PHYSICAL REVIEW B, VOLUME 63, 144523

Coherent mode splitting of microwave-induced fluxons in HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals

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(Received 14 December 2000; published 22 March 2001)

The microwave response of small stacks of intrinsic Josephson junctions in HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals was studied. When irradiated with a microwave of frequencies higher than the junction plasma frequency, the supercurrent branch becomes resistive and splits into multiple subbranches. The number of subbranches turns out to be identical to the number of intrinsic Josephson junctions in the mesa within the experimental error. The behavior of the subbranches fits well the predicted Josephson fluxon dynamics in a strongly coupled stack of junctions.

DOI: 10.1103/PhysRevB.63.144523 PACS number(s): 74.72.Hs, 74.50.+r, 74.80.Dm, 85.25.Cp

Recently, the dynamics of Josephson vortices in vertically stacked superconducting tunnel junctions has attracted substantial theoretical[1–3] and experimental interest.[4–9] Represented by a set of coupled sine-Gordon equations, the vortex system is not only a good example of coupled nonlinear systems but also has a high potential for applications to tetrahertz-range devices, such as local oscillators and mixers.[10]

Highly anisotropic layered superconductors, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystals, can be considered as natural superlattices of the intrinsic Josephson junctions (IJJ's), in which the *c*-axis transport is dominated by the Josephson tunneling.[4] Since the thickness of the superconducting electrodes is much smaller than the London penetration depth λ, the Josephson vortices in different layers are strongly coupled and their collective motion is expected. Applied with a static magnetic field, a stack of IJJ's has been observed to exhibit Josephson flux-flow motion,[5,6] geometric resonances,[7] and non-Josephson radiation.[8] Theoretical studies have shown that for a system with N strongly coupled Josephson junctions, there should be N different characteristic modes of Josephson vortex motion.[1,2] Previous studies have exhibited signatures of such coherent modes[6] but indisputable evidence is still lacking.

In this paper, we report the microwave response of mesas of IJJ's fabricated on the surface of HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+\delta}$ (HgI_2-Bi2212) single crystals. Intercalated single crystals have a plasma frequency that easily becomes lower than the available microwave irradiation frequency, while maintaining a sufficiently strong interlayer coupling to allow a collective vortex motion. We have observed that with irradiation by a 73–76-GHz microwave, the supercurrent branch becomes resistive, splitting into multiple subbranches. The total number of subbranches is close to the number of IJJ's in the mesa and the maximum cutoff voltage of each subbranch fits qualitatively well the theoretical prediction based on the coherent motion of Josephson vortices.

HgI_2-Bi2212 single crystals were synthesized by the stepwise reaction method.[11] X-ray-diffraction analysis indicated that the spacing between the neighboring CuO_2 bilayers expands by 7.2 Å due to the intercalation. The superconducting transition temperature was $T_c = 76.8$ K, lower than that of the pristine Bi2212, which was 82 K.[12] A mesa structure was formed on the surface of HgI_2-Bi2212 single crystals using conventional photolithography and an Ar-ion etching technique.[13] We studied three mesas $R2$, $R3$, and $L4$, fabricated with almost the same lateral dimensions, 20×40 μm^2. The junction critical current I_c at 4.2 K and the *c*-axis normal-state resistivity ρ_c extracted from the high-bias linear portion of I-V curves were 2.5 mA (1.2 and 1.6 mA) and 120 Ω cm (79 and 86 Ω cm) for mesa $R2$ ($R3$ and $L4$). A microwave of frequencies $f = 73$–76 GHz from a frequency-locked Gunn diode oscillator was inductively coupled to the specimens through a rectangular waveguide. For the application of a microwave of relatively low frequencies (3–20 GHz), a synthesized sweeper (HP83751B) and coaxial waveguide were used. All the dc measurements were carried out using a four-probe configuration with a low-pass filter connected to each electrode terminal located at room temperature.

The I-V characteristics of mesa $R3$ without microwave irradiation is shown in the inset of Fig. 1. Clearly shown are multiple quasiparticle branches with maximum voltage spacing of ~ 15 mV. The number of quasiparticle branches is $N = 23$, corresponding to the number of IJJ's in the stack. With irradiation of a microwave of $f = 75$ GHz and power $P = 17.7$ dBm, the junction critical current I_c decreases drastically, together with shrinking of the quasiparticle branches as in Fig. 1, but the voltage interval between the branches remains almost unchanged.

Figure 2(a) shows the gradual evolution of the supercurrent branch with increasing P. I_c keeps decreasing with the increase of the microwave power P. Before the complete reduction of I_c, however, the supercurrent branch becomes resistive when P exceeds a certain onset value P_c. Each curve has a linear region for low biases with its slope increasing with increasing P. One can also notice that each resistive branch splits into multiple subbranches for higher P.

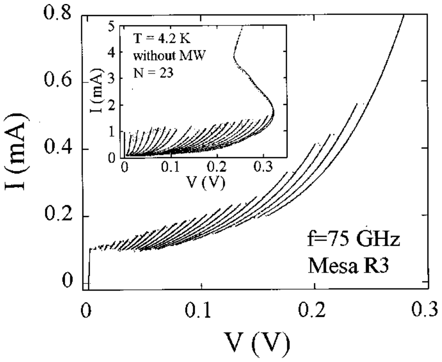

FIG. 1. I-V curves of mesa $R3$ at $T=4.2$ K with irradiation of a microwave of $f=75$ GHz and power $P=17.7$ dBm. Inset: I-V curves without irradiation of a microwave. The total number of IJJ's in the mesa is $N=23$.

A more detailed view of the subbranches in the range of $0.35 \lesssim V \lesssim 0.55$ mV for $P=17.7$ dBm is shown in Fig. 2(b). The voltage spacing between neighboring subbranches is about 3–20 μV, depending on the microwave power and the bias current level. Respective subbranches have maximum cutoff voltages denoted as arrows in Fig. 2(b). Increasing the dc bias current from zero, the I-V curve first follows the outermost subbranch with maximum voltage value for a given bias current. At the cutoff voltage of the subbranch, the I-V curve jumps to the neighboring subbranch, accompanied by a sudden drop of the output voltage. By sweeping the bias current back and forth repeatedly, all the subbranches were identified. The number of distinguishable subbranches in the fully scanned data for $P=13.9$ and 17.7 dBm is 23 ± 2, which is identical to the number of IJJ's in the stack within the experimental error.

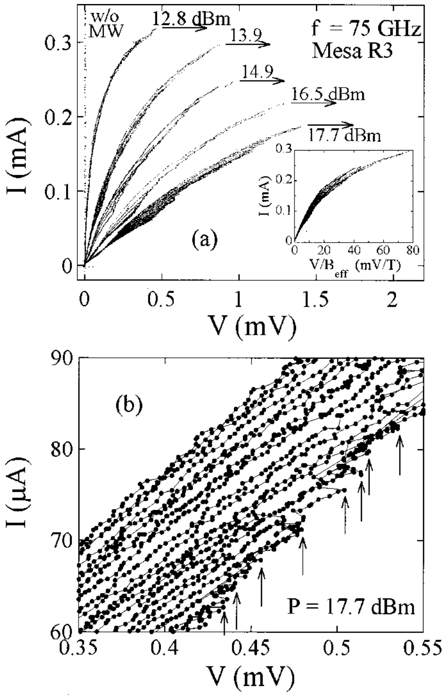

FIG. 2. (a) The evolution of the supercurrent branch with irradiation of a microwave of $f=75$ GHz at $T=4.2$ K. The microwave power was $P=-\infty$, 12.8, 13.9, 14.9, 16.5, and 17.7 dBm, from left to right. The arrows indicate switching to nearby quasiparticle branches. Inset: I-V curves with voltages rescaled by the microwave-induced effective magnetic induction B_{eff}. (b) The enlarged view of the multiple subbranches for $P=17.7$ dBm. The lines are guides to the eyes. The arrows indicate the cutoff voltages for different modes.

A few possible causes for the multiple subbranches can be considered. When irradiated with a microwave of frequency f, a Josephson junction may exhibit discrete current steps at voltages $V_m = m\Phi_0 f$, where m is an integer and Φ_0 is the flux quantum.[14] But the observed voltage spacing between adjacent subbranches does not satisfy the above relation. We believe that the plasma frequency of our intercalated IJJ's $f_p = 51$ GHz, estimated from the junction capacitance $C = 4.3$ μF/cm^2 and the dielectric constant $\epsilon = 9.5$, was not sufficiently lower than the irradiation frequency to satisfy the criterion for the observation of Shapiro steps.[15] Here, the value of ϵ was estimated from the ratio between the critical current and the return current.[16]

Geometric resonance can be another mechanism of the subbranches.[17] Considering phase locking between fluxons for a mesa of N strongly coupled IJJ's, the most prominent Fiske steps are expected at voltages[1,7] $V_{FS,m} = mN\Phi_0 c_N/2L$, where m is an integer, L is the lateral dimension of the mesa, and c_N is the lowest velocity of a triangular fluxon lattice as given by $c_N = c_0/\sqrt{2}$. Here c_0 is the Swihart velocity[16] $c_0 = 2\pi f_p \lambda_j$. For mesa $R3$, the Josephson penetration depth[2] λ_j is about 0.6 μm, giving $c_N = 1.3 \times 10^5$ m/s or the corresponding voltage spacing of $\Delta V_{FS} \approx 160$ μV. However, since the observed voltage spacing is in the range of 3–20 μV, the geometrical resonance cannot be the origin of the branch splitting.

Branch splitting similar to our observation has been obtained by Lee *et al.* in a mesa of Bi2212 with magnetic fields applied parallel to the ab plane.[6] In their study each subbranch has been attributed to a specific mode of coherent Josephson vortex motion in coupled Josephson junctions. However, since the number of identified subbranches ($\lesssim 10$) is far smaller than the number of IJJ's in the mesa ($\gtrsim 200$) their study cannot be considered extensive enough to allow a quantitative comparison to the theoretical prediction.[1,2] In this study, instead of an external magnetic field a microwave was applied. Like a static magnetic field, a high-power microwave is known to produce Josephson vortices in a long Josephson junction, giving rise to flux-flow steps in the I-V characteristics.[9] The average effect of an applied microwave on a Josephson junction can be taken into account by introducing an effective magnetic induction B_{eff} that is proportional to the microwave amplitude or a square root of the microwave power $P^{1/2}$. P_c may correspond to the lower critical field of the IJJ's and Josephson vortices are generated in a stack for $P > P_c$.[18]

Our observation results support the predicted dynamical behavior of microwave-induced Josephson vortices. In the inset of Fig. 3 the flux-flow resistivity ρ_{ff}, extracted from the low-bias linear slope of each resistive branch in Fig. 2(a), is exhibited as a function of $P^{1/2}$. The inset shows that above an

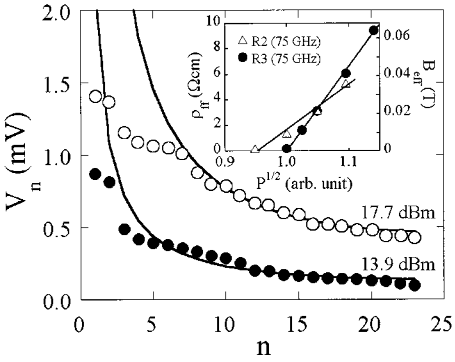

FIG. 3. The cutoff voltage V_n as a function of the mode index n for $P=13.9$ (filled circle) and 17.7 dBm (open circle). The filled lines are calculated results using Eq. (1) with the Swihart velocity as the fitting parameter. Inset: microwave power dependence of the flux-flow resistivity ρ_{ff} and B_{eff}. The lines are guides to the eyes.

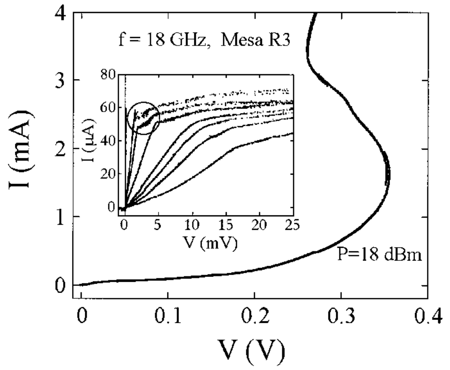

FIG. 4. *I-V* characteristics with irradiation of a microwave of frequency $f=18$ GHz and power $P=18$ dBm. Inset: detailed view of the low-bias flux-flow branches with microwave power of $P=5$, 8, 10, 12, 13, 15, 16, and 18 dBm, from left to right.

onset power P_c, ρ_{ff} increases almost linearly with $P^{1/2}$, consistent with the previous observations.[9] The linear slope and P_c depend on the microwave coupling to a mesa. In Josephson-coupled layered superconductors, the viscous flux motion due to a magnetic induction B can be expressed as[19] $\rho_{\mathrm{ff}}=2.822(B/B^*)\rho_c$ for $B \ll B^*$, in which B^* is the critical field defined as $B^* \equiv \Phi_0/[\lambda_j(t+d)]$ and ρ_c is the normal-state c-axis tunneling resistivity. Here, t and d are the thickness of the barrier of each junction and that of a $\mathrm{CuO_2}$ electrode, respectively. For $\mathrm{HgI_2}$-Bi2212 we have $t=1.9$ and $d=0.35$ nm, giving $B^* \simeq 2.3$ T (1.5 T) for mesa $R2$ ($R3$). For mesa $R3$, $P=17.7$ dBm induces an effective field of $B_{\mathrm{eff}}=0.064$ T that is comparable to an external magnetic field used in previous studies by others.[5–7] Dividing the voltages by the value of B_{eff} for each power level, the resistive branches in Fig. 2(a) exhibit an excellent scaling behavior as illustrated in the inset of Fig. 2(a). This behavior, similar to the one obtained previously in a static magnetic field,[5,6] is consistent with the idea of flux-flow motion of microwave-induced Josephson vortices.

Splitting into multiple subbranches can be explained in terms of the coherent Josephson vortex motion. For N stacked Josephson junctions, N different collective modes of an electromagnetic wave are available with the characteristic velocities given by[1,2]

$$c_n=\frac{c_0}{\sqrt{1-\cos[\pi n/(N+1)]}}, \quad n=1,2,\ldots,N. \tag{1}$$

The velocity of Josephson vortices increases with the bias current until it is bounded by the mode velocity of an electromagnetic wave as represented by Eq. (1). Thus, each mode velocity of an electromagnetic wave corresponds to a different maximum flux-flow velocity, giving rise to a different maximum output voltage. It indicates that each subbranch in Fig. 2(b) represents a specific mode of Josephson vortex motion. The cutoff voltage of the nth mode is given by[5,6] $V_n=Nc_nB_{\mathrm{eff}}(t+d)$. Figure 3 shows V_n for mesa $R3$ as a function of the mode index n. The solid lines are calculated results using Eq. (1) with the best-fit values for the Swihart velocity $c_0=3.5\times10^5$ m/s (2.0×10^5 m/s) for $P=13.9$ dBm (17.7 dBm), respectively, which correspond to $B_{\mathrm{eff}}=0.011$ T (0.064 T) as determined in relation to the inset of Fig. 3. These values are close to the estimated value of the Swihart velocity 1.9×10^5 m/s. But the data deviate significantly for low index n or fast fluxon modes. Such deviation may be attributed to the unstable flux configurations for the fast modes. A possible slowdown of the vortex motion due to the energy loss following the Cherenkov radiation[8] is another cause of the deviation.

With irradiation of a microwave of frequencies 3–20 GHz, no subbranches were observed. In this case, as illustrated in Fig. 4, only single resistive branches were observed with a step feature (inside the circle in the inset) for some power levels, similar to the ones reported by others.[9] For a long Josephson junction only a wave of $f>f_p$ can travel through the junction.[16] For $f<f_p$, due to the resulting nonuniform distribution of a microwave, each IJJ in the mesa may have a different number of Josephson vortices along with a different vortex velocity that in turn results in an incoherent vortex motion. Thus a microwave of $f>f_p$ with $P>P_c$ is required for the observation of the coherent fluxon modes. For $f=73$–76 GHz used in this study, the frequency requirement was satisfied by suppressing the junction critical current via the intercalation of the inert molecules. Although further studies are required to clarify the detailed dynamics of microwave-induced Josephson vortices, to our best knowledge, our data provide the observation in IJJ's of the coherent mode splitting consistent with the existing theoretical prediction.[1,2]

In summary, we have observed multiple subbranches in the *I-V* characteristics of stacks of IJJ's, irradiated with a microwave of frequencies higher than the plasma frequency. Our data provide a strong indication that each subbranch represents a coherent mode of the collective motion of microwave-induced Josephson fluxons with the cutoff voltage in good agreement with the theoretical prediction.

This work was supported in part by KRISS Project No. 00-0502-030. This work was also supported by BSRI and MARC in POSTECH, and by the Center for Excellency (SRC) administered by KOSEF.

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