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Dynamics of microwave-induced fluxons in HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+\delta}$ Josephson stacks

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Abstract

The microwave response of intrinsic Josephson junctions (IJJs) in mesa structures formed on HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals was studied in a range of microwave frequencies above the junction plasma frequency. Under 73–76 GHz microwave irradiation, the supercurrent branch becomes resistive above a certain onset microwave power. At a low current bias, the current–voltage characteristics show linear behavior, while at a high current bias, the resistive branch splits into multiple sub-branches. The voltage spacing between neighboring sub-branches increases with the microwave power and the total number of sub-branches is almost identical to the number of IJJs in the mesa. All the experimental results suggest that each sub-branch represents a specific mode of collective motion of Josephson vortices generated by the microwave irradiation in a stack of IJJs.

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Highly anisotropic layered superconductors such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ and $Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$, where the *c*-axis transport below thesuper conducting transition is dominated by the Josephson tunneling between superconducting CuO_2 bi-layers, can be considered as a series stack of naturally formed intrinsic Josephson junctions (IJJs) in the *c*-axis direction [1]. In a $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal, the thickness of a superconducting layer is far smaller than the London penetration depth, resulting in strong interlayer vortex coupling. Stacks of IJJs in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals are known to exhibit diverse nonlinear behaviors in the presence of an external magnetic field [2–7] or under microwave irradiation [8–11]. Due to their strong coupling, Josephson vortices in different layers of IJJs generated by an external magnetic field tend to move collectively in a bias current. It is known that N different collective modes of Josephson vortex motion are possible for a system with N coupled Josephson junctions [12–15]. Recently Lee et al. have shown that the supercurrent

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branch of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals becomes resistive and splits into multiple sub-branches in the presence of a static magnetic field [4]. The authors attributed each sub-branch to a specific mode of collective motion of Josephson vortices. The number of sub-branches observed, however, was far less than the number of Josephson junctions in their mesa, which casts doubt on the relevance of the observed sub-branches to the specific collective modes of Josephson vortices.

In this paper, we report microwave response of IJJs in mesas formed on HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals. We used the intercalated single crystals to reduce the plasma frequency to a level of experimental convenience, while maintaining strong-enough interlayer vortex coupling to allow a collective vortex motion. We will discuss the results from two typical mesas, R2 and R3. Under microwave irradiation of 73–76 GHz the supercurrent branch becomes resistive and splits into multiple sub-branches, which is similar to what Lee et al. have observed in an external magnetic field but in the absence of a microwave. The voltage spacing between neighboring sub-branches increases with microwave power and the total number of sub-branches turns out to be the same as that of IJJs in a mesa. Our experimental results give a direct evidence for the existence of collective modes of Josephson vortex motion in vertically stacked long Josephson junctions.

Stacks of IJJs were fabricated on the surface of HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals [16] using photolithography and Ar-ion etching technique. Details of the sample fabrication procedure are described elsewhere [17]. The size of a mesa was 20×40 μm^2. All the measurements were done at $T = 4.2$ K using a four-probe dc measurement configuration, while the microwave of frequency 73–76 GHz from a Gunn diode source was transmitted through a rectangular waveguide and inductively coupled to the mesa.

Fig. 1 shows the dc current–voltage (I–V) characteristics of mesa R3 in the absence of microwave irradiation. Clearly shown are multiple quasiparticle branches with maximum voltage spacing of about 15 mV. The number of quasiparticle branches is 23, corresponding to 23 IJJs included in the mesa. The average critical current ~1.2 mA or the critical current density ~150 A/cm^2 is reduced from the value of the pristine $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals by almost a factor of 10. The corresponding junction plasma frequency is about 51 GHz. The Josephson penetration depth $\lambda_J = 0.6$ μm (0.4 μm) for mesa R3 (R2). Thus both of the mesas used in this study are in the long-junction limit.

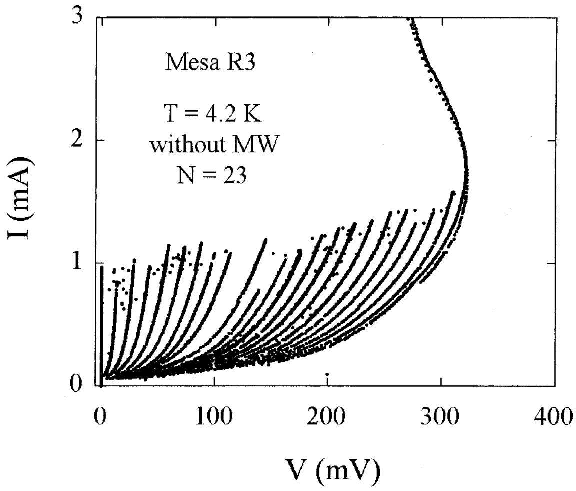

Fig. 1. I–V characteristics of mesa R3 measured at 4.2 K, without any microwave irradiation.

With irradiation of 75 GHz microwave, which is higher than the plasma frequency, the junction critical current is reduced with the shrunken quasiparticle branches (Fig. 2). But even at the maximum available microwave power of 18.4 dBm (nominal value) quasiparticle branches do not disappear completely. Instead, the supercurrent branch becomes resistive. Mesa R2 exhibits a similar behavior of quasiparticle branches both in the absence and in the presence of microwave irradiation. In Figs. 3 and 4 the gradual evolution of the supercurrent branch of mesas R3 and R2, respectively, with varying microwave power is illustrated. There is onset microwave power for both mesas above which the supercurrent branch becomes resistive. It has been known that under a strong enough microwave Josephson vortices can be generated in a long Josephson junction [8–11]. The microwave-generated vortices then move in the presence of an external bias current, inducing a

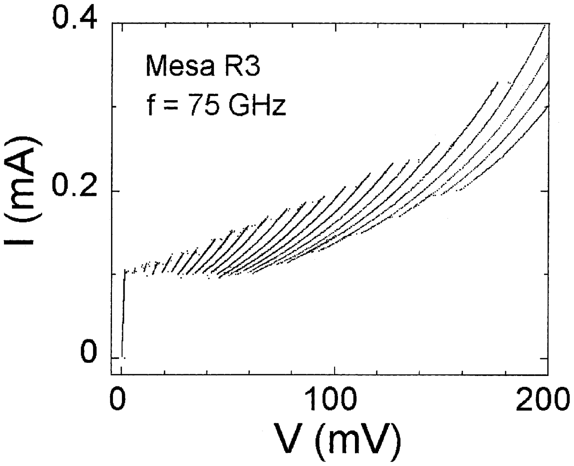

Fig. 2. I–V characteristics of mesa R3 with the irradiation of a microwave of frequency 75 GHz. The nominal microwave irradiation power was 18.4 dBm.

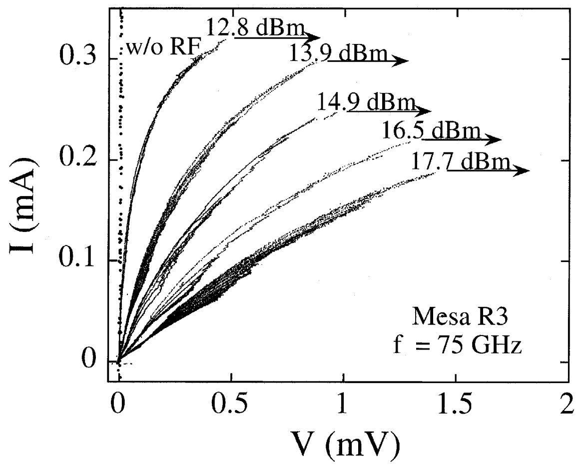

Fig. 3. I–V characteristics of mesa R3 measured at 4.2 K, with increasing the irradiation power of a microwave of frequency 75 GHz. For the power beyond an onset the supercurrent branch becomes resistive and splits into many sub-branches.

flux-flow potential difference across the junction. The number of Josephson vortices should be proportional to the amplitude of the microwave or the square root of the irradiation power. Thus, for a low-enough dc bias, the output voltage due to the motion of Josephson vortices varies linearly with the bias current.

In Fig. 3, with increasing microwave power, the supercurrent branches split into resistive sub-

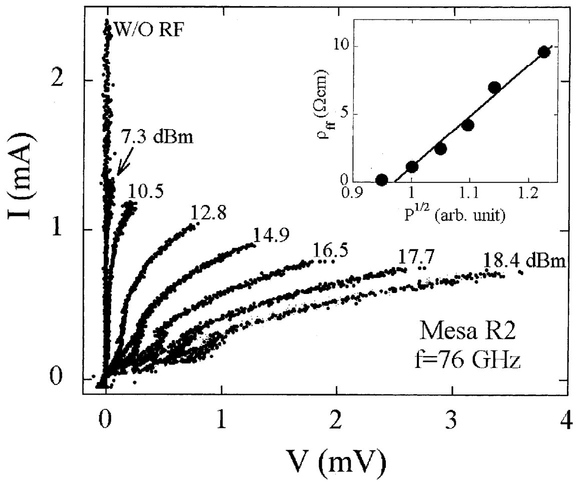

Fig. 4. I–V characteristics of mesa R2 with only a single sweep of the bias current. Inset: observed flux-flow resistivity which exhibits proportionality to the square root of the irradiation power above an onset.

branches. The maximum number of branches for the microwave power of 17.7 dBm is the same as the number of the IJJs in the mesa, $N = 23$, within the experimental error. The branch splitting is characterized by a voltage jump at a certain bias current. Increasing the bias current from zero, the dc I–V characteristics exhibit a linear region where no branch splitting is visible. With increasing the bias current further, the resistive branch becomes unstable and I–V curve jumps to other neighboring branches accompanying a sudden decrease in the voltage. This feature is distinctive from the voltage jumps observable in the main quasiparticle branches, where jumping between branches always takes place in such a way as to increase the voltage. The voltage spacing between neighboring sub-branches depends on the microwave power and the bias current level.

In the inset of Fig. 4 the flux-flow resistivity is plotted as a function of the square root of the irradiated microwave power. The flux-flow resistivity was obtained from the low-bias linear region of I–V characteristics for each power level. The inset confirms that, above a certain onset power, the flux-flow resistivity has a linear dependence on the microwave amplitude. It also confirms that transforming of the supercurrent branch into the set of resistive branch is due to the motion of microwave-generated Josephson vortices.

Similar branch splitting has been observed by Lee et al. in mesas prepared on $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals. In their study, in a static magnetic field parallel to the plane of IJJs, the supercurrent branch becomes resistive and splits into multiple sub-branches. The voltage interval between neighboring sub-branches increases with the magnetic field. In our study, instead of a static magnetic field, a microwave of frequency higher than the plasma frequency was irradiated. One noticeable difference in the feature of the I–V characteristics in comparison with the work by Lee et al. is the curvature of the sub-branches. In this work, the sub-branches in the I–V characteristics have a downturn curvature, i.e., $\partial^2 I/\partial^2 V < 0$, while Lee et al. have observed the branch splitting only in resistive branches with an upturn curvature. They attributed the absence of branch splitting for the mesa with $\partial^2 I/\partial^2 V < 0$ to a large damping effect, usually seen in proximity-type Josephson junctions. This argument does not hold for our mesas, however, since they are in the limit of low damping. In their work the observed number of sub-branches was about 10 which was far smaller than the total number of IJJs $N \sim 250$ in the mesa used. This is another key difference from our observation, where the number of sub-branches 23 is the same as the number of IJJs within the experimental error.

As for the splitting of superconducting branches, a few possible mechanisms can be considered. It is well known that a Josephson junction with a large McCumber parameter ($\beta = 2eI_cR_n^2C/\hbar \gg 1$) can produce discrete voltage steps with irradiation of a microwave of frequency greater than the plasma frequency [18], $f_p = (eI_c/\pi\hbar C)^{1/2}$. Here I_c is the junction critical current, R_n is the junction resistance, and C is the junction capacitance. Microwave-induced voltage steps observable in an underdamped Josephson junction usually cross the zero-bias current line with a regular voltage interval, $\Delta V = hf/2e$, where f is the applied microwave frequency. Our previous study [19] has illustrated that the surface junction of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals with significantly reduced critical current density exhibits zero-crossing constant voltage steps with irradiation of a microwave of frequencies above the plasma frequency. The branch splitting shown in Fig. 2, however, is not related to the zero-crossing constant-voltage steps, since the voltage spacing between adjacent sub-branches is not uniform and does not satisfy the Josephson relation $\Delta V = hf/2e$.

Another possible cause of the branch splitting is the geometrical resonance [20,21] of the supercurrent wave in a long Josephson junction. In the presence of static magnetic and electric fields, the supercurrent in a long Josephson junction oscillates both in time and space. If the lateral size of a junction becomes an integral multiple of the half wavelength of the oscillating supercurrent, it forms a standing wave in the Josephson junction. The formation of a standing wave is evidenced by the current peaks, known as the Fiske steps, in the I–V characteristics. Fiske steps occur at voltages which are independent of microwave power or magnetic field intensity. For our sample, the voltage spacing increase with microwave power, implying that the observed sub-branches are not related to the Fiske resonance.

The observed sub-branches in mesa R3 may be explained in terms of a collective motion of Josephson vortices generated by microwave irradiation. It has been shown that the mode velocity of a electromagnetic wave in a system of N stacked Josephson junctions is given by [12–14]

$$c_n = \frac{c_0}{\sqrt{1 - \cos\left(\frac{n\pi}{N+1}\right)}} \quad (n = 1, 2, \ldots, N), \tag{1}$$

where c_0 is the Swihart velocity [22]. The output voltage is proportional to the mode velocity, implying that for a given bias current, N different output voltages are permitted. In our experiment the maximum number of sub-branches is close to the number of Josephson junctions in the stack, which is consistent with the theoretical prediction.

In summary, we have observed characteristics resulting from the microwave-induced fluxon motion in HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+\delta}$ Josephson stacks in a long-junction limit even in the absence of an external magnetic field. The supercurrent branch becomes resistive and splits into sub-branches with irradiation of high-power microwave above the junction plasma frequency. The number of sub-branches turns out to be the same as that of the intrinsic junctions in a mesa. Each sub-branch represents a specific mode of the collective motion of microwave-induced Josephson vortices.

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