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Zero-crossing Shapiro step generated in a niobium in-line Josephson gate

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Abstract: We demonstrate a zero-crossing Shapiro step generated in a magnetically-coupled Josephson gate, where a long Josephson junction and a control line are placed in-line. The operation is based on the imbalanced evolution of the junction phases owing to the different amplitudes of the positive and negative critical current. A test circuit was fabricated using a Nb/AlO$_x$/Nb junction technology. When we applied a rf signal of 15.2 GHz, we observed a Shapiro step that crossed the zero-current axis at the voltage position of the 1st order. The experimental results were quantitatively reproduced by simulation.

Keywords: Josephson effects, Shapiro step, superconductor, microwave, integrated circuits

Classification: Superconducting electronics

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1 Introduction

It has been well known that a Josephson junction (JJ) irradiated with a rf signal exhibits current steps (Shapiro steps) at constant voltages of $n\Phi_0 f$, where n, Φ_0, and f are an integer, a flux quantum, and the signal frequency, respectively [1]. While the simple Josephson frequency-voltage relationship determines the voltage positions of Shapiro steps, it is rather complicated to describe their current positions. In particular, a Shapiro step crossing the zero-current axis, commonly referred to as a zero-crossing Shapiro step (ZCSS), is currently employed in dc Josephson voltage standard systems [2, 3]. To generate ZCSSs in a small JJ with a sinusoidal rf signal, a hysteretic JJ having a large Stewart-McCumber parameter [4, 5] is essential [6].

ZCSSs generated in a nonhysteretic Josephson device have potential application in programmable Josephson voltage standards (Josephson digital-to-analog converters) [7]. We have reported that ZCSSs can be generated using a nonhysteretic and asymmetric two-junction (2J) superconducting quantum interference device (SQUID) [8, 9]. The tilted critical current-magnetic field characteristics of the asymmetric 2J-SQUID is the key for ZCSS generation. That is, at a finite magnetic field, the critical current amplitudes become different for the plus and minus, which results in imbalanced evolution of the junction phases under rf irradiation. Then a quantized voltage can be generated even under the zero dc bias current [8, 9]. We have applied this technique of ZCSS generation to a 3-bit balanced-ternary bipolar digital-to-analog converter (DAC) comprising 13 asymmetric 2J-SQUID [10].

In this letter, we describe ZCSS generation in an in-line Josephson gate [11] fabricated using a Nb/AlO$_x$/Nb technology. The critical current-magnetic field characteristics of a long JJ over a superconducting ground plane (GP) become tilted owing to the Meissner effect of the GP, which would allow us to generate a ZCSS as well. From another perspective, a single but long JJ is regarded as a simulated model of a $YBa_2Cu_3O_{7-\delta}$ (YBCO) grain boundary (GB) JJ that would be applied for future voltage standards operated at 60 K or over [12, 13].

2 Methods

Figures 1 (a) and 1 (b) show an optical micrograph and a schematic drawing of a Nb/AlO$_x$/Nb in-line Josephson gate. The test circuits were fabricated using the National Institute of Advanced Industrial Science and Technology (AIST) Nb 2.5 kA/cm^2 standard process 2 (STP2). The Josephson penetration length λ_J is calculated as 7.6 μm. (We use the approximated expression of $\lambda_J \simeq \sqrt{\Phi_0/\{2\pi J_c\mu_0(2\lambda_{Nb})\}}$ and $\lambda_{Nb} = 90$ nm, where J_c, μ_0, and λ_{Nb} are the Josephson critical current density, the vacuum permeability, and the penetration depth of the Nb films, respectively.)

Four Nb layers are available in the AIST-STP2. In Fig. 1 (b), BAS, COU, and CTL denote the 2nd, 3rd, and 4th Nb layer. A 2 μm × 16 μm JJ is formed between the BAS and COU layers. RES is a Mo layer for normal resistors. GC denotes a contact hole between the GP (the 1st Nb layer) and

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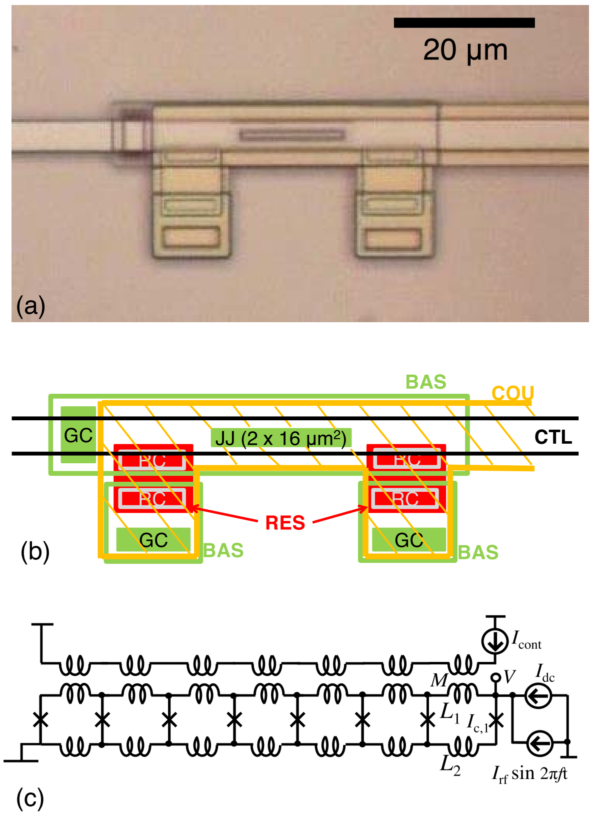

Fig. 1. (a) Optical micrograph of a Nb in-line Josephson gate. A superconducting ground plane (the 1st Nb layer) lies beneath the junction. (b) Schematic drawing of integrated layers. (c) Equivalent circuit used in numerical simulation.

the BAS layer. RC denotes a contact hole between the RES layer and the BAS layer. The dc- and rf-current is supplied between the right edge of the COU electrode and the GC. A control line in the CTL layer is prepared over the JJ in-line. Two shunting resistors are connected parallel to the JJ to make the current-voltage characteristics nonhysteretic. All elements are placed over the GP.

To simulate ZCSS generation, we employ the equivalent circuit shown in Fig. 1 (c). A long JJ is replaced by eight small JJs connected in parallel. A control line is mutually-coupled to each loop. The device parameters are chosen to reproduce the experimental results presented in the next section; $I_{c,1} = 112.5\,\mu\mathrm{A}$, $L_1 = 1.59\,\mathrm{pH}$, $L_2 = 0.792\,\mathrm{pH}$, $M = 0.296\,\mathrm{pH}$, and $R_{n,1} = 2.39\,\Omega$, where $R_{n,1}$ is a junction resistance (not explicitly shown in Fig. 1 (c)).

In measurements, test circuits were cooled at 4.2 K in liquid helium. A two-layer magnetic shield of μ-metal cans reduced the residual magnetic field on the chip to less than 10^{-7} T. The absolute zero temperature is assumed in numerical simulation.

3 Results and discussion

Experimental critical current (I_{crit})-control current (I_{cont}) characteristics are

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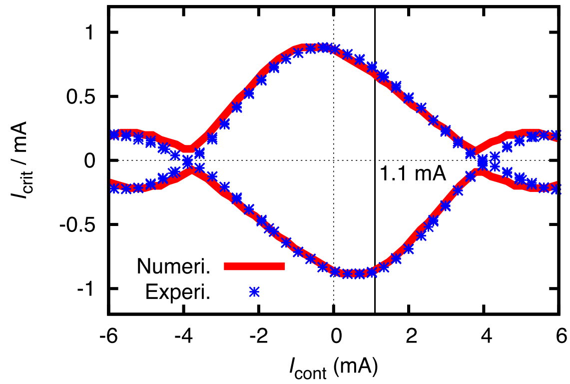

Fig. 2. Critical current (I_{crit})-control current (I_{cont}) characteristics. The vertical line at $I_{cont} = 1.1\,\mathrm{mA}$ indicates the operation condition used for the ZCSS generation in Fig. 3.

shown in Fig. 2. A tilted Fraunhofer-like dependence is obtained. The numerical results quantitatively reproduce the experimental results. As described above, the amplitudes of I_{crit} at a finite magnetic field become different for the plus and minus. For example, at I_{cont} of 1.1 mA, the positive I_{crit} is +0.70 mA (numerical), 0.18 mA smaller than the absolute value of the negative I_{crit} of −0.88 mA (numerical).

Figure 3 (a) shows three experimental current (I_{dc})-voltage (V) characteristics for the operation conditions of (i) no rf signal and no control current (labeled as "RF off, $I_{cont} = 0$"), (ii) a finite rf signal and no control current (labeled as "RF on, $I_{cont} = 0$"), and (iii) a finite rf singal and a finite control current (labeled as "RF on, $I_{cont} = 1.1\,\mathrm{mA}$"). The frequency and power of the rf signal are set to 15.2 GHz and 17.6 dBm, respectively.

The I_{dc}-V characteristics labeled as "RF off, $I_{cont} = 0$" exhibit typical characteristics of a resistively-shunted-junction (RSJ) model. When an rf-signal of 15.2 GHz is applied, Shapiro steps are generated symmetrically for positive and negative I_{dc} ("RF on, $I_{cont} = 0$"), which are also typical Shapiro steps in a RSJ model. By applying I_{cont} of 1.1 mA, the positive 1st Shapiro step crosses the zero-current axis, as expected from the I_{crit}-I_{cont} characteristics.

The corresponding numerical results are shown in Fig. 3 (b), which are likely to reproduce the experimental results. Finite slope and smaller amplitudes of the experimental Shapiro steps in Fig. 3 (a) are attributed to the thermal noise and external noise from the measurement environment.

From these results, we may conclude that an in-line Josephson gate generates a ZCSS as an asymmetric 2J-SQUID does. That is, a DAC would be realized by using an array of in-lines Josephson gates, where their deeper I_{crit} modulation may offer advantages. Besides, because of their simple structure, an array of long JJs would be realized using YBCO GB JJs.

4 Conclusion

We demonstrated a ZCSS on the I_{dc}-V characteristics of an in-line Josephson

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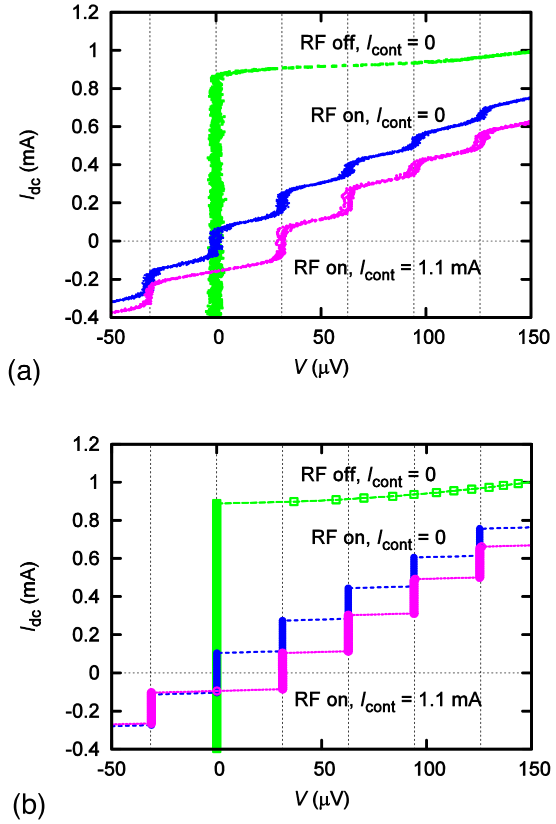

Fig. 3. (a) Experimental and (b) numerical current (I_{dc})-voltage (V) characteristics for three operation conditions. The rf frequency is set at 15.2 GHz in both experimental measurement and numerical simulation. The rf power is set at 17.6 dBm in experimental measurement, whereas I_{rf} is set at 775 μA in numerical simulation. The vertical dotted lines indicate the voltage positions of Shapiro steps for 15.2 GHz.

gate. Tilted I_{crit}-I_{cont} characteristics were the key for generation of a ZCSS. When a rf signal of 15.2 GHz was applied to the 2 μm $\times$ 16 μm Nb JJ, a ZCSS was produced by tuning I_{cont}. The experimental results were quantitatively reproduced by numerical simulation.

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