NOISE IN DC SQUIDS WITH Nb/Al-OXIDE/Nb JOSEPHSON JUNCTIONS*

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Abstract

We have developed a process which incorporates very high quality Nb/Al-oxide/Nb Josephson junctions. The junctions had low subgap conductance yielding \( V_n \), greater than 50 mV for critical current densities of 1000 A/cm². Low inductance SQUIDs made with these junctions were apparently free from junction conductance fluctuations, at least for frequencies above 1 Hz. The SQUIDs exhibited flux noise of currently unknown origin.

Introduction

Many applications require SQUIDs with very low noise at low frequencies. Advances in fabrication of superconducting integrated circuits have resulted in very low noise devices at higher frequencies but significant low-frequency excess noise remains. This excess low frequency noise can be caused by the filling and emptying of charge traps at defects in the Josephson junction tunneling barriers. Junctions with Nb electrodes and Al-oxide tunneling barriers have nearly ideal tunnel junction behavior which suggests a very high quality barrier. Some et al. have shown that such junctions have low levels of excess low-frequency noise and thus may be very desirable for SQUIDs. In the past we have fabricated several SQUID designs with a Nb/Nb-oxide/Pb alloy process. These SQUIDs exhibited low-frequency excess noise attributable to critical current fluctuations. We are now able to compare the performance of SQUIDs with similar designs but different junctions.

Fabrication

The fabrication process was based on Nb/Nb-oxide/Nb trilayer junctions similar to those described in references 5 and 6. The formation of the trilayer is described below; all other layers were evaporated from resistively heated sources. The circuits utilized 7 patterning steps each defined by a 10 times reduction projection printer which provided a minimum feature size of 2 \( \mu \mbox{m} \) and a layer-to-layer registration error of less than 0.5 \( \mu \mbox{m} \). The trilayer was patterned by plasma etching in \( \mbox{C}_4 \mbox{F}_8 \) and the subsequent layers were defined by lift-off. After the base and counter electrodes of the trilayer were patterned, a \( \mbox{Si}_3 \mbox{N}_4 \) insulating layer was deposited making contact with the exposed edges of the trilayer. The Nb/Nb-oxide/Nb trilayer over the entire 2 in \((50.8 \mbox{m})\) wafer. The three layers were deposited in a single load of a cryopumped vacuum system with a base pressure less than 2 \( \times 10^{-6} \) Pa (1.5 \( \times 10^{-7} \) torr). The first Nb film was 250 \( \mbox{nm} \) thick and was deposited with a 5 cm diameter planar magnetron de sputtering source located 7.5 cm from the wafer. Next, an Al film 4 \( \mbox{nm} \) thick was deposited from a 7.6 cm diameter planar magnetron de sputtering source located 10.5 cm from the wafer. The Al film was then oxidized for 30 minutes in ultra high purity \( \mbox{O}_2 \) at a pressure of 100 Pa (750 torr) to produce junctions with a critical current density of 775 A/cm². The system was then pumped to 2 \( \times 10^{-5} \) Pa and the second 250 \( \mbox{nm} \) thick Nb layer was deposited. The sputtering gas was \( \mbox{Ar} \) at a pressure of 0.67 Pa (5 mtorr). The Nb had a resistance ratio, \( R_{\mbox{Nb}}/R_{\mbox{Pb}} \), of 4 - 5 and a transition temperature of 9.15 - 9.2 K. The preceding gas was not subject to processing. We found that the Al-oxide barrier had to be protected from contact with processing chemicals if the highest quality junctions were to be obtained. Junctions with very good characteristics were reliably produced and we observed no cycling induced failures.

![Figure 1. Current-Voltage characteristic for a 9.5 \( \mu \mbox{m} \times 9.5 \mu \mbox{m} \) Nb/Nb-oxide/Nb Josephson junction. The current density was 775 A/cm².](image)

Measurement Apparatus

For testing, the chips were mounted in a Nb chip holder. Electrical contacts to the Pb-alloy coated Nb pads at the edges of the chip were made with BeCu traces on a circuit board in the chip holder. The chip holder was surrounded by a high permeability magnetic shield with a Pb foil liner. The magnetic shield was part of a closed rf shield surrounding the chip holder and the electrical leads connecting the chip to the room temperature electronics. The leads were heavily filtered at room temperature to prevent the transmission of electromagnetic interference to the SQUID. Also included in the cryoprobe was a commercial SQUID which was used as a preamplifier for noise measurements on our SQUIDs. The probe was immersed in liquid helium at 4 K (the boiling point of helium at an altitude of 1600 m). Additional magnetic shielding surrounding the Al de-
and an estimated residual field of less than 100 nT. This system was insensitive to local sources of interference such as rf generators and electric motors. This result gave us confidence that we were measuring noise from the SQUIDs or their immediate environment inside the rf shields.

Figure 2. A simplified sketch of the stripline SQUID showing three of the layers.

**SQUID Parameters**

The measurements described here were of very low inductance stripline SQUIDs. Figure 2 is a sketch of this device. The bottom electrode of the stripline was formed in the base electrode of the trilayer. The top electrode of the stripline was formed in a Pb-alloy wiring layer and was separated from the bottom electrode by 300 nm of SiO. The resistors shunting each junction were at the ends of the stripline. The junctions were 400 nm apart and the stripline width was 40 µm giving a SQUID inductance of approximately 6 pH. The junctions were 4 µm x 4 µm with a critical current of 120 µA and were shunted by 0.58 Ω resistors. The modulation parameter, \( \beta \equiv 2 L J_c/\phi_0 \), was 0.6 and the hysteresis parameter, \( \delta \equiv 2 \pi I_c R_2 C/\phi_0 \), was 0.07, where \( \phi_0 \equiv h/2e \) is the flux quantum, \( I_c \), \( R \), and \( C \) are the single junction critical current, shunt resistance, and capacitance. The SQUIDs were heavily damped to reduce the effects of resonances.

**Noise Measurements**

The voltage versus flux transfer function, \( \partial V / \partial \phi \), is shown in figure 3. The voltage-flux transfer function, \( \partial V / \partial \phi \), was 156 mV/\( \phi_0 \) at the flux bias where the high response noise measurements were taken.

Figure 3. Voltage versus flux characteristic for a bias of 2.03 times the single junction critical current.

The spectral densities of the SQUID noise for two flux biases are shown in figure 4. The lower spectrum is for \( \phi = 0 \), the minimum voltage point. Simulations showed that this is the bias condition for which the SQUID was most sensitive to fluctuations in the junction conductance. Numerical simulations of the SQUID with a junction model including resistance, capacitance and Johnson noise from the shunting resistors yielded a noise consistent with the measured value within the accuracy of the measurement. This implies that all the noise at this bias condition was from the shunting resistors and not from junction fluctuations, at least for frequencies above a few hertz. The noise rise below 10 Hz was not measured for all SQUIDs.

The upper spectrum is for the large \( \partial V / \partial \phi \) bias condition at \( \phi \approx \phi_0 / 4 \). The noise at this bias condition was much higher than predicted for frequencies below 10 kHz. The noise rose as \( f^{-0.7} \) from above 10 kHz to approximately 400 Hz. (We verified that this noise rise was not related to the roll-off of our measurement system which was above 10 kHz.) Between 400 Hz and approximately 40 kHz the frequency noise rose as \( f^{-0.1} \). It was flat between 40 Hz and the lowest frequency measured (0.1 Hz). This excess noise was measured for other responsive bias conditions and was found to be proportional to \( \partial V / \partial \phi \). This result along with the measurement at \( \phi = 0 \) suggests that the excess noise was "flux" noise and did not arise from the junctions. Since the SQUID had an extremely low inductance (the loop area was 400 µm x 300 nm) the noise of this source must have been local, perhaps arising from flux motion in one of the films or from some fluctuating magnetic impurity. The spectral density of the noise was 2.3 \( \mu \phi_0 / H_0^{1/2} \) at 1 Hz. This value is similar to that observed by Wellestod et al. for a series of dc SQUIDs at 1 K. Although the spectral densities of the flux noise were similar at 1 Hz the spectral shapes were quite different with their devices exhibiting an \( f^{-4/3} \) dependence below 2 kHz. The flattening of the noise spectrum at low frequencies for the present SQUIDs was also quite different from the behavior of our Nb/Nb-oxide/Pb-alloy SQUIDs. For these devices the noise continued to rise as \( 1/f^\alpha \) with \( 0.5 < \alpha < 0.8 \) to the lowest frequencies we measured (0.1 Hz).

**Conclusions**

We have developed a process incorporating very high quality Nb/Al-oxide/Nb Josephson junctions which are reliable and reproducible. SQUIDs made with this process exhibited much less noise from critical current fluctuations than our Nb/Nb-oxide/Pb-alloy SQUIDs. Thus, we have observed a correlation between low leakage junctions and low noise from critical current fluctuations. The new SQUIDs exhibited excess low-frequency "flux" noise with an unusual frequency dependence. The origin of this noise is presently unknown and is under investigation.

**References**


