Fabrication and properties of high performance $YBa_2Cu_3O_{7-\delta}$ radio frequency SQUIDs with step-edge Josephson junctions*

Liu Zheng-Hao(刘政豪), Wei Yu-Ke(魏玉科), Wang Da(王 达), Zhang Chen(张 琛), Ma Ping(马 平)†, and Wang Yue(王 越)

Applied Superconductivity Research Center, State Key Laboratory for Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, *China*

(Received 25 December 2013; revised manuscript received 8 April 2014; published online 16 July 2014)

We describe the fabrication of high performance $YBa_2Cu_3O_{7-\delta}$ (YBCO) radio frequency (RF) superconducting quantum interference devices (SQUIDs), which were prepared on 5 mm×5 mm $LaAlO_3$ (LAO) substrates by employing step-edge junctions (SEJs) and in flip-chip configuration with 12 mm×12 mm resonators. The step in the substrate was produced by Ar ion etching with step angles ranging from 47° to 61°, which is steep enough to ensure the formation of grain boundaries (GBs) at the step edges. The YBCO film was deposited using the pulsed laser deposition (PLD) technique with a film thickness half of the height of the substrate step. The inductance of the SQUID washer was designed to be about 157 pH. Under these circumstances, high performance YBCO RF SQUIDs were successfully fabricated with a typical flux-voltage transfer ratio of 83 mV/Φ_0, a white flux noise of 29 $\mu\Phi_0/\sqrt{Hz}$, and the magnetic field sensitivity as high as 80 $fT/\sqrt{Hz}$. These devices have been applied in magnetocardiography and geological surveys.

Keywords: superconducting quantum interference device (SQUID), $YBa_2Cu_3O_{7-\delta}$ (YBCO), step-edge junction, radio frequency

PACS: 74.72.–h, 68.37.Ps, 74.78.–w, 85.25.Dq **DOI:** 10.1088/1674-1056/23/9/097401

1. Introduction

Owing to their very high sensitivity to weak magnetic fields, superconducting quantum interference devices (SQUIDs) have been widely utilized in many applications. Compared with low-T_c SQUIDs, high-T_c SQUIDs using high-temperature superconductors can work at the liquid nitrogen temperature (77 K) and hence have a great advantage in cryogenic cost. By now, almost all practical high-T_c SQUIDs have been fabricated by using $YBa_2Cu_3O_{7-\delta}$ (YBCO).[1] Depending on the number of Josephson junctions in the superconducting loop, either DC or radio frequency (RF) SQUID can be realized. An RF SQUID consists of a single junction and can have a magnetic field sensitivity comparable to that of a DC SQUID which consists of two junctions in the superconducting loop. One way to obtain YBCO RF SQUIDs is to employ step-edge, grain-boundary Josephson junctions in YBCO thin films. The step-edge junctions (SEJs) are introduced by steep steps in the substrates such as $LaAlO_3$,[2] $SrTiO_3$ (STO),[3] and MgO.[4] Here we present our recent results on the fabrication of YBCO RF SQUIDs using SEJs. In our practice, we find that by using the same ion etching technique, the step in the LAO substrate is steeper than that in the STO substrate. Partly because of this we have made the YBCO RF SQUIDs on LAO substrates. It is worth pointing out that these devices have been applied in, among other fields, magnetocardiography,[5,6] geological surveys, and magnetic anomaly detections.

It is known that the quality of SEJs is critical to the performance of YBCO RF SQUIDs. In experiments, however, it is not easy to obtain high-quality SEJs, although the process to fabricate SEJs is relatively straightforward. This is because there are various factors determining the growth of SEJs and some of them are difficult to control. In this paper, we shall pay particular attention to two important factors in preparing the SEJs, that is, the substrate step angle and the ratio of the YBCO film thickness to the step height.[7] For the step angle θ, the previous studies suggested that in order to form grain-boundary SEJs in YBCO thin films, the substrate step should be steep enough with θ larger than 45°.[8] In particular, we note that Wu *et al.* investigated the influence of the step angle on the fabrication of YBCO DC SQUIDs with SEJs.[9] Using MgO as the substrate material, they reported a SQUID having white flux noise around 60 $\mu\Phi_0/\sqrt{Hz}$. As for the ratio of the film thickness d to the step height h, d/h, the previous studies indicated that it should have a value between $2/3$ and 1 for PLD-grown YBCO films and about $1/2$ for sputtered ones.[7] In the present study, we have used the pulsed laser deposition (PLD) technique to deposit the YBCO film, however, different from the previous studies, we find that it might be better to have a ratio d/h of $1/2$ rather than $2/3$ to fabricate YBCO RF SQUIDs with decent qualities.

*Project supported by the National Basic Research Program of China (Grant No. 2011CBA00106), the National Natural Science Foundation of China (Grant No. 11074008), and the Research Fund for the Doctoral Program of Higher Education, China (Grant No. 20100001120006).

†Corresponding author. E-mail: maping@pku.edu.cn

© 2014 Chinese Physical Society and IOP Publishing Ltd

2. Experiment

The steps in the LAO substrates were fabricated by Ar ion etching. Firstly, a mask film with a thickness of 300 nm was deposited on the LAO substrate by DC sputtering. Then the mask film was patterned by chemical etching. Finally, the substrate was etched by Ar ion milling, with an Ar ion energy of 500 eV, a pressure of 2.0×10^{-2} Pa, and a current density of about 0.65 mA/cm^3. According to this procedure, the step angle is determined by the etching speeds of the patterned mask and the substrate via the following relation:

$$\alpha_2 = \arctan(\tan\alpha_1 \Delta h_2/\Delta h_1), \tag{1}$$

where α_1 is the angle of the mask, α_2 is the step angle, Δh_1 is the height of the etched mask, and Δh_2 is the step height. The surface morphology of the step was examined by atomic force microscopy (AFM).

By using PLD, YBCO thin films were deposited on the prepared LAO step-edge substrates. When depositing the film, we used a laser repetition rate of 10 Hz and a laser energy of 200 mJ per pulse. The substrate temperature was kept at 780 °C and the O_2 partial pressure was 30 Pa. The superconducting transition temperature of the film was characterized by AC susceptibility measurement. As mentioned before, the ratio of the YBCO film thickness to the substrate step height is very important in determining the formation of SEJs. In our experiment, we also investigated this issue, which will be addressed later.

With YBCO thin films available, the RF SQUIDs were patterned by the standard photolithography technique. Figure 1(a) shows the layout of the SQUID. The inductance of the washer is about 157 pH, which is calculated through $L = 1.25\mu_0 d$.[10] When testing, the applied magnetic field was perpendicular to the SQUID plane, as shown in Fig. 1(a).

The STO dielectric resonator, which was in the size of 12 mm×12 mm and placed underneath the SQUID, was also fabricated by PLD and standard lithography techniques. Gao *et al*. have reported the properties of the STO resonators.[11] The SQUIDs and the resonators were encapsulated by PCBs, as shown in Fig. 2.

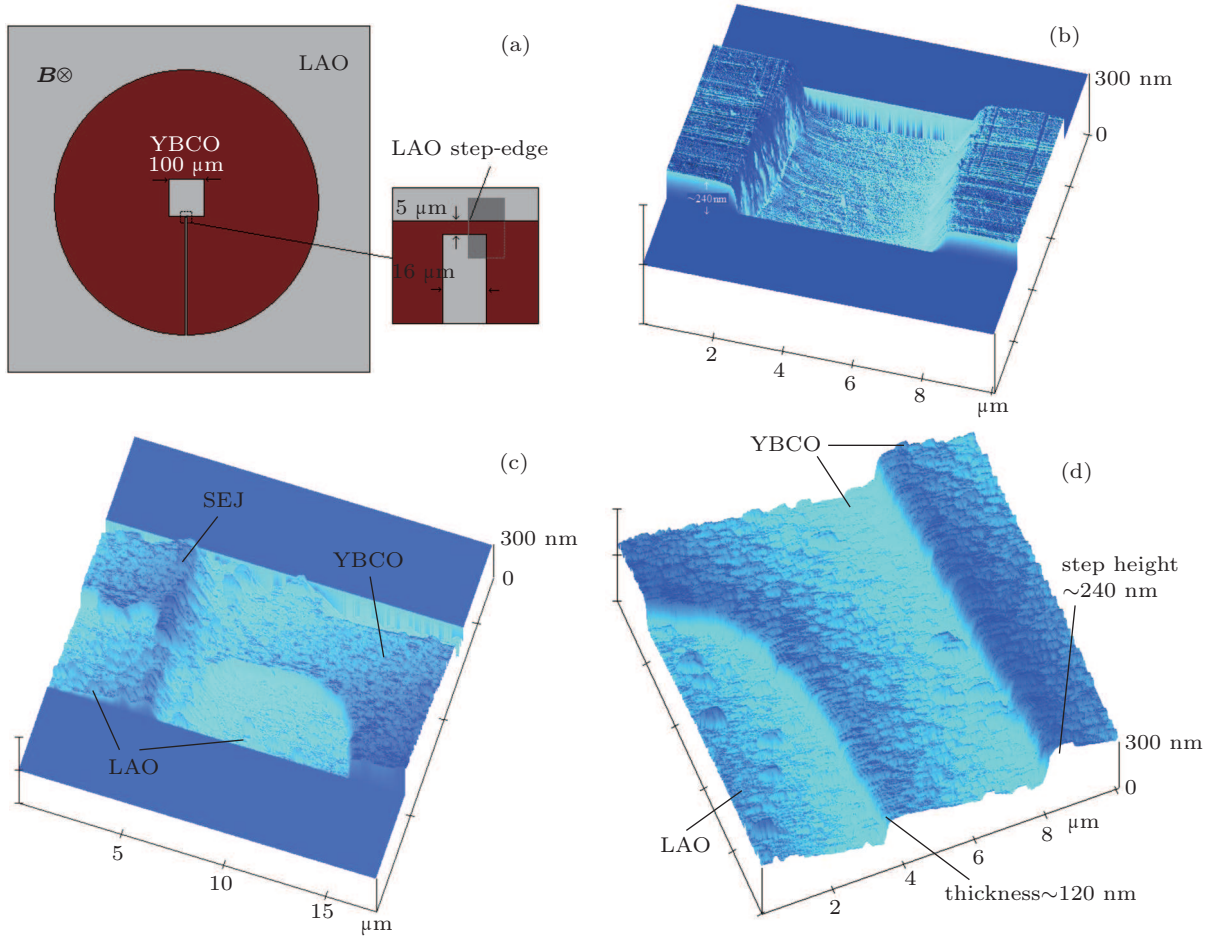


Fig. 1. (a) Schematic diagram of YBCO RF SQUID pattern and size. (b) AFM image of LAO step of about 240 nm. (c) AFM image of the SEJ. (d) AFM image of the other side against the step. The corresponding positions are shown in panel (a).

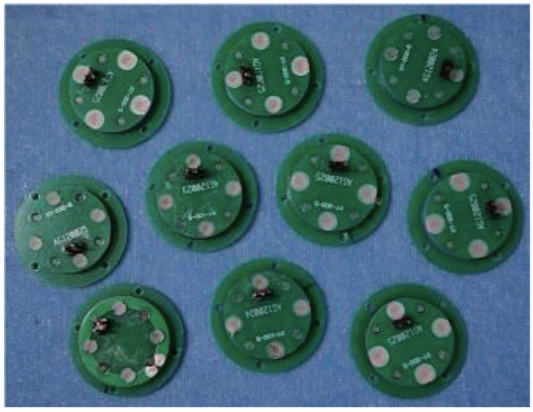


Fig. 2. A series of encapsulated SQUIDs and resonators.

3. Results and discussion

Figure 1(b) shows the morphology of the LAO substrate step with a height about 240 nm. It is seen that the step is relatively steep, although there is some variation in the step angle along the line of the step edge. Figures 1(c) and 1(d) show respectively the AFM images of the SEJ area and the step on the other side as denoted in Fig. 1(a). The thickness of the YBCO film is about 120 nm, that is, half of the step height. It is evident that the roughness of the surface increases after the deposition of the film and the lithography process, which affect the uniformity of the SEJ. As pointed out earlier, the preparation of the SEJ is critical to the fabrication of a SQUID. Therefore, with further improvement in the fabrication technique to obtain more uniform SEJs, the performance of SQUIDs is expected to be further enhanced in the future.

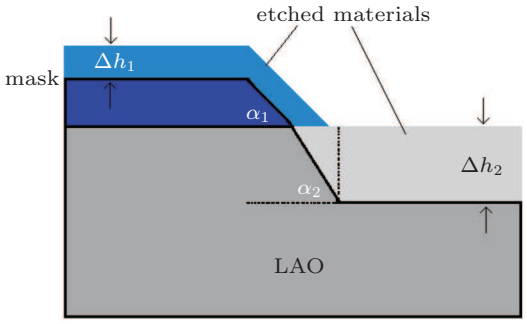


Fig. 3. Schematic diagram of ion etched LAO substrate. The mask film is etched by a chemical method ($\alpha_1 = 45°$).

By measuring the etching speeds of the mask film and the substrate, we have calculated the step angle α_2 via relation (1). Figure 3 schematically illustrates the etched LAO substrate and the mask, where the quantities in relation (1) such as the step angle and the step height have been denoted. In order to obtain steep LAO steps, the etching rate of the mask has been adjusted to be lower than that of the substrate. Table 1 summarizes the etching rates and the step angles of several LAO substrates. As mentioned before, the step angle needs to be larger than 45° to allow the formation of SEJs. It is seen from Table 1 that the step angles lie in the range between 47° and 61°, satisfying this requirement. It should be pointed out that in calculating the step angle from Eq. (1), we have neglected its inevitable fluctuations along the line of the step edge, suggesting that it could be viewed as an average step angle of the substrate.

Table 1. Ion etching rate of LAO substrates, and average step angles.

Δh_1/Å	Δh_2/Å	α_2/(°)
1599	1899	49.90
1973	2361	50.12
2988	3186	46.84
1050	1750	59.04
1120	1620	55.34
1336	2400	60.90

Figure 4 shows the temperature dependence of the real part χ' of the AC susceptibility for several YBCO films. It is seen that the films exhibit narrow superconducting transitions and have transition temperatures between 88 K and 90 K.

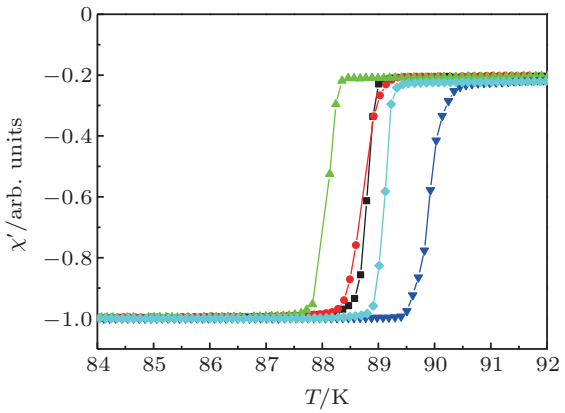


Fig. 4. The χ'–T curves of the YBCO film samples.

The SQUIDs were tested in a sweeping DC magnetic field plus a radio frequency field. Figure 5 shows the oscillogram of the triangular transfer function of one device. At the resonance frequency of 610 MHz, the amplitude of the triangular wave is 0.9 V and the flux-voltage transfer ratio is 83 mV/Φ_0. By calibrating the magnetic field and the flux, the flux-field transfer coefficient is measured to be 2.8 nT/Φ_0. As stated above, for the present devices, the thickness of the YBCO film is half of the substrate step height. We also fabricated YBCO RF SQUIDs with a film thickness about 60% of the step height. Unfortunately, the tests showed that those devices could not show clear triangular waves.

Figure 6 shows the noise spectra of five RF SQUIDs. Note that there are background noises coming from the 50 Hz power line. It is seen that there is a good consistency among

the devices, which illustrates the good reproducibility of our fabrication of YBCO RF SQUIDs. The white noise of the devices is around 100 fT/$\sqrt{\text{Hz}}$ and can be as low as 80 fT/$\sqrt{\text{Hz}}$ with the corresponding flux noise of about 29 $\mu\Phi_0/\sqrt{\text{Hz}}$. This demonstrates that the magnetic field sensitivity of our devices is high and meets the requirement of many low magnetic field applications.

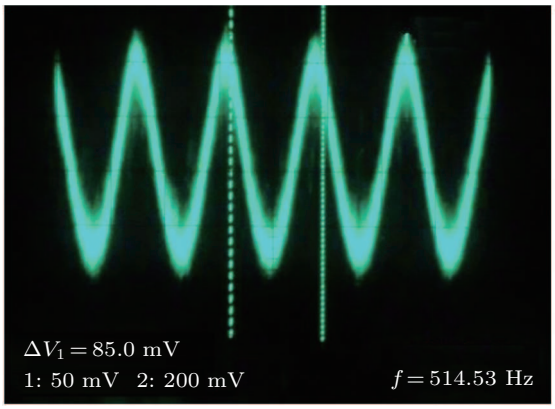


Fig. 5. The V_{rf}–Φ_{e} curves of one RF SQUID sample. The flux–voltage transfer ratio is 83 mV/Φ_0.

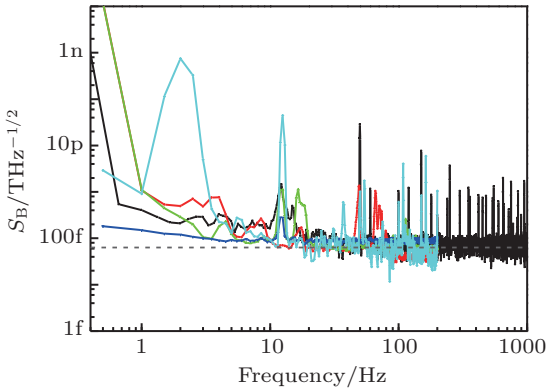


Fig. 6. Noise spectra of several YBCO RF SQUIDs. The white noise is as low as 80 fT/$\sqrt{\text{Hz}}$, corresponding to a flux noise of about 29 $\mu\Phi_0/\sqrt{\text{Hz}}$.

4. Conclusion

In summary, we have presented the fabrication of high performance YBCO RF SQUIDs by employing SEJs on LAO substrates. With the LAO step angle over 45° and the YBCO film thickness half of the step height, grain-boundary Josephson junctions have been successfully prepared at the step edges. Based on this, a series of YBCO RF SQUIDs have been fabricated, which exhibit a magnetic field sensitivity as high as 80 fT/$\sqrt{\text{Hz}}$. The good consistency among the devices also demonstrates the reproducibility of our fabrication of YBCO RF SQUIDs, which is important for practical applications. The performance of the devices is expected to be further improved with further refinements of the fabrication process in the future.

References

[1] Koelle D, Kleiner R, Ludwig F, Dantsker E and Clarke J 1999 *Rev. Mod. Phys.* **71** 631
[2] Yi H R, Gustafsson M, Winkler D, Olsson E and Claeson T 1996 *J. Appl. Phys.* **79** 9213
[3] Millar A J, Romans E J, Carr C, Eulenburg A, Donaldson G B and Pegrum C M 2001 *IEEE Transactionson Applied Superconductivity* **11** 1351
[4] Gohng J, Lee E N, Song I H, Sok J, Park S J and Lee J W 1997 *IEEE Transactionson Applied Superconductivity* **7** 3694
[5] Wang Q, Ma P, Lu H, Tang X Z, Hua N and Tang F K 2009 *Chin. Phys. B* **18** 5566
[6] Wang W Y, Zhao C, Lin Y Z, Zhang S L, Xie X M and Jiang S Q 2013 *Acta Phys. Sin.* **62** 148703 (in Chinese)
[7] Clarke J and Braginski A I 2004 *The SQUID Handbook* (Berlin: Wiley-VCH Verlag) pp. 112–115
[8] Herrmann K, Kunkel G, Siegel M, Schubert J, Zander W, Braginski A I, Jia C L, Kabius B and Urban K 1995 *J. Appl. Phys.* **78** 1131
[9] Wu C H, Chen M J, Chen J C, Chen K L, Yang H C, Hsu M S, Lai T S, Tsai Y S, Horng H E, Chen J H and Jeng J T 2006 *Rev. Sci. Instrum.* **77** 033901
[10] Jaycox J M and Ketchen M B 1981 *IEEE Transactions on Magnetics* **17** 400
[11] Gao J, Yang T, Ma P and Dai Y D 2010 *Acta Phys. Sin.* **59** 5044 (in Chinese)