Current-step-like structure in a YBCO grain boundary Josephson junction coupled to a gigahertz signal

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Abstract. We demonstrate current-step-like structures observed in a YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) grain boundary Josephson junction (GBJJ) coupled to a gigahertz (GHz) signal. It is well known that a microwave-current-driven Josephson junction does not exhibit clear Shapiro steps under a low frequency condition of $f \ll {I_cR_n}/\Phi_0$, where $f$, $I_c$, $R_n$, and $\Phi_0$ are the microwave frequency, the critical current of the junction, the normal resistance of the junction, and a flux quantum, respectively. Instead of Shapiro steps, however, we often observe an anomalous upturn in the current–voltage curve of YBCO GBJJ's coupled to a GHz signal. We refer to the upturn as a current-step-like structure. Numerical analysis using an rf-field-driven two-junction superconducting quantum interference device (SQUID) model indicates that the envelope of small Shapiro steps, including the effects of microwave-induced motion of flux quanta, appears as a current-step-like structure.

1. Introduction
High-$T_c$ Josephson junctions have $I_cR_n$ products as large as a few mV at liquid helium temperature, and hence, the normalized frequency $\Omega (= \Phi_0f/I_cR_n)$ becomes on the order of $10^{-3}$ for a gigahertz (GHz) microwave signal. (Here, $\Phi_0$, $f$, $I_c$, and $R_n$ are a flux quantum, the microwave frequency, the critical current of the junction, and the normal resistance of the junction, respectively.) It is well known that a microwave-current-driven Josephson junction does not exhibit clear Shapiro steps under such low frequency conditions [1].

Instead of Shapiro steps, however, we often observe a current-step-like structure in the current–voltage curve of YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) grain boundary Josephson junctions (GBJJ’s) coupled to a GHz signal [2]. In this paper, we first demonstrate typical current-step-like structures, and then, present our model analysis.

2. Experiments
The YBCO GBJJ’s were fabricated on silicon (Si) bicrystal substrates [3, 4]. The deposition of buffer and YBCO films on Si was done in situ using an excimer laser ablation method with the same deposition parameters for both films. A 100-nm-thick YBCO film was deposited...
immediately following the deposition of 30-nm-thick yttria-stabilized zirconia (YSZ) and 20-nm-thick CeO_2 buffer layers. These films were prepared at the University of Jena [3]. An excimer laser etching method was used to fabricate 10-μm-wide GBJJ’s across the bicrystal boundary. I–V curves of YBCO GBJJ’s were measured by a conventional four-terminal method in a liquid-helium bath. The microwave signal was applied to a sample from an open-ended coaxial cable connected to a synthesized cw generator.

Figure 1 shows typical I–V curves under microwave irradiation at 5.0 GHz with different microwave power levels (P_{rf}). An RCSJ (resistively and capacitively shunted junction) -type I–V curve is observed under no RF irradiation (P_{rf} = −∞). The device parameters are extracted as I_c = 0.48 mA, R_n = 7.3 ohm, and the junction capacitance C_j = 13 fF assuming that the McCumber parameter β_c [5] is 1.0. With increasing P_{rf} from −∞ to −15 dBm, the maximum zero-voltage current decreases and the current-step-like structure with a finite slope appears near the zero-voltage axis. It moves to higher currents and voltages with increasing P_{rf} further, and the most pronounced at P_{rf} = −5 dBm. For P_{rf} > −5 dBm, the current-step-like structure still moves further, but is getting smeared.

The normalized value Ω of the microwave frequency of 5.0 GHz is calculated as small as 3.0 × 10^{-3} for the junction having I_cR_n = 3.5 mV. Clear individual steps could not usually be expected for such low frequency condition. (The voltage spacing of the Shapiro steps corresponding to 5.0 GHz is 10 μV, much smaller than the voltage scale in Fig. 1.)

3. Numerical simulation using an RF-field-driven superconducting quantum interference device model
We have tried simulating GHz responses of several Josephson device models, and found that the rf-field-driven two-junction superconducting quantum interference device (SQUID) model [6, 7, 8, 9, 2], in spite of its simple structure, works well to reproduce the experimental results. Fig. 2(a) shows the model configuration. There are two Josephson junctions having I_c/2, 2R_n, and C_j/2, connected in parallel through two superconducting inductors of L. The rf signal is inductively applied to the SQUID loop. In this paper, the inductance value L is set to 20Φ_0/I_c, which is roughly equal to the value of W/λ_J. (λ_J is the Josephson penetration depth and estimated to be 0.6 μm, assuming that that the critical current density, the ab-axis London penetration depth λ_{ab}, the film thickness d, and the effective London penetration depth Λ_{ab} = 2λ^2_{ab}/d [10] are 4.8 × 10^4 A/cm^2, 0.2 μm, 0.1 μm, and 0.8 μm, respectively.) We assume M = L in our simulation. Thus, the rf magnetic field coupled to the SQUID, B_{rf} sin 2πft, is written as B_{rf} sin 2πft = 2MI_{rf} sin 2πft = 40Φ_0(I_{rf}/I_c) sin 2πft.

The calculated results for the response of the rf-field-driven SQUID model are shown in Fig. 2, in good agreement with the experimental ones in Fig. 1. The dependence of the current amplitude of the current-step-like structure (I_{top} − I_{bttm}) upon the V_{max} value is plotted in Fig. 3(b). (The definitions for V_{max}, V_{min}, I_{max}, and I_{min} are given in Fig. 3(a).) According
Figure 2. (a) Two-junction SQUID model driven by an rf magnetic field. (b) Simulated $I–V$ curves of the two-junction SQUID model driven by an rf field at 5.0 GHz. No thermal noise is included. The curves are with the normalized field amplitude ($B_{rf}/\Phi_0$) of 0, 25, 75, and 167, respectively. These $B_{rf}/\Phi_0$ values are chosen to fit the numerical data to the experimental ones in Fig. 1.

Figure 3. (a) Schematic drawing for the positions of $(V_{\text{top}}, I_{\text{top}})$ and $(V_{\text{bttm}}, I_{\text{bttm}})$. (b) Current amplitude of the current-step-like structure $(I_{\text{top}} - I_{\text{bttm}})$ as functions of $V_{\text{max}}$. Besides the experimental data, the numerical results are plotted with curves.

to the results shown in Figs. 2 and 3, the rf-field-driven SQUID model seems to reproduce the current-step-like structure observed in the case of $\Omega \ll 1$.

To investigate the origins of the current-step-like structure further, we executed detailed calculation around the structure. Shown in Fig. 4 are the detailed $I–V$ curves with and without the thermal noise at 4.2 K. Small but clear steps are seen in the curve for 0 K. On the other hand, the numerical results with the thermal noise at 4.2 K in Fig. 4 show that the step structures are smeared. Because not only the thermal noise but also external noise from the environment smears the Shapiro steps, it would be impossible to observe individual steps in real experiments.

Figure 5 shows the simulated time-domain waveforms of $I_{rf}$, the junction voltages, and the number of flux quanta in the SQUID loop. The junctions generate finite voltages alternatively synchronized with $I_{rf}$, which means that flux quanta enter/exit the loop. In this case, the number of flux quanta oscillates between +64 and −64, that is, 128 flux quanta pass through the SQUID loop per cycle of $I_{rf}$, inducing the 128th Shapiro step.

In general, a long junction model should be used to represent the wide GBJJ of $W/\lambda_J \gg 1$. We have employed the two-junction SQUID model as a first order approximation of the long junction model. However, according to the results described above, we may state that the rf-
field-driven two-junction SQUID model is effective to reproduce the current-step-like structure observed in the case of $\Omega \ll 1$, and that the origin of the current-step-like structure is suggested to be the envelope of small Shapiro steps caused by the rf-field-induced motion of flux quanta.

4. Conclusion
We demonstrated current-step-like structures observed in a YBCO GBJJ coupled to a GHz signal. Instead of Shapiro steps, an anomalous upturn (a current-step-like structure) in the current–voltage curve was observed. Numerical analysis using the rf-field-driven two-junction SQUID model indicates that the envelope of small Shapiro steps, including the effects of microwave-induced motion of flux quanta, appears as a current-step-like structure.

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