

# Collective motion of Josephson vortices in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ mesa structures

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## 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  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  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.

*Key words:* fluxon dynamics, Josephson vortex, intrinsic Josephson junction

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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  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  (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 ( $f_p=150\text{--}200$  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].

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 ( $\sim 12.9$

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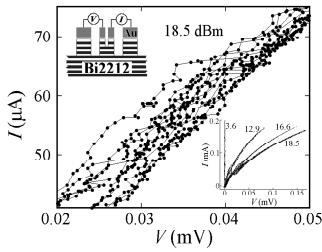


Fig. 1. Sub-branch splitting of Bi2212 single crystal mesa for  $P=18.5$  dBm. Upper inset; schematic measurement configuration. Lower inset;  $IVC$  for various microwave-irradiation power, figures denote the power level in dBm.

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 quasi-particle 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).

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 maxi-

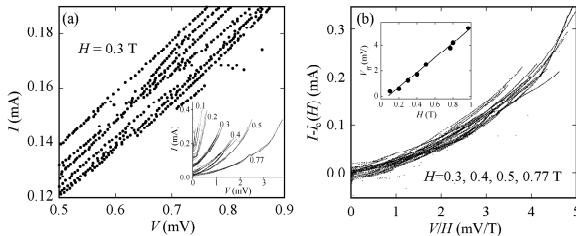


Fig. 2. (a) Sub-branch splitting of Bi2212 single crystal mesa for  $H=0.3$  T. Inset;  $IVC$  for various  $H$  values. (b) Rescaled  $IVC$  for  $H=0.3-0.77$  T. Inset;  $V_{ff}$  vs  $H$ .

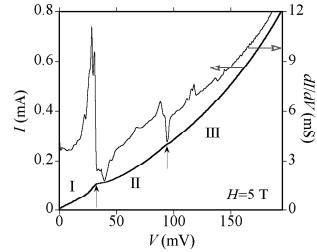


Fig. 3.  $IVC$  and  $dI/dV$  of Bi2212 single crystal mesa for  $H=5$  T. Two kinks divide the  $IVC$  into three regions.

mum 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. Further studies are required to clarify the difference between microwave- and field-generated JVs and to detect the plasma radiation inside the IJJs.

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