Observation of Collective Transverse Plasma Modes in Stacks of $Bi_2Sr_2CaCu_2O_{8+x}$ Intrinsic Josephson Junctions

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Abstract. Collective transverse plasma modes in a stack of $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions (IJJs) can be examined by observing the resonating Josephson vortex motion in the stack. In this study, we observed distinct multiple branches in the Josephson vortex-flow current-voltage characteristics, which suggested a transformation of Josephson vortex configuration among different collective plasma modes. For a dc bias on one of the multiple branches, we also obtained an evidence for the microwave emission from the transverse Josephson vortex motion in a stacked IJJs. The emission was examined by observing the changes in the quasiparticle branches of another stack of IJJs placed in proximity to the stack under study.

Keywords: Collective transverse plasma modes, Multiple Josephson vortex-flow branches, Microwave emission
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The emission of THz-range microwaves using the Josephson vortex motion in intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) singe crystals has recently attracted considerable theoretical and experimental research efforts [1]. Local oscillators utilizing conventional $Nb/Al_2O_3/Nb$ junctions have been successfully tested for frequencies up to 700 GHz, which generate power sufficient to pump an SIS mixer [2]. It is, thus, natural to seek a possibility of obtaining THz-range electromagnetic-wave emission from IJJs. Since the transverse plasma oscillations in the periodically and compactly stacked junctions as in Bi-2212 crystals can be in phase the microwave emission in this system would be effectively amplified. To date, however, there still lacks the direct evidence for the emission of THz-range microwaves.

The effective microwave emission has been predicted to occur in a periodically stacked Josephson vortex-flow oscillator when the Josephson vortex flow resonates with the collective transverse plasma modes [1]. This resonating behavior reveals as the multiple collective branches in the Josephson vortex-flow current-voltage *I-V* curves [3]. For the microwave applications, it is thus essential to identify experimentally the collective Josephson vortex-flow branches. In this study, we report the observation of clear collective multiple branches and symptoms of microwave emission induced by Josephson vortex motion.

As-grown slightly overdoped Bi-2212 single crystals were prepared by the conventional solid-state-reaction method. We fabricated, using the double-side cleaving technique, two stacks of IJJs sandwiched between two Au electrodes, respectively, at each stack's top and bottom without the basal part [the inset of Fig. 1(a)]. Here, the bottom electrode serves as a common electrode. This structure is in contrast to the usual mesa structure fabricated on the surface of a single crystal with a large basal part. The detailed fabrication procedure is described in Ref. 5. The inset of Fig. 1(b) illustrates the configuration of the 'oscillator stack' (the left one) and the 'detector stack' (the right one). The lateral size of oscillator stack was 15×1.4 μm^2. To generate Josephson vortices in the oscillator stack magnetic fields were applied in parallel with planes of IJJs, facing the longer side of the stack. The width of the detector stack along the direction of the applied field was 0.7 μm.

The inset of Fig. 1(a) shows the zero-field $I-V$ curves. The number of junctions in the oscillator stack, estimated from the number of zero-field quasiparticle branches, was 22. Two important parameters of the Josepshon-vortex dynamics, the Josephson penetration depth λ_J(=0.3 μm), and the plasma frequency f_p(=20 GHz), were also determined from the zero-field *I-V* curves [3]. The Swihart velocity $c_0(=2\pi\lambda_J f_p)$, which is the propagation velocity of the electromagnetic waves in the insulating layer, was $\sim3.7\times10^4$ m/s. Since, in Bi-2212, the London penetration depth along the *c* axis is much longer than the thickness of the superconducting CuO_2 double layer any junction is strongly coupled to the neighboring junctions. This inductive coupling in a stack consisting of *N* IJJs leads to the collective transverse plasma modes (eigen-states) with the *N*-different characteristic collective eigen-frequencies.

Fig. 1(a) shows multiple branches of the tunneling *I-V* characteristics in *B*=2.5 T. The branches are divided into two regions; the grey and black curve regions. The higher-bias black curves developed from the quasiparticle branches for zero field as the ones shown in the inset of Fig. 1(a). The quasiparticle branches reduce with in-

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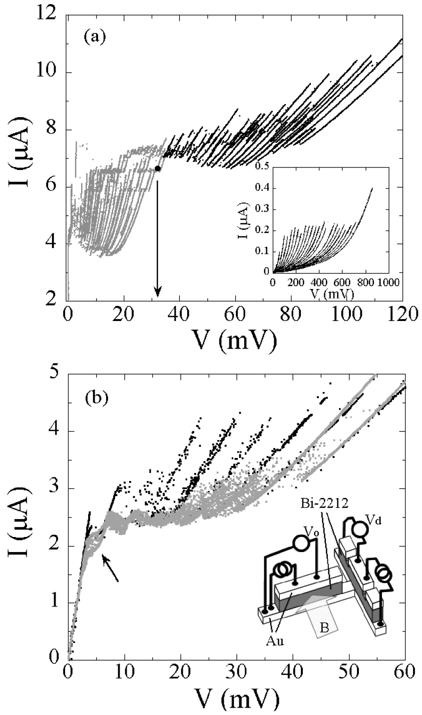

FIGURE 1. (a) Josephson vortex-flow branches (grey curves) and the quasiparticle branches (black curves) of the oscillator stack in *B*=2.5 T. The inset of (a): the current-voltage curves of the oscillator stack in zero field. (b) The quasiparticle branches of detector stack in *B*=2.5 T, without a bias (black curves) and with a bias of 32 mV (grey curves) to the oscillator stack. The inset of (b): the sample configuration.

creasing magnetic fields along with the reduction of the Josephson tunneling critical current, disappearing completely for fields higher than ~4 T. On the other hand, the lower-bias grey curves developed only in relatively high field beyond ~2 T and became more prominent for higher magnetic fields. The grey curves are thus believed to be Josephson-vortex-flow branches. The number of Josephson vortex-flow branches in the low-bias region, 22, is almost the same as that of quasiparticle branches or the number of IJJs in the oscillator stack. This feature is consistent with the theoretical prediction that there should exist the same number of collective plasma modes as that of the IJJs, when the Josephson vortex motion is in resonance with the collective plasma oscillation modes. One notices the slight horizontal misalignment in the Josephson-vortex-flow branches at biases a little below and above 6 μA, which may occur when the outermost junctions near the top and the bottom Au electrodes switch to the resistive state at higher biases.

We examined the microwave emission using the detector stack [inset of Fig. 1(b)], with the oscillator stack biased in the Josephson vortex-flow region. The black curves of Fig. 1(b) is the quasiparticle branches of detector stack in *B*=2.5 T without any bias in the oscillator stack, supposedly corresponds to the absence of microwave emission from the oscillator stack. No noticeable Josephson vortex flow branches are visible in these *I-V* curves, because the magnetic field was applied facing the narrow side of the detector stack. To confirm the microwave emission the oscillator stack was biased at 32 mV, corresponding to the dot position in Fig. 1(a). The grey curves in Fig. 1(b) is the response of the detector stack for this bias. Two distinct features develop in these quasiparticle branches of the detector stack with a finite bias to the oscillator stack: (i) the reduction of the Josephson critical current of quasiparticle branches and (ii) the appearance of a new wiggle structure denoted by the arrow between the contact-resistance branch and the first quasiparticle branch. In general, the microwave irradiation onto IJJs results in zero-crossing Shapiro steps [5] or a finite voltage along with the reduction of the Josephson critical current [as the response (i) above] due to the motion of Josephson vortices arising from the magnetic-field component of the irradiated microwaves [6]. The observed response (ii) of the detector stack may be a precursor of the Shapiro steps with relatively weak microwave irradiation power. It is, thus, believed that the observed change of the response of the detector stack is a direct evidence for the microwave emission from the collective Josephson vortex flow in the oscillator stack. The detection of this microwave emission can be taken as a direct confirmation of the excited collective plasma modes, which also provides the important key to developing ultra-high-frequency Josephson-vortex-flow oscillators.

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