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Dynamical transition of Josephson vortex lattice in serially stacked $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions

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Abstract

The inductive coupling theory in serially stacked $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions predicts that the lattice structure of the Josephson vortices along the *c* axis gradually changes from the triangular to the rectangular lattice with increasing the vortex velocity. This lattice transition appears as voltage jumps or sub-branch splitting in the Josephson vortex-flow region of current-voltage characteristics (IVC). We report the IVC in external magnetic fields from 2 to 4 T. The stack, with the lateral size of $1.4\times15\ \mu m^2$, was fabricated by using the double-side cleaving technique. The sub-branches in the Josephson vortex-flow region, corresponding to a plasma propagation mode in serially coupled intrinsic Josephson junctions, were also observed in the range of 2 ~ 4 T. Switching from one branch to another in Josephson vortex-flow region suggests the structural transition of the moving Josephson vortex lattice.

Keywords : Josephson vortex lattice, collective resonance mode, intrinsic Josephson junctions

I. Introduction

In a high external magnetic field applied in parallel with the *ab* planes of layered superconductors such as $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) single crystals a triangular Josephson vortex lattice (JVL) forms in insulating layers of intrinsic Josephson junctions (IJJs) along the *c* axis. In a bias current along the *c* axis the triangular lattice moves along insulator layers, which can be transformed to a rectangular lattice while undergoing several intermediate states corresponding to the collective transverse plasma modes. In the current-voltage characteristics (IVC) this structural transformation of JVL gives the voltage jumps or sub-branch splitting in the Josephson-vortex-flow branches (JVFB) [1].

Recently, the multiple sub-branches in Josephson-vortex-flow characteristics in the highly dense vortex regime were observed in our group [2]. The observed sub-branches or collective resonance modes were interpreted as the resonances among various JVL and collective transverse plasma modes. Various stable states of the JVL moving with different velocities are manifested as sub-branches in IVC.

This report will focus on the dynamical transition and the stable range of the JVL with increasing external magnetic fields in a few T range. We observed that the stable field regions corresponding to fast flux modes of the rectangular lattice moves toward the higher voltage region. The number of sub-branches is less than the number of junctions by two. It may be due to the additional charge-imbalance potential at the outermost superconducting electrodes with a Au-sandwiched stack geometry.

II. Experiments

As-grown slightly overdoped Bi-2212 single crystals were prepared by the conventional solid-state-reaction method. Stacks of IJJs were

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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 [3].

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 degrees [4].

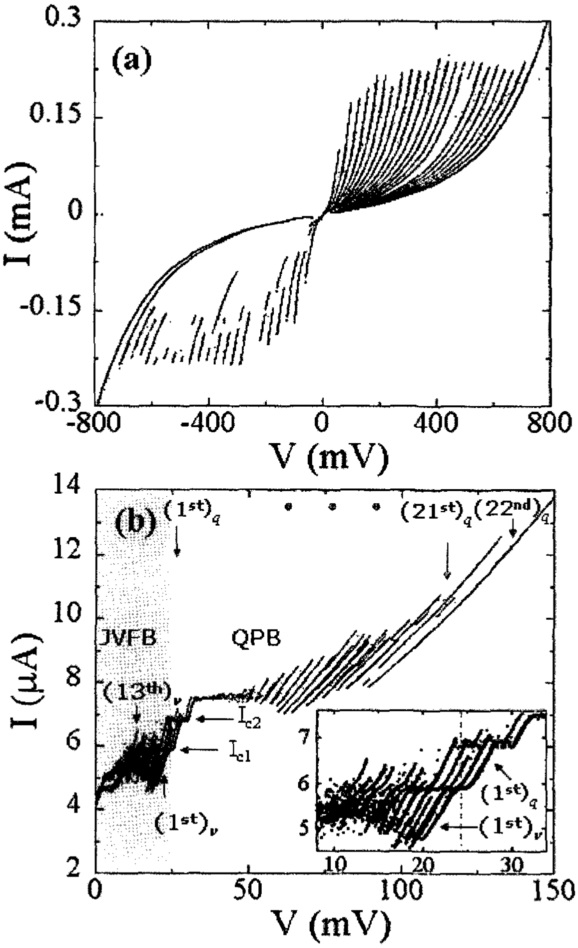

Fig. 1. (a) Current-voltage characteristics of a Au-sandwiched stack of size 1.4 × 15 μm^2 in zero external magnetic fields at T=4.2 K. (b) Current-voltage characteristics in an external field of 2.3 T. The inset of (b): details of the Josephson vortex flow branches.

III. Results and Discussion

Fig. 1(a) shows the IVC of a Au-sandwiched stack of size 1.4 × 15 μm^2 in zero magnetic field. The total number of junctions was 22 as evidenced by the total number of the quasi-particle branches. The resistance of the first branch in the low bias region was caused by the contact resistance between the Au electrode and the top-most IJJ in the mesa. The average critical current density was about 1 kA/cm^2 and the normal-state resistance per junction, estimated from the liner portion in the high-bias range above the sum-gap voltage (not shown in the figure), was 8.27 Ω. The value of the Josephson penetration depth λ_J, 0.3 μm, determined from the critical current density, leads to the critical value of highly dense field H_d to be 2.3 T. At H_d [$=\phi_0/2\lambda_J(t+d)$] the spacing between two fluxons becomes comparable to the diameter of a fluxon, $2\lambda_J$. 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 that of the superconducting layers, respectively. Fig. 1(b) displays the JVFB and quasi-particle branches in H=2.3 T in the low and high bias regions, respectively. The voltage regions of JVFB and quasi-particle branches are separated at V_{cut}=24 mV for the bias I_{c1}, which is the suppressed critical current by the external field [see Fig. 1(b)]. In the bias range above I_{c1} one can see the first quasi-particle branch and the suppressed critical current of the first quasi-particle branch denoted by $(1^{st})_q$ and I_{c2}, respectively. The number of quasi-particle branches was 22 consistently. In the JVFB bias region lower than V_{cut} [the dotted line in the inset of Fig. 1(b)], sub-branches appeared. The V_{cut} corresponds to the maximum velocity of JVL. Using the relation of $V_{max}=Nc_{max}H(t+d)$, the speed of JVL, c_{max}, was obtained to be 3.16 × 10^5 m/s [4]. According to the inductive coupling model [4] there are transverse plasma modes corresponding to the number of junctions in the stack with the characteristic velocities

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

Here, c_0 is the Swihart velocity, which is the phase velocity of small-amplitude oscillation modes in a single Josephson junction. Until recent days the velocity range of 1-3 × 10^5 m/s had been considered as the lowest transverse plasma mode (n=N) in many reports because no sub-branches corresponding to other plasma modes was observed in JVFB [5]. However, recently we were able to observe the sub-branches for the bias smaller than V_{cut}. We identified the sub-branches as the collective resonance modes between JVL and plasma modes [2]. To calculate c_0, we estimated the junction capacitance, C_J to be 71.3 pF, based on the resistive shunted junction model [6]. The c_0 estimated by C_J and λ_{ab}=200 nm was about 3 × 10^4 m/s so that, in the purely inductive coupling model, the electromagnetic wave velocities in junctions with N=22 range from 2 × 10^4 m/s (the lowest velocity mode) to 3 × 10^5 m/s (the highest velocity mode). Here, λ_{ab} is the London penetration depth. Interestingly, the predicted velocity of the highest mode is nearly the same as the maximum velocity c_{max} of JVL at V_{cut}. We interpret this c_{max} is the mode velocity corresponding to the highest mode (n=1).

Fig. 2(a) displays the evolution of collective resonance modes with the increase of external magnetic fields from 2.5 T to 4.2 T. The gray color-areas in low, intermediate, and high bias regions in Fig. 2(a) are the stable voltage ranges of the lowest mode (n=20), the mode of n=9, and the highest mode (n=1), respectively. The stable range of all modes and the increasing rate of the resonance voltage of faster modes with the decrease of mode number, n, grow with the increase of the field as predicted by the inductive coupling model [also see the arrows in Fig. 2(b)]. The starting point indicated by the arrow in stable range of the $(1^{st})_v$ mode, however, is nearly the same as 25 mV, regardless of external fields. The stable range of the mode of n=9 is overlapped with the stable range of the $(1^{st})_v$ mode from 3.6 T, which is not like in the case of 2-3 T. This behavior is consistent with the prediction of A. E. Koshelev based on the ab-plane dissipation in Ref. [1]. The number of observed resonance modes is twenty, which is two modes smaller than the number of junctions in Fig. 2(b). Recently, Ryndyk proposed that the additional dissipation due to charge imbalance relaxation in junction can prevent the JVL transformation [7]. In our case quasi-particles are injected directly from outside through the outermost two junctions. This quasi-particle injection may bring about the non-equilibrium charge imbalance effect in the outermost two CuO_2, reducing the number of observed resonance modes. In the case of inner CuO_2 planes we can neglect the quasi-particle injection due to tunneling of Cooper pairs below the critical current of the junction. There was a possibility of prohibition of contribution in the transformation of JVL in the outermost junctions that were affected by additional potential of charge imbalance relaxation.

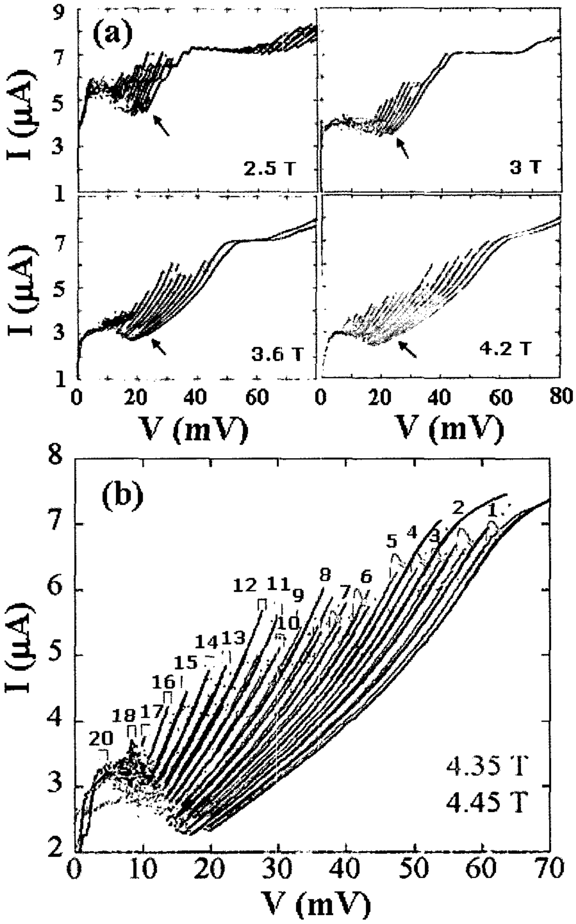

Fig. 2. (a) The evolution of collective resonance modes with increasing external magnetic fields at T=4.2 K. (b) Collective resonance modes in 4.35 and 4.45 T.

IV. Summary

We fabricated Au-sandwiched stacks without basal crystal parts using the double-side cleaving technique The stack showed a wealth of flux dynamics for various external magnetic fields. The evolution of each mode with increasing fields is consistent with the prediction of theoretical analysis. Measurements of the signal of the microwave irradiation emitted from the each mode may confirm the interpretation along this line.

Acknowledgments

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