High transfer coefficient niobium nano-SQUID integrated with a nanogap modulation flux line

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Abstract
Nano-superconducting quantum interference devices (nano-SQUIDs) with high energy sensitivity and spatial resolution are essential in many applications such as single spin detection, nano-electromechanical vibration detection and microscale magnetic imaging. This paper studies a Dayem-type niobium nano-SQUID using focus ion beam milling technology. The device has two 42 nm × 60 nm nano-bridges and an integrated on-chipNb modulation flux line located beside the SQUID loop with a 100 nm nanogap. The non-hysteretic temperature range of the nano-SQUID is about 1.4 K from 4.6 K to 6.0 K, which could broaden the operation temperature range of the device. The maximal transfer coefficient $V_\Phi$ and peak-to-peak voltage $\Delta V$ are 8.53 mV/\Phi_0 and 430 µV at 4.8 K, respectively.

Keywords: nano-SQUID, focus ion beam, Josephson junctions, SQUID

(Some figures may appear in color only in the online journal)

1. Introduction
The superconducting quantum interference device (SQUID) is one of the most sensitive flux–voltage sensors. Compared to traditional microscale SQUIDs consisting of trilayer Josephson junctions, Dayem bridge nano-SQUIDs are made of weak-linked bridge junctions and have features such as higher junction current density, lower parasitic capacitance and compact size, which result in advantages of high energy sensitivity and spatial resolution. Nano-SQUIDs are therefore especially useful in applications such as single-spin detection, nano-electromechanical vibration detection, microscale magnetic imaging, the readout of inductive superconducting transition edge sensors, and so on [1–10].

The junctions in Dayem bridge nano-SQUIDs are made of nano-scale superconductor bridges. Two nanofabrication methods are commonly used to fabricate nano-SQUIDs. One is the electron beam lithography (EBL) technology method [8, 10, 11] and the other is the focused ion beam (FIB) milling technology method [12–14]. Compared to the EBL method, the FIB method is more flexible, faster, photoresist-free and sample size friendly. However, the problem with the FIB method is that there is an ion implantation issue when the ions hit the surface of the Nb superconducting film. The implantation damage leads to the quenching of the Nb bridge junction in the scale of tens of nanometers and influences the junction property. To prevent ion implantation damage, heavy metal films such as tungsten are usually deposited over the FIB etching area before FIB etching to protect the Nb film, which will be kept. Therefore, it is not easy to make high quality FIB nano-SQUIDs.
In this paper, we report an FIB-nano-SQUID integrated with an on-chip magnetic flux modulation line. The voltage–flux transfer coefficient and the operational temperature range show vast superiority. Compared to the conventional external coil type of voltage–magnetic flux modulation, an on-chip modulation with a nanogap modulation flux line is used to simplify the system and improve the flux coupling. The mutual inductance between the flux line and the SQUID is about 72 mA/Φ0. The Dayem bridge junctions and nanoscale loops of nano-SQUIDs are directly milled by FIB without any protecting layer. In order to increase the coupling effect, the distance between the flux current line and the SQUID bias line was shrunk to 100 nm.

For the fabrication process, 144 nm Nb film was firstly deposited on a SiO2/Si substrate by a sputtering process. The background pressure of the sputtering chamber is better than 4 × 10−6 Pa. The sputtering pressure was controlled at 0.67 Pa. Common photolithography and dry etching techniques were used to form the structure with scales above 2 µm and pads for bonding. SF6 was used to etch Nb with positive photoresist structure protection. The power and reactive pressure of the reactive ion etching were 50 W and 2 Pa respectively. FIB was then used to mill the Nb film to form the nanoscale structure of the devices, including the Dayem bridge junctions, nanoscale loops and the nanogap between the loop and the flux line, as shown in figure 1(b). In our FIB system, a gallium ion species was used and its beam energy was kept at 30 keV. The ions from the FIB beam were inevitably implanted in the junctions and consequently formed a shunt resistor. Therefore, ion dose was adjusted for different thicknesses of Nb films in order to avoid damage to the bridge junction.

3. Measurement results and discussions

The chip was adhered to a ceramic device holder using GE 7031 varnish. The holder was attached to a copper sink of which the temperature could be measured and controlled by a Lakeshore temperature controller. The electrode pads on the chip were wire-bonded to the holder by 25 µm diameter aluminum wires. The device was mounted inside a stainless steel can with the lead shield and characterized using a home-made system composed of a probestick, Keysight B2901A/B2961A current sources, a Keithley 2000 multimeter and data acquisition software.

3.1. R–T curve

Figure 2 shows the resistance vs temperature (R–T) curve of the nano-SQUID device made in 144 nm Nb film. The inset is the enlarged part from 6 K to 9.5 K. Clearly there are two superconducting transition temperatures Tc. The first transition at about 9.10 K (Tc1 in figure 2) is the transition temperature of the Nb film. At this temperature, two bridge junctions are still at normal state with a few ohms resistance because of the Ga+ implantation damage. The FIB process causes the flux, as shown in figure 1(a), from +FB to −FB.
3.2. I–V curve

Figure 3(a) shows the I–V curves of the nano-SQUID at different temperatures. The critical current $I_c$ of the device decreases from 180 µA to 64 µA when the temperature increases from 4.6 K to 6.0 K. The device shows a non-hysteretic characteristic above 4.6 K. Therefore, the operating temperature range of the SQUID is about 1.4 K.

The I–V curve changes periodically with the external magnetic field. In this paper, an on-chip modulation flux line is applied to produce the external magnetic field. The currents of 0 mA, 19 mA and 38 mA flowing through the flux line produce fluxes of $0\Phi_0$, $\Phi_0/4$ and $\Phi_0/2$, respectively. Figure 3(c) shows the I–V curve at 4.8 K for $0\Phi_0$, $\Phi_0/4$ and $\Phi_0/2$, and the corresponding critical currents $I_c$ in these cases are 170 µA, 152 µA and 115 µA. $I_c$ decreases nonlinearly with increasing flux from 0 to $\Phi_0/2$. The flux modulating depth $\Delta I/I_c$ is 32.4% at 4.8 K [15]. The black line in figure 3(b) shows the change of the flux modulating depth $\Delta I/I_c$ with the temperature. The maximum value is 41.5% at 5.8 K.

3.3. V–$\Phi$ curve

The voltage across the nano-SQUID was measured with external magnetic flux at different biased current $I_b$ and temperatures. Figure 4(a) illustrates the V–$\Phi$ curves with different $I_b$ from 110 to 170 µA at 4.8 K. $\Delta V$ is defined as the peak-to-peak modulation voltage. The SQUID transfer coefficient $V_\Phi$ is the maximum absolute value of $\partial V/\partial \Phi$. $V_{\Phi+}$ and $V_{\Phi-}$ represent the $V_\Phi$ at the rising and falling edge of the V–$\Phi$ curve. The $V_\Phi$ value reflects the sensitivity of the SQUID to magnetic flux changes. The higher the value, more sensitive the SQUID device is. Figure 4(b) illustrates $\Delta V$, $V_{\Phi+}$ and $V_{\Phi-}$ as function of $I_b$. It shows that $\Delta V$ increases with $I_b$ from 110 to 160 µA and then decreases. $V_{\Phi+}$ and $V_{\Phi-}$ have the same trend, as expected. From the data we can derive that the 160 µA bias current corresponds to the best working point at this temperature. The optimal bias current is chosen to be the point where $V_{\Phi+}$ is the best. At this working condition, $V_{\Phi+}$ and $\Delta V$ of this device are 8.53 mV/$\Phi_0$ and 430 µV, respectively. This result is much better than the 2D Dayem bridge devices reported in the literature, with the transfer coefficient in the range of 0.1–2.5 mV/$\Phi_0$ [8, 11–13].

Figure 5(a) illustrates the V–$\Phi$ curves of the optimal transfer characteristic at different temperatures from 4.4 K to 6.0 K. The corresponding optimal bias current at each temperature is shown on the upper-right corner of figure 5(a). When the temperature increases, the optimum of the bias current $I_b$ decreases. Figure 5(b) illustrates the change of the transfer
higher than the nominal one. Considering these two factors, the effective area of the SQUID can be calculated using [17]:

\[ A_{\text{eff}} = \gamma_A \cdot d \cdot (d + 2w) \gamma_A = 1 - 0.68/(d/w + 2.07)^{1.75}, \]

the effective side length \( d \approx 392 \) nm and washer width \( w \approx 300 \) nm. \( A_{\text{eff}} \) is calculated to be 0.357 \( \mu \text{m}^2 \), which is very close to the estimated \( A_{\text{eff}} \) of 0.36 \( \mu \text{m}^2 \).

This small effective area induces a very high spatial resolution, but also reduces the capture ability of the magnetic flux. A large magnetic field intensity is needed for the device to collect a quantum flux \( \Phi_0 \). The magnetic field intensity generated by a long straight wire is proportional to the current and inversely proportional to the distance. A large current will cause the quenching effect of the modulation line, which will affect the operation of the nano-SQUID. When the distance is reduced by one order of magnitude from 1 micron to 100 nanometers, the current inducing the same magnetic field intensity is reduced by one order of magnitude, and the coupling between the SQUID and the modulation flux line will be increased. This will significantly increase the coupling between the SQUID and the modulation flux line, and may make the SQUID operate in a flux-locked loop mode.

The theoretic intrinsic flux noise is estimated according to the following equation [1, 18]:

\[ S_{\Phi}^{1/2} \approx \frac{4(1 + \beta_k)\Phi_0 k_B TL}{I, R_0} \, \frac{1}{\gamma^2}, \]

where \( k_B \) is the Boltzmann constant, \( T \) is the working temperature and the normal resistance of the SQUID’s \( R_0 \) is about 4.9 \( \Omega \) from the \( I-V \) curve. \( L \) is the total inductance of the SQUID, which is the sum of the bridge inductance and the loop inductance. The evaluation is performed at 4.8 K with maximum critical current of 170 \( \mu \text{A} \). For our design, the bridge inductance is 7.4 \( \text{pH} \) and the loop inductance 0.3 \( \text{pH} \). The calculated \( S_{\Phi}^{1/2} \) is 0.037 \( \mu \text{V}\Phi_0/\text{Hz}^{1/2} \) when \( \beta_k \rightarrow 1 \). The actual measurement results will be one to two orders of magnitude larger than the theoretical calculation.

4. Conclusion

A Dayem-type niobium nano-SQUID with 42 nm × 60 nm nano-bridges and a loop of which the side length was 200 nm was fabricated using FIB milling and characterized. At 4.8 K, the device’s flux modulating depth is 32.4%. The maximal transfer coefficients \( V_\Phi \) and \( \Delta V \) are as large as 8.53 mV/\( \Phi_0 \) and 430 \( \mu \text{V} \) with 160 \( \mu \text{A} \) bias current, respectively.

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