Quantitative identification of the fluxon-flow modes in a stack of intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals

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Abstract

We observed the splitting of the fluxon-flow branches in the current-voltage characteristics of serially stacked intrinsic Josephson junctions (IJJs) formed in $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals in the long-junction limit. Stacks of IJJs were sandwiched between two Au electrodes deposited on the top and the bottom of the stack using the 'double-side cleaving technique'. In all the samples studied, the branch splitting started occurring for a dense fluxon configuration around 2 T and became more distinct in a higher magnetic field range. This observation can be explained in terms of switching between different Josephson fluxon modes in resonance with the collective plasma oscillations induced by both inductive and capacitive coupling between stacked IJJs. This is the first detailed and quantitative identification of the coherent flux-flow modes in stacked.

Keywords : fluxon dynamics, intrinsic Josephson junctions, collective plasma oscillations, mode splitting, fluxon resonance steps

I. Introduction

Since the discovery of intrinsic Josephson junction effect in $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals (Bi-2212) [1], the dynamics of Josephson fluxons in stacked superconducting tunnel junctions formed in Bi-2212 single crystals has been studied intensively as a model system of nonlinear dynamics and for possible applications to active-device elements.

A THz oscillator element based on the fluxon-flow motion in stacked intrinsic Josephson junctions (IJJs) is one example of such efforts. To make a fluxon oscillator using intrinsic-Josephson-junction stacks in a high in-plane magnetic field, however, it is required to find exact conditions of coherent fluxon motion and to match the impedance of a stack of IJJs to the free space or a detector of oscillations.

Recently, to investigate the coherence condition of fluxons in IJJs, Heim *et al.* used a quasi-one-dimensional mesa structure, where the width of the mesa is comparable to the Josephson penetration depth λ_J [2]. Other fluxon-dynamics studies have been also done using mesa structures prepared on the surface of single crystals [2-4]. The presence of the basal stack underneath a mesa, however, may distort the fluxon-flow characteristics in the mesa itself by the strong inter-junction coupling of Josephson fluxons that are present in the mesa and in the basal stack. Thus, to observe coherent fluxon-flow modes more clearly, we should not only reduce the width of a mesa but also should remove the basal stack located underneath the mesa structure.

In this paper we report a new approach to study the Josephson fluxon dynamics using an Au-sandwiched stack geometry. We observed multiple voltage steps in the Josephson fluxon-flow branches (JFFBs) in the field range of 2-5 T. We find that observed unusual structures in the Josephson fluxon-flow regime of the curves is due to collective fluxon motion coupled to the plasma oscillations by the inductive and the capacitive inter-junction interaction [5].

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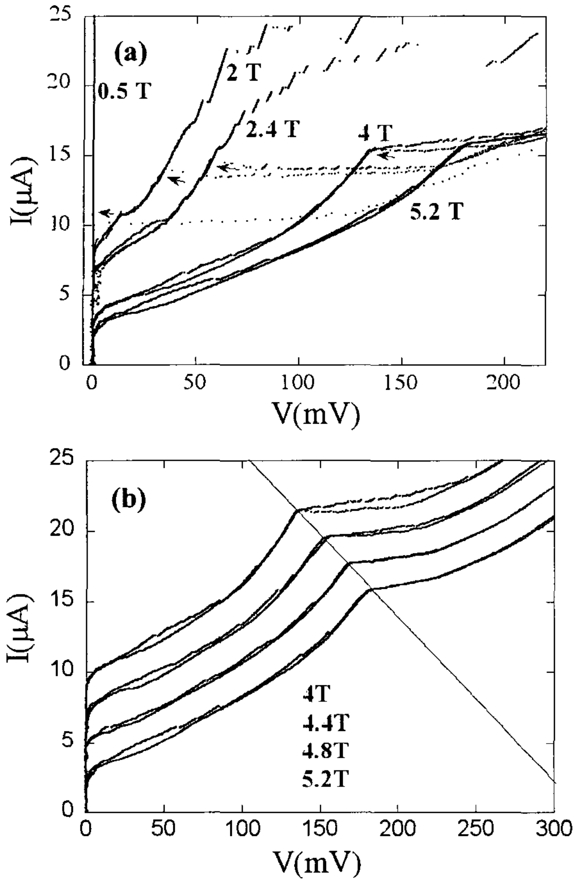

Fig. 1. (a) The Josephson fluxon-flow branches of an Au-sandwiched stack of size 1.5×17 μm^2 in various high magnetic fields. The arrows indicate the return-current values to the supercurrent branches from the quasiparticle branches at T=4.2 K. (b) Details of the Josephson fluxon-flow branches in the dense fluxon regime. Each curve is shifted upward by 2μA from the adjacent curve for the sake of clarity.

II. Experiments

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 [6]. Details of the sample fabrication are described elsewhere [7].

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 1.5 T at temperature of 60 K with the alignment resolution of 0.01 degrees [4].

III. Results and Discussion

Fig. 1 shows the JFFBs of an Au-sandwiched stack of size 1.5×17 μm^2 in various magnetic fields. The arrows in Fig. 1(a) indicate the return-current values from the quasiparticle state to the supercurrent branches. The number of junctions N is about 53. The intervals between quasiparticle branches become smaller and smeared for further higher magnetic fields [Fig. 1(b)]. The hysteresis in the quasiparticle branches above the maximum voltage of the Josephson fluxon-flow state, V_m [the voltages of the points crossed by the solid line in Fig. 1(b)], completely disappears for a field above 4.8 T. The discrete voltage steps in the JFFBs, however, become clearer for higher fields. These discrete voltage steps may be related with the collective resonance behavior of Josephson fluxons over the whole junctions. The resonance has been observed in a dense fluxon lattice [8], that forms when the spacing between two fluxons becomes comparable to the diameter of a fluxon, $2\lambda_J$. The condition corresponds to an applied field of $H_c=\phi_0/2\lambda_J(t+d)$. Here, ϕ_0 is the magnetic flux quantum, and t (=1.2 nm) and d (=0.3 nm) are the thickness of the insulator and the superconducting layers, respectively. We obtained the value of λ_J and H_c to be 0.3 μm and 2.3 T, respectively, for the tunneling critical current density of 1 kA/cm^2. In Fig. 1(a) one notices that, with increasing field, the step-like structure in the JFFBs starts appearing from about 2 T. The field agrees with the predicted value of H_c very well. The appearance of the step-like structures in about 2 T was observed in all measured Au-sandwiched stacks. The V_m in Fig. 1(b) increases linearly with an external field H, which represents the Josephson fluxon-flow resistance satisfying the relation

$$V_{max}=Nc_{max}H(t+d), \qquad (1)$$

where c_{max}, the maximum fluxon velocity, is the maximum slope of a curve in the Josephson-fluxon-flow state in Fig. 1(b) is found to be about 4.1×10^5 m/s. We clearly observed both the quasiparticle branches and the discrete voltage steps in the JFFBs in 4 T as in Fig. 1(b). In this field the spacing between two fluxons is comparable to λ_J. Therefore, it is reasonable to conclude that the observed discrete voltage steps are related with the collective resonance behavior of the fluxon lattice.

Recently, by observing oscillations of fluxon-flow resistance with period of $\Phi_0/2L(t+d)$, it has been shown that a triangular lattice forms along the c axis in fields of about 0.7 to 0.9 T [9]. Here L is the length of the junction. This implies that all junctions contain nearly the same number of fluxons. In our sample we expect that a triangular lattice forms in the range of fields used. When the low-bias current was applied along the c-axis, fluxons forming a triangular lattice move through the insulating layer. The motion of this fluxon lattice generates a traveling electromagnetic wave along the layers with the frequency v/d_f, where v is the fluxon velocity corresponding to the bias current. The fluxon lattice transforms from a triangular (out-of-phase mode) to a square lattice (in-phase mode) with increasing velocity.

There are also transverse plasma modes corresponding to the number of junctions in the stack with the characteristic velocities in the case of inductive coupling as [2]

$$c_n = c_0/[1-\cos(n\pi/(N+1))], \quad n = 1,2,\ldots,N. \qquad (2)$$

Here c_0 is the Swihart velocity, which is the phase velocity of small-amplitude oscillation modes in a single Josephson junction. If the velocity of the fluxon-lattice transformation matches to any of the plasma mode velocities, resonant radiations are expected to appear as voltage steps in JFFBs.

Fig. 2 displays the details of the JFFBs in 5.2 T. The length of the subbranches between discrete voltage steps keeps increasing with increasing bias. The general trend of the length of the subbranches qualitatively coincides with the velocity difference between adjacent plasma oscillation modes predicted by Eq. (2). In the analysis we adopted theory of the combined coupling; inductive and capacitive [5]. Taking the charge fluctuations in the CuO_2 superconducting layers into account is the key to an understanding of the longitudinal Josephson plasma modes [10]. Combining the capacitive and the inductive coupling, one obtains the velocities of plasma modes as

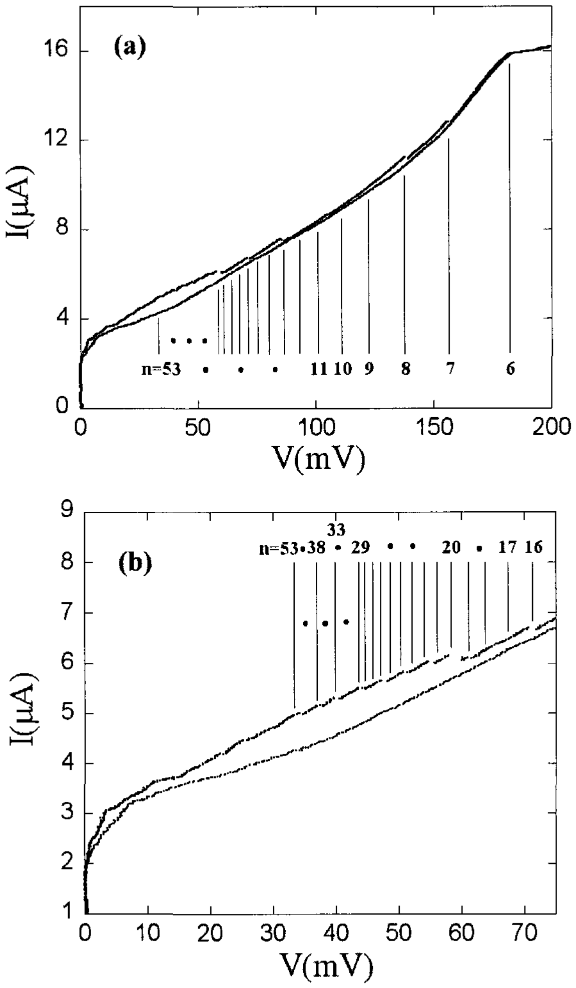

Fig. 2. The Josephson fluxon-flow branches of an Au-sandwiched stack of size 1.5×17 μm^2 in 5.2 T. The vertical lines correspond to resonance voltages calculated based on transverse plasma modes using Eq. (3). n is the index of plasma modes.

$$c_n^{\alpha} = c_0 \sqrt{\frac{1+2\alpha(1-\cos[\pi n/(N+1)])}{1-\cos[\pi n/(N+1)]}},$$

$$n = 1,2,\ldots,N, \qquad (3)$$

where the capacitive coupling parameter α is $\varepsilon\varepsilon_0 /2e^2N(0)d$ with the two-dimensional density of states $N(0)$. The charging effect enhances the mode velocities as $c_N^{\alpha}=[(1+4\alpha)]^{1/2}c_N$ for the N-th mode. The vertical lines correspond to resonance voltage values predicted by modified transverse plasma modes using Eq. (3) for N=53 and α=0.03. The best-fit value of the Swihart velocity c_0 was found to be 1.08×10^5 m/s for the sixth and the seventh modes in Fig. 2(a). The voltage positions of the jumps are in good quantitative agreement with the switching points of plasma oscillation modes, estimated on the basis of the inductive coupling and the capacitive coupling. This leads us to conclude that the discrete voltage steps in JFFBs occur when the velocity of fluxons resonate with any mode velocities of the transverse plasma motion.

IV. Summary

We fabricated stacks without basal crystal parts using the double side cleaving technique. The curves in the fluxon-flow region for fields below 2.4 T were unstable so that the resonance behavior was not observed. In the range of 4 T to 5 T, however, the fluxon dynamics becomes stable and clear. The observed discrete voltage steps in JFFBs were analyzed as collective resonant modes with combined theory of the inductive and capacitive couplings. In the fluxon-flow state in 4.6 T the spacing between fluxons becomes equal to λ_J so that one can expect that the electromagnetic wave generated in the stacked junctions with frequencies up to a few THz will be radiated with enhanced power by collective resonance through whole junctions.

Acknowledgments

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