Progress in Superconductivity Vol.9 No.2 pp.140-145 30 April 2008

Josephson Vortex Dynamics in Tilted Magnetic Fields

Yong-Duk Jin, Dong-Keun Ki, Hu-Jong Lee

Department of Physics, Pohang University of Science and Technology, Pohang 790-784.

Received 02 April 2008

경사 자기장 하에서의 조셉슨 볼텍스 동역학

진용덕, 기동근, 이후종

Abstract

We report on the Josephson vortex dynamics in $Bi_2Sr_2CaCuO_{8+\delta}$ natural Josephson junctions by *c*-axis tunneling measurements. Beside the quasiparticle branches in the current-voltage characteristics, a new set of multiple branches, referred to as Josephson-vortex-flow branches (JVFBs), are observed. The JVFBs emerge in an in-plane magnetic field above $H_0 = \Phi_0/\gamma s^2$ and show highly hysteretic behavior, which can be explained in terms of the recently proposed dynamic-phase-separation model. In this work we examined the effect on the JVFBs by the presence of pancake vortices generated as the external magnetic field was applied slightly tilted from the in-plane direction. JVFBs were found to become larger and prominent with increasing pancake vortex density as the tilt angle increased, which were presumably caused by slowing down of a Josephson vortex lattice in the presence of pancake vortices.

Keywords : Josephson vortex dynamics, Dynamic phase separation, JVFB, Crossing lattice

I. Introduction

Rich features of the dynamics of Josephson vortices [1, 2], existing in a Josephson junction in a high magnetic field, are of high current interest. In particular, the interaction between Josephson vortices and the Josephson plasma oscillations [3, 4] in a system of vertically stacked natural Josephson junctions formed in high-T_c cuprate superconductors such as $Bi_2Sr_2CaCuO_{8+\delta}$ (Bi-2212) has attracted much research interest. Detailed studies on the static and dynamic states of Josephson vortices have been carried out extensively.

In the static state, Josephson vortices in a stack of Bi-2212 natural Josephson junctions appear as a triangular lattice in a magnetic field H that is stronger than $1.4\Phi_0/2\pi s\lambda_J$ [5]. The lattice formation occurs due to the repulsive interaction among Josephson vortices and the resulting high overlap of Josephson vortices in H above $\Phi_0/\gamma s^2$ [6], where Φ_0, s, λ_J, and γ are the flux quantum, the unit thickness of a natural Josephson junction, the Josephson penetration depth, and the anisotropy ratio, respectively. In the dynamic

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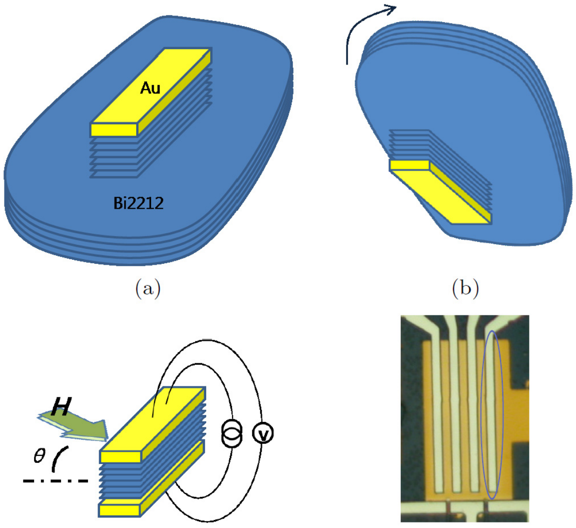
*Corresponding author. Fax : +82 54 279 5564
e-mail : hjlee@posteeh.ac.kr

state, however, the moving Josephson vortex lattice resonates with the plasma excitation modes in stacked junctions at a specific plasma mode frequency. The resonance of Josephson vortex motion with the plasma oscillation modes was studied both theoretically and experimentally [7 - 9], which confirmed the existence of the coherent Josephson vortex lattice motion and the structural transformation between different Josephson vortex configurations.

On the other hand, another Josephson-vortex dynamic behavior called as 'the dynamic phase separation' in the moving Josephson vortex configuration was theoretically proposed by Koshelev and Aranson [10]. In the scenario, two different Josephson-vortex-lattice phases move with different velocities and configurations, along with intermediate states generated as the two phases are diversely combined. While in-depth studies, both theoretical and experimental, were carried out for the resonance between the Josephson vortices and the discrete plasma modes the dynamic phase separation was suggested only theoretically without any experimental confirmation.

In a tilted magnetic field, Josephson and pancake vortices coexist and form a *crossing lattice* in a highly anisotropic superconductor such as Bi-2212 with the attractive interaction between the two different kinds of vortices [11, 12]. The effect of the presence of pancake vortices on the Josephson-vortex-lattice configuration is not well understood to date, although it is known that the pancake vortices slow down the Josephson vortex motion [13]. In this work, we study the Josephson vortex dynamics in stacked Bi-2212 natural Josephson junctions in various in-plane magnetic fields. We focus on the influence of the presence of pancake vortices on the motion of Josephson vortices by investigating the *c*-axis tunneling current voltage characteristics in various fields and at different tilt angles. We observed two separate branch structures in a high-enough in-plane magnetic field. The two different sets of branches are identified as quasiparticle branches (QBs) and Josephson-vortex-flow branches (JVFBs). By examining the dependence of JVFBs on the field strength and on the pancake vortex population, we verify that the JVFBs originate from the dynamic phase separation.



(a) (b)

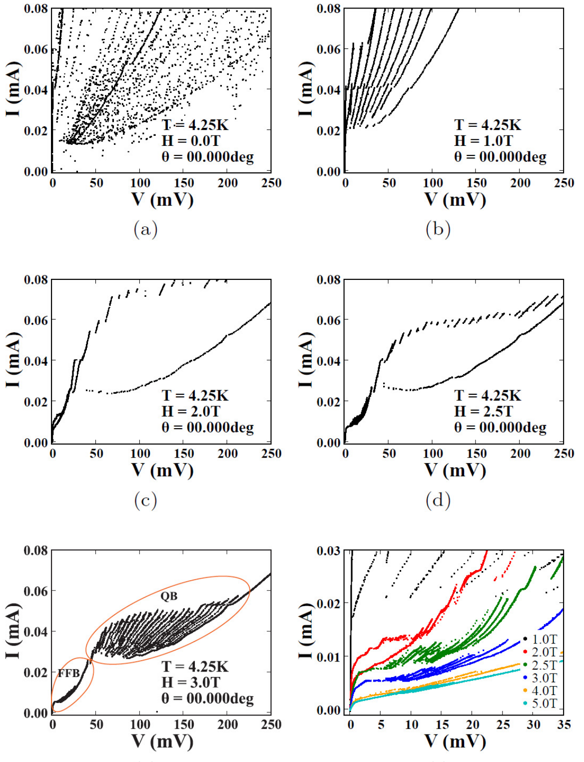
(c) (d)

Fig. 1. Sample fabrication processes using the 'double-side cleaving' technique. (a) A mesa structure fabricated on a Bi-2212 single crystal. (b) Removing the basal part after flipping the crystal and gluing down the mesa structure on a separate substrate. (c) A completed sample stack and the measurement scheme for a *c*-axis tunneling measurements in an external magnetic field at a tilt angle θ with respect to the *ab*-plane of a crystal. (d) The optical-microscopic image of a real sample, where the stack marked by a circle was used in this study.

II. Experiments

A Bi-2212 single crystal is prepared by the solid-state-reaction method. The stack with a finite number of junctions sandwiched between two gold layers without a basal part is fabricated using the so-called double-side cleaving technique developed by Wang *et al.* [14]. The technique eliminates the influence of Josephson vortices in a basal part on the Josephson vortex dynamics in the sample stack itself. The fabrication process is described in Figure 1. We first deposit a gold layer on a clean Bi-2212 single crystal right after cleaving and make a mesa structure using the electron-beam lithography and the ion-beam dry etching as in Figure 1(a). Then, we flip the single crystal and remove the basal part by successive cleaving [Fig. 1(b)], followed by depositing another gold layer. We complete the sample fabrication by using another process of electron-beam lithography and dry etching as in Figure 1(c). Figure 1(d) is the optical-microscopic image of a real sample. In this study, we use the stack marked by an oblique circle. The lateral size of the sample was 15×1.5 μm^2, which was in a long junction limit. The sample stack contained 26 natural Josephson junctions as determined by the number of quasiparticle branches in the observed tunneling current-voltage curves in zero field at the base temperature of 4.3 K.

Josephson-vortex-flow characteristics were obtained by taking the tunneling current-voltage curves in a two-probe configuration, with varying magnetic fields and the field-application angle θ with respect to the junction plane as illustrated in Figure 1(c). The field was aligned to the ab-plane of the single crystal within the accuracy of 0.02 degree by measuring angle dependent flux-flow resistance around 60 K. The tilt angle was varied within 0.3 degree from the in-plane aligned position so that the relative population of the pancake vortices must have been sufficiently low.



(a) (b)

(c) (d)

(e) (f)

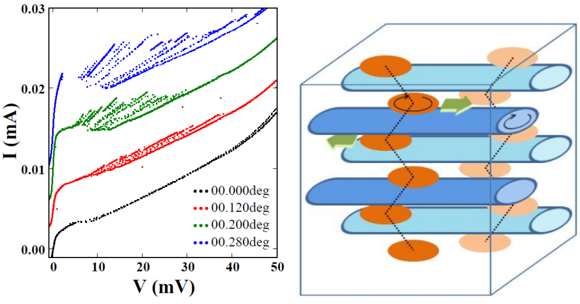
Fig. 2. Current-voltage characteristics in various in-plane magnetic fields. (a) and (b) Quasiparticle branches are seen to be reduced with increasing the field strength. (c) In a field above H0, a new structure emerges below 20 μA. (d) In 2.5 T, the new structure develops into a multiple branch structure. (e) Two different sets of multiple branches are observed; the quasiparticle branches (QBs) in a high-bias region and the Josephson vortex flow branches (JVFBs) in a low-bias region. (f) Evolution of the JVFBs in various in-plane fields. The maximum number of JVFBs observed in this study is about 16, which is comparable to the total number of junctions 26 in the sample stack.

III. Results and Discussion

In the measurements, we first varied the field strength for the best-aligned field angle ($\theta = 0.000$) at the base temperature of T=4.3 K. The resultant current-voltage characteristics are exhibited in Figure 2(a). In zero field, we get the usual multiple quasiparticle branches with the number same as the total number of junctions in the sample stack [15]. With increasing the in-plane magnetic field, the quasiparticle branches are suppressed as the critical current decreases [refer to Figs. 2(b), (c), and (d)]. Note that in Figs. 2(c) and (d) only the outline of the quasiparticle branches are taken in fields of 2 and 2.5 T while sweeping the bias up and down only once. In 2 T, we observe that a new structure starts to appear below 20 μA, which develops into a clearer branch structure at 2.5 T. This field range is comparable to $H_0 = \Phi_0/\gamma s^2$ (~1.8 T for Bi-2212) [6], at which Josephson vortices strongly overlap. This indicates that the new branch structure originates from the motion of collectively moving Josephson vortex lattice. Thus, the branches are referred to as the Josephson-vortex-flow branches (JVFBs). In Fig. 2(f), the variation of JVFBs is illustrated in various magnetic fields. JVFBs emerge in planar fields above H_0 and evolve into a clear multiple-branch structure for a field up to 2.5 T. The branches, however, get suppressed gradually for further higher fields. The number of branches in 2.5 T, where the JVFBs develop most clearly, is about 16, which are comparable to the total number of junctions in the sample stack, 26. Like quasiparticle branches, JVFBs also show a highly hysteretic behavior for both current and voltage biases.

Although the resonance of collective motion of Josephson vortices with discrete plasma modes formed in a finite number of inductively coupled Josephson junctions is predicted to cause JVFBs with the branch number the same as the total number of junctions in a sample stack [7], the resonance should occur at only specific voltages as the Josephson-vortex-flow velocity matches with the plasma-mode-propagation velocity. In this case, the hysteresis in the voltage bias cannot take place, indicating that the JVFBs shown in Fig. 2 cannot be explained by the resonance of Josephson vortices with the discrete plasma excitation modes.

The dynamic-phase-separation model proposed by Koshelev and Aranson [10] brings about multiple JVFBs also and it agrees with our observed results: the number of branches, the hysteretic behavior and the suppression of the hysteresis in high-enough magnetic fields. The model predicts that, in coupled Josephson junctions with a symmetric boundary condition along the *c* axis, the stability of a moving Josephson vortex lattice is determined by κ and ω_E. κ is the phase shift between adjacent layers, which determines the Josephson vortex lattice structure and ω_E is the Josephson frequency, which determines velocity of the lattice. A Josephson vortex lattice has two stable regions referred to as the slow and fast phases, separated by unstable regions in the ω_E-κ plane (see Fig. 1 in Ref. 10). As the Josephson vortex lattice is driven by a tunneling bias current, it evolves gradually in the slow phase until it jumps to the fast phase across the neighboring unstable region and evolves gradually in the fast phase again. In a current-voltage curve, this behavior appears as two separate stable branches that correspond to the slow and the fast phases. The two branches can coexist in a finite range of currents referred to as a *bistable region*, where the upper limit of the bistable region corresponds to the current required for the Josephson vortex lattice in the slow phase to reach the boundary of the unstable region. This bistable region diminishes as increasing the field strength (see Fig. 2 of Ref. 10). In addition to the slow and fast phases, there also exists an intermediate state referred to as the phase-separated state in the bistable region, in which a part of the junction is in the fast phase while the other part remains in the slow phase. The total number of cases of separating the entire stack into two different parts is N - 1, where N is the total number of the junctions. The phase separation results in multiple JVFBs in the current-voltage characteristics, where each JVFB corresponds to a different configuration of the two phases.



(a) (b)

Fig. 3. Current-Voltage characteristics at various tilt angles. (a) Josephson-vortex-flow branches (JVFBs) are totally suppressed in the best-aligned field of 4 T. JVFBs become larger and prominent with increasing pancake vortex density by detuning the field angle. Each data set is shifted in the vertical direction for the sake of clarity. (b) Pancake vortices are deformed to a zigzag shape as a current surrounding Josephson vortices in the crossing lattice is established in a slightly detuned magnetic field.

The hysteretic behavior of JVFBs in a current bias is natural, because the JVFBs exist in the bistable region. In addition, since a Josephson vortex lattice in the slow or the fast phase exists over a broad range of voltage, different JVFBs can have the same voltage as long as the condition $n_1\omega_{f1} + (N - n_1)\omega_{s1} = n_2\omega_{f2} + (N - n_2)\omega_{s2}$ is satisfied, where n_i is the number of junctions in the fast phase, ω_{fi} and ω_{si} are the Josephson frequency of a junction in the fast and slow phases, respectively. This explains the hysteretic behavior of JVFBs in a voltage bias. The reduction in the bistable region in a higher magnetic field causes the suppression of the JVFBs, which is again consistent with our observation in this study.

To examine the effect of pancake vortices on the dynamics of JVFBs, we varied the field strength along the *c*-axis direction by detuning the field angle within 0.3 degree at fixed field strength of 4 T at temperature 4.3 K. Results are exhibited in Figure 3(a). Contrary to our general belief, JVFBs disappear for the best-aligned angle but they get larger and prominent as more pancake vortices are introduced on the Cu-O planes by a more-detuned field angle. As illustrated in Figure 3(b), in the presence of Josephson vortex lattice, pancake vortices are deformed in a zigzag shape due to a current flowing around Josephson vortices. The deformed pancake vortices oscillate in an ab-plane along with the motion of Josephson vortices, which slows down the motion of a Josephson vortex lattice [13]. As a result, a higher current is required for the Josephson vortex lattice in the slow phase to reach the boundary of the unstable region, which enlarges the bistable region along with the expansion of the JVFBs, as observed in this study.

IV. Conclusion

We observe a multiple Josephson-vortex flow branches in an in-plane magnetic field above H_0. The behavior of the branches agrees with the prediction of the recently proposed dynamic-phase-separation model. Interpretation of the Josephson vortex motion in terms of the gradual evolution and the jump between two stable flow regions of a Josephson vortex lattice in our sample is more consistent than the picture in terms of the resonance between the Josephson vortices and discrete plasma excitation modes with the corresponding Josephson vortex lattice transformation. The appearance of pancake vortices on the Cu-O planes by an off-plane component of a slightly tilted magnetic field exerts an attractive pinning force on the crossing Josephson vortex lattice. Thus, increasing the pancake vortex population in a larger tilt angle, the Josephson vortex flow branches become longer and more prominent because of slowing down of the motion of Josephson vortex lattices, which are caused by the zigzag oscillation of pancake vortices.

Acknowledgments

We thank M. Machida for helpful discussion. This work was supported by a Pure Basic Research Grant R01-2006-000-11248-0 administered by KOSEF, by a Korea Research Foundation Grant KRF-2005-070-C00055, and by the POSTECH Core Research Program.

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