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Operation of a High-T_c Rapid Single-Flux-Quantum 4-stage Shift Register

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Abstract

We have designed and fabricated a single-flux-quantum(SFQ) four-stage shift register using YBCO bicrystal Josephson junctions, and tested its operations using a digital measurement set-up. The circuit consists of 4 shift register stages and a read SQUID placed next to each side of the shift register. Each SQUID was inductively coupled to the nearby shift register stage. The major obstacle in testing the circuits was the interference between the two read SQUIDs, and we could get over the problem by determining the correct operation points of the SQUID from the simultaneously measured modulation curves. Loaded data ("1" or "0") were successfully shifted from a stage to the next by a controlled current pulse injected to the bias lines located between the stages, and the corresponding correct data shifts were observed with the two read SQUIDs.

Keywords : Rapid single-flux-quantum circuit, YBCO thin film, Bicrystal junction, Shift register

I. Introduction

Over the past few years, there has been considerable development of superconducting digital electronics based on the rapid single-flux-quantum (RSFQ) logic family[1]. The main advantages of this new digital technology are its unparalleled speed and very low power consumption. Due to the continuous work on RSFQ circuits using low-T_c Nb multilayer technology, some devices are on the stage of becoming practical system components[2],[3]. In contrast, circuits based on high-T_c technology to date[4]-[11] are still quite simple because no mature fabrication technology has yet been found to implement more than 10^3 reproducible junctions on a chip with critical current spread of a few percent. And the multilayer process incorporating a ground plane with associated epitaxial insulators is also still immature. Nevertheless, continuous research on simple high-T_c RSFQ circuits is very important in several aspects. To begin with, possible higher operating temperature can reduce cooling costs. Next, the maximum operating speed of RSFQ devices, generally limited by the I_cR_n values of junctions, can be increased by using high-T_c superconductors instead of low-T_c ones. This is because high-T_c junctions are generally known to have larger energy gaps than conventional superconductor junctions and thus higher I_cR_n values. Finally, high-T_c digital circuits can have more advantage on a wide variety of applications where the less cooling load is required. Shift register is a basic component in a wide variety of RSFQ circuits and simple enough to be fabricated in a single YBCO layer. We have designed, fabricated and tested a 4-stage shift register consisting of 9 YBCO bicrystal Josephson junctions. Two read SQUIDs, in particular, were fabricated next to each side of the shift register to monitor the data shifts correctly.

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II. Experimentals

The circuit was fabricated on an asymmetric 24° $SrTiO_3$ bicrystal substrate. An epitaxial 200 nm-thick YBCO film was deposited by a pulsed laser ablation technique and patterned by standard optical lithography and ion milling technique. A gold layer was evaporated and patterned by lift-off and annealed at 500 °C for 1 hour for good electrical contacts. Fig. 1 shows the micrograph of the fabricated circuit. The complete circuit consists of 4 shift register stages (five Josephson junctions), two read SQUIDs (4 Josephson junctions), each of them placed next to each side of the shift register, and two control lines tuning the two read SQUIDs to have the maximum transfer functions. All the Josephson junctions forming the shift register had a width of 8 μm and were separated by the holes with the dimension of 4×6 μm^2. The read SQUID junctions had a width of 4 μm and the SQUID loop had a hole with the dimension of 4×10 μm^2.

The correct operation of the circuit has been demonstrated in the following ways. In the first step, binary input data "1" was produced by the generation of a single SFQ pulse by pulsing the Data-in(I_{in}) line(see Fig. 1) with a controlled current value and a flux quantum was stored in the first stage (leftmost) of the shift register. Then this loaded data was shifted to the second, to the third and to the final stage (right-most) by the subsequent Shift 1(I_1)–Shift 2(I_2)–Shift 3(I_3) pulses, respectively. Finally, the shift register was reset by the Data-out(I_{out}) pulse. Both of the read SQUID voltages were measured simultaneously after each pulse injection.

The shift register circuit was tested in a liquid helium dewar with a single cryoperm magnetic shield. The temperature of the sample was controlled to 70 ±0.02 K. All the bias currents to the two read SQUIDs and the control lines were supplied by Keithley 220/224 current sources and the current pulses to the shift register bias lines were supplied by a set of D/A converters(HP E1328A), operating in voltage mode with 2 kΩ resistors in series. The voltages of two read SQUIDs were simultaneously measured using Keithley 181 nano-voltmeters, and all the lines were filtered with RC filters with a cutoff frequency of 10 Hz to minimize external noise.

III. Results and Discussions

Fig. 2 shows the I-V curves of the two read SQUIDs measured at 70 K, exhibiting resistively-shunted-junction(RSJ)-like behavior suitable for making superconducting digital circuits.

The major obstacle in testing the circuit was the interference between the two read SQUIDs. There was a large difference in shape between the inde-

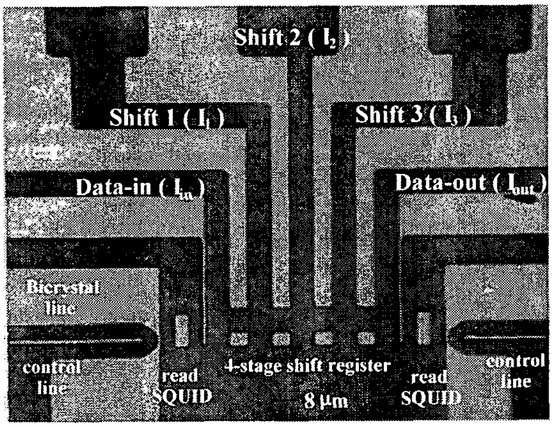

Fig. 1. Microphotograph of the fabricated 4-stage shift register circuit.

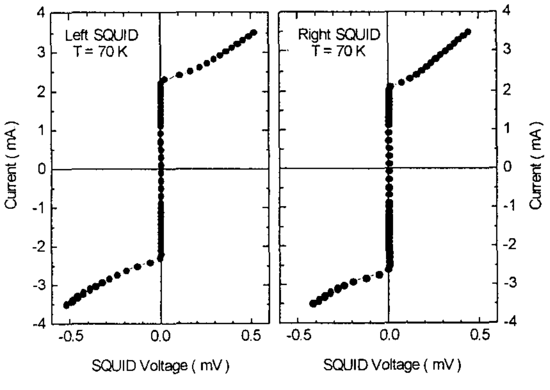

Fig. 2. Current-voltage characteristics of the two read SQUIDs at 70K, exhibiting RSJ-like behavior.

pendently measured V-Φ modulation curves of the two read SQUIDs and the simultaneously measured curves obtained by applying the same control current. This could be explained by the fact that the magnetic field caused by one control line might have influence on the magnetic state of the read SQUID at the opposite side to a certain extent. In order to avoid this interference, we simultaneously measured the V-Φ modulation curves of the two read SQUIDs and determined the correct operation points of the read SQUIDs from them.

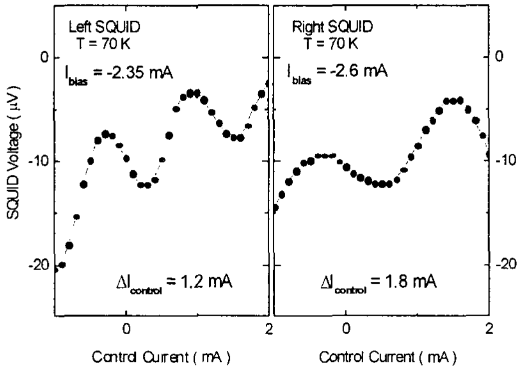

Fig. 3. Simultaneously measured V-Φ modulation curve of the two read SQUIDs, which were obtained by applyin the same control current at 70K.

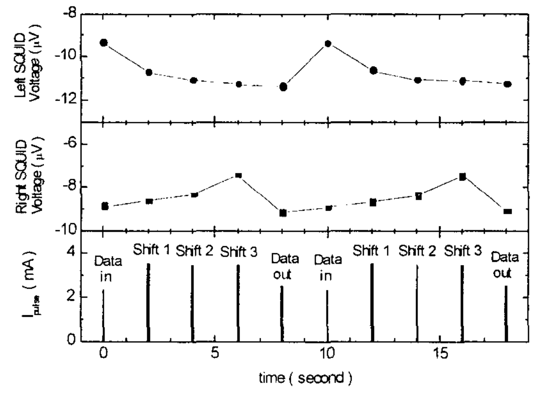

Fig. 4. Voltage responses of the two read SQUIDs during the operation of the shift register for data "1".

Fig. 3 shows the simultaneously measured V-Φ modulation curves at 70 K. From the curves, we could calculate the mutual inductance, *m*, between the two read SQUIDs and the control lines through the following relation.

$$m = \Phi_0 / \Delta I_{control} \tag{1}$$

where Φ_0 is the flux quantum and $\Delta I_{control}$ is the period of voltage modulation. The obtained mutual inductance between the left SQUID and control line was about 1.7 pH which is somewhat larger value than that measured between the right SQUID and control line, 1.2 pH. The two read SQUIDs were operated near the points where they could have the maximum values of the transfer function on these curves.

In Fig. 4, the correct operation of the shift register is shown for data "1". When the data "1" was loaded into the first stage(leftmost) by the Data-in(I_{in}) pulse, the left SQUID voltage changed to the high level. The magnitude of this voltage change corresponds to a change of one flux quantum in the first stage. By the next shift 1(I_1) pulse, the data was moved into the second stage and the left SQUID voltage abruptly changed to the low level, but not initial level. And it decreased subsequently to the slightly lower values as the data was shifted away to the third and to the final stage. Finally, the SQUID voltage returned to its initial level as the data was shifted out from the shift register by the Data-out(I_{out}) pulse. In the meantime, the right SQUID voltage increased to the slightly higher values as the data was subsequently shifted to the third stage. When the data was moved into the final stage, the SQUID voltage showed abrupt change to the high level and returned to the initial level after the data was shifted out.

Fig. 5 shows the results of operation of the shift register for 20 times. The measurements were done by repeating the operation described in Fig. 4 with only changing the amplitude of the Data in pulse. In Fig. 5(a), we can see that if data "0" instead of "1" is loaded into the first stage by applying a small Data-in pulse with its amplitude of 2.1 mA, the voltages of the both read SQUIDs remain at their initial levels except one time's error denoted by dotted circles. We may notice that the misloaded data "1" by thermal fluctuation or/and external noise is successfully shifted to the last stage resulting in the right SQUID response. In Fig. 5(b), the probability of generating the data "1" sharply rise as the amplitude of Data-in pulse is increased to 2.35 mA. However, the right SQUID remains at its initial voltage whenever the data "0" are misloaded, reflecting a successful shift of "0" to the last stage. These results can be strong evidence that the shift lines themselves, which only have to play a role of data shifting, do not generate data. From these results, we were able to confirm that the shift register circuit operated correctly.

IV. Conclusions

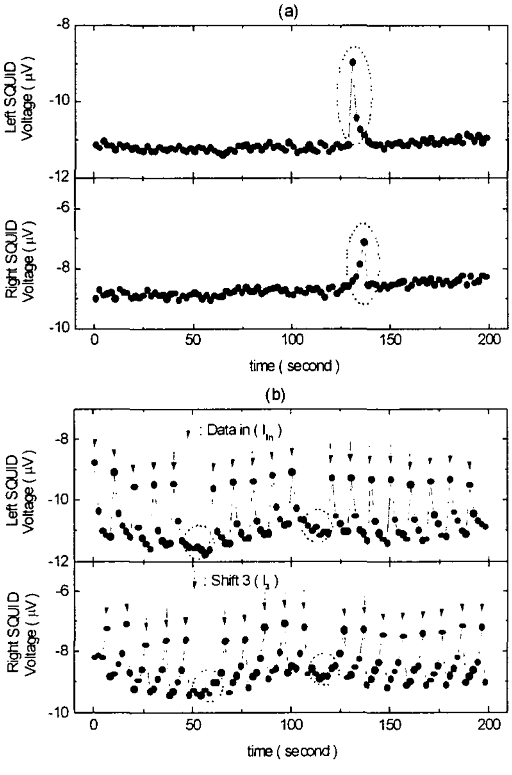

Fig. 5. Results of 20 times' repeated operation of the shif register measured with different amplitude of the Data-i pulse; (a) I_{in}=2.1 mA, (b) I_{in}=2.35 mA. I_1=3.55 mA I_2=3.5 mA, I_3=3.5 mA, I_{out}=2.55 mA, which are all th same values as the ones used in Fig. 4.

We have fabricated a 4-stage shift register using YBCO bicrystal Josephson junctions and tested its correct operation. The interference between the two read SQUIDs was found to be a major obstacle in testing the circuit. However, we got over it by finding the correct operation points of the read SQUIDs from the simultaneously measured V-Φ curves. We could observe that loaded data ("1" or "0") were success-fully shifted from a stage to the next and the correct data shifts were observed with the two read SQUIDs.

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