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Microwave generation by Josephson vortex motion in stacked high-T_c intrinsic junctions

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Abstract

We report the observation of the collective transverse plasma (CTP) modes induced by the Josephson vortex lattice motion and the excitation of corresponding electromagnetic waves in a stack of intrinsic Josephson junctions (IJJs) in $Bi_2Sr_2CaCu_2O_{8+x}$. The existence of the CTP modes was confirmed by observing the sub-branches in the tunneling current–voltage curves of staked junctions in the Josephson vortex-flow region. For a proper bias in the sub-branches, the emission of the electromagnetic waves by the collective vortex resonance motion in a stack of IJJs (the oscillator stack) was examined using another on-chip stack of IJJs (the detector stack). The microwave emission from the oscillator stack and the resulting irradiation onto the detector stack was evidenced by the increase of Josephson vortex-flow voltages in the detector stack.

Keywords: Intrinsic Josephson junctions; Collective transverse plasma modes; Emission of electromagnetic waves

1. Introduction

A single crystal of $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) high-T_c superconductor constitutes an anisotropic three-dimensional superconducting system by the *c*-axis Josephson coupling between the Cu–O layers. These stacked junctions are referred as intrinsic Josephson junctions (IJJs) [1]. In the naturally stacked IJJs the gauge-invariant phase difference across a junction is strongly coupled to neighboring junctions via inductive and charging couplings, both of which play an important role in the Josephson vortex (JV) dynamics [2]. It has been predicted that collective transverse plasma (CTP) waves excited by a fast moving JV lattice can enhance the radiation power of the electromagnetic waves caused by the oscillating Josephson currents at an edge of the stacked junctions [3]. Since the Josephson plasma frequency in a stack of Bi-2212 IJJs is in a terahertz range, much effort has been made to apply the JV dynamics to the development of sub-millimeter-wave emitting elements [4].

In this paper, we present the observation of the collectively resonant sub-branches originated from the transverse plasma modes that formed in a stack of IJJs. Resonant sub-branches were manifested in the JV-flow region of the current–voltage (*I*–*V*) characteristics of a stack of IJJs in a strong in-plane external magnetic field. We also confirmed the vortex-motion-induced microwave emission by the appearance of a finite voltage in the JV-flow region in an on-chip detector stack of IJJs that was placed in proximity to the emitter stack.

2. Results and discussion

The inset of Fig. 1 shows the two stacks of IJJs prepared on a substrate, where the left and right stacks are the oscillator and detector stacks, respectively. Both of these stacks were sandwiched between two Au electrodes, deposited on the top and the bottom of the stacks. The detector stack was placed about 1 μm from the oscillator stack. The width of the detector in the direction of the external field was 0.7 μm. The oscillator and the detector stacks were connected by an Au common-ground electrode, which itself may have acted as a microwave coupler.

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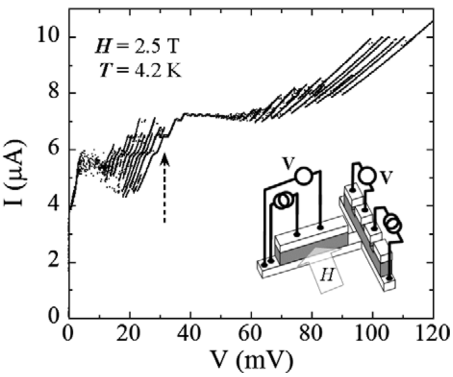

Fig. 1. I–V curves of the oscillator stack in an in-plane field of $H = 2.5$ T. Inset: the measurement configuration.

Fig. 1 shows the I–V curves of an oscillator stack with the lateral size of $1.4 \times 15\ \mu m^2$ in $H = 2.5$ T at $T = 4.2$ K. The number of junctions N was 22. The multiple branches in the curves are divided into two groups: quasiparticle branches above $V_m \sim 30$ mV and collectively resonant sub-branches below V_m, where V_m indicated by a vertical arrow is the maximum voltage induced by the moving Josephson vortices [2]. With increasing external field, the quasiparticle branches were smeared and disappeared at $H \sim 3.5$ T. However, the collectively resonant JV sub-branches below V_m became more distinct (not shown).

The CTP oscillations induced by moving JVs emit electromagnetic waves at a junction edge [5]. To confirm the microwave emission we investigated the response of the on-chip detector stack. The upper inset of Fig. 2 shows the bias condition, V_{osc}, marked on the JV-flow sub-branches of the oscillator stack in $H = 4$ T at $T = 4.2$ K. The portion of I–V curves denoted by an arrow in the lower inset of Fig. 2 reveals the JV-flow sub-branches of the detector stack without any bias in the oscillator stack, where the dotted line indicates V_m of the detector stack in $H = 4$ T.

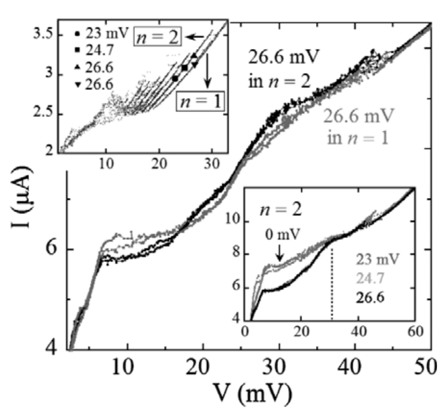

Fig. 2. Response of the detector stack. Upper inset: bias conditions of the oscillator stack. Lower inset: response of the detector stack to the varied bias within the $n = 2$ mode.

The lower inset of Fig. 2 shows the response of the detector stack in the bias voltage V_{osc} =23, 24.7 and 26.6 mV (corresponding to 500, 540 and 580 GHz) applied on the $n = 2$ sub-branch of the oscillator. The frequency corresponding to V_{osc} was estimated based on the frequency–voltage (per junction) conversion relation, $f = 2eV_{osc}/Nh$ (=483.6 GHz/mV $\times\ V_{osc}/N$), where h is the Planck's constant. One gets a significant change in the JV-flow sub-branch of detector stack, which is in clear contrast to the steady quasi-particle branches for above V_m. We attribute this variation to the flow of additional Josephson vortices induced by the H-field component of the emitted microwaves from the oscillator stack. One notices that the on-chip detector does not show any significant change in its JV sub-branches to the frequency tuning by varying the voltage bias within the $n = 2$ mode. On the contrary, as shown in the main panel of Fig. 2, the mode change between $n = 1$ and $n = 2$ in the oscillator induces a distinct change in the response of the detector even in the same bias voltage V_{osc} =26.6 mV. It has been predicted that the radiation power in CTP modes grows as a lower-index mode is adopted and reaches a maximum in the $n = 1$ in-phase mode [3]. For a fixed voltage bias higher power is expected in the $n = 1$ mode than in the $n = 2$ mode. This prediction is consistent with our observation that, in the range above $V \sim 18$ mV in Fig. 2, the JV-flow sub-branch of the detector in response to the bias in the $n = 1$ mode reveals larger voltages in the detector stack for any bias current than in the $n = 2$ mode. Thus, the distinct change of the JV-flow branches in the detector for a fixed-voltage bias in outer resonant sub-branches strongly points to the successful radiation of electromagnetic waves by the collectively resonant JV motion. For the microwave emission by the excitation of the CTP modes, however, many frequency components by the Cherenkov radiation [6] may be mixed together. One can examine the frequency distribution of the emission by using the incoherent spectroscopy developed by Divin et al. [7].

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References

[1] R. Kleiner et al., Phys. Rev. Lett. 68 (1992) 2394.
[2] M.-H. Bae, H.-J. Lee, Phys. Rev. B 70 (2004) 052506.
[3] M. Machida, M. Tachiki, Curr. Appl. Phys. 1 (2001) 341.
[4] G. Hechtfischer et al., Phys. Rev. Lett. 79 (1997) 1365.
[5] M.-H. Bae, H.-J. Lee, Appl. Phys. Lett. 88 (2006) 142501.
[6] V.M. Krasnov, Phys. Rev. B 63 (2001) 64519.
[7] Yu.Y. Divin, O.Yu. Polyanski, A.Y. Shul'man, IEEE Trans. Magn. 19 (1983) 613.