



Fabrication and measurement of Nb-based SQUID magnetometer

Xue Zhang^{a,b,c}, Guofeng Zhang^{a,b,*}, Liliang Ying^{a,b}, Wei Xiong^{a,b,c}, Haoxuan Han^{a,b,c},
Yongliang Wang^{a,b}, Liangliang Rong^{a,b}, Xiaoming Xie^{a,b,c}, Zhen Wang^{a,b,c}

^a State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology (SIMIT), Chinese Academy of Sciences (CAS), Shanghai 200050, China

^b Chinese Academy of Science, Center for Excellence in Superconducting Electronics, Shanghai 200050, China

^c University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

We have developed low-noise direct current-superconducting quantum interference devices (DC-SQUIDs) based on Nb/Al-AlO_x/Nb Josephson junctions on thermally oxidized silicon substrate. The SQUID fabrication was realized with a simple 5-mask-level process, in which one single insulating layer (SiO₂) was used not only to insulate different metal layers, but also to protect the junction shunt resistor from oxidation or corrosion. In our SQUID design, a washer-type loop with an inductance of 140 pH and a coupled flux transformer with a multi-turn spiral input coil connecting to a pickup coil of 8.5 × 8.5 mm² were used, thus leading to a SQUID magnetometer with magnetic field sensitivity of 0.7 nT/Φ₀. We measured the voltage-flux characteristics and flux noise in superconducting niobium shielding at 4.2 K. The measured white flux noise in a flux-locked loop was 5 μΦ₀/√Hz, corresponding to magnetic field noise of 3.5 fT/√Hz.

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1. Introduction

As the most sensitive magnetic flux sensor, SQUID could be used to detect any physical quantities which can be converted to magnetic flux. State-of-the-art LTS SQUIDs are mostly fabricated in planar integrated circuit process since Jaycox and Ketchen demonstrated a planar washer-type SQUID design in 1980s [1,2]. For SQUID fabrication based on Nb/Al-AlO_x/Nb Josephson tunneling junctions, film resistor used for damping junction hysteresis is necessary. In practical applications, SQUID has to tolerate thermal recycling which may lead to the resistance value change due to oxidation or corrosion. To avoid this, one can add insulation or protection layer at the cost of one more step of process [3,4].

In this paper, we introduce a 5-mask-level fabrication process for SQUID magnetometer based on Nb/Al-AlO_x/Nb Josephson junctions. In this process, all the films are etched except the lift-off Ti-Pd film resistor. The resistor is formed on the silicon substrate after the definition of Josephson junction. One single insulating layer is then deposited and connection windows for junctions and resistors are opened. The connection between junction electrodes and resistors is realized by the last Nb wiring layer. The main advantages of the process include: 1) precise resistance value can be obtained

which is only determined by the geometric size since the resistor film is smooth without any edge step; 2) no additional protection layer is needed to prevent the resistor from oxidation or corrosion.

The SQUID magnetometers were fabricated on the superconducting integrated circuit platform at SIMIT. We designed a Ketchen-type SQUID magnetometer to verify the process. For the magnetometer with a SQUID loop inductance of 140 pH and pickup size of 8.5 × 8.5 mm², a white magnetic field noise of 3.5 fT/√Hz was obtained.

2. Design and fabrication

The SQUID was designed with the similar configuration of the planar coupling scheme devised by Jaycox and Ketchen mentioned above. The two resistively-shunted junctions are located on the outer edge of the SQUID square loop, and multi-turn spiral input-coil is fabricated directly above the SQUID washer to realize the tight coupling. In order to increase the effective flux capture area, a pickup coil with a large area of 8.5 × 8.5 mm² is connecting in series to the input-coil. Fig. 1 shows the SQUID magnetometer layout, in which the SQUID loop inductance is 140 pH and the Josephson junction area is 4 × 4 μm². More specific design parameters of the SQUID magnetometer are listed in Table 1.

The fabrication process of the SQUID magnetometer is outlined in Fig. 2 and described in detail as follows.

* Corresponding author.

E-mail addresses: gfzhang@mail.sim.ac.cn (G. Zhang), zwang@mail.sim.ac.cn (Z. Wang).

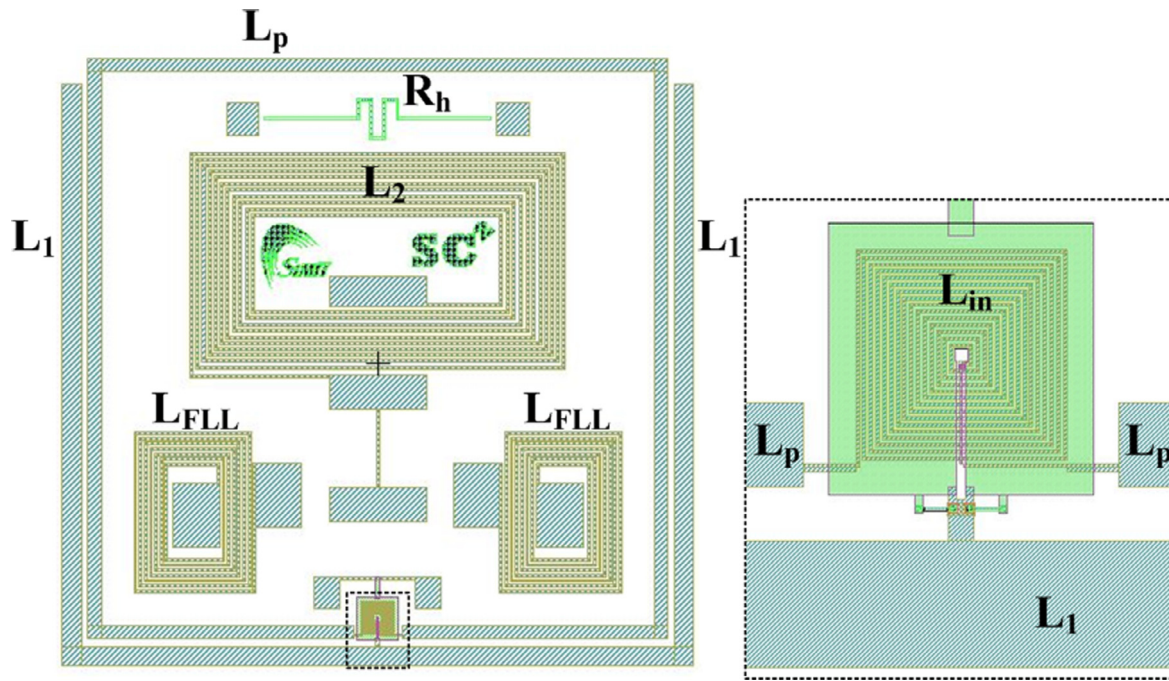


Fig. 1. Layout of the SQUID magnetometer. Several coils are integrated on the chip served as feedback coil (L_{FLL}) and SBC coils (L_1 and L_2) [5]. R_h is the heating resistor to expel the frozen flux in the superconducting film.

Table 1

Specific design parameters of the SQUID magnetometer.

Parameter	value
Chip size	$10 \times 10 \text{ mm}^2$
Washer loop	
Hole dimension	$30 \text{ }\mu\text{m}$
Outer edge dimension	$630 \text{ }\mu\text{m}$
Inductance of SQUID washer L_s	140 pH
Input coil	
Number of turns n	15
Line width w_i	$8 \text{ }\mu\text{m}$
Line spacing s_i	$8 \text{ }\mu\text{m}$
Inductance of input-coil L_i	40 nH
Pickup coil	
Size of pickup coil	$8.5 \times 8.5 \text{ mm}^2$
Line width w_p	$200 \text{ }\mu\text{m}$
Inductance of pickup coil L_p	30 nH
Area of Josephson junction	$4 \times 4 \text{ }\mu\text{m}^2$

- (a) Deposition of Nb/Al-AlO_x/Nb trilayer. All the films are sputtered with magnetron sputtering continuously. Before deposition, the silicon substrate is surface cleaned with argon ion bombardment. Both Nb and Al films are sputtered in constant current mode, 1.5 A for Nb and 0.3 A for Al. After the first 200 nm-thick Nb is sputtered, 30 minutes' waiting is necessary to ensure the sample is enough cooled to avoid the interfacial diffusion between Nb and Al films. The barrier layer is formed by depositing 10 nm Al and then oxidized a part of it in the pure oxygen environment. The critical current density J_c of Josephson junctions can be controlled by adjusting the oxidization condition of Al films, including oxygen pressure and oxidization time. J_c of 100 A/cm^2 is obtained in the pressure of 2.6 kPa for 5 hours. Samples are cooled during sputtering by the cooling water flowing through the sample table. More detailed deposition parameters of Nb/Al-AlO_x/Nb trilayer are shown in Table 2.
- (b) Definition of SQUID washer. The top Nb film of Nb/Al-AlO_x/Nb trilayer is firstly patterned and etched using reactive ion etch-

ing (RIE) with CF₄. Subsequently, the exposed Al-AlO_x layer is then etched using Ar ion beam to form the SQUID washer outline. The bottom Nb film except the washer part is thus exposed and reserved to be processed in the next step.

- (c) Definition of Josephson junctions, interconnection and base electrodes. In this step, top and bottom Nb films of Nb/Al-AlO_x/Nb trilayer are synchronously patterned and RIE etched. Here, junctions are defined by etching the top of the Nb film while interconnection and base electrodes are defined by etching the bottom Nb film left in process (b). Note that the Al-AlO_x layer could be regarded as a natural etching stop for junction definition due to its inactivity to RIE with CF₄. Furthermore, in order to avoid the undercutting effect [6], the same film thickness for top and bottom Nb films of Nb/Al-AlO_x/Nb trilayer is recommended. The size of junctions is $4 \times 4 \text{ }\mu\text{m}^2$.
- (d) Deposition and pattern of Ti-Pd shunt resistors. In this step, neither top nor bottom electrode of junctions is connecting to Ti-Pd shunt resistors. Ti-Pd film is deposited by magnetron sputtering, in which Ti serves as the buffer layer to enhance adhesion of Pd on silicon substrate. Ti is deposited in constant current 0.59 A and Ar pressure 0.5 Pa, while Pd is deposited in constant current 1.09 A and Ar pressure 0.5 Pa. The Ti-Pd sheet resistance can be conveniently adjusted by changing the film thickness (see Fig. 3), e.g. thicknesses of Ti and Pd are 8 nm and 60 nm, respectively, resulting in a sheet resistance of $1 \text{ }\Omega/\square$ at 4.2 K. To protect the junction from damage or contamination in Ti-Pd shunt resistors process, a lift-off technique is suggested. In this way, shunt resistor of $5 \text{ }\Omega$ for each junction is realized.
- (e) Deposition and pattern of SiO₂ insulator. The SiO₂ film is deposited by PECVD (plasma-enhanced chemical vapor deposition) and reactive ion etched with CHF₃ to form an insulating layer between SQUID washer and input coil, while contact windows on both top and bottom electrodes of Josephson junctions and resistors are opened. The size of the holes on Josephson junctions is $3 \times 3 \text{ }\mu\text{m}^2$.
- (f) Deposition and pattern of top Nb electrodes and flux transformer. Nb film is magnetron sputtered and reactive ion etched

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