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Fluxon resonance steps in stacked intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals

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Abstract

We observed jumps in the low-bias fluxon-flow branch of current–voltage characteristics of serially stacked intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) single crystals in the long-junction limit. A stack of IJJs (1.5 μm wide and 17 μm long) was fabricated to be sandwiched between two Au electrodes. Measurements were made in relatively high magnetic fields up to 5 T. The jumps can be explained in terms of switching between different Josephson fluxon modes in resonance with the collective plasma oscillation modes, presumably induced by both inductive and capacitive coupling.

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Closely packed Josephson junctions form along the c axis of highly anisotropic $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) high-T_c superconductors. As the thickness of the CuO_2 superconducting layers in Bi-2212 material is smaller than the London penetration depth, either the inductive [1,2] or the capacitive [3] interlayer coupling is known to generate the collective modes of plasma oscillations inside the intrinsic Josephson junctions (IJJs). The dynamics of the plasma wave is described by sine-Gordon differential equations with solutions of different modes corresponding to the number of IJJs in a stack. Recently a theory resorting to the combined effect of the inductive and the capacitive interlayer coupling has been proposed [4].

In this study we investigated the high-magnetic field fluxon-flow characteristics of stacks of long IJJs in the one-dimensional limit, i.e., the length (the width) of a stack was longer than (shorter than or comparable to) the Josephson penetration depth. A stack of IJJs was sandwiched between two Au electrodes along the c axis without a large basal part of the single crystal that is present in the usual mesa structure. Thus, in our sample geometry, the motion of fluxons in a stack was supposedly not interfered by a large number of fluxons that could have been present in the basal part. In the current dependence of the fluxon-flow voltage we obtained multiple jumps, which were similar to our previous observation [5]. The jumps arose as the collective motion of Josephson vortices was in resonance with the transverse propagation modes of plasma oscillations.

Slightly overdoped as-grown Bi-2212 single crystals were grown by the solid-state reaction method. For the usual mesa structure prepared on the surface of a single crystal with a large basal part the Josephson fluxons in the mesa can be coupled strongly to the ones in the basal part, which are likely to distort the fluxon-flow characteristics in the mesa itself. Thus, in this study, we eliminated the basal part by employing the double-side cleaving technique [6], with a stack of size 1.5×17 μm^2 sandwiched between Au electrodes (refer to the lower inset of Fig. 2). Measurements were made in a two-terminal configuration. The contact resistance in the data was subtracted numerically. The magnetic field was aligned to the Josephson junction plane within the resolution of 0.01 degree [7]. Any field misalignment

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generates pancake vortices which tend to pin Josephson vortices.

The inset of Fig. 1 shows current–voltage (*I–V*) characteristics of the stack in the absence of an external magnetic field. Although no details of the quasiparticle branches were taken the feature in the inset exhibits very uniform critical currents of IJJs, except for a few junctions with reduced critical currents that are supposed to be from the junctions near the bottom and top surfaces of the stack [8]. The number of junctions N estimated from the sum-gap value 1350 mV, with the contact resistance being eliminated, was about 55.

The main panel of Fig. 1 displays highly hysteretic *I–V* characteristics in various magnetic fields up to 5.2 T. Each curve exhibits a fluxon-flow-induced finite resistance in the low-bias range, with its value increasing with increasing external fields. The hysteresis is visible for fields below 4 T, above which the hysteresis almost disappears and the low-bias fluxon-flow bias regime can be differentiated from the McCumber bias regime by the pronounced shoulder denoted by the arrows in the figure. The step features in the *I–V* curves with increasing bias current for field up to 2.4 T are the jumps between different quasiparticle branches arising from different IJJs. Intervals between neighboring quasiparticle branches get smaller and smeared for larger external magnetic fields. For a field above 4 T in the quasiparticle branches above the critical currents (denoted by the arrows) these step features almost completely disappear along with the hysteresis.

Above 4 T, new step-like jumps start emerging in the fluxon-flow region of the curves below the critical currents. In contrast to the case of low magnetic fields, the feature of the step-like jumps become clearer with increasing fields as shown in the expanded drawing in the main panel and the upper inset of Fig. 2. Since these jumps occur below the critical current they cannot

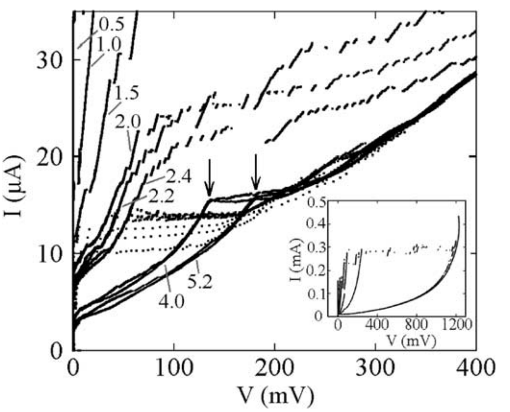

Fig. 1. *I–V* characteristics in different magnetic fields; from zero field (the inset) up to 5.2 T. The values of fields are denoted by the numbers.

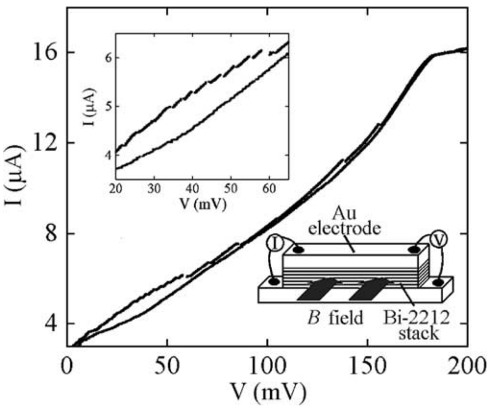

Fig. 2. *I–V* characteristics in 5.2 T, showing steps in the low-bias fluxon-flow region. Each step represents transiting to a different collective fluxon-flow state which corresponds to a resonating plasma oscillation mode. Upper inset: details of the low-bias region. Lower inset: the measurement configuration.

originate from the jumps between quasiparticle branches. The length of the sub-branches in the fluxon-flow bias region keeps getting shorter for a lower bias, seemingly corresponding to a smaller fluxon speed. The general feature of the sub-branch length coincides qualitatively with the velocity difference between adjacent plasma oscillation modes. Although not shown, careful analysis indicated that the voltage positions of the jumps were in good quantitative agreement with the plasma oscillation modes estimated on the basis of the inductive coupling modified by the capacitive coupling [9]. This leads us to conclude that the step-like jumps arose as the velocity of fluxons resonated with any mode velocity of the transverse plasma motion. Curves in the fluxon-flow region for fields below 2.4 T, however, were unstable so that the resonance behavior could not be identified. The field value of 5.2 T corresponds to 64 fluxons in an IJJ. Highly correlated motion of well defined fluxon lattice configuration is theoretically expected for this high fluxon density [10].

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