Progress in Superconductivity Vol.1, No1 pp 31-35 15 August 1999

A Single-Flux-Quantum Shift Register based on High-T_c Superconducting Step-edge Josephson Junctions

G. Y. Sung * [a], C. H. Choi[a], J. D. Suh [a], S. K. Han[a], K. Y. Kang [a],
J.-S. Hwang [b], S.-G. Yoon [b], K. R. Jung[c], Y. H. Lee[c], J. H. Kang[c],Y. H. Kim[d], and T. S. Hahn[d]
[a] *Electronics and Telecommunications Research Institute, P.O.Box 106, Yusong, Taejon 305-600,Korea*
[b] *Dept. of Mat. Eng., Chung Nam Nat'l Univ., 220 Gung-dong, Yusong-gu, Taejon 305-764, Korea*
[c] *Dept. of Physics, Univ. of Inchon, Inchon 402-749, Korea*
[d]*Korea Institute of Science and Technology, P.O.Box 131, CheongRyang, Seoul 130-650,Korea*
Received 21 June 1999

Abstract

We have fabricated and tested a simple circuit of the rapid single-flux-quantum(RSFQ) four-stage shift register using a single layer high-T_c superconducting (HTS) $YBa_2Cu_3O_{7-x}$ (YBCO) thin film structure with 9 step-edge Josephson junctions. The circuit includes two read superconducting quantum interference devices(SQUID) and four stages. To establish a robust HTS RSFQ device fabrication process, we have focussed on the reproducible process of sharp and straight step-edge formation as well as the ratio of film thickness to step height, t/h. The spread of step-edge junction parameters was measured from each 13 junctions with t/h=1/3, 1/2, and 2/3 at various temperatures. We have demonstrated the simplified operation of the shift register at 65 K.

Keywords: Rapid single flux quantum circuit, Step-edge Josephson junction, High temperature superconducting thin films, Shift register.

I. Introduction

Rapid single-flux-quantum (RSFQ) circuit is a promising digital application of Josephson junctions because of their intrinsic ultra-high switching speed and low power dissipation[1]. These circuits, using overdamped Josephson junctions as active elements, store binary information in the form of single flux quantum, $\Phi_0=h/2e \cong 2\times10^{-15}$ Wb, while transferring and processing it in the form of picosecond SFQ pulses with the quantized area $\int V(t)dt = \Phi_0 \cong 2\text{mV} \times \text{ps}$. Recently, complicate circuits using high T_c superconductor (HTS) $YBa_2Cu_3O_{7-x}$ (YBCO) SFQ logics have been demonstrated by developing the multilayer SNS ramp-edge Josephson junctions [2]-[6]. Up to date, the ramp-edge junctions without deposited interlayers exhibited the best electrical characteristics and parameter spreads [7],[8].

Among the HTS YBCO Josephson junctions, the step-edge Josephson junction possesses the advantage of good transport properties, low 1/f-noise, remarkably simple fabrication, and circuit layout flexibility [9]. It consists of two tilt angle grain boundary junctions in series created by depositing a superconducting film across a steep step in the substrate and patterning of a microbridge. Before depositing the superconducting film epitaxially on a single crystal substrate, a step is etched into the substrate using photolithography and argon ion milling. If the step

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*Corresponding author. Fax: +82 42 860 6836
e-mail: gysung@etri.re.kr.

angle is correct, a simple grain boundary structure will form at the step's edge during the subsequent deposition of a HTS thin film; one grain boundary forms at the top of the step and one at bottom. The microstructure of the edge depends on the orientation of the edge in relation to the substrate. Preferably, the edges will follow the direction of the major crystal axis. The major obstacle is their reproducibility in the device fabrication. Grain boundaries form in a more or less random process, so the local geometry and number of grain boundaries can not be specified exactly.

We have investigated the spread of 13 step-edge Josephson junctions' parameters as a function of the ratio of film thickness (t) to step height (h), t/h. We have designed, fabricated, and tested a simple circuit of the RSFQ shift register using the HTS YBCO step-edge junctions with t/h=2/3. The circuit consists of 9 step-edge Josephson junctions including two read superconducting quantum interference devices(SQUID) and four stages.

II. Fabrication Details

Typical step-edges were formed by depositing a 50 nm-thick Au film onto a $SrTiO_3$ (100) substrate and spin-coating AZ5214E photoresist(PR). In order to develop the PR into sharp edge shape, the Au film was used as a protective layer for the light reflected from the bottom of $SrTiO_3$ substrate during exposing the PR on contact-aligner. The sharp profiles of the developed photoresist's edges were obtained by the Au film. The exposed Au film and $SrTiO_3$ substrate were etched by an Ar ion milling process. To obtain the desired step-edge profile, it was necessary to have the optimized geometry during ion beam etching as well as the sharp profiles of the developed PR's edges. The substrates were attached to a water-cooled stage of the ion mill at an angle of 45° with respect to e ion beam. The step-edge line was aligned at an anti-clockwise rotation angle of 15° with respect to the ion beam axis. During the ion milling the stage was rotated at 1 r.pm. about the ion beam axis. The profile of the step, the step height, and the step angle have been observed by scanning electron microscopy (SEM).

Epitaxial c-axis oriented YBCO thin films were deposited by conventional pulsed laser deposition(PLD) [10],[11] at an oxygen pressure of 100 mTorr and a substrate temperature of 820 °C. The film thickness was varied with the t/h of 1/3, 1/2, and 2/3. The 13 junctions of 10 μm width were patterned on a 700 μm-long step-edge line by conventional photolithography and argon ion milling. For good ohmic contact a 300 nm-thick Au film was deposited by PLD and patterned by lift-off technique. Finally, the samples were annealed in 500 Torr oxygen atmosphere.

III. Results and Discussion

1. Junction Characterization

Fig. 1. shows SEM images of a step on $SrTiO_3$ (100) substrates. The step height is 180 nm, and the edge angle is greater than 80°. The step edges are sharp and straight. We have fabricated the 13 junctions and one test SQUID on the step-edge line. The current-voltage (I-V) characteristics of the junctions and SQUID were measured at various temperatures. Fig. 2 shows the I_c values for the 10 μm-wide junctions with the t/h of 1/3, 1/2, and 2/3 as a function of temperature. Parameters of the junctions are summarized in Table I. T_c of the junctions increased up to 89 K with increasing the t/h ratio. At 60 K, the I_cR_n spread (1_σ) of 68.8, 48.9, and 33.9 % were obtained for the t/h = 1/3, 1/2, and 2/3, respectively, which were relatively broad because of their 10 μm junction width. From the spread data, we have determined the best value of the t/h ratio for the fabrication of our

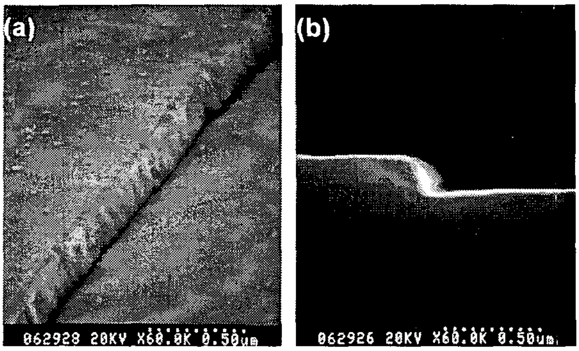

Fig. 1. Scanning electron micrographs showing the step-edge of $SrTiO_3$ (100) substrate. (a) a bird's-eye view and (b) a cross-sectional view.

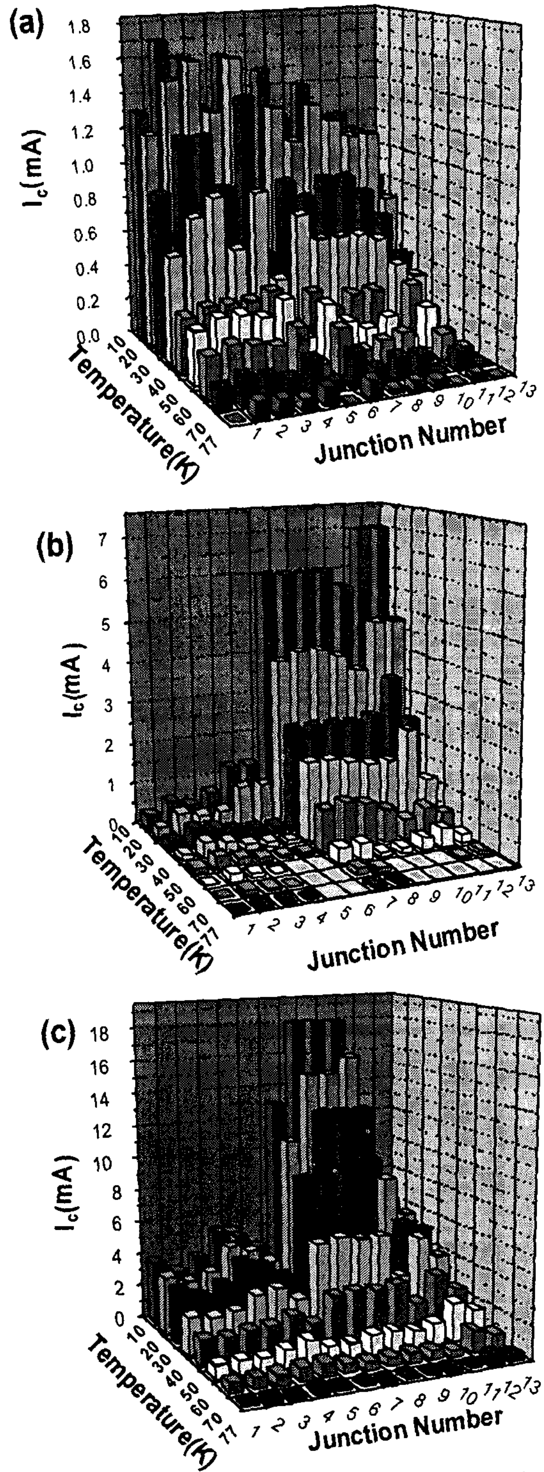

Fig. 2. The I_c values of 13 junctions as a function of temperature for (a) t/h = 1/3, (b) t/h = 1/2, and (c) t/h = 2/3.

Table I . Parameters of the step-edge Josephson junctions with three t/h ratio from the 13 junctions at each step-edges measured at 60 K.

t/h	1/3	1/2	2/3
T_c (K)	69 ~ 72	60 ~ 82	81~89
I_c (mA)	0.17	0.21	1.19
J_c (A/cm^2)	2.47x10^4	2.78x10^4	7.2x10^4
I_cR_n (mV)	0.31	0.31	0.84
R_nA* (Ω-cm^2)	1.77x10^{-8}	1.34x10^{-8}	1.21x10^{-8}
I_c-1σ (%)	52.7	75	35.5
I_cR_n-1σ (%)	68.8	48.9	33.9

*A means the area of the junction.

RSFQ shift register using step-edge junctions. The t/h of junctions was 2/3 in order to have the smallest spread of the junction parameters and the highest T_c, I_c, and I_cR_n product.

2. Circuit Design and Testing

The equivalent circuit diagram of a 4-stage shift register circuit and an optical micrograph of the fabricated circuit using the step-edge junctions with t/h ratio of 2/3 are shown in Fig. 3. It consisted of 4-stage shift register and the two read SQUIDs positioned on each side of the shift register. The read SQUIDs were magnetically coupled to the shift register. The circuit was tested in a cryogenic dewar where the sample temperature was controlled in the range of 60 ~ 70 K. The test equipments used in this work include several DC current sources (Keithley model 224) and a nanovoltmeter (Keithley model 181). All instruments were controlled and data were recorded by a personal computer. To reduce the external noise produced by these instruments, all lines were filtered with RC filters that had a cut-off frequency of about 30 Hz [12].

In order to qualify the step-edge junctions of which the circuit is comprised, the I-V characteristics of the read SQUID 1 and 2 were measured at 65 K. The shapes of the I-V curves are qualitatively consistent with the resistive shunted junction (RSJ) model, indicating that they are adequate to make superconducting digital circuits.

Fig. 4 shows the typical V-Φ modulation curve of the read SQUID 1 measured at 65 K. The amplitude

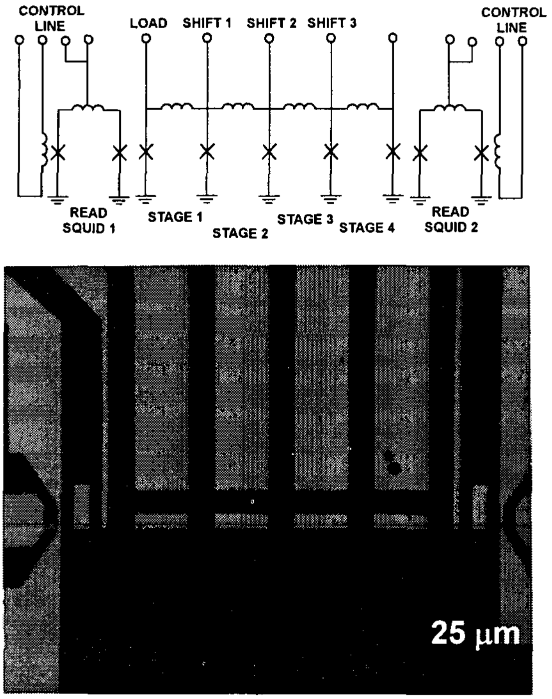

Fig. 3. Circuit diagram and optical micrograph of the four-stage shift register using HTS YBCO step-edge junctions on $SrTiO_3$ (100) substrate.

of the V-Φ modulation was about 7 μV. The period of voltage modulation ($\Delta I_{control}$) was 0.9 mA. The mutual inductance, m, between the read SQUID and control line could be calculated through the equation of m = $\Phi_o/\Delta I_{control}$, where Φ_o is the flux quantum ($\Phi_o = 2.07 \times 10^{15}$ Tm^2). From this equation, we could obtain the mutual inductance, m, which was about 2.3 pH. From this curve, we could determine the SQUID bias current($I_{b,SQUID}$) and the control current (I_{contol}) to operate the read SQUID.

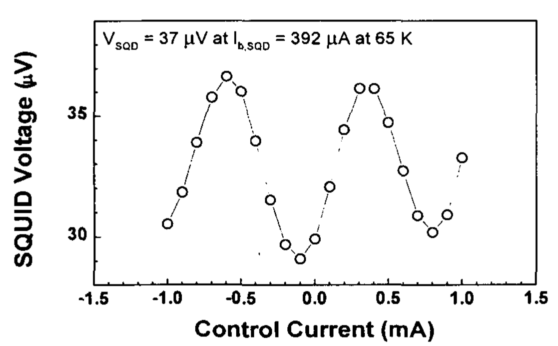

Fig. 4. V-Φ characteristics of the read SQUID 1.

As a preliminary step, we tested the circuit by using only stage 1 and read SQUID 1. First, we loaded one flux quantum in the stage 1 by injecting the current pulse to LOAD. And then we released it into the next stage by injecting the current pulse to SHIFT 1. The magnitude of the current pulses injected to LOAD and SHIFT 1 were 0.3 mA and 0.8 mA, respectively. In this experiment, the operating temperature was 65 K. Fig. 5 shows that this preliminary test was successful. Two quantized voltage states of the read SQUID 1 were observed. The steps between two quantized voltage values result from the change of one flux quantum in the stage 1.

Based on this result, we operated the shift register circuit in a simplified manner, in which the flux quantum loaded in the stage 1 was shifted to the stage 4 at once. In this experiment we used only one current source and the current was equally divided into the three shift lines (SHIFT 1, 2, and 3) by the resistors of equal value. The magnitude of the current pulses injected to LOAD and three SHIFTs were 0.3 mA and 1 mA, respectively. Even though many errors in shifting flux quanta were observed in this measurement, we think we can improve this by properly optimizing the circuit components.

IV. Conclusions

We have determined an optimized junction fabrication condition to obtain the smallest spread of the HTS YBCO step-edge Josephson junction parameters by investigating the spread of 13 junctions' parameters as a function of the t/h ratio as well as the angle

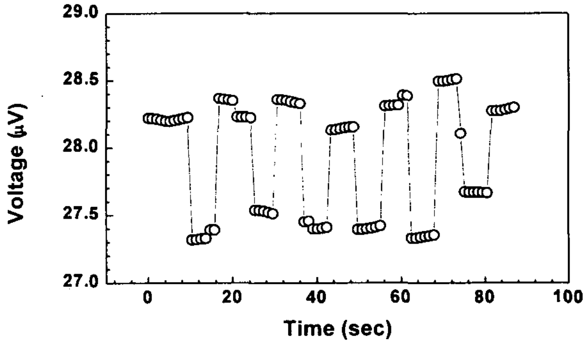

Fig. 5. Operation of the single flux quantum shifting in the stage 1 at 65 K.

of step-edge. We have learned that the step-edge junctions was not suitable for the digital circuits because of their inherent inhomogeneity. We have demonstrated the simplified operation of the RSFQ four-stage shift register fabricated with the HTS YBCO step-edge junctions with t/h=2/3. The operating temperature was 65 K.

Acknowledgments

The authors acknowledge the support by the Ministry of Information and Communications and the Ministry of Science and Technology, REP. OF KOREA. The work at University of Inchon was supported in part by the Korea Science and Engineering Foundation through the Multimedia Research Center at University of Inchon. The authors would like to thank Dr. Bun Lee for his supports, and also thank Prof. Soon Gul Lee for useful discussions.

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