Investigation of nano-SQUIDs with Dayem bridges by e-beam lithography and reaction ion etching

Xueshen Wang, Jinjin Li, Yuan Zhong, and Qing Zhong

Key Laboratory for the Electrical Quantum Standard of AQSIQ
National Institute of Metrology, Beijing, China, zhongq@nim.ac.cn

***Abstract* – Nano-SQUIDs are sensitive devices for quantum detection and precision measurements due to the ultra-low noise level. This paper reports the fabrication and characterization of nano-SQUIDs fabricated by e-beam lithography and reaction ion etching (RIE). The Nano-SQUIDs were comprised by two Dayem nanobridges and a loop based on the monolayer Nb film. The width of the nanobridges was 94 nm and the diameter of the loop was 20 µm. A measurement system based on a physical properties measurement system and source-meters. The voltage-bias current (I_{bias}-V) properties at different temperatures showed that the working range of the nano-squid was 8.3 K to 7.0 K. The voltage-modulation flux (V-Φ) were characterized at 8.2 K and the flux modulation depth was large to be 74.5% with the bias current 287 µA. The I_{bias}-V and V-Φ (I_{coil}) showed that the e-beam lithography and RIE process were suitable for fabrication of nano-SQUIDs.**

***Keywords* – Nano-SQUID, E-beam, RIE, Measurement**

I. INTRODUCTION

SQUIDs were the most sensitive devices for the detection of a variety of physical quantities through magnetic flux change [1-3]. Nano-SQUIDs were a kind of SQUIDs of which the junctions were Dayem type nanobridges [4-8]. The scale of the nanobridge should be in the order of the coherent length of the superconducting films. Nano-SQUIDs have attracted great attentions becasues of the ultra-low noise [9, 10] and energy sensitivity [11, 12], and have shown high critical magnetic field and great superiority on the spin measurements of nanoparticles [13]. Another important application is to comprise a kind of single photon detector called inductive superconducting transition edge detector (ISTED) [12] with a superconducting absorber in the loop. The inductance change induced by the incident photon was directly readout by low noise nano-SQUIDs.

Several methods have been used to fabricate nano-SQUIDs, such as focus ion beam (FIB) milling [5], 3-D nano-manufacture [10] and e-beam lithography [14]. FIB milling was an efficient rapid method to fabricate nano-SQUID with special structures and dimentions. However, Ga^+ damaged partial region of the Nb films and a protective layer was needed such as W films [15]. We fabricated nano-SQUIDs on Nb films by FIB milling before [16]. 3D nano-manufacture was a very long-term process to fabricate thin junctions nano-SQUID. E-beam lithography and RIE were effective methods to define nanostructures with the same scale and were convinient for the fabrication of nano-SQUID series amplifier. And several materials have been used to fabricate nano-SQUID, such as Nb [17], NbN [18] and HfTi [19]. In these films, the conherent length of Nb [20] was proper for device design and nano-fabrication .

In this paper, we demonstrate the fabrication of nano-SQUIDs by e-beam lithography and RIE based on monolayer Nb films, the set up of the measurement system, and charaterization of I_{bias}-V and V-$\Phi(I_{coil})$ properties.

II. EXPERIMENTS

70 nm Nb films were deposited on SiO_2/Si substrates by a dc sputtering process with a high vacuum Lesker system [21]. The base pressure was below 3×10^{-8} Torr to assure the high purity of the Nb films. The sputter power was 500 W with the Ar pressure was 5.1 mTorr. The deposition rate was 0.8 nm/s and the thickness of Nb was controlled by the time.

20 µm Nb tracks [16] by which nano-SQUID was connected to the measurement electronics and the superconducting loop of nano-squid were defined by UV lithography and RIE with CF_4 and O_2. The junctions were defined by e-beam lithography with ZEP 520A and RIE. The fabricated nano-SQUID is shown in Fig. 1. The diameter of the loop is 20 µm which is convenient for the fabrication of absorbing layer for the application of inductive superconducting transition edge detectors. The width of the junction is ~ 94 nm. The cross section of the etched Nb film is sloping and this makes the width of the bottom of the junction be larger than 100 nm. The etch

parameters will be optimized in the future works.

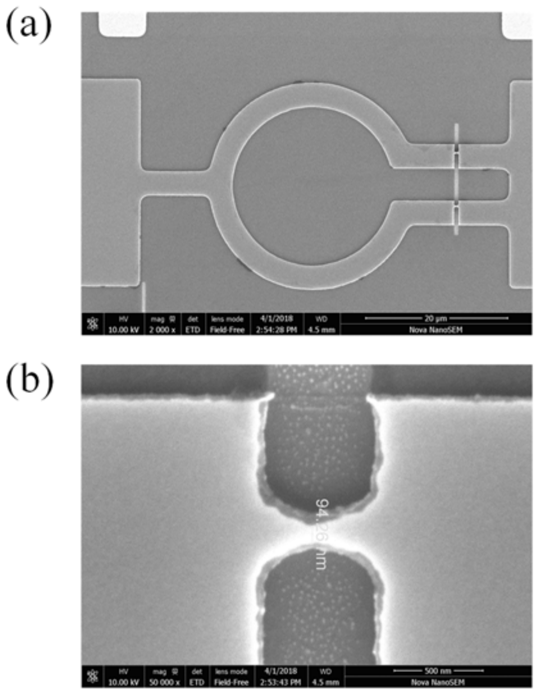

Fig. 1. The SEM images of the (a) nano-SQUIDs;(b) junction.

The schematic of the measurement system is shown in Fig. 2. A physical property measurement system (PPMS, Quantum Design Inc.) was used to provide the low temperature condition to 1.9 K for the nano-SQUID and superconducting modulation coil. Two current sources were used as the bias source of the nano-SQUID and the modulation coil. A voltage meter was used to read out the voltage across the nano-SQUID. To avoid damage of the ESD to the devices, a home-made wire connection box was manufactured for the measurements. The nano-SQUIDs were mounted on a PPMS TO-8 carrier on which a superconducting coil was winded for providing the modulation magnetic flux. This system was not prepared for the noise measurement because there was no magnetic shield and the system noise was too large for the measurement of ultra-low noise for nano-SQUIDs.

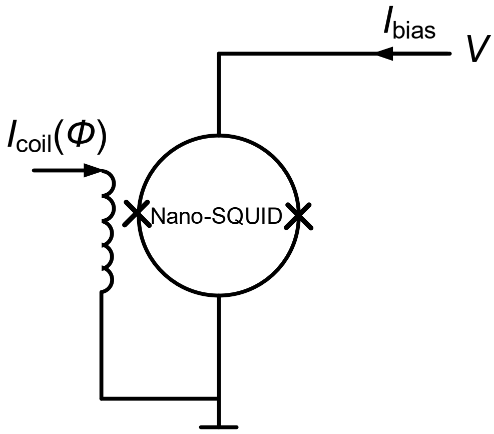

Fig. 2 The schematic of the measurement system.

The I_{bias}-V curves of the nano-SQUID from 7.1 K to 8.3 K are shown in Fig. 3. I_{bias} and V were the current and voltage across the nano-SQUID respectively. The device shows hysteresis I_{bias}-V below 7.1 K which limits the working range. The hysteresis was due to the structure of the devices. There was no shunt resistor layer fabricated on the Nb films. In the newly designed devices a layer of Al film will be sputtered on the Nb film as the etch mask and shunt resistor. The critical currents I_c at different temperatures is shown in Fig. 4. The I_c is 20 μA at 8.0 K and 125 μA at 7.1 K.

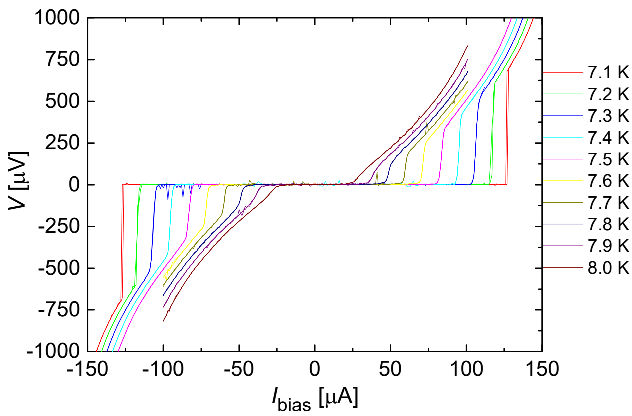

Fig. 3 The I_{bias}-V of the nano-SQUID at different temperatures.

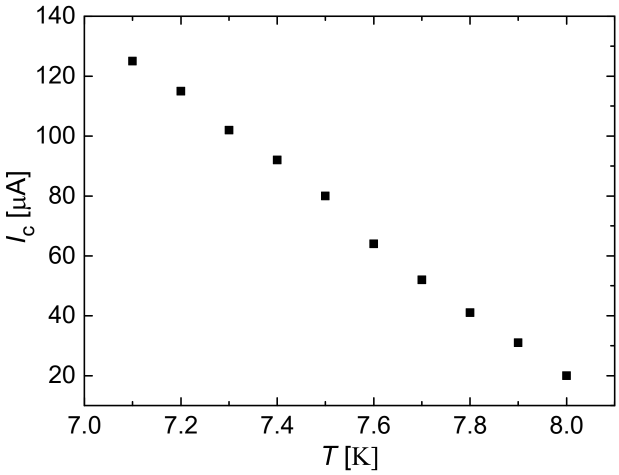

Fig. 4 The I_c-T of the nano-SQUID.

A bias current I_{coil} was apllied to the superconducting modulation coil to characterise the V-Φ (I_{coil}), the flux modulation depth and the voltage - flux transfer function,

$$\frac{\mathrm{d}V}{\mathrm{d}\Phi_0}=\frac{\mathrm{d}V}{\mathrm{d}I_{coil}}\times\frac{\mathrm{d}I_{coil}}{\mathrm{d}\Phi_0} \quad (1)$$

Φ_0 is the flux quantum。

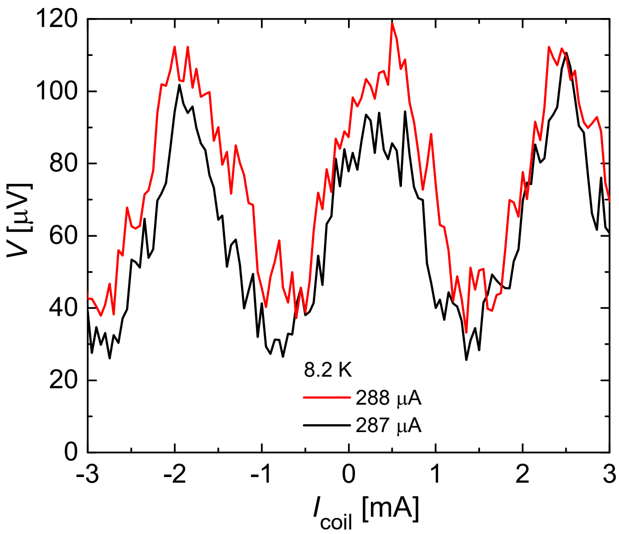

Fig. 5 The V-Φ(I_{coil}) of the nano-SQUID at 8.2 K, I_{bias}=287 μA and 288 μA.

The V-Φ (I_{coil}) characterization at 8.2 K is shown in Fig. 5 for the I_{bias}=287 μA and 288 μA. The modulation period $\mathrm{d}I_{coil}/\mathrm{d}\Phi_0$ is 2.1 mA. The period is same for different I_{bias}. The flux modulation depth (V_{max}-V_{min})/V_{max} was as large as 74.5% for 287 μA and 67.0% for 288 μA. The maximum of the transfer function at the point Φ_0 /4 (I_{coil}=0.8 mA) for 287 μA was 0.24 V/A, and then the transfer function was 0.5 mV/Φ_0. The measurement system was still not perfect for the measurement of nano-SQUID. We are now preparing set up of a new system based on a probe stick with a magnetic shield can, Helmholtz coils and a variable temperature sample holder. Also a low temperature SQUID series amplifier will be used to read out the noise spectrum of nano-SQUIDs.

III. CONCLUSIONS

Nano-SQUIDs based on monolayer Nb films were fabricated by e-beam lithography and RIE which was a more affordable and effective method. A measurement system based on a PPMS, current sources and voltage meters was set up to characterise the I_{bias}-V and V-Φ (I_{coil}) of nano-SQUIDs The non-hysteresis working range of the typical device was 8.3 K to 7.0 K. The flux modulation depth was as large as 74.5% at 8.2 K with 287 μA bias current, and the voltage - flux transfer function was 0.5 mV/Φ_0

IV. ACKNOWLEDGEMENT

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