

## Quantitative Identification of the Flux-flow Modes in a Stack of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ Intrinsic Josephson Junctions

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We have measured the current-voltage characteristics of Josephson vortex-flow branches (JVFB), corresponding to a highly dense Josephson vortex regime, in stacks of intrinsic Josephson junctions of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$  single crystals sandwiched between two Au electrodes. We observed splitting of JVFB and switching between neighboring branches in the low current bias region in fields of about 4 T, with a spread in the resistivity of the branches. The result strongly indicates the existence of the resonance between the vortex lattice and collective transverse plasma modes, mediated by the inter-junction charging coupling incorporated with the strong inductive coupling.

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### I. INTRODUCTION

Intrinsic Josephson junctions (IJJs) forming in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$  (Bi-2212) single crystals, with the large superconducting energy gap in the  $\text{CuO}_2$  double-layers, provide high potential of THz-range applications [1, 2]. Especially, realizing THz-range radiation using vortex flow in stacked IJJs in the long-junction limit has been studied extensively [3–7]. It has been known that the formation of the rectangular lattice configuration of the moving vortices in stacked IJJs is required for in-phase and thus high-intensity radiation [4]. Collective resonance between transverse plasma modes and moving Josephson vortex lattice leads to the phase locking of the radiation that is mediated mainly by the inductive coupling of Josephson vortices between the neighboring junctions [5]. In a higher field range of  $H > H_d (= \phi_0/2d\lambda_J)$  collective resonance can be identified, where  $\phi_0$  is the flux quantum,  $d$  is the thickness of a junction, and  $\lambda_J$  is the Josephson penetration depth. In this dense-vortex state the non-Josephson-like emission [8] and the Shapiro resonance steps [9] in the Josephson vortex-flow characteristics have been observed, which confirmed the coherent motion of the Josephson vortex lattice over the whole stacked IJJs. In addition, inter-junction coupling by the nonequilibrium charging effect [10–12] can also affect the collective resonance behavior. The interplay between Josephson vortices and the plasma modes, however, still lacks clear understanding.

In this study, we identified the existence of the transverse plasma modes and the charging coupling effect manifested in the Josephson vortex flow branches (JVFB) of stacked IJJs in the field range above  $H_d$ . The charging coupling strength parameter, estimated from the width of the spread of multiple branches in JVFB, was 0.24, which is in a reasonable

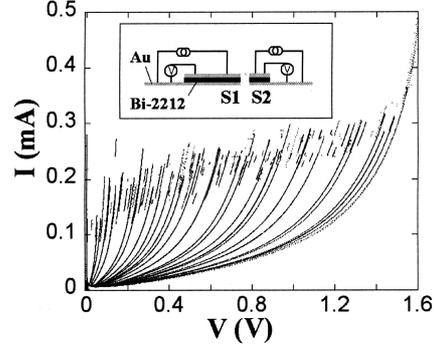


FIG. 1: The current-voltage characteristics of Au-sandwiched stack S1 in zero-field. Inset: the schematic sample geometry and two-terminal measurement configuration of each stack used in experiment

agreement with the theoretical estimation [12].

## II. EXPERIMENTAL DETAILS

Slightly overdoped Bi-2212 single crystals were grown by the solid-state-reaction method. Samples were micropatterned on the crystals into the geometry of a stack of junctions sandwiched between top (400 nm thick) and bottom (100 nm thick) Au electrodes [inset of Fig. 1]. The two samples, S1 and S2, used in this study were fabricated at the same time on the surface of a single crystal. The lengths of the two stacks were  $15.8 \mu\text{m}$  (S1) and  $7.5 \mu\text{m}$  (S2), respectively, and both stacks had the same width of  $1.4 \mu\text{m}$ . Superconducting-bilayer electrode in an intrinsic Josephson junction is much thinner than the  $c$ -axis London penetration depth  $\lambda_{ab}$  ( $\sim 0.17 \mu\text{m}$ ). Thus, the motion of Josephson vortices in the usual mesa structure is dragged by vortices in the basal stack, which may significantly distort the vortex dynamics in the mesa itself. Thus, in this study, the basal stack was removed by using the double-side-cleaving technique [2] to get rid of this undesired effect. The detailed sample preparation process is described elsewhere [13]. 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 pancake vortices. All the measurements in this study were done at 4.2 K in a two-terminal configuration [see the inset of Fig. 1]. The contact resistance was subtracted numerically.

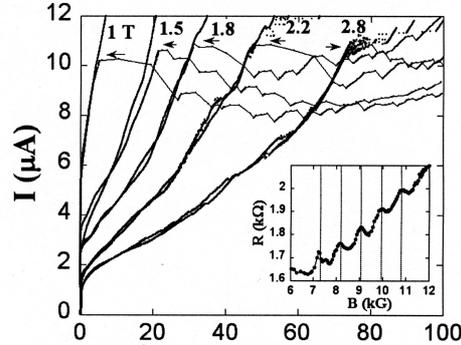


FIG. 2: Josephson vortex-flow branches of Au-sandwiched stack S1 in field ranges corresponding to  $H > H_d (= \phi_0/2d\lambda_J)$ . The arrows indicate the quasiparticle return currents in given fields. The inset shows the oscillation of the resistance in the sample S2, possibly due to the vortex lattice motion in the boundary potential of a stack.

### III. RESULTS AND DISCUSSION

Fig. 1 shows the current-voltage ( $I$ - $V$ ) characteristics of the sample S1. The total number of junctions, estimated from the number of quasiparticle branches, was 60. The average critical current density was  $1.27 \text{ kA/cm}^2$  and the normal-state resistance per junction, estimated from the linear portion in the high-bias range above the sum-gap voltage (not shown in the figure), was  $4.67 \text{ } \Omega$ . The value of the Josephson penetration depth  $\lambda_J$ ,  $0.27 \text{ } \mu\text{m}$ , leads to the characteristic field  $H_d$  to be  $2.5 \text{ T}$ .

The inset of Fig. 2 shows the vortex-flow resistance of S2 as a function of the external magnetic field. In the field range above about  $7 \text{ kG}$  the vortex-flow resistance exhibits the periodic oscillation with a field period of  $H_p \sim 900 \text{ G}$ , which is believed to be the same kind of resistance oscillation as observed previously by Ooi *et al.* [14]. The field corresponding to one flux quantum per junction of area  $7.5 \text{ } \mu\text{m} \times 1.5 \text{ nm}$  is  $1.84 \text{ kG}$ , which is about two times of  $H_p$ . It implies that, starting from about  $7 \text{ kG}$ , a regular triangular vortex lattice formed along the  $c$ -axis of the stack. The appearance of this periodic oscillation of the vortex-flow resistance indicates that a stack of IJJs sandwiched by Au films provide an ideal system to study the collective Josephson-vortex dynamics.

The main panel of Fig. 2 displays the JVFB of sample S1 for a single up-down bias sweep. With increasing the applied field the slope of the JVFB keeps increasing linearly with the field increase. Some wiggling of JVFB starts appearing for  $1.5 \text{ T}$ , which changes to voltage jumps for  $2.8 \text{ T}$ . This unusual structure takes place for a bias range below the return current  $I_r$  in each field, thus in the vortex-flow state. The onset field,  $2.8 \text{ T}$ , of the voltage jumps almost coincides with the value of  $H_d$ ,  $2.5 \text{ T}$ . For a higher field range (like at  $4.15 \text{ T}$  as shown in Fig. 3) in the sample S1 repeated up-down bias sweeps give rise to the multiple sub-branch structure in JVFB. On the other hand, the structure of JVFB shows voltage jumps for a single up-down bias sweep as seen in Fig. 2 for  $2.8 \text{ T}$ . Voltage

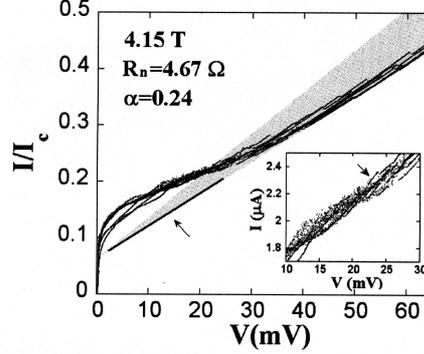


FIG. 3: Multiple sub-branches in JVFB of S1 in 4.15 T in comparison with the prediction of Eq. (1) for the inter-junction charging-coupling parameter  $\alpha = 0.24$  (as denoted by the grey region). The inset shows the chaotic behavior of the flux-flow resistivity in the low-bias region.

jumps and multiple sub-branch splitting in JVFB for a stack of IJJs in a long Josephson junction limit in external magnetic fields were observed previously and interpreted as an evidence for the coherent collective motion of the Josephson vortices [3, 15, 16]. According to an inductive-coupling model [4, 7, 17] the moving Josephson vortex lattice evolves from a triangular one to a square one with increasing the tunneling bias current. The vortex lattice resonates with the transverse plasma oscillation modes of number  $N$ , the number of IJJs in a given stack. Since transverse plasma modes have different velocities with each other so that they generate the multiple sub-branches in the JVFB in inductively coupled junctions. Voltage jumps to another sub-branches occur as velocity of the vortex lattice exceeds any of the plasma mode velocity. Thus, the occurrence of the voltage jumps and the switching between neighboring multiple sub-branches as in Figs. 2 and 3, respectively, strongly indicates that coherent collective motion of the vortex lattice was present.

Each multiple sub-branch in Fig. 3 is linear in the bias range shown. When linear sub-branches of S1 are extrapolated from a high bias to a low bias all of them converge to a single point on the current axis, so that one can define the width of spread of the multiple sub-branches (denoted by the grey region in Fig. 3). This convergent behavior can also be shown for shorter linear portion in the case of single up-down bias sweep as shown in Fig. 2 for the sample S1. The convergent current value almost coincides with the current bias where a finite resistance starts appearing in the  $I$ - $V$  curve, which implies that the current value corresponds to the vortex depinning current.

Recently, it has been reported [12] that the width of spread of multiple sub-branches at the linear  $I$ - $V$  regime of low bias JVFB can give information on the inter-junction charging coupling strength in a stack of IJJs, represented by the parameter  $\alpha$ . According to charging coupling model [10] the voltage due to the time-varying gauge-invariant phase difference in one Josephson junction is coupled with neighboring junctions as  $\frac{\phi_0}{2\pi} \frac{\partial \phi_{n,n-1}}{\partial t} = V_{n,n-1} - \alpha(V_{n+1,n} - 2V_{n,n-1} + V_{n-1,n-2})$ . Here  $\phi_{n,n-1}$  is the difference in the gauge-invariant phase difference  $\phi$  between the  $n$ th and  $(n-1)$ th superconducting layers,  $\alpha = \frac{\epsilon \mu^2}{st}$  (0.1~0.4)

is charging coupling parameter, and  $\mu$  is the Debye length of the superconducting charges.  $s$  ( $=0.3$  nm) and  $t$  ( $=1.2$  nm) are the thicknesses of the superconducting and the insulating layers, respectively. The time variation of the interlayer phase difference  $\frac{\partial\phi_{n,n-1}}{\partial t}$  due to vortex motion gives rise to the JVFB which is coupled to that in the neighboring junctions. A moving vortex lattice corresponding to each plasma mode exhibits different flux-flow resistivity. Thus, the splitting of the linear JVFB in the low-bias region strongly suggests the existence of the collective motion of the Josephson vortices in the presence of the finite charging effect. In the absence of the charging effect the JVFB are supposed to appear as a single curve. Since the width of the spread is related to the strength of the charging effect, the spread can be used as a convenient way to measure its strength.

In this study we analyzed the  $I$ - $V$  data by adopting the relation suggested by the charging-coupling model, while adding a phenomenological term to take into account the resistivity arising from the motion of vortices generated by the external magnetic field  $H_{\text{ext}}$ .

$$V_m = N \frac{I - I_p}{I_c} \left[ \frac{V_c}{A_m} + k H_{\text{ext}} \right], \quad (1)$$

where  $A_m = 1 + 2\alpha(1 - \cos(m\pi/N + 1))$ ,  $V_c = I_c R_n$  ( $=1.31$  mV).  $I_c$  is the critical Josephson tunneling current at a given applied field,  $I_p$  is the depinning current, and  $k$  is a constant. The mode index  $m$  varies from 1 to the total number of IJJs in a stack,  $N$ . Since samples are in the quasi-particle state for  $V > V_{co}$  (the maximum voltage in JVFB; not shown) we define  $I_c$  as the critical current corresponding to  $V_{co}$  at a given field. The velocity of vortices is assumed to change linearly for varying bias current with  $k$  as a proportionality constant.

Fig. 3 shows the JVFB of S1 in comparison with the spread (the grey region) predicted on the basis of Eq. (1), where the value of  $\alpha$  was determined. Without the charging effect ( $\alpha=0$ ) the spread of multiple branches disappears as shown by the single line pointed by an arrow in the main panel of Fig. 3, where the value of  $k$  determines the slope of the lines. With increasing the value of  $\alpha$  the width of spread increases from the lines to the left. In the analysis the sub-branch denoted by an arrow in the inset of Fig. 3 was taken as the lowest-resistance branch, corresponding to the lowest mode velocity. In the very low bias region the JVFB become nonlinear without any voltage jumps in the  $I$ - $V$  curves as seen in detail in the inset of Fig. 3. The region was excluded in the analysis. The best-fit value of  $\alpha$  of S1 at 4.15 T was 0.24, which was in the range of theoretical estimate [12], 0.1~0.4, and in a reasonable agreement with the values of 0.36~0.44, observed recently in  $\text{SmLa}_{1-x}\text{Sr}_x\text{CuO}_{4-\delta}$  by optical measurements [18]. The corresponding value of the  $k$  was 0.377 mV/T. For more detailed analysis the inter-junction coupling arising from the charge-hole imbalance [11] as well as the dissipation effect of quasiparticles in the  $ab$ -plane [17] should be taken into account.

#### IV. CONCLUSION

In summary, we studied the JVFB of stacks of intrinsic Josephson junctions sandwiched between Au electrodes in the range of dense vortex state. The double-side-cleaving technique made it possible to investigate the dynamics of coupled Josephson vortices without interferences from the addendum basal stack. We observed the voltage jumps for a single up-down sweep and multiple branches for repeated up-down sweeps. The observed vortex flow characteristics were in reasonable quantitative agreement with the inter-junction charging coupling incorporated with the inductive coupling. The multiple branches in JVFB were shown to be caused by the charging coupling effect and the estimated value of the charging coupling parameter  $\alpha$  was in good agreement with the theoretical prediction. The strong emission of electromagnetic wave is expected to occur at each position of voltage jumps [8]. The observation of the multiple subbranches in this study from sandwiched stacks may serve as a crucial guidance to setting up a proper condition to extract THz-range radiation from a stack of IJJs.

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