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Shapiro Step Responses in the Flux-Flow State of Bi-2212 Intrinsic Josephson Junctions With Cooperation of Pancake Vortices

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***Abstract*—Flux-flow properties of one-dimensionally long Bi-2212 intrinsic Josephson junction stacks are studied. Quasioptically irradiated millimeter waves drives Josephson vortices and reveals current steps in equal voltage intervals corresponding to the Josephson relation. Differential conductance properties and the power dependence of the current step height are also measured. The experimental results indicate that the responses are consistent with the Shapiro step. Periodic potentials produced by pancake vortices are considered to be effective to realize the in-phase collective motion of the Josephson vortices.**

***Index Terms*—High-T_C superconductors, intrinsic Josephson junctions, Josephson effects, Shapiro step.**

I. Introduction

DISCOVERY of the intrinsic Josephson effect of highly anisotropic copper superconductors such as $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) [1] paves the way for their single crystals to be used as nanoscale intrinsic Josephson junction (IJJ) stacks. The nanoscale stacks, which have never been realized by conventional low T_C junction systems, reveal unique vortex phase diagram under strong magnetic fields [2], [3]. Among them, the collective Josephson vortex motion over the IJJ stack [4] has been attracting much attention because it is feasible to electromagnetic wave oscillators with high-performances exceeding the conventional low T_C flux-flow oscillators (FFO) [5] in both the emission power and utmost frequency. For the Bi-2212 IJJ stacks, the utmost frequency limited by the superconducting energy gap lays on terahertz regime and the emission power expected to be the square of the number of stacked junctions [6]. Though it is of interest how to realize the actual emission from the IJJ stacks, most of experiments have been devoted to the static dc current-voltage ($I-V$) properties exhibiting flux-flow features [7] except for a few foresight reports [8]. In the conventional low T_C FFO, the dc $I-V$ properties show a particular current step structure [5] caused by the velocity matching of moving Josephson vortices to the characteristic phase velocity in the junction. In reversible, applying external electromagnetic waves to the FFO reveals unique responses on the $I-V$ properties [9] caused by the phase-locking of vortex flow to the externally applied RF signals. Therefore, studies on the response properties of Bi-2212 IJJ stack to the externally applied electromagnetic waves may have fundamental significance for their FFO applications. We have reported the phase-locking of collective vortex motion in the flux-flow state of Bi-2212 one-dimensionally long IJJ (LIJJ) stacks to an externally applied millimeter wave [10]. On the other hand, Latyshev *et al.* have reported the Shapiro-step-like response in Bi-2212 LIJJ stacks in the flux-flow state [11]. They insist that a coherent motion of Josephson vortices over the IJJ stacks is essential to produce the Shapiro-step-like responses and the responses only appear under very strong DC magnetic fields. The coherent motion is favorable to maximize the emission power, but the strong magnetic fields prevent the velocity matching that is the principle necessary to the flux-flow oscillation. In this paper, we report that the Shapiro-step-like responses are observed for the flux-flow state even if the magnetic field is much lower than that in the previous report [11]. This paper also aims to study how to increase the degree of coherency of moving Josephson vortices with corporation of pancake vortices.

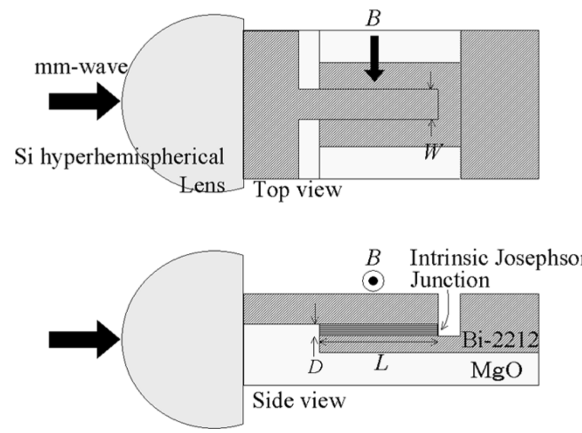

Fig. 1. Schematic views the one-dimensionally long intrinsic Josephson junction stack to measure millimeter wave response.

II. Experimental Procedure

LIJJ stacks were prepared on Bi-2212 films epitaxially grown on step engraved MgO substrates by standard photolithography and a focused ion beam etching. Fig. 1 shows schematic view of the LIJJ stacks. The step height was about 0.5 μm and the

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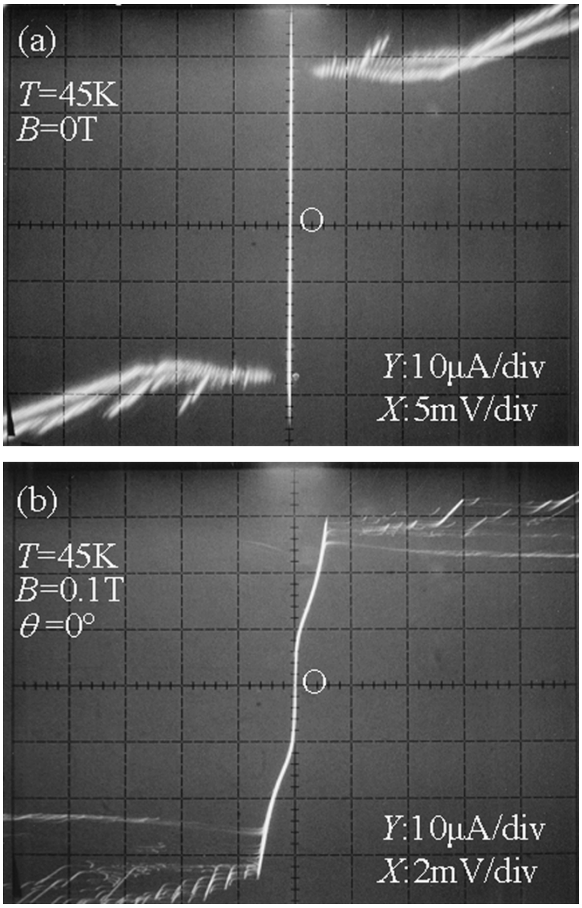

Fig. 2. Static $I-V$ properties of the LIJJ stacks without external magnetic field (a) and with the in-plane external magnetic field, $B = 0.1$ T in the lock-in state (b).

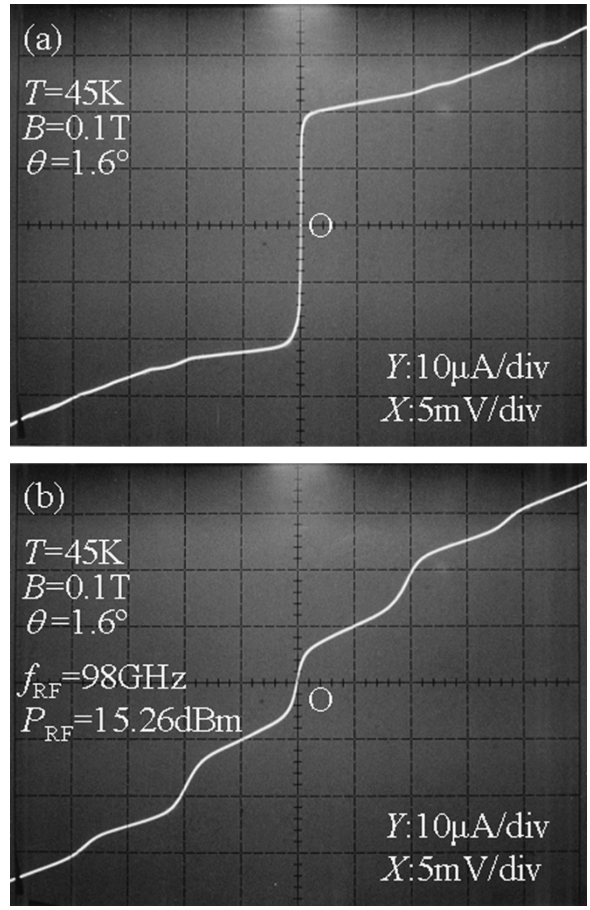

Fig. 3. (a) Static $I-V$ property of the LIJJ stack measured under the magnetic field of $B = 0.1$ T tilted 1.6° out from the CuO_2 planes. (b) $I-V$ property of the same LIJJ stack measured with the millimeter wave of 98 GHz as well as the magnetic field.

thickness of Bi-2212 film was a few μm. The dimension of the LIJJ stack was 2 μm wide and 80 μm long. The LIJJ stacks were annealed in low oxygen partial pressure of 50 Pa at 300°C for 30 minutes to reduce I_C. The LIJJ stack was mounted on a sample head consisting of a polytetrafluoroethylene (PTFE) lens and a silicon hyper-hemispherical lens that quasioptically focuses millimeter waves at the close edge of the MgO substrate. A single stage pulse tube refrigerator cooled the head as low as 45 K. $I-V$ properties were measured by a four terminal method under external magnetic fields up to 1 T using a variable field permanent magnet system. The magnetic field was rotated by 0.1 degree resolution. Power calibrated millimeter waves of 63 GHz and 98 GHz generated by Gunn oscillators were radiated by horn antennas and quasioptically coupled to the LIJJ stacks to measure the responses on the $I-V$ properties. With this experimental setup, it has been anticipated that the alternative magnetic field component of millimeter waves drives the Josephson vortices at one edge of the LIJJ stacks.

III. Results and Discussions

Fig. 2(a) shows an $I-V$ property measured at 45 K for the LIJJ stack with the critical temperature of 68 K. The annealing procedure reduced the critical current density as low as 12.5 $\mathrm{A/cm^2}$. The number of branches corresponding to the number of stacked junctions was counted for 46 from the $I-V$ curve measured at 4.2 K. By applying magnetic field of 0.1 T parallel to the superconducting double CuO_2 layers of the LIJJ stack, that is the lock-in state, the $I-V$ property reveals the flux-flow voltage as shown in Fig. 2(b). The fact that the critical current is almost completely suppressed suggests that the pinning potential for Josephson vortices would not so much influenced their dynamics. On the other hand, Fig. 3(a) indicates that the flux-flow feature is extinguished by tilting the field direction off the CuO_2 layers within a few degrees. This is, of course, the influence of the effect of strong pinning caused by pancake vortices introduced in the CuO_2 layers. This is the pancake state. In other words, the Josephson vortices in this sample are free from pinning mechanism other than intrinsic one due to the pancakes. Millimeter wave responses are quite different between the lock-in and pancake states. In the lock-in state, the Josephson vortices free from pinning potentials are driven by an ac signal and reveal a distinguish zero-crossing constant voltage step at $V = N\Phi_0 f$, where N is the number of junctions included in the stack, Φ_0 is the flux quantum, f is the frequency of applied millimeter wave. On the other hand, once the field direction tilted off the CuO_2 layers and turn into the pancake state, the zero-crossing is completely extinguished.

Fig. 3(a) shows the $I-V$ property measured for the pancake state of the LIJJ stack with the magnetic field, $B = 0.1$ T tilted

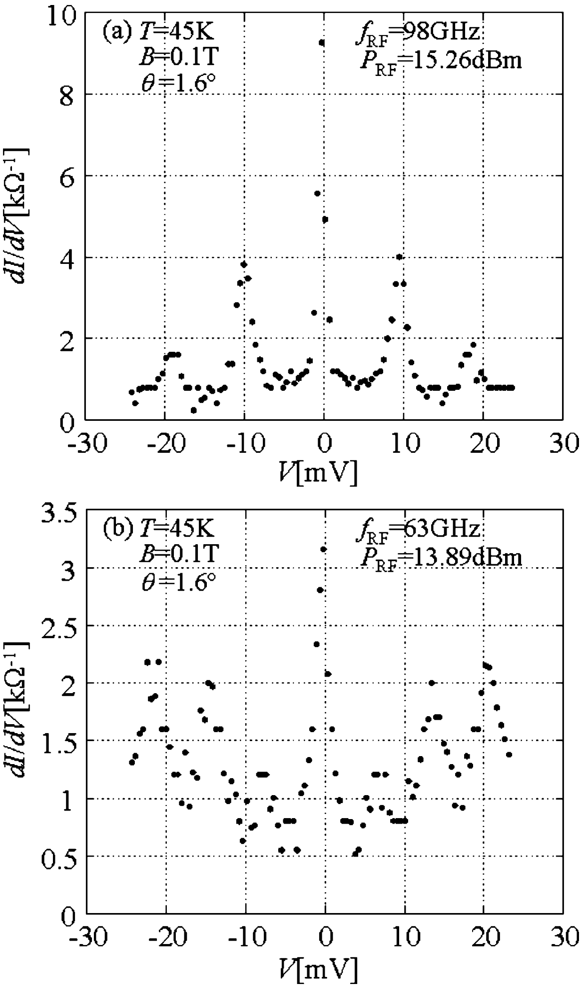

Fig. 4. Differential conductance peaks observed for the millimeter wave driven $dI/dV - V$ properties in the pancake state for $f = 98$ GHz (a) and 63 GHz (b), respectively.

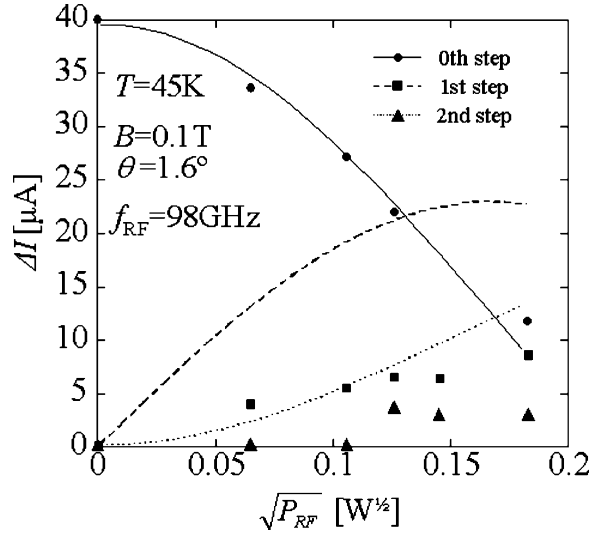

Fig. 5. Millimeter wave power dependences of current peak height measured for the millimeter wave driven current-voltage characteristics in the pancake state.

1.6° off the CuO_2 layers. The critical current is recovered from the lock-in state shown in Fig. 2(b) indicating a strong pinning effect of the pancake vortices. However, even in the pancake state, millimeter wave application starts the flux-flow again as shown in Fig. 3(b). This means that the alternative field of applied millimeter electromagnetic wave releases the Josephson vortices from pancake originating pins. The remarkable thing of the flux-flow in the pancake state is that current steps appearing at equal voltage intervals. Fig. 4 shows the $dI/dV - V$ properties measured for the same sample with applying the millimeter wave of 98 GHz and 63 GHz. The voltage interval of the conductance peaks is quite consistent with that given by $V = N\Phi_0 f$ for both frequencies. Fig. 5 shows the millimeter power, $\sqrt{P_{RF}}$ dependence of the step heights measured for the responses to 98 GHz compared with the Bessel function dependences representing the voltage source drive model. Though the measured step height is not well fitted except for the 0th order step, the Bessel function seems to be substantially adapted to the power dependence. These results strongly suggest that the Josephson vortex dynamics under the pancake originating pinning generates DC current components quite resemble to the Shapiro step. Latyshev *et al.* have reported the similar response [11] in the flux-flow step but the pinning effect on their response remains ambiguous. Koshlev has reported that the pancake vortices introduced in the IJJ stacks generates periodic potentials to the Josephson vortices parallel to the stacks [12]. It is supposed that the present Shapiro-step-like response in the flux-flow with pancake vortices closely relate to the Josephson vortex dynamics under the periodic potentials generated by the pancake vortices. Numerical simulations based on the coupled sine-Gordon equations are helpful to understand the nature of the electromagnetic wave responses in the flux-flow state. The result of numerical studies will be published elsewhere.

IV. Summary

The Shapiro-step-like responses were observed for the Bi-2212 LIJJ stack in the flux-flow state with cooperation of pancake vortices introduced in CuO_2 layers. It is considered that periodic potentials developed by the pancake vortices enhance the degree of in-phase regularity of moving Josephson vortices over the stack. The in-phase motion of Josephson vortices realized by the periodic potentials expected to facilitate the development of the flux-flow oscillator using Bi-2212 IJJ stacks.

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