J Supercond Nov Magn (2010) 23: 1071–1074
DOI 10.1007/s10948-010-0739-3

ORIGINAL PAPER

Non-collective Josephson-Vortex Motion Induced by Pancake-Vortex Pinning in Stacked Josephson Junctions

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Received: 8 January 2010 / Accepted: 11 January 2010 / Published online: 29 January 2010

Abstract We experimentally studied the dynamic-state characteristics of Josephson vortices (JVs) and influence of pancake vortices (PVs) on the JV dynamics in a stack of inductively coupled $Bi_2Sr_2CaCuO_{8+\delta}$ intrinsic Josephson junctions. In a few-tesla magnetic field range, we observed Josephson-vortex-flow branches (JVFBs) in the current–voltage characteristics. We show that the JVFBs are generated by the non-collective pinning (depinning) of Josephson vortices in individual junctions by (from) pancake vortices. Results of our study suggest a convenient means of controlling JVs for quantum-electronics applications utilizing stacked Josephson junctions.

Keywords Josephson vortex motion · Interaction between Josephson and pancake vortices · Intrinsic Josephson junctions · Bi-2212 cuprates

A stack of intrinsic Josephson junctions (IJJs) formed in cuprate superconductors such as $Bi_2Sr_2CaCuO_{8+\delta}$ (Bi-2212) provides a coupled non-linear system, which is described by the coupled sine-Gordon differential equations [1]. The soliton states of the system, called Josephson vortices (JVs) in an in-plane magnetic field, and their dynamic characteristics have attracted much research attention. Theoretical studies on the structure of a Josephson vortex (JV) in a stack of IJJs [2] show that the screening supercurrent around the JV in a junction spreads over many junctions because the superconducting CuO_2 layer is far thinner than the London penetration depth λ. Inductive coupling across junctions via this supercurrent generates diverse JV dynamic characteristics. The interaction of JVs with collective plasma excitation modes [3] is such an example. JVs are also known to coexist with pancake vortices (PVs) in a highly anisotropic superconductor such as Bi-2212 and the influence of PVs on JV dynamics has been the focus of studies [4–7]. In this study, we investigated the JV dynamics in detail in stacked IJJs, focusing on the influence of PVs on the JV dynamics.

We fabricated a Bi-2212 stack with a finite number of IJJs without a basal part to exclude the interference of JVs confined in the basal part with the dynamics of JVs in the stack under investigation. The *c*-axis-tunneling current–voltage characteristics (IVC) were measured in various magnetic fields and field tilt angles θ from the ab-plane direction. IVC contain information on JV dynamics as moving JVs induce a voltage difference across a junction, proportional to their flow velocity (or the time rate of variation of the interjunction phase difference ϕ) according to the ac Josephson relation, $\frac{d\phi}{dt} = \frac{2eV}{\hbar}$. In an external magnetic field of a few-tesla range, along with the remnant quasiparticle-tunneling branches (QTBs), we observed additional Josephson-vortex-flow branches (JVFBs) in a low-bias current/voltage region. In our study, JVFBs revealed themselves below the voltage bias of 0.6 mV/junction/tesla and extends into a higher bias current region as more pancake vortices are introduced by tilting the field angle θ close to 0.5°. The maximum voltage and θ dependence of JVFBs lead us to the conclusion that JVFBs are caused by the non-collective pinning and depinning of JVs at individual junctions. The JV pinning disappeared at temperatures above ∼30 K.

A slightly overdoped Bi-2212 single crystal was fabricated into a stack with a finite number of junctions sandwiched between two gold layers by using the double-side cleaving technique [8] along with the usual electron-beam

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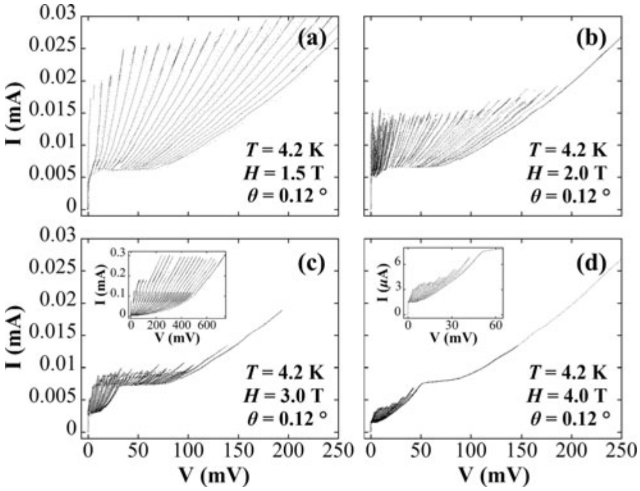

Fig. 1 JVFBs and QBs in various magnetic fields at $\theta = 0.12°$. (**a**) QBs shrink with suppression of critical current of junctions as increasing in-plane magnetic field strength. (**b**), (**c**) Beside the suppressed QBs, a new branch structure, so called JVFBs, below ∼20 mV (∼30 mV) appears in 2 T (3 T). (**d**) On increasing an external magnetic field up to 4 T, JVFBs are completely separated with the QBs. *Inset* of (**c**): Multiple QBs are observed in IVC without an external magnetic field. *Inset* of (**d**): Magnified JVFBs acquired in 4 T. Clear multiple branches are observed

lithography and subsequent Ar ion etching. The lateral size of the sample was designed to be $10 \times 1.5\ \mu\text{m}^2$. Tunneling measurements were made along the c-axis of the sample in various magnetic fields and field tilt angle θ where the tilt angle was controlled by using a stepper motor placed at room temperature, with the resolution of ∼0.002°. The best-aligned planar direction was adjusted by obtaining the maximal flux-flow voltage [9] within an accuracy of 0.05°. As in the inset of Fig. 1(c), multiple QTBs were obtained at 4.2 K without an external magnetic field. The number of junction N (=22) was determined from the number of the QTBs. We also observed an unusual side branch per each QTB, which arose from a junction with an unusually high retrapping current and a small critical current. However, this single peculiar junction (most possibly a surface junction) does not affect the bulk properties of the JV dynamics.

Figure 1 shows the gradual variation of IVC in various external in-plane magnetic fields from 0 T up to 4 T for $\theta = 0.12°$. With increasing magnetic field strength (Fig. 1(a)), the quasiparticle branches shrink along with the suppression of the critical current [10, 11]. When the field strength is increased above 2 T (Fig. 1(c), (d)), along with the original QTBs, a number of new branches appear on the low-bias part of the IVC. Increasing the field strength even further up to 4 T (Fig. 1(d)), the new branches are completely separated from the original QTBs. The number of new branches is 20, which is comparable to the number of junctions N. The development of the separated new branch structure in a planar magnetic field was observed previously by Bae et al. [12] and identified as JVFBs as they appeared only in the presence of JVs in a few-tesla-range in-plane magnetic field. The maximum flux-flow voltage per junction is about ∼0.6 mV/junction/tesla, which corresponds to the flux-flow velocity of $\sim 4 \times 10^5$ m/s. The value is an order of Swihart velocity $\bar{c} = \mu_0 d' C$, where d' is the effective magnetic thickness of a junction and C is the unit-area capacitance per junction [13, 14]. The maximum flux-flow velocity close to $\bar{c}$ suggests that the Josephson vortex structure is triangular [15, 16].

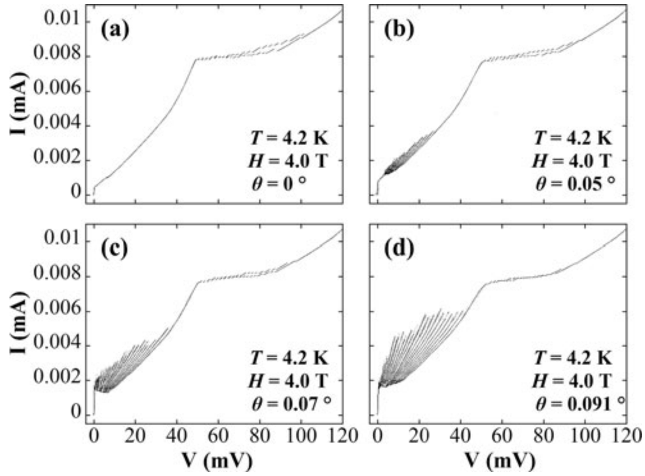

Fig. 2 The θ dependent JVFBs behavior. At $\theta = 0°$, the JVFBs are hardly visible and they appear to extend into higher bias current region on introducing more PVs by tilting the field angle

We now tilt the field angle θ in a fixed magnetic field of 4 T to examine the effect of pancake vortices on the Josephson vortex dynamics and JVFBs. As in Fig. 2, JVFBs which are hardly visible at $\theta \simeq 0°$ become evident as the tilt angle θ slightly increases below 1° and extends into a higher current region as more pancake vortices are introduced by increasing θ.

The JVFBs can be generated by one of the following mechanisms. (1) Resonance between a moving JV lattice and the plasma excitation modes. (2) Dynamic phase separation. (3) Non-collective pinning and depinning process of JVs in individual junctions. It has been theoretically proposed that a moving JV lattice in stacked IJJs can be coupled with the Josephson plasma modes. This is supposed to lead to the enhancement of current in IVC when the velocity of moving JVs are in resonance with a plasma mode frequency. Multiple subbranch splitting observed previously in tesla-range magnetic fields was attributed to this resonance phenomenon [12]. However, according to this resonance picture, the JVFBs are expected to shrink at a higher tilt angle, which is in contradiction with the observed θ dependence of JVFBs in this study.

The JVFBs can also be caused by the dynamic phase separation, where JV lattices in different flow-velocity phases coexist in different part of junctions [17]. JVs in a slow

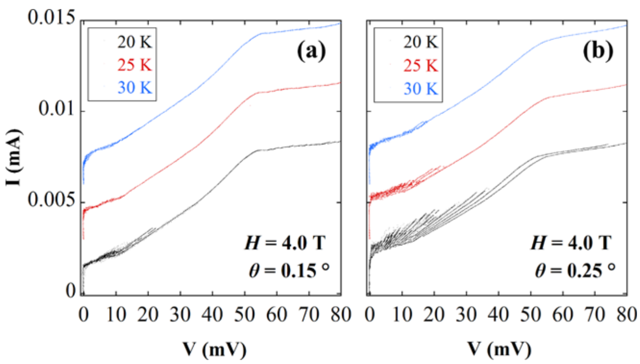

Fig. 3 JVFBs are suppressed as raising temperature and disappear above 30 K at all the field angle

phase at a low-bias current jump into a fast phase at a certain velocity with increasing the bias current. With the total $N + 1$ number of cases dividing the whole stack into two different phases in N junctions, the formation of $N + 1$ JVFBs is possible. Dynamic phase separation qualitatively fits the θ dependence because JVs slow down as more pancake vortices are introduced [7]. This leads to the transition from a slow phase into a fast phase in a higher bias current, which extends the JVFBs bias region for a more tilted field angle. However, the JV lattice structure in a fast phase is oblique and becomes closer to a rectangular structure at a higher velocity, which is in contradiction with the feature that supports the triangular JV lattice as described above.

If the JVFBs result from a non-collective pinning and depinning process of JVs in individual junctions, the field strength and θ dependence of JVFBs can be consistently explained. As the initially pinned JVs at each layer are depinned and start to move in a large-enough bias current, jumping between adjacent JVFBs takes place and the number of JVFBs becomes the same as the total number of junctions. As PVs are introduced by tilting the field angle, they are easily pinned by crystal defects such as the oxygen vacancy and exert additional pinning force on JVs with attractive interaction between them [7, 18]. As a result, a higher bias current is required for JVs to overcome pinning force and JVFBs are extended into a higher bias current region. The JV lattice, in its dynamic state, is supposed to be triangular as in the case of the static JV state, if there is no other effects such as the resonance between a moving JV lattice and Josephson plasma excitations.

We also examined the temperature dependence of JVFBs by controlling the temperature with a PID controlled heater placed at the sample holder. Figures 3(a) and 3(b) shows the IVC obtained at various temperatures up to 30 K in a magnetic field of 4 T at $\theta = 0.15°$ and $0.25°$, respectively. The JVFBs are suppressed with increasing temperature and disappear above ∼30 K at all the field angles. JVFBs above 30 K disappear as all the JVs are depinned from the pinning potential by the thermal activation.

In summary, we observed JVFBs at a low-bias current/voltage region in the IVC obtained in a c-axis-tunneling measurement on a Bi-2212 stack in a field of tesla range. The observed maximum flux-flow voltage of ∼0.6 mV/junction/tesla, which turns out to be comparable to the Swihart velocity $\bar{c}$, suggests that the JVs in the dynamic state form a triangular lattice structure. The JVFBs were extended into a higher bias current region with increasing the population of PVs by tilting the field angle. This is caused by the increase of the depinning current as the density of PV pinning centers increases rapidly along with the slight increase of the field tilt angle. The tilt-angle dependent JVFBs behavior leads us to the conclusion that JVFBs originate from the sequential non-collective pinning and depinning process of JVs in individual junctions with increasing the bias current. We also illustrate that, for the temperature above ∼30 K, all the JVs become thermally depinned for the field angles investigated along with the disappearance of the multiple JVFBs. This study clarifies the Josephson vortex-flow characteristics, which is essential for designing the Josephson-vortex-induced devices like THz-range electromagnetic-wave generators. At the same time, the high controllability of the JVs motion by the PVs suggests a means of utilizing JVs motion for the future quantum electronics such as qubit applications, based on the high-critical-temperature superconductors.

Acknowledgements This work was supported by Acceleration Research Grant (No. R17-2008-007-01001-0) administered by Korea Science and Engineering Foundation.

References

1. Sakai, S., Bodin, P., Pedersen, N.F.: J. Appl. Phys. **73**, 2411 (1993)
2. Clem, J.R., Coffey, M.W.: Phys. Rev. B **42**, 6209 (1990)
3. Kleiner, R., Müller, P., Kohlstedt, H., Pedersen, N.F., Sakai, S.: Phys. Rev. B **50**, 3942 (1994)
4. Grigorenko, A., Bending, S., Tamegai, T., Ooi, S., Henini, M.: Nature **414**, 728 (2001)
5. Bulaevskii, L.N., Ledvij, M., Kogan, V.G.: Phys. Rev. B **46**, 366 (1992)
6. Koshelev, A.E.: Phys. Rev. Lett. **83**, 187 (1999)
7. Koshelev, A.E., Latyshev, Y.I., Konczykowski, M.: Phys. Rev. B **74**, 104509 (2006)
8. Wang, H.B., Wu, P.H., Yamashita, T.: Appl. Phys. Lett. **78**, 4010 (2001)
9. Hechtfischer, G., Kleiner, R., Ustinov, A.V., Müller, P.: Phys. Rev. Lett. **79**, 1365 (1997)
10. Latyshev, Y.I., Pavlenko, V.N., Kim, S.-J., Yamashita, T.: Physica C **362**, 251 (2001)
11. Irie, A., Heim, S., Schromm, S., Mößle, M., Nachtrab, T., Gódo, M., Kleiner, R., Müller, P., Oya, G.: Phys. Rev. B **62**, 6681 (2000)
12. Bae, M.-H., Choi, J.-H., Lee, H.-J.: Phys. Rev. B **75**, 214502 (2007)

13. Swihart, J.C.: J. Appl. Phys. **32**, 461 (1961)
14. Sakai, S., Ustinov, A.V., Kohlstedt, H., Petraglia, A., Pedersen, N.F.: Phys. Rev. B **50**, 12905 (1994)
15. Artemenko, S.N., Remizov, S.V.: Phys. Rev. B **67**, 144516 (2003)
16. Hechtscher, G., Kleiner, R., Schleng, K., Walkenhorst, W., Müller, P.: Phys. Rev. B **55**, 14638 (1997)
17. Koshelev, A.E., Aranson, I.S.: Phys. Rev. Lett. **85**, 3938 (2000)
18. Bulaevskii, L.N., Maley, M., Safar, H., Domínguez, D.: Phys. Rev. B **53**, 6634 (1996)