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Coherent motion of fluxons in stacked intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals

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$Bi_2Sr_2CaCu_2O_{8+x}$ 단결정 선천성 조셉슨 접합에서의 플럭손 결맞음 운동

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Abstract

We studied the flux-flow current-voltage characteristics of microwave-generated fluxons formed in serially stacked intrinsic Josephson junctions fabricated on HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) single crystals. With increasing the irradiation power of 73□76 GHz microwave, the supercurrent branch became resistive and split into multiple sub-branches. Each sub-branch represented a specific mode of collective motion of Josephson fluxons. We also observed similar branch splitting in a mesa prepared on an underdoped Bi2212 single crystal in a static magnetic field.

Highly anisotropic layered superconductors, such as $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) single crystals, form naturally stacked intrinsic Josephson junctions (IJJs), the *c*-axis transport of which is dominated by the Josephson tunneling [1]. The dynamics of Josephson fluxons in such IJJs is represented by a set of coupled sine-Gordon equations [2]. Since the thickness of the superconducting layers is much smaller than the London penetration depth λ, the Josephson fluxons in different layers are strongly coupled and their collective motion is expected. For a system with *N* strongly coupled Josephson junctions, *N* different characteristic modes are expected for the Josephson fluxon motion [2].

We report on the dynamics of the Josephson fluxons formed in mesas of IJJs which were fabricated on the surface of either HgI_2-intercalated $Bi_2Sr_2CaCu_2O_{8+x}$ (HgI_2-Bi2212) crystals or underdoped Bi2212 crystals. We generated Josephson fluxons by the irradiated microwave in HgI_2-Bi2212 crystals or by external magnetic fields in underdoped Bi2212 crystals. HgI_2-Bi2212 crystals had a plasma frequency which easily became lower than the available measuring microwave frequency, while maintaining a sufficiently strong interlayer coupling

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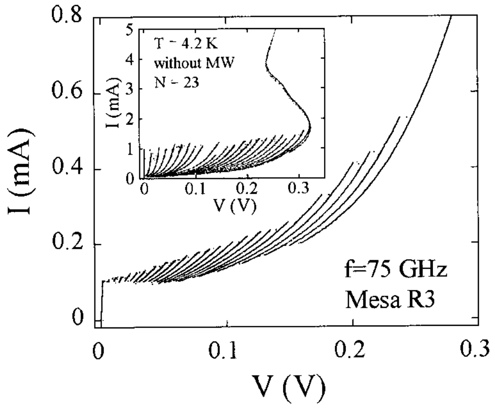

Fig. 1. *I-V* curves of mesa R3 at T=4.2 K with (main panel) and without (inset) microwave irradiation

to allow a collective fluxon motion. In both cases we observed that the lowest-bias branch split into multiple sub-branches corresponding to the number of junctions in the mesa under study.

HgI_2-Bi2212 single crystals were synthesized by the stepwise reaction method. The spacing between the neighboring CuO_2 bilayers expanded by 7.2 Å with reduced interlayer coupling. The superconducting transition temperature T_c was 76.8 K, lower than that of the pristine Bi2212, 82 K. The underdoped crystal was obtained by first growing a crystal using traveling solvent floating zone methods and annealing subsequently in a low-concentration oxygen gas mixed with a nitrogen gas. The T_c was about 83 K. A mesa structure was formed on the surface of the crystals using photolithography and Ar-ion etching. Details of the sample fabrication are described elsewhere [4]. We studied four different mesas, three on HgI_2-Bi2212 crystals and one on an underdoped Bi2212 crystal. The dimension of the mesas 20×40 μm^2 was almost identical for all the mesas. A microwave of frequencies f=73–76 GHz from a Gunn diode oscillator was inductively coupled to the HgI_2-Bi2212 crystals through a rectangular waveguide.

The *I-V* characteristics of a typical HgI_2-Bi2212 mesa R3 without microwave irradiation are shown in the inset of Fig. 1. One clearly notices multiple quasiparticle branches with maximum voltage spacing of ~15 mV. The number of quasiparticle branches, N = 23, corresponds to the number of IJJs 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 as in Fig. 1.

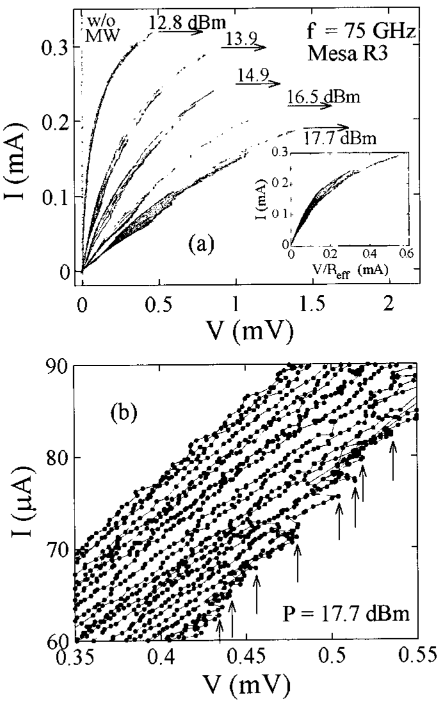

Fig. 2. (a) The supercurrent branches evolved for a microwave of f=75 GHz at T=4.2 K. Inset: *I-V* curves with voltage rescaled by the flux-flow resistance of each curve. (b) Details of the multiple subbranches for P=17.7 dBm.

As shown in Fig. 2(a) I_c keeps decreasing with the increase of P and the supercurrent branch becomes resistive when P exceeds a certain onset value P_c (~12 dBm). Each curve has a linear region for low biases with its slope increasing with increasing P. Each resistive branch splits into multiple sub-branches for higher P. A more detailed view of the sub-branches is shown in Fig. 2(b). At a certain cutoff voltage of the sub-branch as denoted by an arrow in Fig. 2(b), the *I-V* curve jumps to the neighboring sub-branch. By sweeping the bias current back and forth repeatedly, all the sub-branches were identified. The number of distinguishable sub-branches for P=13.9 dBm and 17.7 dBm is 23±2, identical to the number of IJJs in the stack within the experimental error.

Like a static magnetic field, a high-power microwave produces Josephson fluxons in a long

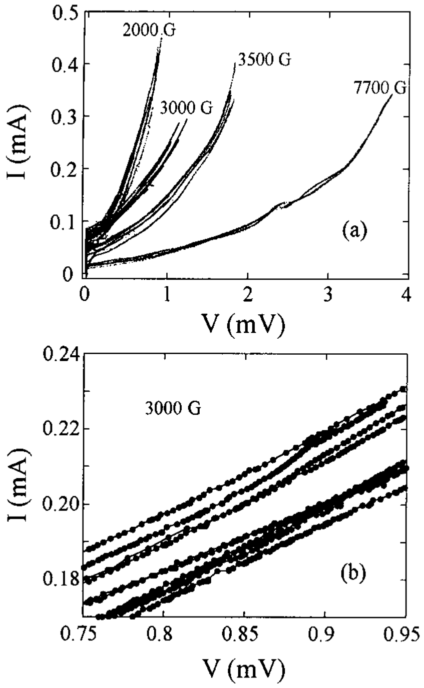

Fig. 3 (a) Splitting of the first low-bias branch of a mesa prepared on an underdoped Bi2212 crystal in various magnetic fields. (b) Details of the splitting for a field of 3000 G.

Josephson junction, giving rise to flux-flow steps in the *I-V* characteristics [5]. Dividing the voltages by the slope of the low-bias linear portion, which corresponds to the typical flux-flow resistance for each power level, the resistive branches in Fig. 2(a) exhibit an excellent scaling behavior as illustrated in its inset. Splitting into multiple sub-branches can be explained in terms of the coherent Josephson fluxon motion. For N stacked Josephson junctions, N different collective modes of an electromagnetic wave are available with the characteristic velocities given by Eq. (1) in [4].

The velocity of Josephson fluxons increases with the bias current until it is bounded by the mode velocity of an electromagnetic wave, which corresponds to the voltage denoted by an arrow in Fig. 2(b). Each sub-branch in Fig. 2(b) represents a specific mode of Josephson fluxon motion.

As illustrated in Fig. 3(a) similar branch splitting was also observed in a mesa fabricated on an underdoped Bi2212 crystal in a magnetic field, which generated Josephson fluxons in this case. The details are shown in Fig. 3(b). We observed somewhat fewer sub-branches than the actual number of IJJs in the mesa, 12, and the curves had upturn curvatures. These features are consistent with the previous observation [6] but are in contrast with the characteristics of the microwave-induced fluxons described above. The origin of the downturn curvature, $\partial^2 I/\partial V^2 < 0$, in the *I-V* curve is not clear yet. In Ref. [6] Lee *et al.* have attributed the downturn curvature to a large damping effect in overdoped specimens. This argument, however, does not hold for our mesas since they are in in a low-damping limit.

In summary, we have observed multiple subbranches in the *I-V* characteristics of IJJs in HgI2-Bi2212 single crystals with irradiation of an external microwave. Each subbranch corresponds to a coherent mode of the collective motion of microwave-induced Josephson fluxons. Similar behavior was observed for a stack of underdoped Bi2212 single crystal in a static magnetic field applied in parallel to the *ab* plane.

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