Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Physica C 426–431 (2005) 61–64
PHYSICA C
www.elsevier.com/locate/physc

Observation of Josephson-vortex-flow submodes in $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions

Myung-Ho Bae, Hu-Jong Lee *

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

Received 23 November 2004; accepted 22 February 2005
Available online 1 July 2005

Abstract

Stacked intrinsic Josephson junctions form in highly anisotropic high-T_c superconductors such as $Bi_2Sr_2CaCu_2O_{8+x}$. Josephson-vortex dynamics in such systems attracts much research interests, both academic and application points of view. In a dense Josephson-vortex state (in the range of 4–5 T external magnetic field applied in parallel with the junction planes) of $Bi_2Sr_2CaCu_2O_{8+x}$ stacked intrinsic Josephson junctions vortex-flow motion is in resonance with the collective plasma oscillation modes. With increasing magnetic fields beyond ~2 T hysteretic quasiparticle branches keep shrinking, while the collective Josephson-vortex-flow branches start appearing and become clearer. The Josephson-vortex-flow branches split into multiple sub-branches corresponding to the number of coupled junctions in the stack. The low-bias characteristics of the Josephson-vortex-flow sub-branches fit well to the inductive-capacitive hybrid coupling model.

PACS: 74.72.Hs; 74.50.+r; 74.78.Fk; 85.25.Cp

Keywords: Josephson-vortex-flow branches; Collective resonance modes; Intrinsic Josephson junctions

1. Introduction

The propagation of the transverse electromagnetic wave and Josephson vortices in a single long Josephson junction can be described by a nonlinear sine-Gordon differential equation. For intrinsic Josephson junctions (IJJs) in $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) the thickness of the superconducting Cu–O double layers is thinner than the *c*-axis London penetration depth and is comparable to the Debye charge screening length. Thus, the nonlinear equation in a junction of serially stacked IJJs

* Corresponding author. Tel.: +82 54 279 2072; fax: +82 54 279 5564.
E-mail address: hjlee@postech.ac.kr (H.-J. Lee).

0921-4534/$ - see front matter
doi:10.1016/j.physc.2005.02.036

is coupled both inductively and capacitively to the equations in neighboring junctions, to form coupled sine-Gordon differential equations. The phase difference in each junction of a stack is then coupled inductively to neighboring junctions by the following relation:

$$-\frac{\hbar}{2e}\frac{\partial}{\partial x}\phi_n = d_n B_n + s_n B_{n+1} + s_{n-1}B_{n-1}, \quad (1)$$

where ϕ_n is the gauge-invariant phase difference across the junction, d_n and s_n are the effective thickness of the tunneling barrier and the inductive coupling parameter, respectively, and B_n is the magnetic field present in nth junction [1]. In addition, the capacitive coupling in Bi-2212 single crystals modifies the AC Josephson relation as

$$\frac{\hbar}{2e}\frac{\partial}{\partial t}\phi_n = V_n - \alpha(V_{n+1} - 2V_n + V_{n-1}), \quad (2)$$

where V_n is the voltage difference across the nth intrinsic Josephson junction and α is the capacitive coupling constant [2] defined as $\alpha = \varepsilon r_d/td$ (ε is the dielectric constant of the insulating layer, r_d the Debye charge screening length, t and d are the thickness of the insulating and superconducting layers, respectively).

The coupled sine-Gordon differential equations by the two coupling mechanisms generate separate branches in the current–voltage characteristics (IVC) due to the resonance between the moving Josephson-vortex lattice and the collective plasma modes. The interlayer capacitive coupling [3,4] gives different vortex-flow resistance for different plasma resonant modes, which in turn generates the multiple Josephson-vortex-flow branches. The extent of the spread in slopes of the sub-branches is proportional to the strength of the capacitive coupling. In this study, we observed the development of the multiple Josephson-vortex-flow branches (JVFB) in stacked IJJs in high external magnetic fields in the range of 2–5 T. The behavior of the low-bias sub-branches is in good agreement with the prediction of the combined model of the inductive and the capacitive coupling [3]. The capacitive coupling constant α obtained from the spread of the multiple-branches is about 0.45, which is reasonably close to the theoretical prediction [3], $0.1 < \alpha < 0.4$.

2. Experimental

As-grown slightly overdoped Bi-2212 single crystals were prepared by the conventional solid-state-reaction method. Stacks of IJJs were sandwiched between two Au electrodes deposited on the top and the bottom of the stacks using the double-side cleaving technique. Details of the sample fabrication are described elsewhere [5]. Transport measurements were performed in a two-terminal configuration with a low-pass filter connected to each electrode located at room temperature to avoid the external noise. The magnetic field alignment in parallel with the ab-plane of a stack was done in a field of 4 T at temperature of 60 K with the alignment resolution of 0.01° [6].

3. Results and discussion

The inset of Fig. 1 shows the zero-field IVC of a Au-sandwiched stack of size $1.4 \times 15\ \mu m^2$ at $T = 4.2$ K. The total number of junctions was 22 as evidenced by the total number of the quasiparticle branches. The average critical current density was about 1 kA/cm^2, from which the value of the Josephson penetration depth λ_J, 0.3 μm, was calculated. In terms of the Josephson penetration depth we define a characteristic field H_d [$=\Phi_0/2\lambda_J(t+d)$],

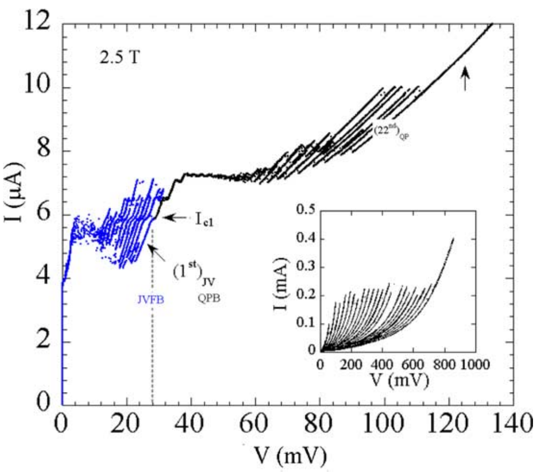

Fig. 1. Current–voltage characteristics (IVC) in the field of 2.5 T. The contact resistance was subtracted numerically. The inset: the zero-field IVC.

which is 2.3 T for the current sample. For the field value of H_d the spacing between two Josephson vortices becomes comparable to the diameter of a Josephson-vortex, $2\lambda_J$. Here, Φ_0 is the magnetic flux quantum. The values of t and d are 1.2 nm and 0.3 nm, respectively.

In a field of 2.5 T in Fig. 1 one sees the separation between the regions below and above 28 mV (denoted by the dotted line). All the quasiparticle branches are positioned in the bias range above I_{c1} in Fig. 1, which contains 22 branches, the same as the total number of quasiparticle branches in zero field. This indicates that the observed multiple branches below 28 mV are not related to the quasiparticle branches. Since they develop only in a high magnetic field they should be the Josephson-vortex-flow branches (JVFB) [4]. The number of clearly countable multiple branches starting from $(1st)_{JV}$ in the region of JVFB below 28 mV is 13. In the low bias region of JVFB, one cannot trace the other sub-branches because of the random voltage jumping.

Fig. 2(a) shows the IVC in fields of 2.8 and 4.5 T. Contrary to the complete disappearance of the quasiparticle branches at 4.5 T the sub-branches of the JVFB become more distinct with an increase in the interval between the neighboring branches. As shown in Fig. 2(b) all the sub-branches in the Josephson-vortex-flow region exhibit the linearity with different slopes with each other in the low bias range, which converge to a single point on the current axis. According to the inductive–capacitive hybrid coupling model they should converge to the origin. Thus converging to the finite bias current value should have arisen from the depinning of Josephson vortices. The pinning of Josephson vortices may have been caused by any defects in the stacked junctions or by the presence of the pancake vortices generated by any slight field misalignment. According to the inductive–capacitive hybrid coupling model [3], the spread in the slope is directly related to the strength of the capacitive coupling represented by the capacitive coupling parameter α as

$$V_n = \left(\frac{I - I_p}{I_c}\right)\frac{V_c}{1 + 2\alpha[1 - \cos(n\pi/21)]},\quad n = 1, 2, \ldots, 20 \qquad (3)$$

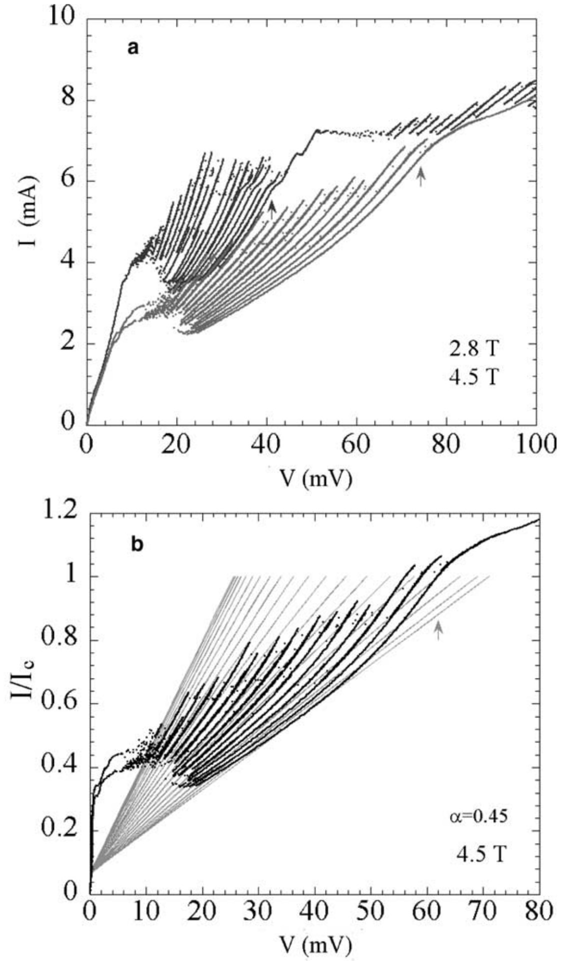

Fig. 2. (a) The current–voltage characteristics (IVC) in 2.8 T and 4.5 T. (b) The IVC in 4.5 T, where the current axis is normalized by the critical current for 4.5 T. The contact resistance was subtracted numerically. The straight lines are the best fit to the inductive–capacitive hybrid coupling model.

for a stack of 22 junctions, where I_p is the depinning current of the Josephson-vortex, I_c is the tunneling critical Josephson current at a given applied field. Here V_c is the maximum mode voltage corresponding to a given bias current as represented by the curve denoted with the arrows in Fig. 2(b). The straight extrapolation illustrates the best fit to the sub-branches in the low-bias region. The best-fit value of α turns out to be 0.45, which is reasonably close to the theoretical expectation [3] of $0.1 < \alpha < 0.4$.

4. Conclusion

Josephson-vortex dynamics in Bi-2212 IJJs is studied with increasing magnetic fields using a stack of IJJs sandwiched between two Au electrodes. Splitting of the JVFB and the convergence of the linear low-bias region of the branches to a single point on the current axis fits well to the theoretical expectation based on the inductive–capacitive hybrid coupling model. The best-fit value of the capacitive coupling constant is 0.45, which is in the reasonable range of theoretical expectation. This study indicates that incorporation of the interlayer capacitive coupling with the inductive coupling is required to properly describe the Josephson-vortex-flow characteristics in serially stacked and multiply coupled Josephson junctions.

Acknowledgments

This work was supported by the National Research Laboratory (NRL) Program administered by KISTEP and by the Asian Office of Aerospace Research (AOARD) of the US Air Force.

References

[1] S. Sakai, P. Bodin, N.F. Sakai, J. Appl. Phys. 73 (1993) 2411.
[2] M. Machida, T. Koyama, Phys. Rev. B 70 (2004) 024523.
[3] Ju H. Kim, J. Pokharel, Physica C 384 (2003) 425.
[4] M.-H. Bae, H.-J. Lee, Phys. Rev. B 70 (2004) 52506.
[5] M.-H. Bae, H.-J. Lee, J. Kim, K.-T. Kim, Appl. Phys. Lett. 83 (2003) 2187.
[6] G. Hechtfischer, R. Kleiner, A.V. Ustinov, P. Muller, Phys. Rev. Lett. 79 (1997) 1365.