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Manipulation of pancake vortices by rotating a Josephson vortex lattice

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Abstract
Scanning Hall probe microscopy has been used to demonstrate the manipulation of pancake vortices by rotating the Josephson vortex lattice in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals in the interacting crossing lattices regime. Creation of one-dimensional pancake vortex chains trapped on Josephson vortices, and the subsequent rotation of the chains were realized by independently controlling magnetic fields in three orthogonal directions. The anisotropy parameter determined from the in-plane distances between vortex chains in various in-plane fields is consistent with commonly accepted values.

1. Introduction

In high critical temperature superconducting (HTS) cuprates, a magnetic field (H_z) applied perpendicular to the superconducting CuO_2 layers (*a–b* planes) creates stacks of two-dimensional (2D) pancake vortices (PVs), with circulating supercurrents in the CuO_2 layers, weakly coupled along the *c*-axis, which interact to form well-ordered hexagonal Abrikosov lattices in disorder-free samples [1]. When the field is applied in the *a–b* plane ($H_\parallel$) Josephson vortices (JV) are formed, with 'cores' residing in the spaces between CuO_2 planes and with circulating currents derived partly from weak Josephson coupling between them. This anisotropic current distribution leads to strongly anisotropic JV–JV interactions and the JV lattice is a rhombic one, with the unit cell greatly stretched out in the *a–b* plane.

In weakly anisotropic layered superconductors under arbitrarily orientated magnetic fields, there are uniformly tilted vortices, composed of a staircase of pancake vortices linked by segments of Josephson vortices. However, in extremely anisotropic HTS, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO), the tilted vortices are unstable with respect to the formation of independent, perpendicular hexagonal PV and rhombic JV lattices [2]. Furthermore, small PV displacements driven by the underlying JV supercurrents lead to an attractive interaction between these two 'crossing' lattices [3, 4]. Since the symmetries of the projected JV and PV lattices in any given direction are, in general, incommensurate, a rich variety of broken symmetry phases can arise in the crossing lattices regime. Scanning Hall probe microscopy (SHPM) has earlier been used to directly observe discrete PVs in BSCCO single crystals under independently applied H_z and $H_\parallel$ fields, leading to an unambiguous experimental verification of the interacting crossing lattices scenario [5, 6]. At very low H_z a one-dimensional (1D) vortex chain state was observed [5] where all PV stacks become trapped on underlying JVs (so-called JV 'decoration'). Distortions of the JV lattice, induced by varying $H_\parallel$, enabled the indirect manipulation of PVs trapped on them, allowing one to conceive of vortex pumps, diodes and lenses based on this principle [5, 7, 8].

In this paper we demonstrate the manipulation of PVs trapped on JVs by *rotating* the JV lattice under independently controlled H_x and H_y magnetic fields.

2. Experimental details

The SHPM used is a modified commercial low temperature STM in which the usual tunnelling tip has been replaced by a microfabricated GaAs/AlGaAs heterostructure chip. Electron beam lithography and wet chemical etching were used to define a 0.6 μm Hall probe in the two-dimensional electron gas approximately 5 μm from the corner of a deep mesa etch, which was coated with a thin Au layer to act as an integrated STM tip. The sample is first approached towards the sensor until tunnelling is established and then retracted about 100–200 nm allowing rapid scanning. The Hall probe makes an angle of about 1° with the sample plane so that the STM tip is always the closest point to the surface, and the Hall sensor was typically ~500–700 nm above the sample during imaging. The temperature-dependent scan field, ~28 μm × 28 μm at 80 K and ~29 μm × 29 μm at 83 K, is divided into 128 × 128 pixels. The local magnetic induction at a pixel $B_{i,j}$ $(i, j = 1, \ldots, 128)$ is an average of 13 consecutive measurements. Each image presented is an average of 25 scans, resulting in a map of the local magnetic induction, B_{ij}, an average value of induction over the entire scan area, and a greyscale, $(B_{i,j}^{\max} - B_{i,j}^{\min})$. A more detailed description of the instrument and scanning technique is given elsewhere [9]. In the studies described here we were able to independently apply a fixed out-of-plane field, H_z, as well as a 'rotating' in-plane field, $H_\parallel$, produced by two pairs of orthogonal Helmholtz coils outside the cryostat, each pair generating the independent components H_x and H_y of the in-plane field. The sample studied here was a good quality as-grown BSCCO ($500 \times 500 \times 30\ \mu\text{m}^3$, $T_c = 90$ K) single crystal grown by the floating zone method [10].

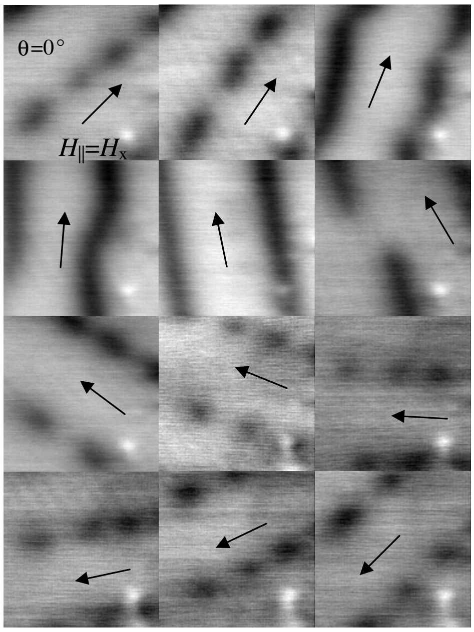

Figure 1. SHPM scans at $T = 80$ K, $H_\parallel = 27.5$ Oe, with the JV lattice rotated by (left to right, top to bottom, anticlockwise rotation): 0°, 15°, 30°, 45°, 60°, 75°, 105°, 120°, 135°, 150°, 165°, and 180°. (Scan size ~ 28 μm × 28 μm.)

3. Results and discussion

After realizing the conditions for one dimensional (1D) PV chains ($H_\parallel \gg H_z$), the rotation of the JV lattice was achieved by gradually increasing/decreasing the current in the two independent Helmholtz coils in such a way that $H_\parallel = \sqrt{H_x^2 + H_y^2} = \text{const}$. Starting from the initial state of 1D chains, SHPM images were recorded at discrete rotation angles $\theta = \arctan(H_y/H_x)$ in steps of 15° at $T = 80$ K. The SHPM images of figure 1 show that 1D chains follow the rotation of the JV lattice, with in-plane field angles, left to right and top to bottom, of 0°, 15°, 30°, 45°, 60°, 75°, 105°, 120°, 135°, 150°, 165°, and 180°. PV stacks are represented by dark dots (negative H_z). Due to the Earth's magnetic field, and small parasitic H_z components from the in-plane Helmholtz coils, the exact values of H_z are not known. Moreover, changes in the density of the chains at different angles reveal that H_z was not constant during the rotation of the JV lattice. However, even if the linear density of PVs trapped on JVs is not constant, PVs clearly follow the rotation of the JV lattice. It can also be seen that, at the highest PV densities (highest perpendicular field), e.g. at 30° and 45°, 1D chains start to meander due to the competition between the attractive crossing lattice interaction and the PV–PV repulsion. Nevertheless the manipulation of PVs upon rotating the JV lattice is still evident. The bright dot present in the bottom right-hand side on each image is a 'topographic' artefact due to a small particle on the sample.

Within anisotropic London theory the expected rhombic JV lattice produced by an in-plane magnetic induction, B_x, in the interacting crossing lattices regime has a c-axis vortex separation, a_z, and a lateral stack spacing, a_y, given by [11]

$$a_z = \sqrt{2\Phi_0/(\sqrt{3}\gamma B_x)}, \qquad a_y = \sqrt{\sqrt{3}\gamma\Phi_0/(2B_x)}, \quad (1)$$

where γ is the anisotropy parameter and Φ_0 the flux quantum. On the basis of this, the measurement of the distance between 1D chains at various in-plane fields $H_\parallel$ enables a fairly precise estimation of γ assuming that the JV lattice is unperturbed by decoration, and the spacing $d = a_y$. SHPM images of 1D PV chains at $T = 83$ K and $H_\parallel = 19.25$, 30.25, and 52.3 Oe are shown in figures 2((a)–(c)), while figure 2(d) shows a typical linescan used for determining the distance d between 1D PV chains.

Figure 3 illustrates the dependence of $1/d^2$ versus $H_\parallel$ obtained after constructing many such linescans through several SHPM images.

It can be seen that the resulting anisotropy parameter, $\gamma = 550 \pm 25$ is well within the commonly accepted range for as-grown BSCCO single crystals with a similar T_c.

Formation of the 1D vortex chains and their manipulation depend on the interplay between the crossing and pinning forces. The relative strengths of the crossing and pinning forces can be estimated from known expressions. The attractive force per unit length along the c-axis, f_x, between a PV stack and a JV stack is given by [12]

$$f_x = \frac{1.4\Phi_0^2}{4\pi^2 a_z \gamma^3 s^2 \ln(\lambda_{ab}/s\beta_f)}, \quad (2)$$

where s is the interlayer spacing, λ_{ab} is the in-plane London penetration depth and $\beta_f \sim 1$. In our experiments, the lowest in-plane field that led to 1D chain formation was 16.5 Oe, for which, following equation (1), we find $a_z = 5.65 \times 10^{-6}$ cm. Inserting this value and the resulted anisotropy factor into equation (2), f_x is found to be about 1.5×10^{-5} dyn cm^{-1}. As a comparison the averaged pinning force per unit length

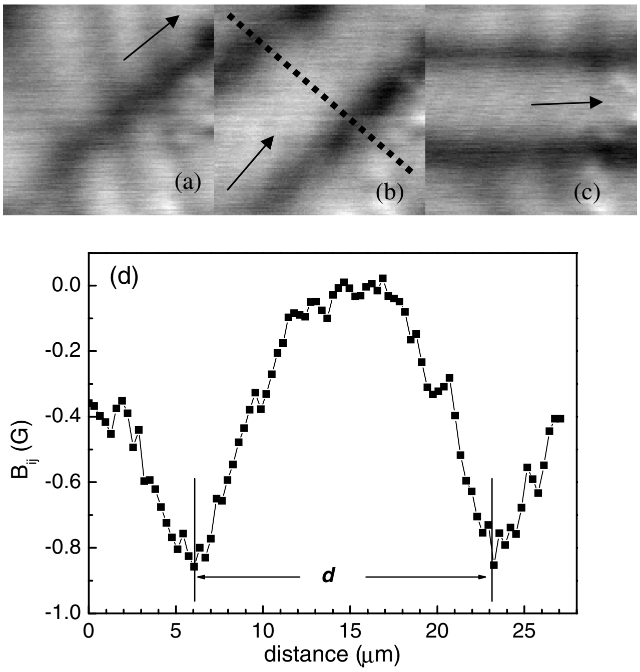

Figure 2. ((a)–(c)) SHPM scans at $T = 83$ K and $H_{\|} = 19.25$, 30.25, and 52.3 Oe, respectively (scan size $\sim 29\ \mu$m $\times$ 29 μm. Arrows indicate the directions of the in-plane field, while dotted lines indicate the directions on the linescans used for estimation of the anisotropy factor); (d) linescan across the indicated direction from (b).

of a PV stack can be estimated from the critical current density, j_c, by $f_p = j_c\Phi_0$. From magnetization measurements performed on a similar single crystal, the resulted critical current density led to pinning forces of 8.3×10^{-5}, 4.8×10^{-5}, and 2.1×10^{-5} dyn cm^{-1}, at 50, 60, and 70 K, respectively [13]. Extrapolation of these data to 80 K leads to an approximate value for f_p of about 0.5×10^{-5} dyn cm^{-1}, i.e., about three times smaller than the attractive force.

In conclusion, the independent control of applied fields in three orthogonal directions during SHPM imaging has allowed us to demonstrate the manipulation of PVs trapped on JVs (1D vortex chains) while rotating the JV lattice. PV manipulation by rotating the JV lattice is an additional verification of the model of interacting crossing vortex lattices in highly anisotropic HTS, and may have important applications, e.g. for the removal of unwanted flux in HTS devices, or in HTS ratchets. The in-plane field dependence of the distance between 1D vortex chains has allowed the estimation of the anisotropy parameter for our BSCCO single crystal. The resulting value

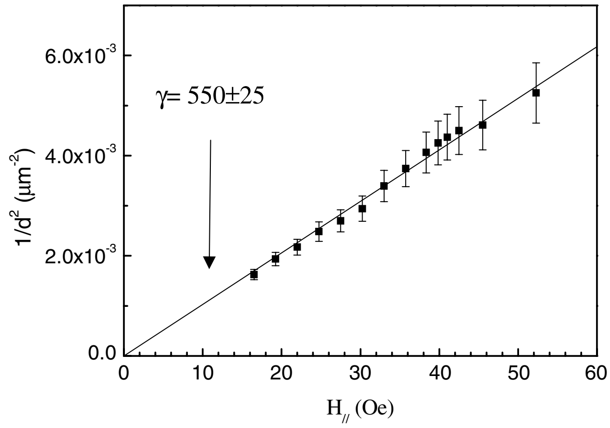

Figure 3. Dependence of the PV 1D chain separation $d = a_y$ on the in-plane field $H_{\|}$. The straight line is the linear fit to equation (1).

of 550 ± 25 lies well within the commonly accepted range for as-grown single crystals of this material.

Acknowledgments

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