacing. Within anisotropic London theory, the lateral separation of adjacent JV stacks is $c_y(B_{\|}) = \sqrt{\sqrt{3}\gamma\Phi_0/2B_{\|}}$, where γ is the anisotropy parameter and Φ_0 is the flux quantum [5,17].

Figure 1 illustrates how the chain separation c_γ (at various small values of $H_{\vec{c}}$) at four different temperatures in the range 77–85 K falls close to a single universal line when plotted versus $1/\sqrt{H_{\|}}$. These distances have been accurately estimated after calibration of the temperature-dependent range of the scanner using a magnetic reference sample, and the slope of the linear regression fit to the 81 K data (black line) yields an anisotropy parameter $\gamma = 640 \pm 25$, slightly larger than our earlier determination [15] and in reasonable agreement with other estimates [18]. The right-hand inset of Fig. 1 shows that the temperature dependence of the measured anisotropy at $H_\parallel = 38$ Oe is extremely weak in this temperature range. Note that spatial fluctuations of the JV lattice [19] and the renormalization of the JV structure due to the presence of PVs [5] may influence this evaluation. At very high in-plane fields, the layered nature of BSCCO crystals breaks the continuous London approximation [17] and the linear fit to the data consequently intersects the y axis below the origin at -1.3 ± 0.3 μm. Computing corrections to the Josephson vortex interactions due to the layered structure and the corresponding deformation of the lattice, we obtain [20]

$$c_y \approx c_{y0}\left(1 - \frac{9\sqrt{3}\gamma s^2 H_\parallel}{32\Phi_0}\right), \tag{1}$$

where c_{y0} is the uncorrected chain spacing and s is the separation of the CuO_2 layers in the crystal. This behavior is plotted as the gray line in Fig. 1 and, although it qualitatively describes the trends observed, it underestimates the experimental deviations somewhat. This is not fully understood and is the topic of ongoing research.

Quenched disorder in BSCCO single crystals shows a pronounced anisotropy, frequently leading to the formation of pinned PV chains along the crystallographic a axis [21]. We have exploited this phenomenon to *directly* observe the relaxation of the PV stack structure in the presence of JV currents, which has been proposed [5] to give rise to an attractive PV/JV interaction in the crossing lattices regime. Figure 2(a) shows an image of two weakly pinned (a-axis) chains after field cooling a BSCCO sample to 83 K in $H_{\vec{c}} = 1.8$ Oe ($H_\parallel = 0$) followed by the application of a small in-plane field $H_\parallel = 11$ Oe along the a axis. Figure 2(b) shows exactly the same vortex configuration after the in-plane field was increased to $H_\parallel = 16.5$ Oe, at which point a pronounced smearing of the top right-hand vortex chain was observed while all other flux structures remained unchanged. The smearing reflects small PV displacements which are driven by the currents due to the JV stack which is now aligned along it. Figure 2(c) shows line scans along the relevant chain before and after the increase of in-plane field, clearly illustrating how the field modulation along the chain falls by about a third for $H_\parallel = 16.5$ Oe. The nth PV above a given JV core is predicted [5] to experience a lateral displacement $u_n \approx 2C_n\lambda^2/[(n - 1/2)\gamma s \ln(\lambda/r_w)]$, where λ is the in-plane PV penetration depth, $r_w \sim \lambda^2/\gamma s$ is a measure of the maximum PV displacement in the JV core, and $C_n \cong 1 - 0.265/[(n - 0.835)^2 + 0.566]$. The solid lines through the data represent fits generated by entering u_n into a pancake vortex model due to Clem [14] which yields the following expression for the magnetic

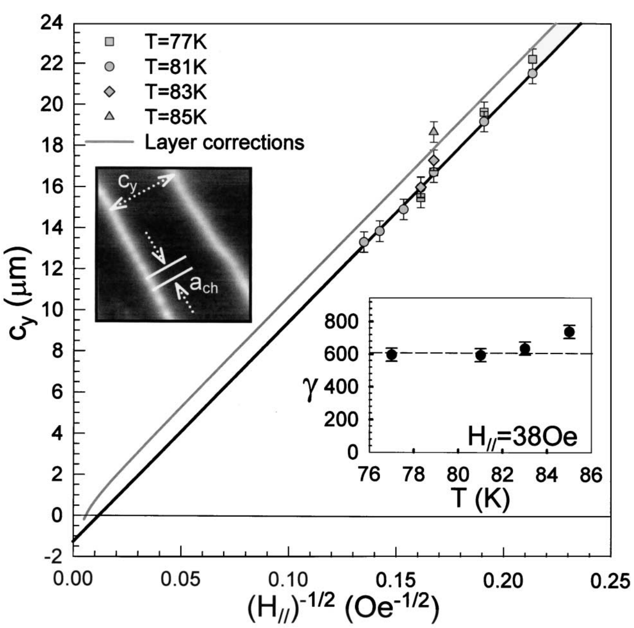

FIG. 1. Plot of the mean separation of 1D pancake vortex chains as a function of $(H_\parallel)^{-1/2}$ at various temperatures. Left-hand inset shows an image of pancake vortex chains in a BSCCO single crystal under a tilted magnetic field at 81 K ($H_\parallel = 49.5$ Oe, $H_{\vec{c}} = 0.7$ Oe, image size $\sim 27 \times 27$ μm^2). Right-hand inset shows the temperature dependence of the anisotropy at $H_\parallel = 38$ Oe.

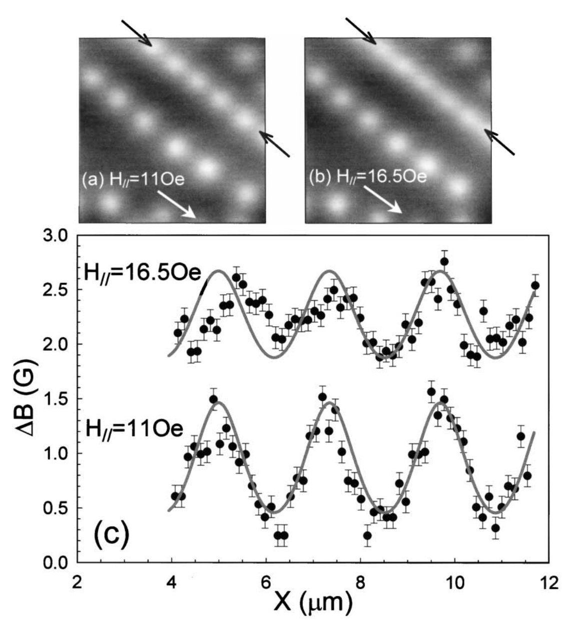

FIG. 2. (a) Image of pinned pancake vortex stacks after field cooling to 83 K in $H_{\vec{c}} = 1.8$ Oe ($H_\parallel = 0$) followed by the application of a small in-plane field $H_\parallel = 11$ Oe along the crystalline a axis (image size $\sim 14 \times 14$ μm^2). (b) Same region of the sample after the in-plane field was increased to $H_\parallel = 16.5$ Oe. (c) Line scans along the directions indicated in (a), (b). Smooth gray curves are fits to Eq. (2) for appropriate parameters (see text).

induction at a height h above the center of an isolated chain of PV stacks:

$$B_z(x,h) = \frac{s\Phi_0}{2\pi\lambda^2 a_{ch}} \sum_n \sum_{G_i} \int_{-\infty}^{\infty} \frac{\exp(-\sqrt{G_i^2 + q_y^2 + \lambda^{-2}}ns)\exp(-\sqrt{G_i^2 + q_y^2}h)\cos[G_i(x - u_n)]}{\sqrt{G_i^2 + q_y^2 + \lambda^{-2}} + \sqrt{G_i^2 + q_y^2}} dq_y. \quad (2)$$

Here $G_i = 2\pi i/a_{ch}$ are the reciprocal lattice vectors of the chain and n is summed over all CuO_2 bilayers down through the thickness of the sample. Care was taken to include the effects of surface barriers on the JV lattice, the depth of the first JV beneath the sample surface being given by $z_1 = c_z/4[1 + \sqrt{1/3 + (2/\sqrt{3}\pi)\ln(2.86\Phi_0/2\pi\gamma s^2 H_{\parallel})}]$ [22], where $c_z = \sqrt{2\Phi_0/\sqrt{3}\gamma H_{\parallel}}$ is the c-axis separation between JVs in a stack (assumed constant below the first JV). Equation (2) was solved numerically assuming $\lambda(83\text{ K}) = 450$ nm, $r_w = 270$ nm, $s = 1.5$ nm, $c_z = 48$ nm, $a_{ch} = 2.35$ μm, and $\gamma = 640$. The scan height h was treated as a fitting parameter for the $H_{\parallel} = 11$ Oe data, and the $H_{\parallel} = 16.5$ Oe trace was then calculated with effectively no free parameters. With $h = 650$ nm and $u_n = 0$ an excellent fit was achieved to the line scan from Fig. 2(a), while the degree of broadening due the PV displacements shown in Fig. 2(b) is also well reproduced when $u_n \neq 0$. (Note that we expect very few of the pancakes probed near the top of a given stack to be influenced by the pinning potential.) *Figure 2 represents the most direct verification of interacting crossing lattices to date, illustrating that Josephson vortices can pass right through PV stacks, leaving them unchanged, as well as directly visualizing the PV stack relaxation in the presence of JVs.*

The second goal of this Letter is to show that the influence of quenched disorder on the interacting crossing lattices ground state leads to a wide range of novel phenomena. Remarkably, we find that the JV/PV interaction is sufficiently strong that JV stacks become *indirectly* pinned at the location of pinned PV stacks since they can interact with a higher density of PVs in these regions. Indirect pinning of JVs is more pronounced at high PV densities due to the increased intrachain PV repulsion. The crooked bright line on the right-hand side of Fig. 3(a) represents a strongly "kinked" stack of JVs due to indirect pinning by PVs along the crystalline a axis (in the direction of the arrow shown) down a 9 μm long segment in its center at 85 K ($H_{\parallel} = 35.8$ Oe, $H_{\vec{c}} = 8.8$ Oe). Similar, but less dramatic, behavior is observed in Fig. 3(b) at 83 K with a lower PV density ($H_{\parallel} = 35.8$ Oe, $H_{\vec{c}} = 4.4$ Oe). The problem of indirect pinning shown in Fig. 3(a) is formally almost identical to the deformation of vortices near planar defects provided the strong anisotropy is included [23]. For an in-plane field applied at an angle θ to the strong pinning axis, we find that the length of an indirectly pinned JV stack is given by

$$w = \sqrt{\frac{8U_p}{K\sin^2\theta\cos\theta}} - \sqrt{\frac{\sigma}{K\cos^2\theta}}, \quad (3)$$

where $K = \Phi_0 B/4\pi\gamma^2\lambda^2$ arises from the "cage potential" interaction with other Josephson vortices and $\sigma \cong \Phi_0^2/[(4\pi)^2\gamma\lambda^2]$ is the JV line tension. U_p is the *indirect* pinning potential per unit length estimated as the interaction between a JV and the "sheet" of PVs in the pinned chain. Assuming that this can be approximated by $U_p = E_\times \Delta(1/a_{ch})$, where $E_\times = -2.1\Phi_0^2/[4\pi^2\gamma^2 s\ln(3.5\gamma s/\lambda)]$ is the crossing energy for a single PV stack crossing, one JV [5] and $\Delta(1/a_{ch})$ is the difference in PV chain density between the strongly pinned region and elsewhere, we get quantitative agreement between the pinned length calculated from (3) and the measured one in Fig. 3(a) using the same parameters as before and $\Delta(1/a_{ch}) \cong 1$ PV stack/μm. In reality, the downwards renormalization of the JV line tension due to the repulsive PVs attached to it would lead to a smaller pinning potential and our modeling of the images suggests that this estimate is probably a factor of 5–10 too large.

Finally, we show that fragmentation of PV and JV stacks can occur when decorated stacks of JVs are forced abruptly through a region of disorder which is inhomogeneous along the c axis. Figure 4(a) shows an image of a pinned chain of PV stacks ($H_{\vec{c}} = 0$, $T = 85$ K) after the in-plane field was suddenly reduced from $H_{\parallel} = 36$ Oe to zero. Note that a "fractional" pancake vortex stack has now formed in the middle of the chain which "healed" back to a connected stack after the in-plane field was cycled back up to $H_{\parallel} = 11$ Oe [Fig. 4(b)]. Figure 4(d) shows line scans across these images in the indicated directions, and we find that the pancake vortex model [14] describes the data well if we assume that a PV stack has split cleanly, at a depth of ~480 nm below the surface, into two segments a lateral distance 2.3 μm apart [Fig. 4(c) and gray curve in Fig. 4(d)]. Similarly, Fig. 4(e)

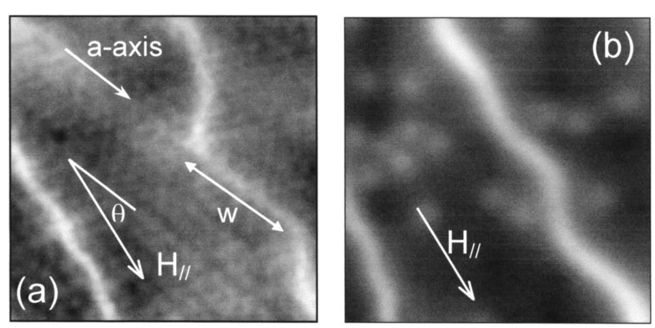

FIG. 3. (a) Image of kinked pancake vortex chains at 85 K ($H_{\parallel} = 35.8$ Oe, $H_{\vec{c}} = 8.8$ Oe, image size ~27.5 × 27.5 μm^2). (b) Kinked chains at a lower c-axis magnetic field at 83 K ($H_{\parallel} = 35.8$ Oe, $H_{\vec{c}} = 4.4$ Oe, image size ~14 × 14 μm^2).

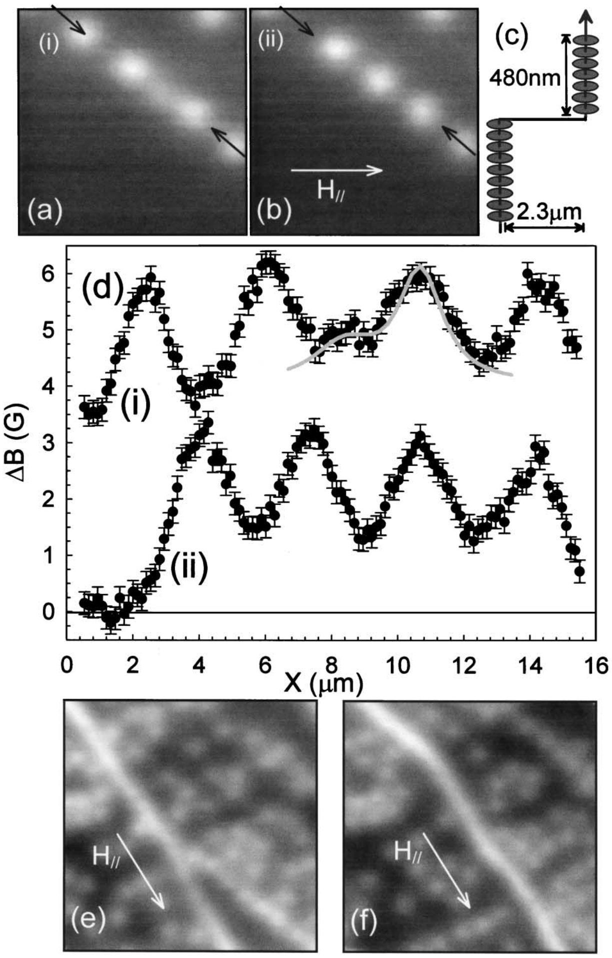

FIG. 4. (a) Image of a split PV stack ($H_{\hat{c}} = 0$, $T = 85$ K) after the in-plane field was suddenly reduced from $H_{\|} = 36$ Oe to zero (image size $\sim 14 \times 14$ μm^2). (b) Healing of split PV stack after the in-plane field was cycled up to $H_{\|} = 11$ Oe. (c) Sketch of the split PV stack used to model line scans in (d). (d) Line scans along the indicated directions. The gray curve is a fit to the pancake vortex model (see text). (e) Decoration of a forked JV stack after the in-plane field was abruptly increased to $H_{\|} = 33$ Oe at 77 K ($H_{\hat{c}} = 1$ Oe, image size $\sim 26 \times 26$ μm^2). (f) Healing of the fork observed in (e) after the in-plane field was reduced to $H_{\|} = 22$ Oe.

illustrates the splitting of a decorated JV stack into two "forks" at 77 K after $H_{\|}$ was abruptly increased from -33 Oe to 33 Oe ($H_{\hat{c}} = 1$ Oe). Note that the PV chain density in each fork is approximately the same, indicating that the JV stack must have split into two almost equal sections. Figure 4(f) shows how the split chain has recombined after the in-plane field was reduced to $H_{\|} = 22$ Oe in the subsequent scan.

In conclusion, we have imaged interacting crossing lattices in BSCCO crystals under tilted magnetic fields. We find good quantitative agreement with all theoretical predictions which yield an almost temperature-independent anisotropy parameter $\gamma = 640 \pm 25$. We have directly observed the relaxation of PV stacks in the presence of JV currents and show that quenched disorder can lead to indirect JV pinning. Our experiments also demonstrate that fragmentation of PV and JV stacks occurs naturally in HTS during dynamical measurements under tilted fields, an important feature to incorporate into models of flux dynamics. Finally, we note that the decoration of JVs by PV stacks opens up exciting new possibilities for investigating JV dynamics in layered superconductors.

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