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Vortex pumps in the crossing lattices regime of highly anisotropic layered superconductors

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Abstract

It is now well established that vortex dynamics in samples with a spatially asymmetric pinning potential can lead to rectifying vortex 'diode' behaviour. Spatial asymmetry is not a fundamental requirement for the control of vortex motion, however, and we demonstrate that vortex 'lensing' is possible in highly anisotropic layered superconductors simply under the action of non time-reversible trains of in-plane magnetic field pulses. Our devices depend crucially on the existence of 'crossing' pancake vortex (PV) and Josephson vortex (JV) lattices in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single crystals under tilted magnetic fields. An attractive interaction between these two sub-lattices makes it possible to indirectly manipulate the PV distribution by modifying the JV lattice, and a number of functional devices based on this principle have been proposed. In our experiments a BSCCO single crystal is placed on a Hall probe array, and cooled below T_c in a small out-of- plane magnetic field. Trains of sawtooth in-plane field pulses are then applied to the system and different elements of the Hall array used to demonstrate PV lensing or antilensing behaviour, depending on the pulse shape. The mechanism leading to lensing will be discussed and results compared with molecular dynamics simulations.

Keywords: Type II superconductors; Crossing vortex lattices; Vortex pumps

1. Introduction

Several distinct ways of using asymmetric pinning to control vortex motion in type II superconductors have recently been proposed [1] and realized [2–6]. A common feature of all these device structures is the presence of an asymmetric 'ratchet potential' which is created using some form of nanoscale processing. The resulting asymmetric vortex dynamics leads to a net mean vortex velocity, even when the ac driving force (e.g. transport current) time-averages to zero. An asymmetric potential is not, however, an essential feature of a vortex ratchet. Inspired by recent proposals [7,8] of ways to control the motion of tiny particles in binary mixtures, we have investigated a novel form of vortex ratchet in the crossing vortex lattices regime of highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) superconducting crystals. In this example the binary mixture is comprised of weakly coupled Josephson and pancake vortices, and it is possible to directly drive one species and indirectly drag along the second. In this case vortex motion control can be achieved using periodic time-asymmetric magnetic fields, and no spatially asymmetric ratchet substrate is required.

Superconductivity in high temperature superconductors (HTS) is known to reside in weakly coupled CuO_2 layers lying parallel to the crystalline *a–b* planes. Under *c*-axis magnetic fields vortices have their circulating supercurrents flowing within the CuO_2 planes and are formally viewed as stacks of 2D pancake vortices (PVs) which interact to form well-ordered hexagonal Abrikosov lattices in disorder-free samples. When the field is applied in the *a–b* plane Joseph-

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son vortices (JVs) arise whose 'cores' reside in the spaces between CuO_2 planes and whose circulating currents derive partly from weak Josephson coupling between them. This anisotropic current distribution leads to strongly anisotropic vortex–vortex interactions and a rhombic lattice whose unit cell is greatly stretched out in the *a–b* plane. In extremely anisotropic HTS uniformly tilted vortices, composed of a staircase of PVs linked by segments of JV, are unstable with respect to the formation of independent, perpendicular hexagonal PV and rhombic JV lattices [9]. Furthermore, small PV displacements, driven by the underlying JV supercurrents, lead to an attractive interaction between these two 'crossing' lattices [10] with rather profound consequences since the symmetries of the projected JV and PV lattices in any given direction are, in general, incommensurate. Thus a rich variety of broken symmetry phases can arise in the crossing lattices regime which remain largely unexplored. We have recently succeeded in using high resolution scanning Hall probe microscopy of PVs in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single crystals to demonstrate a novel 'decoration' technique [11,12] that relies on the fact that PV stacks migrate to the location of underlying (invisible) JVs due to their mutual attraction, in analogy with conventional Bitter decoration. We were able to show that the attractive interaction between stacks of JVs and PVs leads to a new phase transition to an "isolated chain state" where all pancakes condense onto Josephson vortices, reducing the dimensionality and symmetry of the Abrikosov lattice [11]. This chain state exhibits many remarkable dynamic properties; for example stacks of JVs can be forced towards the sample center by increasing the in-plane magnetic field. In doing so they drag along PV stacks which are attracted to them, allowing indirect control of the PV density within the sample [8,11]. This paper describes our progress in developing a PV lens and PV ratchet based on these properties of interacting vortex matter in BSCCO.

2. Method

The simplest type of vortex lens one could envisage, which exploits the properties of interacting crossing lattices, is one where the out-of-plane field (PV stack density) is kept constant while the in-plane field is swept up and down, compressing and expanding the JV lattice. If, for example, the JVs are gradually swept into the sample they drag the PV stacks with them towards the sample center. The sequence of scanning Hall probe microscope (SHPM) images shown in Fig. 1 illustrates this magnetic 'brush' effect rather graphically. In this case a BSCCO sample had been field-cooled to 81 K in $H_z \sim 1.7$ Oe ($H_{\parallel} = 0$). Across the five frames shown the in-plane field has then been slowly swept up to $H_{\parallel} = 55$ Oe, generating JV stacks which flowed across the sample. In doing so it is clear that they have gathered up a lot of PV stacks into 1D chains, and then moved these towards the center of the sample in the direction of the arrows shown.

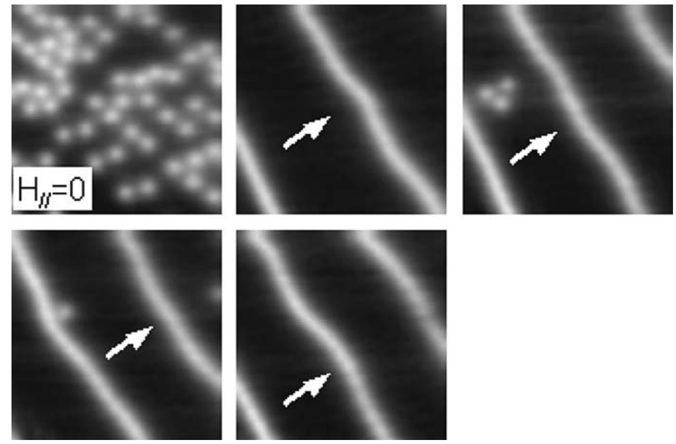

Fig. 1. Sequence of five consecutive scanning Hall probe images showing moving Josephson vortex stacks "sweeping up" weakly pinned pancake vortices as $H_{\parallel}$ is increased from 0 to 55 Oe (left to right and top to bottom) at 81 K ($B_z \sim 1.7$ G). Each image size $\sim 26 \times 26\ \mu m^2$.

In vortex pump experiments it is vital that the in-plane field be precisely aligned with the crystallographic *a–b* planes to avoid a parasitic out-of-plane component of the in-plane field, which would *directly* change the PV density. We have developed an accurate procedure to achieve this based around a pair of Helmholtz coils, one of which can be moved very precisely up and down on a micrometer-driven stage (see Fig. 2). Using the 'lock-in' transition at very small net out-of-plane fields as an alignment measure we are able to adjust $H_{\parallel}$ to within $\pm 0.005°$ of the *a–b* crystallographic planes. The PV stack density was monitored locally using a GaAs/AlGaAs heterostructure Hall sensor array fixed beneath the crystal (spatial resolution of each element $\sim 25 \times 25\ \mu m^2$). In practice only data for one centrally located element of the array are shown here.

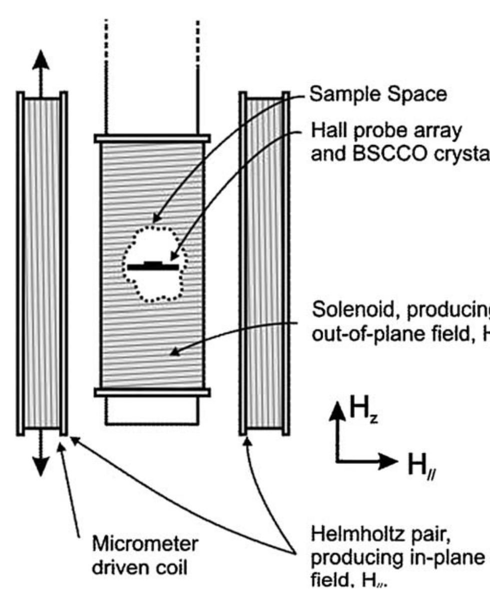

Fig. 2. Schematic diagram of the experimental apparatus used to align and apply in-plane and out-of-plane magnetic fields.

Two distinct types of experiment have been performed. To realise a vortex 'lens' the sample was field-cooled in the desired value of H_z ($H_{\|} = 0$) to the target temperature, and an in-plane field then slowly swept (1.7 Oe/s) up and down in the range $H_{\|} = \pm 150$ Oe while the Hall voltage (= PV density) was monitored at different points on the Hall array. To realise a vortex 'ratchet' the sample is again field-cooled at $H_{\|} = 0$, and then $H_{\|}$ slowly swept to a fixed 'offset' value. A train of sawtooth in-plane field pulses, with zero average value, is then superimposed on the fixed offset to induce vortex motion. The sawtooth was designed so that PVs were trapped on (and moved with) JV stacks during the low slope segments of the waveform, but became dragged off (decoupled from) JVs during the high slope segments. In this way a net forwards PV motion can be reversed simply by switching to a time-reversed waveform.

3. Results and discussion

3.1. Vortex lens

Fig. 3 shows the results of lensing experiments at 77 K in an out-of-plane field, $H_z = 10.7$ Oe. These, and data at other out-of-plane magnetic fields, all show a characteristic ''butterfly'' structure which reflects the interplay between the PV–JV attractive interaction and inter-vortex (PV–PV) repulsion. We understand our data in the following qualitative way. (i) When $H_{\|}$ is first applied the small number of JVs present pick up fairly mobile PV stacks and start to compress them. (ii) As $H_{\|}$ is increased further there are more JVs present, but the non-equilibrium PV density starts to generate a force which opposes any additional compression. Hence the PV density shows a saturation and JVs start cutting freely through PV stacks. (iii) Once the in-plane sweep direction is reversed this force now acts in the same direction as the JV force and a rapid decompression of the PV system takes place. At relatively large values of H_z this even causes the system to 'undershoot' and reduce the PV density below its starting value (negative lensing). (iv) The same set of events occurs again when $H_{\|}$ is increased with the opposite sign. The strongest lensing effect under these conditions ($T = 77$ K) is at $H_z \sim 5$ Oe, in reasonable agreement with predictions by Koshelev for the maximum PV pinning force (by JVs) [13], and corresponds to an efficiency of $\Delta B_z/B_z = 40\%$. Rather surprisingly the lensing amplitude measured in this way drops virtually to zero above $T = 84$ K, even though this is well below the critical temperature of the BSCCO crystal ($T_c \sim 91$ K) or the first order vortex melting transition ($H_m(84\text{ K}) \sim 30$ Oe), and the crossing lattices interaction strength is only very weakly temperature dependent [10]. We note that the lensing potential is only one-dimensional in our geometry, and conclude that a small amount of pinning must be crucial to achieving high lensing efficiencies as it prevents PV stacks drifting away out of the crystal parallel to the JV stacks. This suggests that the controlled introduction of disorder, e.g. by local irradiation with columnar defects (e.g. at the edges of the crystal parallel to the JV motion [8]), could be used to optimise device performance and experiments of this type are currently being performed.

3.2. Vortex ratchet

The application of a sawtooth in-plane waveform drives the PV system into a strongly non-equilibrium state, which relaxes very slowly to the equilibrium state. In order to ensure that each new measurement starts from the same configuration we have developed a protocol based on 'dithering' the pancake vortex system with a *symmetric* periodic $H_{\|}$ signal [14]. After experimenting with various waveforms we find that a symmetric (in-time) triangular wave having amplitude $H_{\|}^c = 32$ Oe and frequency 10 Hz (Fig. 4(a)) is most effective at 'conditioning' the PV system in our field and temperature regime. A typical measurement involves applying the conditioning waveform for 4 min, followed by a pump (Fig. 4(b)) or time-reversed anti-pump (Fig. 4(c)) sawtooth waveform for 4 min, after which the ratchet signal was switched off entirely. After a few cycles the pump(anti-pump) drive leads to a fairly steady increase(decrease) in the PV density of a few percent. Once the drive

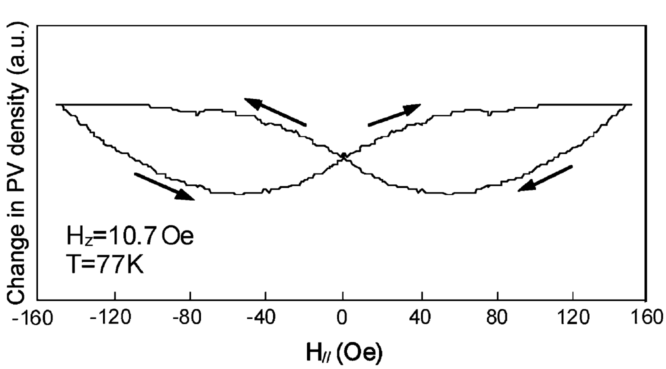

Fig. 3. Pancake vortex lensing data collected as the in-plane field was swept slowly between ±150 Oe at 77 K ($H_z = 10.7$ Oe). Arrows indicate the direction of sweep.

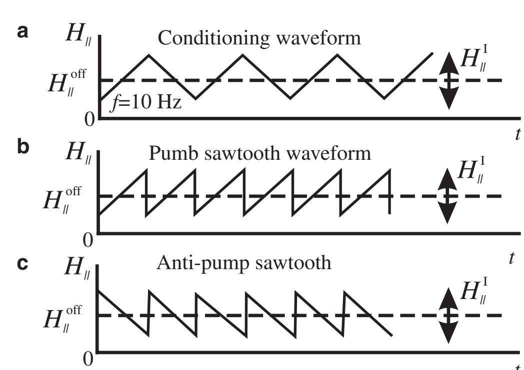

Fig. 4. Sketch of the in-plane field waveforms used in vortex ratchet experiments. (a) The conditioning triangular wave, (b) the sawtooth pump and (c) the time-reversed sawtooth anti-pump.

was switched off the non-equilibrium pumped state relaxed rapidly back towards the equilibrium (conditioned) state, although the presence of finite pinning prevents it from fully equilibrating on the timescale of our measurements.

The pumping amplitude measured in this way exhibited pronounced peaks as a function of frequency and H_z which can be qualitatively understood in the following way. At very low frequencies, the repetition rate is low, the PV system can follow the JV drive during both "slow" and "fast" changes of the sawtooth waveform, and the ratchet is ineffective. At very high frequencies the PV system is unable to follow the JV drive at all, even during relatively "slow" changes of the in-plane field $H_\parallel$. Optimal pumping occurs when the PVs adiabatically follow the slow changes of $H_\parallel$ but cannot follow the fast changes in $H_\parallel$. Likewise at very low values of H_z the mean PV density is low and a few strong pinning centers tend to dominate the PV–JV dynamics. At very large out-of-plane fields the system becomes dominated by intervortex (PV–PV) repulsion and the dragging effect. The ratchet efficiency peaks at fields in-between when there are many more PV stacks than strong pinning sites, but their density is not so high that PV–PV interactions become dominant.

3.3. Molecular dynamics simulations

The minimum model to simulate the observed lensing and ratchet effects describes the overdamped dynamics of JV and PV rows within a set of coupled equations of motion $\gamma\eta_J(dx_i^J/dt)/a^J = f_i^{JJ} + f_i^{JH} + f_i^{JP}$ and $\eta_P(dx_k^P/dt)/a^P = f_k^{PP} + f_k^{PH} + f_k^{PJ}$ where x_i^J and x_k^P are the positions of JV and PV rows with distances between JVs and PVs in a row a^J/γ and a^P, respectively. Here, γ is the anisotropy parameter, and the JV and PV viscosities are η_J and η_P. The viscous forces slowing down the vortex motion are balanced by: (1) the repulsive force f^{JJ} between vertical JV rows (including images of rows with respect to the sample surface); (2) the interaction f^{JH} of JV rows with Meissner currents generated by the externally applied time-dependent magnetic field $H_\parallel(t)$; (3) the repulsion f^{PP} between rows (including images) of PV stacks; (4) the interaction f^{PH} of PV rows with the c-axis magnetic field, H_z; and (5) the attractive forces f^{JP} and f^{PJ} between rows of JVs and PVs.

The simulations follow the experiments as closely as possible, and lensing measurements have been approximated by increasing $H_\parallel$ from zero to $H_\parallel^{max}$ and then decreasing back to zero over the same period of time. The simulation is then continued for negative fields. Fig. 5 shows a typical "butterfly" loop generated in this way far a relatively small equivalent value of H_z. Note that all the features of the experiments are well reproduced (c.f. Fig. 3). (The small reduction in PV density on the increasing branch of the loop at high in-plane fields is probably not clearly visible in the experimental data due to limits on the maximum possible in-plane field which could be applied.)

Molecular dynamics simulations of ratcheting were realised by slowly increasing $H_\parallel$ to $H_\parallel^{min}$ at which point $H_\parallel$ was cycled between $H_\parallel^{min}$ and $H_\parallel^{max}$ either; slowly increasing $H_\parallel$ up to H^{max} followed by a fast decrease (pumping), or a fast increase followed by a slow decrease (anti-pumping). Ratchet simulations also qualitatively match experiments, and the calculated amplitude also exhibits a strongly peaked dependence on the drive frequency and out-of-plane field.

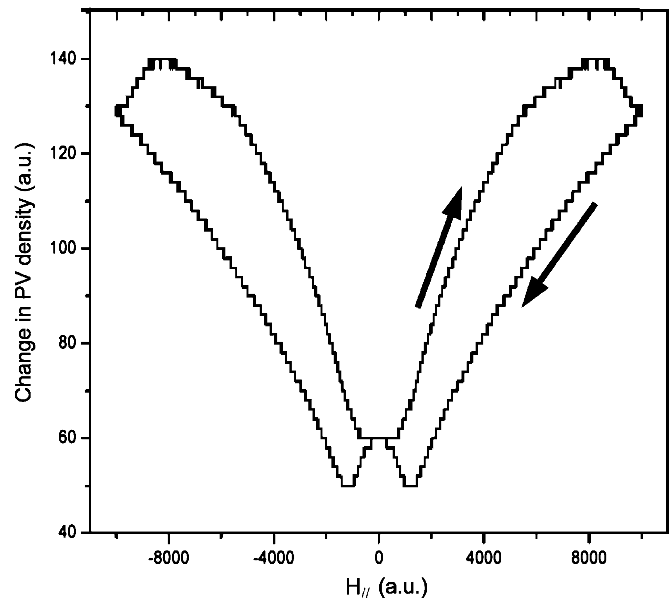

Fig. 5. Molecular dynamics simulation of vortex lensing for a relatively small equivalent value of H_z.

4. Conclusions

In conclusion we have realised simple pancake vortex lenses and ratchets in the crossing lattices regime of a BSCCO single crystal, whereby distortions of the JV lattice lead to the controlled compression/expansion of the coupled PV stack system. Lensing efficiencies as high as 40% have been measured under optimal conditions at low temperatures. Surprisingly, above 84 K we observe no appreciable lensing at all, and attribute this to the fact that significant PV pinning is required to prevent them from drifting in/out of the crystal parallel to JV stacks. A vortex ratchet has also been demonstrated by driving the JV system with a sawtooth in-plane waveform such that PVs were trapped on (and moved with) JV stacks during the low slope segments of the waveform, but became dragged off (decoupled from) JVs during the high slope segments. We have shown that the PV pump action can be reversed (anti-pump) simply by switching to a time-reversed waveform. Molecular dynamics simulations of our system qualitatively reproduce all the main features of our measurements, including the strongly peaked dependence of vortex ratchet amplitude on drive frequency and H_z.

Given that this type of vortex ratchet is contactless and requires no nanoscale sample preparation, vortex devices based on interacting crossing lattices could come to be of significant practical interest.

Acknowledgements

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