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SUB-BRANCH SPLITTING IN JOSEPHSON-VORTEX-FLOW CHARACTERISTICS OF A STACK OF $Bi_2Sr_2CaCu_2O_{8+x}$ INTRINSIC JOSEPHSON JUNCTIONS

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We observed subbranch splitting in the low-bias vortex-flow branch of a dense-Josephson-vortex state in current-voltage characteristics of $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions in the long-junction limit. We suggest that each subbranch corresponds to a plasma mode in serially coupled Josephson junctions, manifested in the Josephson vortex-flow current-voltage characteristics resonating with the plasma modes.

Keywords: Plasma oscillation modes; mode splitting of Josephson vortex-flow branches; intrinsic Josephson junctions.

1. Introduction

The Josephson vortex dynamics in a single Josephson tunnel junction is characterized by the Josephson penetration depth λ_J, which determines the size of a Josephson vortex and the Josephson plasma frequency ω_J, the frequency of the Cooper-pair oscillation across a Josephson junction. The Swihart velocity $\bar{c}$, which is the propagation velocity of an electromagnetic wave in a single tunnel junction, is expressed in terms of λ_J and ω_J as $\bar{c} = \lambda_J \omega_J$.

The Josephson vortex dynamics can also be constructed in serially stacked intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) single crystals. Due to large anisotropic characteristics of the material stacked IJJs show various critical phenomena related to the vortex dynamics. The coupled sine-Gordon equations, describing the Josephson vortex dynamics in these stacked N IJJs, predict the formation of N different transverse plasma modes. The Josephson vortex lattice formed by an external field can resonate with these transverse plasma modes, which can be shown as voltage jumps in current-voltage characteristics (IVCs) in the current bias configuration.[1]

In this study, we measured the IVCs of a stack of coupled IJJs formed in $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) single crystals with varying magnetic fields up to 5 T. The high-field-range characteristics are typified by the appearance of the subbranches in the Josephson vortex-flow dynamics. We suggest that these subbranches correspond to the coherent vortex resonances with the transverse plasma waves.

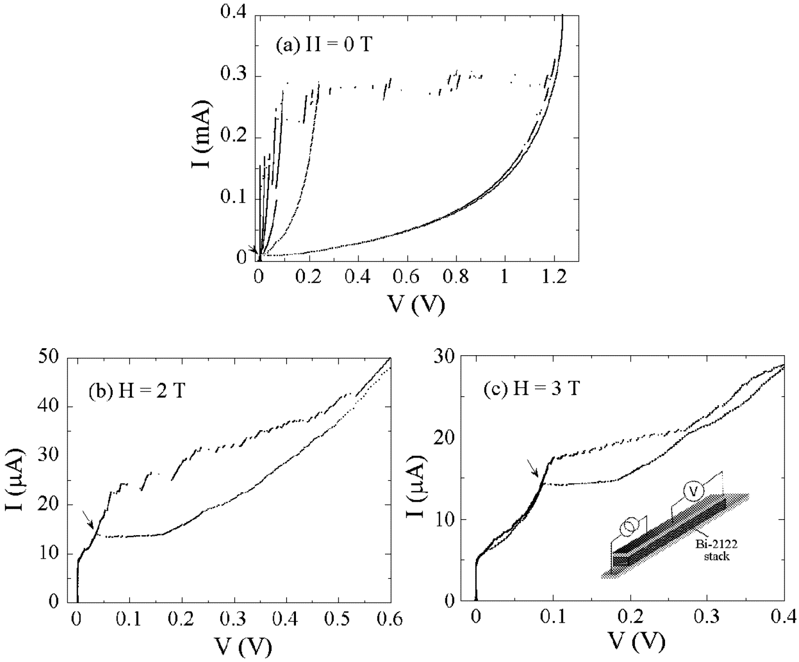

Fig. 1. (a) Zero field IVCs. (b)-(c) Josephson vortex-flow and quasiparticle branches of the stack in fields of 2 and 3 T. The arrow in each figure indicates the return current from the quasiparticle branch to the Josephson branch. Inset of (c): the measurement configuration.

2. Experiments and Results

We fabricated, using the double-side cleaving technique,[2] a 17 × 1.5 μm^2 stack of IJJs sandwiched by Au electrode films at its top and bottom without the basal part [the inset of Fig. 1(c)]. This structure is in contrast to the usual mesa structure fabricated on the surface of a single crystal with a large basal part. Adopting the geometry with the basal part eliminated enables one to measure the Josephson vortex dynamics in coupled IJJs without the interference of the vortex motion in the basal stack. The detailed fabrication procedure is described in Ref. [3]. The magnetic field was aligned in parallel with the plane of junctions within the resolution of 0.01 degree to minimize the pinning of Josephson vortices by the pancake vortices formed in CuO_2 bilayers. All the measurements were done at 4.2 K in a two-terminal configuration. The combined contact resistance for bottom and top interfaces was subtracted numerically.

3. Discussion and Conclusion

Fig. 1 shows the gradual evolution of the IVCs with increasing external fields. From the zero-field IVCs in Fig. 1(a) we determined the number of junctions in the stack to be 55 and the Josephson critical current density j_c to be ~1 kA/cm^2. The λ_J

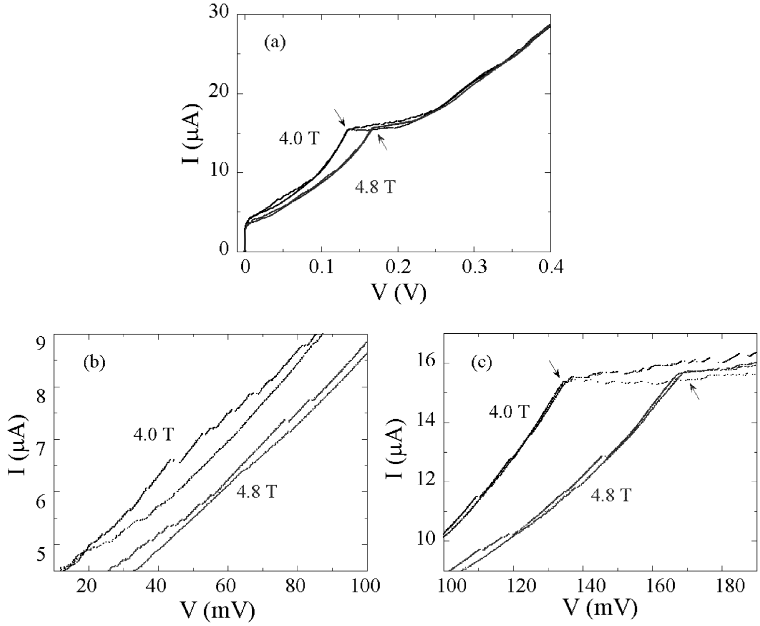

Fig. 2. (a) Josephson vortex-flow and quasiparticle branches of the stack in fields of 4 T and 4.8 T. The arrow in each figure indicates the return current from the quasiparticle branch to the Josephson branch. (b)-(c) Detailed Josephson vortex-flow branches of 4 T and 4.8 T.

corresponding to the critical current was about 0.3 μm. A junction in the stack, which was about 57 times longer than λ_J, was in the long-junction limit. The arrow in each figure indicates the return current, I_r, from a quasiparticle branch to a Josephson branch. Increasing the magnetic field, the slope of the Josephson branch below I_r increased and up-turn curvature started appearing from 3 T. This behavior is well known as arising from the Lorentz-force-driven vortex-flow dissipation by the tunneling bias current. Interesting observation in this case is that, as in Fig. 2, several subbranches are visible in the Josephson vortex flow regime for fields of 4 T and 4.8 T.

One may assume that these subbranches are the suppressed quasiparticle branches with increasing the external field. The voltage of each quasiparticle branch in the IVCs of Fig. 1(b)-(c) for a given bias current is contributed by both the dissipative quasiparticle tunneling and the additional dissipation from the Josephson-vortex flow. The last quasiparticle branch does not exhibit the field dependence, because all the junctions were in the quasiparticle state [Fig. 2(a)]. For a stack of N IJJs, the first quasiparticle branch has the vortex-flow-resistance contribution from the rest of $N-1$ junctions. A simple analysis based on the combined contribution of Josephson-vortex flow and the dissipative quasiparticle tunneling may indicate that the voltage of the pure vortex-flow branch in the IVCs cannot exceed that of the first quasiparticle branch affected by vortex flow. Thus, the subbranches in the bias region below I_r in 4 T and 4.8 T cannot be the suppressed quasiparticle branches in a high magnetic field. One also notices that the voltage of an inner quasiparticle branch above I_r for a given bias current changes more sensitively to the magnetic field than that of an outer quasipaticle branch, because in the former case more Josephson vortices contribute to the vortex-flow dissipation. In contrast, the inter-branch voltage spacing for the inner multiple branches below I_r for a given field is less sensitive to the magnetic field than that for the outer multiple branches [Fig. 2(b)-(c)]. This also indicates that the observed multiple subbranches below I_r cannot be the suppressed quasiparticle branches in a high magnetic field.

Previous theoretical and numerical calculations predict that the voltage jumps due to collective resonance between the Josephson vortex motion and the plasma oscillation take place in a high vortex dense regime.[1] This regime can be supported by an external magnetic field H_d, defined as $H_d = \Phi_0/2\lambda_J d$, which corresponds to the field where an overlap between neighboring Josephson vortices starts taking place. Here, Φ_0 is the magnetic flux quantum and d (=1.5 nm) is the spacing between neighboring periodic junctions in a stack of IJJs. In our sample, H_d is about 2.2 T and the distinct voltage jumps in vortex flow regime started appearing around $2H_d$. All the voltage jumps between neighboring subbranches take place in the vortex-flow region [Fig. 2(b) and (c)] and positions of the jumps shift progressively to the higher voltage values with increasing the external field, which is consistent with the prediction of the vortex-flow dynamics in the inductive coupling theory.[1] Coherently moving vortex lattice remains in a certain transverse plasma mode as long as the vortex-lattice velocity is smaller than the propagation mode velocity of the plasma oscillation. If the velocity of Josephson vortex exceeds the mode velocity at a higher bias current, however, the resonating dynamic state of the Josephson vortex lattice suddenly switches to the adjacent plasma mode with a higher propagation velocity, which gives a collective voltage jump we observed.

In conclusion, we suggest that the unusual jumps in the current-voltage characteristics taking place in the vortex-flow state for a bias below the quasiparticle-state return current I_r in each field is caused by switching of coherent vortex-lattice motion between different plasma modes.

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