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Microwave Standing Modes in Stacked Intrinsic Josephson Junction of $Bi_2Sr_2CaCu_2O_{8+x}$ Single Crystals

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We studied the distribution of the microwave intensity along the *c*-axis inside a stack of $Bi{-}2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions (IJJs) by monitoring the tunneling critical current of the IJJs with varied microwave power for frequencies in the W band. The stack was microfabricated into a transmission line geometry (15 μm$\times$ 0.72 μm$\times$ 60 nm), with a few-hundred-nm thick Au layers deposited on top and bottom of the stack. Irradiated microwaves was found to form a standing wave-like mode along the *c*-axis inside the stack for frequencies above a characteristic cut-off frequency. The information on the microwave distribution in a stack of junctions may be conveniently utilized for high-frequency device applications using IJJs, such as fluxon-flow THz oscillators.

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I. INTRODUCTION

The large gap value in CuO_2 superconducting bilayers composing intrinsic Josephson junctions (IJJs) in $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) single crystals offers a high possibility of developing Josephson-fluxon-flow oscillators operating in a THz frequency range [1–5]. In order to devise local fluxon-flow-oscillator devices using IJJs, one often adopts a transmission-line geometry, so that understanding the propagation characteristics of the fluxon-flow-induced microwaves in a stack of IJJs become utterly important.

In this paper we compared the progressive change of current-voltage (I–V) characteristics when dc-magnetic fields and W-band microwaves (72–95 GHz) were applied to a transmission-line-geometry stack of IJJs. Application of an external magnetic field caused uniform suppression of the tunneling critical current over the whole junctions in the stack. The trend of the critical-current suppression under microwave irradiation, for increasing frequencies up to a cut-off frequency of f_c 84 GHz, was similar to that for the magnetic-field application. Above the cut-off frequency, however, the critical current of the junctions located close to the Au electrodes tended to be recovered, while that of the inner junctions tended to be suppressed in a fast rate. This trend indicated that the electromagnetic standing-wave mode formed inside the transmission-line-shaped stack. In addition, the propagation velocity c_d $(= 2df_c)$ of microwaves in the stacked Josephson junctions of thickness d was estimated from the cut-off frequency in this transmission-line geometry.

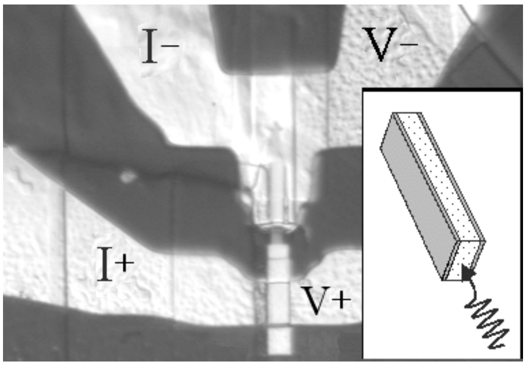

FIG. 1: Optical micrograph of a stack fabricated by the double-side-cleaving technique. The inset shows the direction of microwaves irradiation to the sample.

II. EXPERIMENTAL DETAILS

A 20–μm–long quasi-one-dimensional stack of IJJs was prepared in the following way. Slightly overdoped as-grown Bi-2212 single crystals were first grown by the solid-state-reaction method [6]. A selected single crystal was then glued on a sapphire substrate using negative photoresist (OMR-83) and the upper part of the crystal was cleaved away until an optically clean surface was obtained. Then, a 100-nm-thick Au layer was thermally deposited on top of the crystal to protect the newly exposed surface from oxidation or contamination during the further sample fabrication processes. A mesa with a Au layer of suitable size was patterned using positive photoresist (Shipely-1805) and Ar-ion-etching. The top of patterned mesa was then fixed to another sapphire substrate using negative photoresist and the mesa was separated by cleaving away the basal part of the junctions, on which a second 100-nm-thick Au layer was deposited immediately. This technique, called the double-side cleaving (DSC) [2], allows one to prepare a stack of IJJs sandwiched between two normal-metallic electrodes without the basal stack. A few-μm-long portion on one end of the stack was then etched away to get the bottom electrode exposed for c-axis transport measurements, leaving 15-μm-length portion of the stack. Finally, 300-nm-thick Au extension pads were attached. Fig. 1 illustrates the optical micrograph of the stack of IJJs (15 μm$\times$ 0.72 μm$\times$ 60 nm) prepared in such a way. The microwave generated by a Gunn diode oscillator was transmitted through a waveguide and coupled inductively to the stack. The power was tuned by using a level set attenuator. The measurements were done in a two-terminal configuration using a low-pass filter connected to each measurement electrode at$T$ = 4.2 K.

A dc-magnetic field applied in parallel with the plane of Josephson tunnel junction generates Josephson vortices inside the stacked junctions. In a tunneling bias current the Josephson vortices move in parallel with the junction planes, which causes finite vortex-flow voltages and associated Josephson vortex-flow branches (JVFB), satisfying the ac Josephson effect. Figs. 2(a) and 2(b) exhibit the progressive change of I–V characteristics of the stack

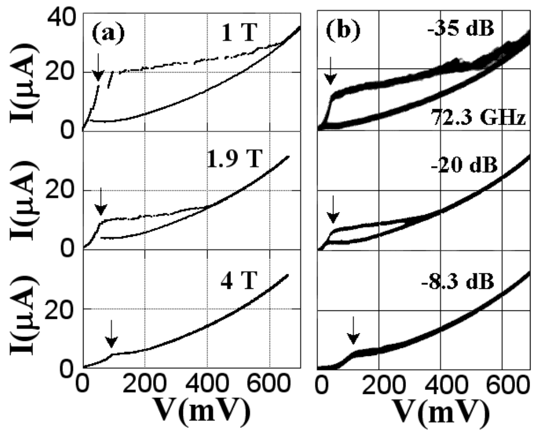

FIG. 2: I–V characteristics of the stack (a) in a dc-magnetic field applied in parallel with the *ab*-plane and (b) under irradiation of 72.3-GHz microwaves with varying intensity. The arrows indicate the maximum cut-off voltages of the Josephson-vortex-flow region.

in a dc-magnetic field applied in parallel with the *ab*-plane and under irradiation of 72.3–GHz microwaves, respectively, with gradually increasing the microwave irradiation power. The number of the branches indicates that the stack contained 40 IJJs, which corresponded to the stack thickness of 60 nm. Branches in the low-bias region indicate that about eight junctions had smaller critical current I_c than the other junctions in zero field, possibly due to the proximity effect by the Au layers on the stacks located close to the top and the bottom [6] or due to any surface degradation during the fabrication. Thus, in the remainder of this paper, these junctions will be identified as 'the surface junctions'.

In Fig. 2 we put a pair of figures side by side, in such a way that the suppression of the critical currents in an external magnetic field as in Fig. 2(a) has similar tendency as that under microwave irradiation as in Fig. 2(b). The magnectic-field component of a microwave generates Josephson vortices inside tunnel junctions. These microwave-induced Josephson vortices also exhibit similar fluxon-flow characteristics as the field-generated vortices [3-5]. In Fig. 2, as the critical current of quasiparticle branches is suppressed, both the resistance of the JVFB and the maximum cut-off voltages of the flux-flow region (as indicated by the arrows) increase with fields.

The distribution of irradiated microwaves along the *c*-axis of a stacked junctions can be figured out from the spatial distribution of the suppressed tunneling critical currents. In general, the tunneling critical current of a Josephson junction keeps being diminished with increasing the microwave irradiation power. As shown in the inset of Fig. 3, however, the irradiation of 93.5 GHz microwaves of power −22 dB leads to an anomalous behavior in the suppression of critical current in the surface-junction branches. Under this irradiation condition the suppression of critical currents of inner junctions was similar to that under the irradiation of 72.3 GHz microwaves with power −20 dB as in Fig. 2(b). However, for

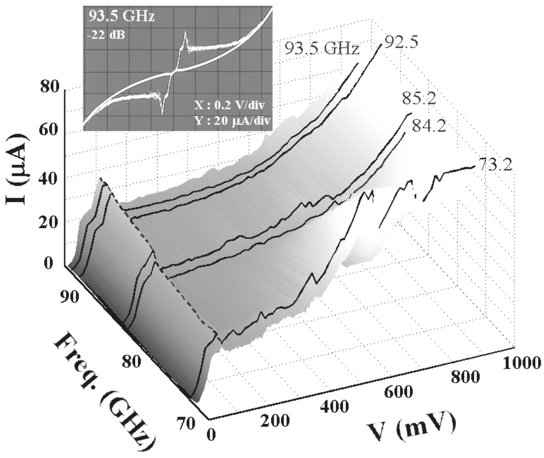

FIG. 3: Gradual change in the I–V characteristics under microwave irradiation in the frequency range between 71.7 GHz and 94.5 GHz for varying power. The upper inset shows the I–V curves at 93.5 GHz. The lower inset illustrates the formation of the lowest-order standing wave along the c-axis direction.

93.5 GHz microwaves, one notices the appearance of peaks in quasiparticle branches of the surface junctions. This implies that the critical current of the surface junctions ($I_c^{\rm surf}$) under the irradiation condition of the inset of Fig. 3 was almost undiminished, although the critical current of inner junctions ($I_c^{\rm inner}$) was significantly suppressed. Thus, the intensity of the microwaves in the surface junctions is supposed to be lower than that of inner junctions.

Fig. 3 illustrates that the critical current of the surface junctions $I_c^{\rm surf}$, denoted by dotted line, increases with increasing the microwave frequency. In contrast, the critical current of the inner junctions $I_c^{\rm inner}$ decreases in the frequency range of 71.7–84.2 GHz, beyond which it remains almost unaltered. The data were taken for the irradiation power between -20 and -30 dB, varied in such a way as to obtain the maximum difference between $I_c^{\rm surf}$ and $I_c^{\rm inner}$ for a given frequency. Fig. 3 indicates that the microwave distribution along the c-axis of the stacked junctions depends on the irradiated frequency range. The microwave was almost uniformly distributed across the stack for frequencies below 84 GHz, as evidenced by the overall suppression of I_c in Fig. 2(b), but it was more intense in the middle of the stack for frequencies above 84 GHz (see the lower inset of Fig. 3).

III. RESULTS AND DISCUSSION

The feature shown in Fig. 3 can be explained, if one assumes that the sandwiched stack of IJJs supports modes of standing waves along the c-axis, for frequencies higher than a certain characteristic frequency f_c ($= c_d/2d = 84.2$ GHz in our sample of thickness d=60 nm). We assume that the frequency 84.2 GHz is the cut-off frequency f_c, because at frequencies above this value the $I_c^{\rm surf}$ starts showing anonymous behavior as in Fig. 3. This value of f_c gives the microwave propagation velocity $c_d = 1.01 \times 10^4$ m/s.

For a stack of N Josephson junctions the same number of propagating transverse plasma modes are available. The lowest mode velocity [7] is close to $c_0/\sqrt{2}$, where c_0 ($=2\pi f_p \lambda_J$) is the Swihart velocity [5]. With the critical current I_c ($= 0.1$ mA) of the inner junctions and the normal-state resistance R_n ($= 33\ \Omega$) per junction, the Josephson plasma frequency f_p and Josephson penetration depth λ_J turn out to be 30 GHz and 0.34 μm, respectively. The corresponding Swihart velocity c_0 is 6.35×10^4 m/s, which leads to the lowest mode velocity c_N ($=c_0/\sqrt{2}$) of 4.5×10^4 m/s for our stack. This value is in reasonable agreement with the value c_d obtained above using the standing-wave-mode analysis.

IV. CONCLUSION

In summary, we identified the formation of the standing-wave mode along the c-axis in a stack of IJJs sandwiched between two Au layers by observing the suppression of the tunneling critical current of the IJJs for varying microwave power at frequencies in the W band. The sandwiched-stack geometry served as a transmission line with a characteristic cut-off frequency, above which the lowest standing wave mode was established. The estimated propagation velocity of electromagnetic waves in the stack of IJJs was consistent with the value of the velocity for the lowest plasma mode, as predicted by mutual inductive coupling theory. The technique used in this study may provide valuable information for the device applications using IJJs in the microwave frequency range.

Acknowledgments

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