Progress in superconductivity Vol.1, No.2 pp 110-114 29 February 2000

$Bi_2Sr_2CaCu_2O_{8+\delta}$ Intrinsic Josephson Junctions in a Parallel Magnetic Field

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Received 30 November 1999

Abstract

We have investigated the Josephson vortex dynamics in $Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junctions subjected to a magnetic field parallel to CuO_2 planes. We investigated mesas with 40×40 μm^2 in size and containing 6 and 20 intrinsic junctions. The zero field I-V characteristics exhibited a typical hysteretic, multi-branched nature of the intrinsic Josephson effect. At high magnetic fields ($H > 1.5$ T), I-V characteristics showed flux flow steps. The Swihart velocity obtained from this observation was about 4.2×10^5 m/s, which was the lowest mode electromagnetic wave velocity of N coupled stack. The experimental I-V curves fitted well into the simple model of Cherenkov radiation including Ohmic and non-linear dissipation terms. This suggests that the dissipation mechanism of Josephson vortex be due to both Cherenkov radiation and quasiparticle tunneling current.

Keywords : $Bi_2Sr_2CaCu_2O_8$, intrinsic Josephson junction, Josephson vortex, flux flow step

I. Introduction

In the layered high-T_c superconductor (HTSC) such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO), the coherence length in c axis direction is much shorter than the interlayer spacing between the superconducting CuO_2 planes. Therefore, a highly anisotropic HTSC compound can be considered as a stack of intrinsic Josephson junctions (IJJs) [1,2], where superconducting CuO_2 planes of thickness 3 Å are coupled by the insulating layers of thickness 12 Å. The analysis in this system can give information on the electrodynamics of intrinsic Josephson junction and possibly on the pairing mechanism of HTSC. In practical application, the intrinsic Josephson junction is a promising candidate for high-frequency tunable oscillator [3] with a characteristic frequency up to a THz range and excellent coherence between adjacent junctions.

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The IJJ shows dc and ac Josephson effect in some-what modified way. In most experiments, fabricated IJJs are in the long junction regime with in-plane size L_{ab} larger than the Josephson penetration depth λ_J(~1μm). In this case, the dynamics of Josephson vortices (fluxons) are described by the coupled sine-Gordon equation [4]. Motions of fluxons are characterized by the zero field step [5] due to the fluxon–antifluxon motion under zero magnetic field and flux flow step at a high magnetic field.

Recently, vertical stacks of long junction have drawn increasing attention in studying the non-local electrodynamics of Josephson junction. The available experimental system includes Nb-Al/AlO_x-Nb tunnel junction stack [6] and BSCCO IJJs. These systems are mainly aimed for use in the flux flow oscillator, and thus the interaction of Josephson vortices and nonlinear EM wave in IJJ is not only of theoretical interest but also an important topic to increase the radiation power in the flux flow oscillator.

In this paper, we report the measurement of flux flow step in the current-voltage (*I-V*) characteristics of IJJ with different number of junctions at a high magnetic field. Also we discuss the model of Cherenkov radiation in the intrinsic Josephson junction that agrees well with our experimental *I-V* characteristics.

II. Experimental

The BSCCO crystals were grown in an oxygen atmosphere by the floating-zone method. X-ray diff-raction measurement confirms that the crystal is in single phase. Typical size of the crystals used in this work is ~ 2 mm × 3 mm × 100 μm.

We deposited 40 nm thick gold layer directly after *in-situ* cleaving of the surface layer of BSCCO. Then the mesa structure was fabricated using standard photolithography and Ar ion-beam etching.

The size of mesa is 40×40 μm with its height varying between 50 Å to 300 Å, which corresponds to 3 ~ 20 intrinsic stacked Josephson junctions. The upper electrode was made by the deposition of 500 nm thick gold. Since the contact resistance is less than 0.1 Ω, it will not give significant influence on the *I-V* characteristics, which we measured in the three-terminal configuration. Inset of Figure 1(a) shows the schematic diagram of sample geometry.

We performed experiments at sufficiently low temperature (mainly at 10 K) and applied high magnetic field up to 5 T. The *I-V* curves are taken by sweeping bias current and measuring the voltage across the stack through a low noise preamplifier. The results of the multiple sweep was stored in the digital oscilloscope where each sweep gives diffrent quasiparticle branches.

III. Results and discussion

Fig. 1 shows zero field *I-V* characteristics of mesa containing 20 and 6 IJJs, respectively. The *I-V* curves exhibit a well-developed gap structure, and gap voltage ($2\Delta/e$) is ~ 25 mV. Due to our three terminal geometry, the intrinsic Josephson junctions include the information on the topmost junction of Normal metal/Superconductor interface. The proximity effect

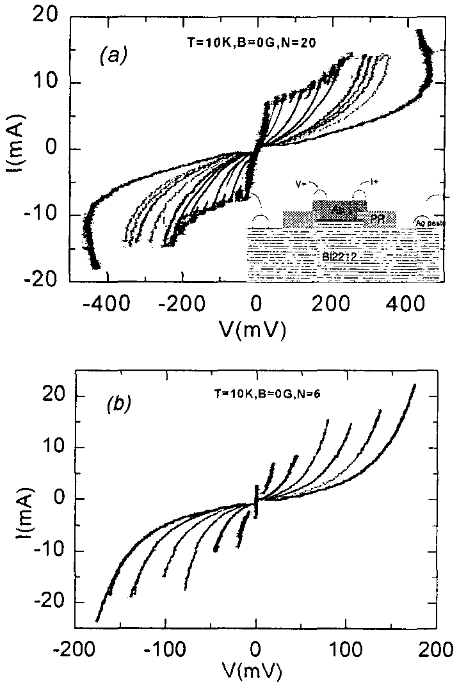

Fig. 1. I-V characteristics for mesa with the lateral dimension of 40 μm× 40 μm at 10 K in the absence of magnetic field. (a) The mesa contains about 20 IJJs. The inset shows a schematic view of the fabricated mesa. (b)The mesa contains 6 IJJs.

of the normal metal layer (Au) reduces the superconducting gap in the surface junction. This will lead to the reduction of critical current and maximum current of first few resistive branches [7].

The McCumber parameter of junction can be ob-tained using the hysterisis of first resistive branch [8],

$$\beta_c = \frac{2\pi I_c R_n^{\,2} C_J}{\Phi_0} \approx \left(\frac{4I_c}{\pi I_R}\right)^2, \qquad (1)$$

in the limit $\beta_c >> 1$.

The McCumber parameter β_c of junction in the 20-IJJ stack was estimated to be 690. With the critical current I_c ~ 7 mA, return current I_R ~ 0.35 mA, and normal resistance R_n ~ 0.6 Ω, we can obtain junction capacitance C_J ~ 87 pF, which corresponds to the junction dielectric constant $\varepsilon_J \sim 7.4$. This is close to the value reported by other groups [9].

In the absence of the bias current, the magnetic field penetrates inside the superconductor forming vortices with spatial periodicity which constitutes the vortex lattice. The shape of the vortex lattice is deter-mined by the anisotropy γ and the Josephson coupling strength between the layers. In contrast to the Abrikosov vortex with normal core, the vortex in this geometry has a core that is similar to the Josephson vortex. The Josephson vortex core has the Hori-zontal size of the Josephson penetration depth λ_J and the vertical size of the interlayer spacing s.

If we adopt the simple RSJ model in the IJJs, when we apply the bias current across the stack, the Josephson, Ohmic, and displacement currents are flowing in the c-direction. These currents act Lorentz force on the Josephson vortex and make vortices move with a velocity v. This allows the coupled sine-Gordon equation to describe the system. If we neglect dissipation term, it can be written as

$$\frac{\partial^2\varphi_n}{\partial x^2}-\frac{1}{v_c^{\,2}}\frac{\partial^2\varphi}{\partial t^2}-\frac{1}{v_J^{\,2}}\frac{\partial^2}{\partial t^2}[2\varphi_n-(\varphi_{n-1}+\varphi_{n+1})] \quad (2)$$
$$=\frac{1}{\lambda_c^{\,2}}\sin\varphi_n+\frac{1}{\lambda_J^{\,2}}[2\sin\varphi_n-(\sin\varphi_{n-1}+\sin\varphi_{n+1})]$$

where $\varphi_n=\phi_n-\phi_{n+1}-\frac{2\pi}{\Phi_0}\int_{ns}^{(n+1)s}dzA_z$ is the gauge-invariant phase difference for n-th junction, $\lambda_J=s\gamma=s\frac{\lambda_c}{\lambda_{ab}}$ is the Josephson penetration depth, λ_{ab},λ_c is the London penetration depth, and $v_J=\bar{c}=\frac{cs}{\lambda_{ab}\sqrt{\varepsilon_c}}$ is the Swihart velocity in of single junction.

The solution of Eq. (2) in a single junction under zero bias current is well known and given by

$$\varphi(x,t)=4\tan^{-1}\exp[\frac{x-vt}{\lambda_J\sqrt{1-v^2/\bar{c}^2}}] \quad (3)$$

This fluxon solution describes Josephson vortex moving like a relativistic particle with velocity v.

As we increase the bias current, fluxons are driven by the Lorentz force $f=J_z\times\Phi_0$. This motion of fluxons changes the phase difference between adjacent layers in time, and this results in the flux flow voltage across the junction via Josephson relation.

At high magnetic field ($H>\Phi_0/\gamma s$), fluxons are known to form a triangular vortex lattice [10]. This triangular vortex lattice is rigid enough to move as a whole when we drive a current across the layers. As we increase the bias current, the lattice velocity increases and saturated to Swihart velocity $\bar{c}$ (the velocity of EM wave in the junction). In this situation, there appears a resonance step (flux-flow step) in the *I-V* characteristics.

The flux flow step voltage V_{ffs} is given by [11],

$$V_{ffs}=N\bar{c}sH, \quad (4)$$

where N is the number of layers involved in the moving vortex lattice, s interlayer spacing, $\bar{c}$ the Swihart velocity.

In the IJJs, there are *N* different Swihart velocity modes. The triangular vortex lattice moves with the lowest mode velocity since it is energetically favorable. Thus in the IJJs, we regard $\bar{c}$ as the Swihart velocity of the lowest mode,

$$\bar{c}\approx\frac{c}{2}\sqrt{\frac{ts}{\lambda_{ab}^{\,2}\varepsilon_J}}\text{, for } N\gg1, \quad (5)$$

with *t* as the thickness of insulating layer and *N* as the number of stacks.

In Fig. 2, we can see the step structure in the *I-V* curves and this step (flux flow step) moves to higher voltage as we increase the magnetic field. As we increase the bias current, the curvature of *I-V* curves changes near the step and there appear quasiparticle branches above this step. The maximum voltage value of nonhysteretic *I-V* curves matches with flux flow step and this implies the collective dynamics of Josephson vortices.

In Fig. 2(a), flux flow step is seen at 40 mV at *H*=3 .

T. Using the values of t=12 Å, s=15 Å, λ_{ab}= 1700 Å and $\varepsilon_J \sim 8$, we can obtain $\bar{c}\sim1.4\times10^{-3}$ c. (This

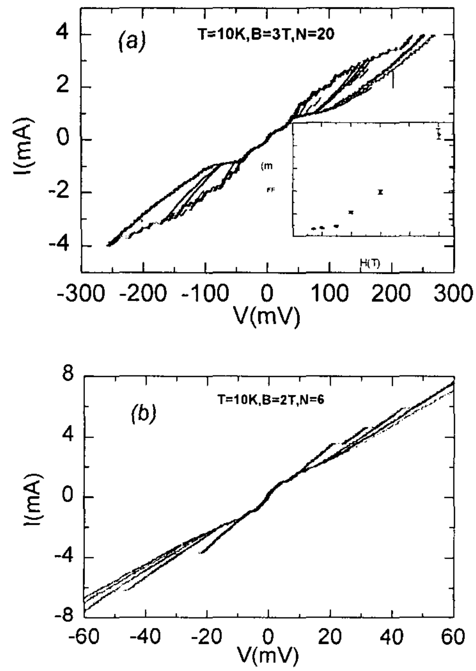

Fig. 2. *I-V* characteristics of IJJ at a high magnetic field parallel to CuO_2 planes. Flux flow steps are seen in both samples. (a) Mesa containing 20 IJJs show flux flow step (FFS) around 40 mV at 3 T. The inset exhibits magnetic field dependence of FFS of this sample. (b) Mesa containing 6 IJJs show FFS around 5 mV at 2 T

corresponds to the flux flow step at 38 mV in the case of N=20) [12].

This suggests that the vortex lattice moves with the lowest mode Swihart velocity and also that all junctions are involved in the dynamics of Josephson vortex.

Fig. 2(b) shows slightly different type of *I-V* curves. The quasiparticle branches are developed almost linearly and there appears resonant step at voltage of about 5 mV. This value is close to the prediction (~ 7 mV) obtained by Eq. (4) using above parameters.

The inset of Fig. 2(a) shows the magnetic field dependence of maximum nonhysteretic voltage of the *I-V* curve. We can see the flux flow step voltage (V_{ffs}) increases over H_{cr}~ 1.5 T. This increase of V_{ffs} cannot be explained simply by the increase in the number of junctions because nearly all junctions are already in the flux flow state. The reason is that at this value, Josephson vortices overlap strongly since the diameter of the Josephson vortex (~ 2 λ_J) is nearly same as the distance between two vortices (~ 0.8 μm at H = 1.5 T). We note that this value of H_{cr} is close to $H_0 = \Phi_0 / \gamma s^2$, which is a magnetic field for the formation of triangular vortex lattice.

Here, we will discuss the dissipation mechanism in IJJs. Bulaevskii *et al.* [13] suggested a dissipation mechanism due to the quasiparticle tunneling current. Ustinov and Kleiner *et al.* [14] reported the observation of non-Josephson microwave emission signal at the flux flow step in the BSCCO IJJs as a broad peak and suggested that this may be the Cherenkov radiation from IJJs. The spectrum of emitted microwave signal from IJJs has broad band spectrum and the frequency of the signal is order of 10 GHz, which is much less than Josephson frequency.

It is known that a particle moving at the phase velocity of EM wave emits radiation, *i.e.* Cherenkov radiation. In the IJJ, coupled sine-Gordon equation is not invariant to Lorentz transform, so the velocity of moving fluxon may exceed the lowest mode Swihart velocity c_N. Thus the fluxons can move with the velocity that matches with the phase velocity of lower electromagnetic mode.

Cherenkov radiation of the generalized Swihart wave was discussed in the case of non-local Josephson junction [15], when λ_J is smaller than or comparable to λ. According to the theory, the frictio-nal force per unit length f_{fr} exerted on the Josephs-on vortex by Cherenkov radiation is given by [16],

$$f_{fr} = \frac{2\pi^2 \hbar j_c}{e} \frac{\omega_J^2 l^2}{v^2} \exp(-\frac{2\omega_J^2 l^2}{v^2}), \quad (6)$$

where ω_J is the plasma frequency, v is the velocity of moving fluxon, and $l = \lambda_J^2 / \lambda$.

Then we can induce the steady state velocity when we apply the bias current by equating the Lorentz force acting on the vortex and Cherenkov radiation frictional force $f_{fr} = \frac{\Phi}{c} j$,

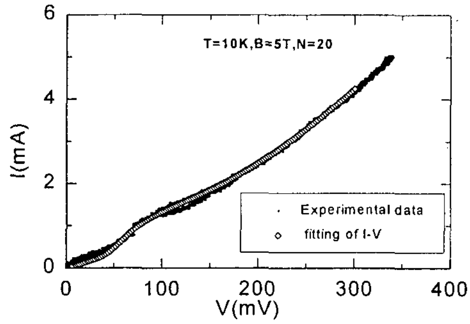

Fig. 3. *I-V* characteristics of mesa containing 20 IJJs at T=10 K, B=5 T. Experimental *I-V* curve is well fitted with simple model of Cherenkov radiation. Flux flow step voltage is around 90 mV

$$\frac{j}{j_c} = \frac{2\pi^2\omega_j^2 l^2}{v^2}\exp\left(-\frac{2\omega_j^2 l^2}{v^2}\right). \qquad (7)$$

Including this term, we assume the following form of *I-V* characteristics that includes both Cherenkov radiation and quasiparticle tunneling current,

$$I(V) = \alpha V + \beta V^2 + \gamma\frac{1}{V^2}\exp\left(-\frac{1}{V^2}\right), \qquad (8)$$

where α, β are coefficients for Ohmic and non-linear quasiparticle dissipation terms respectively and γ is the coefficient for the dissipation term due to the Cherenkov radiation.

Fig. 3 shows *I-V* characteristics of a mesa containing 20 IJJs at H=5 T. Fitting the *I-V* curves using Eq. (8) gives a good agreement with the experimental data with the fitting parameters α=2, β =0.8, γ=4. In this curve, there appears flux flow step in the *I-V* curves around 90 mV, where the velocity of Jose-phson vortex is close to the lowest mode value of Swihart velocity.

IV. Conclusions

In summary, we present the observation of the flux flow step in the *I-V* characteristics under high magnetic field with different number of IJJs. The obtained Swihart velocity is close to the lowest mode velocity of EM wave in the N stacked Josephson junction and the number of moving vortex lattice is nearly same as the number of stacks. This implies the whole stacks are involved in the formation of vortex lattice. We also discuss the dissipation mechanism of the fast moving vortex as Cherenkov radiation in addition to the quasiparticle tunneling current and this model agrees well with the experimental *I-V* characteristic.

References

[1] R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Müller, Phys. Rev. Lett. **68**, 2394 (1992); R. Kleiner and P. Müller, Phys. Rev. B **49**, 1327 (1994).

[2] A. Yurgens, D. Winkler, N. Zavaritsky, and T. Claeson, Phys. Rev. B **53**, R8887 (1996).

[3] E. Goldobin, H. Kohlstedt, and A. V. Ustinov, Appl. Phys. Lett. **68**, 250 (1996).

[4] R. Kleiner, P. Müller, H. Kohlstedt, N. F. Pedersen, S. Sakai, Phy. Rev. B **50**, 3942 (1994).

[5] H. L. Johnson, G. Hechtfischer, G. Gotz, R. Kleiner, P. Müller, J. Appl. Phys. **82**, 756 (1997).

[6] G. Carapella, G. Costabille, P. Sabatino, Appl. Phy. Lett. **74**, 90 (1999).

[7] N. Kim, Y. Doh, H. Chang, Hu-Jong Lee, Phys. Rev. B **59**, 14639 (1999).

[8] K. K. Likharev, Dynamics of Josephson junctions and Circuits (Gordon and Breach, Philadelphia, PA 1986).

[9] A. Irie, Y. Hirai, G. Oya, Appl. Phys. Lett. **72**, 2159 (1998).

[10] L. Bulaevskii, J. R. Clem, Phys. Rev. B **44**, 10234 (1991).

[11] G. Hechtfischer, R. Kleiner, K. Schlenga, W. Walkenhorst, P. Müller, H. Johnson, Phys. Rev. B **55**, 14638 (1997).

[12] Y. I. Latyshev, P. Monceau, V. N. Pavlenko, Physica C **293**, 174 (1997).

[13] L. Bulaevskii, D. Dominguez, M. Maley, A. Bishop, Phys. Rev. B **53**, 14601 (1996).

[14] G. Hechtfischer, R. Kleiner, A. V. Ustinov, P. Müller, Phy. Rev. Lett. **79**, 1365 (1997).

[15] R. G. Mints, I. B. Snapiro, Phy. Rev. B **52**, 9691 (1995).

[16] V. P. Silin, A.V. Studenov, Phy. Solid State **39**, 384 (1997).