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Collective motion of Josephson vortices in $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa structures

H.-S. Chang [a,c,*], D.-I. Chang [a], J. Kim [b], H.-J. Lee [a], M.-H. Bae [a], B.-C. Woo [b], M. Oda [d]

[a] *Department of Physics, Pohang University of Science and Technology, Pohang 790-784, South Korea*
[b] *Electronic Device Group, Korea Research Institute of Standards and Science, Taejon 305-600, South Korea*
[c] *Material Science Team, Korea Basic Science Institute, Taejon 305-333, South Korea*
[d] *Department of Physics, Hokkaido University, Sapporo 060-0810, Japan*

Abstract

We studied the collective motion of Josephson vortices generated by microwave irradiation and by an external dc magnetic field applied in parallel with the planes of intrinsic junctions of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals. In both cases, for a low vortex density and driving current, splitting of the 'supercurrent' branch corresponding to different plasma excitation modes was observed in the current–voltage characteristics (IVC). For a high vortex density in fields beyond 3–4 T, the IVC merged into a single non-hysteretic curve with kinks, similar to those arising from the theoretically proposed structural transformation of moving vortex patterns.

Keywords: Fluxon dynamics; Josephson vortex; Intrinsic Josephson junction

In a previous study [1] we observed the collective motion of Josephson vortices (JVs) generated by the magnetic field component of irradiated microwaves in a stack of intrinsic Josephson junctions (IJJs). The collective motion was revealed as splitting of the 'supercurrent' branch in the current–voltage characteristics (IVC) of a mesa formed on the surface of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystals. The number of the split sub-branches coincided with the number of quasiparticle branches in the IVC or, in turn, the number of IJJs in a mesa, which is a typical characteristic of the coherent modes of collective JV motion [2].

In this study we compared the IVC resulting from the collective motion of the JVs generated by microwave irradiation and an external dc magnetic field H in an identical mesa of Bi2212 single crystal. In both cases the IVC exhibited similar sub-branch splitting arising from the coherent motion of microwave- and dc-field-generated JVs. In high dc magnetic fields, where the IVC merged into a single non-hysteretic curve, we observed kink structures which were similar to the predicted ones by the structural transformation of moving JV configuration [3].

In our sample, we reduced the doping level of the Bi2212 single crystals to lower the plasma frequency (f_p) of the stacked junctions ($f_p = 150$–200 GHz in as-grown crystals) below the experimentally available microwave-irradiation frequency ($f = 76$ GHz). Details of the sample fabrication procedure is described elsewhere [4]. The measurement configuration of the IVC is illustrated in the upper inset of Fig. 1. The IVC were obtained by repeatedly sweeping a home-made battery-powered current source with an output resolution better than 50 nA. The number of IJJs in the mesa determined from the number of quasiparticle branches in the IVC at $H = 0$ (not shown) was 12. The field-alignment procedure we adopted was similar to the one introduced in Ref. [5].

* Corresponding author. Address: Department of Physics, Pohang University of Science and Technology, Pohang 790-784, South Korea.
E-mail address: chsik@kbsi.re.kr (H.-S. Chang).

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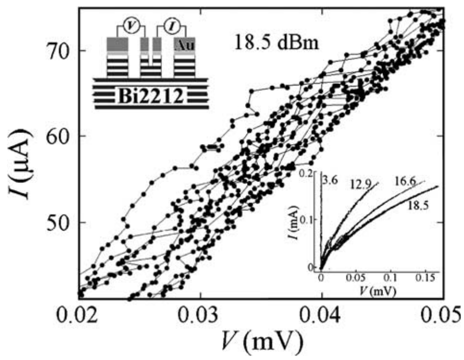

Fig. 1. Sub-branch splitting of Bi2212 single crystal mesa for $P = 18.5$ dBm. Upper inset: schematic measurement configuration. Lower inset: IVC for various microwave-irradiation power, figures denote the power level in dBm.

The lower inset of Fig. 1 shows the IVC for various microwave-irradiation power P. As observed previously [1], when P exceeds a certain onset value ($\sim$12.9 dBm) the supercurrent branch turns into a resistive state due to the flux-flow motion of JVs. The collective motion of the JVs which is coherent with the plasma excitation modes, is suggested by the appearance of multiple sub-branch splitting in the supercurrent branch as shown in Fig. 1 for $P = 18.5$ dBm. Although the sub-branch splitting itself is not as clearly distinguishable as it was in Ref. [1], the total number of the branches appears not to deviate much from that of the quasiparticle branches.

The IVC of the IJJs for various H values are shown in the inset of Fig. 2(a), which exhibit features different from those of the microwave-irradiated case. The IVC in the lower inset of Fig. 1 have downturn curvatures, while the IVC under external dc magnetic field show upturn curvatures. Furthermore, zero-resistance state and flux-flow resistive state coexist up to $H \approx 1$ T in a single curve as observed earlier by others [6]. Thus, the magnetic field component of the irradiated microwave cannot be directly simulated by the dc-field-generated JVs. The coherent motion of the field-generated JVs also manifests itself as multiple splitting of the supercurrent branch in the IVC as shown in Fig. 2(a) for $H = 0.3$ T. The number of branch splitting ($\sim$8) turns out to be a little smaller but still quite close to that of quasiparticle branches (12).

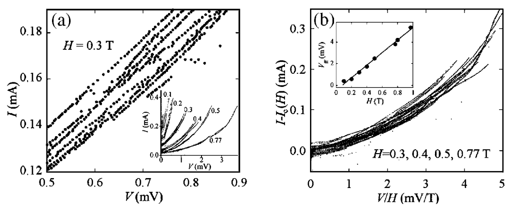

Fig. 2. (a) Sub-branch splitting of Bi2212 single crystal mesa for $H = 0.3$ T. Inset: IVC for various H values. (b) Rescaled IVC for $H = 0.3$–0.77 T. Inset: V_{ff} vs H.

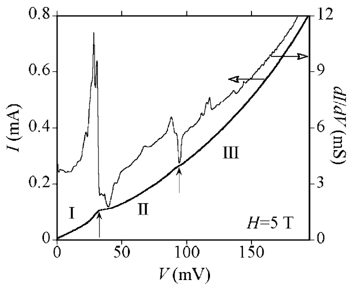

Fig. 3. IVC and dI/dV of Bi2212 single crystal mesa for $H = 5$ T. Two kinks divide the IVC into three regions.

As evident in the inset of Fig. 2(b), a linear proportionality exists between the flux-flow voltage V_{ff} and H, except for a small H offset due to finite pinning. The value of V_{ff} was extracted by taking the maximum voltage of the supercurrent branch for each H. When the pure resistive part of the IVC in the inset of Fig. 2(a), namely $I - I_c(H)$, is plotted as a function of the reduced voltage V/H, a scaling behavior is apparent as shown in Fig. 2(b). Such facts confirm that the resistive part of the supercurrent branch was indeed a result of the flux-flow resistance of JVs.

Increasing H above $\sim$1 T the zero-resistance part of the supercurrent branch disappears. Beyond $H = 3$–4 T the IVC of the IJJs merge into a single non-hysteretic curve with two distinctive kinks as designated by the two vertical arrows in Fig. 3 for $H = 5$ T. Sharp drops in the dI/dV curve confirm the existence of those kinks. The shape of the IVC is very similar to the numerically proposed one, where the kinks correspond to the boundaries dividing regions with different moving patterns of the JVs [3]. To confirm the proposition more directly, detection of the coherently radiating state in region III of Fig. 3 is required.

In summary, we confirmed the coherent motion of JVs by observing multiple sub-branch splitting of the supercurrent branch corresponding to different plasma-oscillation modes, generated by both microwave irradiation and an external dc magnetic field H. For $H > 3$–4 T the IVC displayed features similar to the structural transformation of moving JV patterns.

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