A RELIABLE DC SQUID MADE WITH TUNNEL JUNCTIONS[†]
 John Clarke^{*}, Wolfgang M. Goubau[†], and Mark B. Ketchen^{*}

ABSTRACT

DC SQUIDS of cylindrical geometry have been fabricated using Nb-NbO_x-Pb tunnel junctions. The SQUIDS can be thermally cycled repeatedly and cooled in the earth's magnetic field without significant loss of performance. Flux resolution of $3 \times 10^{-5} \phi_0/\text{Hz}$ above a frequency of 1 Hz has been achieved through optimization of electronic circuitry and careful shielding. Fluctuations and drift in the temperature of the helium bath are found to be the major source of long-term noise. With a simple temperature stabilizer, drift has been reduced to less than $8 \times 10^{-5} \phi_0/\text{hr}$ over a three hour period.

I. INTRODUCTION

A variety of superconducting quantum interference devices (SQUIDS) has been successfully used as magnetometers, gradiometers, and voltmeters over the past few years.¹ The earliest type was the dc SQUID^{2,3} involving two Josephson junctions. In recent years, the rf SQUID, which involves only a single junction, has become the more popular type.⁴ In this paper we describe an improved dc SQUID which is more sensitive than most rf SQUIDS, and more robust than adjustable point contact devices. Our SQUID makes use of Nb-NbO_x-Pb tunnel junctions sputtered and evaporated onto a quartz tube. These junctions are known to be remarkably reliable and long lived.⁵ The SQUIDS have been thermally cycled up to thirty times and stored at room temperature for periods of several months without significant deterioration.

The voltage developed across the SQUID is amplified by a helium temperature tank circuit which optimally matches the low resistance of the SQUID ($< 1 \Omega$) to a room temperature FET preamplifier. This optimization is largely responsible for the improved performance of the SQUID. The preamplifier noise is on the order of, or less than, the inherent SQUID noise and/or the externally induced noise. The resolution of the SQUID at frequencies above 1 Hz is typically $2 \times 10^{-4} \phi_0/\text{Hz}$ to $5 \times 10^{-5} \phi_0/\text{Hz}$ with a SQUID inductance of 10^{-9} H; the best resolution obtained at 4.2K was $3 \times 10^{-5} \phi_0/\text{Hz}$. The long term drift has also been reduced by comparison with other SQUIDS. By using a simple bath temperature stabilizer drift over a three hour period has been lowered to less than $8 \times 10^{-5} \phi_0/\text{hr}$.

The electronics associated with the SQUID are inexpensive and require fewer tuning adjustments than rf electronics. All of the active circuits are situated in a compartmentalized box mounted on the top of the cryostat for compactness. Our SQUID and associated electronics have been used successfully in the field as a magnetometer.

II. SQUID FABRICATION

The design of our SQUIDS is illustrated in Fig. 1. The configuration of the films is such that masks used for their depositions require no critical alignment. The quartz substrate is a 18 ± 0.05 long, 3 ± 0.05 wide, 1.4 d. cylinder which has been washed in tap water with

Fig. 1. Cylindrical dc SQUID with two Nb-NbO_x-Pb Josephson tunnel junctions.

Labtane cleaner and has been flame polished with a torch. Two electrodes of platinum paint are baked onto the substrate prior to the deposition of the films to allow soldering of electrical leads to the SQUID.

The SQUIDS are made by first evaporating a 1 cm long 3300 Å thick lead (alloyed with about 5% indium) band around the circumference of the quartz tube. The band is the sensor element of the SQUID; its length is chosen to give an inductance of 10^{-9} H. The lead film makes electrical contact with the platinum electrode on the back side of the cylinder. Next a 250 μm wide, 1200 Å thick gold strip with a 500 Å thick underlayer of chromium is evaporated as shown in the figure. The strip serves as the resistive shunt for both tunnel junctions. The shunt is necessary to avoid hysteresis in the I-V characteristic of the SQUID. The lead band and gold shunt are linked by two 150 μm wide, 1400 Å thick parallel strips of niobium separated by 1 μm. The niobium is dc sputtered at a rate of about 1000 Å/min using a model S-300 Sloan Sputtergun.

The tunnel junctions are prepared following the procedure of Hansma.⁵ The niobium strips are oxidized in air at 125°C for times ranging between 8 min. and 10 min. A lead tee whose crossbar overlays the oxidized niobium strips is then deposited. The stem of the tee bisects the gold shunt and makes electrical contact with the second platinum electrode. The width of the lead tee at the junctions is 75 μm, giving each junction an area of $1.1 \times 10^{-4} \text{ cm}^2$. The dc resistance R of the two shunted junctions in parallel ranges between 0.1 Ω and 0.5 Ω at 4.2K, while the capacitance per junction C is estimated to be 190 pF (assuming that the oxide has a dielectric constant of 4 and a thickness of 20 Å). The critical current I_c of a SQUID will lie between 15 μA and 0.5 μA for the oxidation times given above. A typical value of I_c for a 9 min. oxidation is 5 μA.

The SQUIDS are completed by slitting the lead band between the two niobium strips (as shown in Fig. 1) and evaporating a superconducting ground plane (not shown in the figure) over the front surface of the

Manuscript received September 30, 1974.

[†] This work was supported by the U.S.A.E.C.

^{*} Dept. Phys., Univ. of Calif., Berkeley; and, INRD, Lawrence Berkeley Lab., Berkeley, Calif. 94720

[†] IBM Postdoctoral Fellow.

quartz cylinder. The ground plane reduces flux leakage through the slit and eliminates the inductive impedance of the various metal strips. Without the ground plane the impedance near the Josephson frequency would be greater than the ohmic resistance of the shunts. The ground plane is a 1200 Å thick lead film with a 500 Å thick overlay of silver for protection against atmospheric moisture. It is insulated from the underlying metal films with a layer of Duco cement which is applied by dipping the quartz cylinder twice into a solution of 1 part (by volume) cement diluted with 5 parts acetone.

The hysteresis parameter β_c of Mcumber⁶ can be estimated for our SQUIDS by assuming that the two tunnel junctions are symmetric. In terms of previously defined quantities, β_c has the form

$$\beta_c = \frac{4\pi R C I_c}{\phi_0} \quad (1)$$

where ϕ_0 is the flux quantum. Typically $I_c = 5$ mA and $R = 0.3 \Omega$ giving $\beta_c = 0.5$. SQUIDS with β_c between one and two are noticeably noisier than those with $\beta_c < 1$ while SQUIDS with $\beta_c \geq 2$ cease to function.

The magnitude of the signal developed across the SQUID is proportional to the critical current modulation ΔI_c . The critical current modulation is in turn a function of the quantity $L_0 I_c / \phi_0$. For $I_c = 5$ mA, $L_0 I_c / \phi_0 = 2.5$, which leads to a calculated value for ΔI_c approximately equal to $\phi_0 / 2L_0 = 1$ μ A. In practice, the observed values of ΔI_c are somewhat smaller than predicted.

III. SQUID EVALUATION TECHNIQUES

The performance of a SQUID is evaluated by measuring noise and drift characteristics with the SQUID screened from external magnetic field fluctuations by a superconducting shield. The SQUID is mounted inside a 7.6 cm long, 0.6 cm i.d. lead tube, as shown in Fig. 2. It is held in position by two counting screws.

Fig. 2. SQUID mounting arrangement. The lead tube attenuates external dc magnetic fields by more than eleven orders of magnitude.

One of the screws also supports a delrin rod around which a five turn niobium wire modulation coil is wound. The entire assembly is situated in a vacuum chamber and is cooled to liquid helium temperatures in the presence of exchange gas. Connection with room temperature electronics is made with coaxial cables.

A block diagram of the SQUID electronics is shown in Fig. 3. The SQUID is biased with a dc current $I_b \approx I_c$. An ac magnetic flux with a peak-to-peak amplitude $\phi_0/2$ is coupled to the SQUID by means of the modulation coil which is driven at the oscillator frequency of 10^5 Hz. The ac voltage developed across the SQUID is amplified by a tank circuit located inside the vacuum chamber. The output of the tank circuit is enhanced at room temperature by a broadband preamplifier followed by a tuned amplifier. The signal is then synchronously detected with a lock-in detector also tuned to the oscillator frequency. The output of

Fig. 3. Schematic of the SQUID electronics.

the lock-in is fed back to the modulation coil in the standard way so that the SQUID acts as a null detector. The noise and drift are determined by measuring variations in the feedback current.

The major difference between our electronics and the standard dc SQUID system is the use of the low temperature tank circuit rather than a room temperature transformer to properly match the SQUID impedance to the preamplifier. The tank circuit consists of a 0.012 μ F mica capacitor and a 0.2 mH inductor wound of niobium wire on a teflon form. A variable capacitor at the input of the preamplifier allows for the fine tuning of the tank circuit resonant frequency. For our preamplifier the optimum signal to noise ratio is achieved when the Q of the tank circuit is such that $Q^2 R = 10^5 \Omega$. For our SQUIDS $Q^2 R$ is always between $10^4 \Omega$ and $10^5 \Omega$ so that coupling is nearly ideal in all cases.⁷

IV. NOISE AND DRIFT PERFORMANCE

SQUIDS with sufficiently small values of β_c were found to work well at any temperature in our measurement range of 1.4K to 7K. Between 4.2K and 1.4K I_c increases by about 50%. Although our SQUIDS are usually shielded from external magnetic fields with mu-metal cylinders during cooldown, cooling in the presence of the earth's magnetic field does not significantly degrade performance. At 4.2K, the noise of our SQUIDS at frequencies above 1 Hz is typically in the range of $2 \times 10^{-4} \phi_0 / \sqrt{\text{Hz}}$ to $5 \times 10^{-5} \phi_0 / \sqrt{\text{Hz}}$. We will briefly discuss the noise limitations set by the Johnson noise in the SQUID shunts and by the preamplifier noise.⁸

The Johnson noise in the shunts generates a mean square voltage at the output of the tank circuit of $4 k_B T Q R B$, where B is the bandwidth (assumed to be within the passband of the tank circuit). Let the mean square preamplifier noise be V_{AB}^2 . The signal voltage from the tank circuit when the applied flux is changed from $a\phi_0$ to $(a + 1/2)\phi_0$ is approximately $Q I_c R \approx Q \phi_0 R / 2L_0$. The fraction of a flux quantum that can be resolved, δ , is therefore given by

$$\delta = [6 J^2 + \delta_A^2]^{1/2} = \frac{[4 k_B T Q R^2 B + V_{AB}^2]^{1/2}}{Q \phi_0 R / L_0} \quad (2)$$

If we set $T = 4.2K$, $L_0 = 10^{-9}$ H, $R = 0.3 \Omega$, $\phi_0 = 2 \text{ mV}/\sqrt{\text{Hz}}$, we find $\delta = 1.5 \times 10^{-3} / \sqrt{\text{Hz}}$ with the Johnson noise and preamplifier noise making approximately equal contributions. For our best SQUIDS, the measured resolution was $3 \times 10^{-5} / \sqrt{\text{Hz}}$, which is close to this value. For most SQUIDS, the observed resolution is several times worse than expected for Johnson noise and preamplifier noise alone. This may be a result of residual hysteresis or reduced modulation depth caused by trapped flux in the junctions.

Long term noise and drift in the SQUIDS appear to

V. SUMMARY

be governed by electromagnetic pickup and by temperature changes in the helium bath. While the effects of low frequency and dc magnetic fields are attenuated with the lead shield by at least eleven orders of magnitude, high level rf discharges (caused for example by pulsed lasers and switching of heavy electrical equipment) still influence the SQUID. Temperature changes in the bath are produced both by variations in atmospheric pressure and by decreases in hydrostatic pressure with decreasing helium level. These changes affect the SQUID system in two ways. The first is through variations in cable capacitance which can alter the tank circuit tuning. The second is through changes in the characteristics of the SQUID itself. For our present tank circuit we believe the first effect is negligible. The second effect is not yet fully understood and is currently under investigation. Possible variations in I_c (together with junction asymmetry) or the movement of trapped flux are responsible for the sensitivity of the SQUID to thermal fluctuations. It should be noted that our feedback circuitry discriminates against a change in signal associated with a change in I_c when the junctions are symmetric.

To demonstrate the influence of thermal fluctuations on SQUID performance, we constructed a simple but effective temperature stabilizer for the helium bath and monitored the output signal of a SQUID as a function of time both with and without this stabilizer. The stabilizer regulates the temperature by controlling the pressure of the helium vapor above the liquid. The temperature of the helium bath is measured with a carbon resistor using an ac bridge circuit. The amplified off-balance signal of the bridge is fed to a solenoid valve which adjusts the rate of gas blow-off from the cryostat such that the bridge remains balanced.

Figure 4 shows the SQUID output for a period of three hours both with and without bath stabilization.

Fig. 4. SQUID signal as a function of time. The upper trace was taken with the helium bath temperature stabilized. The lower trace was without stabilization.

The upper trace was begun within ten minutes after the end of the lower trace. The data show two interesting features: First, there is no measurable drift over three hours with the temperature controller, while there is a drift of about $3 \times 10^{-4} \phi_0/\text{hr}$ without stabilization. Second, the noise on a scale of a few minutes is about a factor of two smaller with the bath stabilized than without stabilization. The root mean square width of the upper trace represents a flux resolution of about $2.5 \times 10^{-4} \phi_0$. This line width sets an upper limit for the drift rate of less than $8 \times 10^{-5} \phi_0/\text{hr}$. The bath temperature drift was less than $20 \mu\text{K}/\text{hr}$. A drift of $8 \times 10^{-3} \phi_0/\text{hr}$ represents about an order of magnitude improvement over drift obtained for the best commercial rf SQUIDS.

It has been demonstrated that reliable, low noise dc SQUIDS can be produced with Nb-NbO_x-Pb tunnel junctions. Flux resolutions close to the limit set by pre-amplifier noise and Johnson noise in the SQUID shunt can be achieved in a shielded environment. It has also been shown that variations in the temperature of the helium bath are a major source of SQUID noise and drift. With a simple temperature stabilizer SQUID noise on a scale of a few minutes has been reduced by a factor of two over the noise seen without bath stabilization. Furthermore, long term drift has been lowered considerably in comparison with that observed for commercially available rf SQUIDS.

ACKNOWLEDGMENTS

We wish to thank P. K. Hansma for informative discussions concerning the fabrication of Nb-NbO_x-Pb junctions and T. R. Komersar and C. D. Tesche for their assistance in preparing the SQUIDS. In addition, we thank M. d. Frommer for his aid in assembling the niobium sputtering system and J. B. Kruger for his work on the early development of the SQUID electronics. We are also indebted to J. DeVries and L. Garner of our electronics shop for their assistance in circuit design and construction.

REFERENCES

1. For a review, see J. Clarke, "Low-Frequency Applications of Superconducting Devices," *Proceedings of the IEEE*, Vol. 61, pp. 8-19, 1973.
2. R. C. Jaklevic, J. Lambe, A. H. Silver, and J. E. Mercereau, "Quantum Interference Effects in Josephson Tunneling," *Physical Review Letters*, Vol. 12, pp. 159-160, 1964.
3. P. L. Forgacs and A. Warnick, "Digital-Analog Magnetometer Utilizing Superconducting Sensor," *Review of Scientific Instruments*, Vol. 38, pp. 214-220, 1967.
4. J. E. Mercereau, "Superconducting Magnetometers," *Rev. Phys. Appl.*, vol. 5, pp. 13-20, 1970. M. Nisenoff, "Superconducting Magnetometers with Sensitivities Approaching 10^{-10} Gauss," *Rev. Phys. Appl.*, vol. 5, pp. 21-24, 1970. H. A. Notarys and J. E. Mercereau, "Dynamics of Small Superconductors," in *Proc. Int. Conf. Science of Superconductivity* (Stanford, Calif., Aug. 26-29, 1969), F. Chilton, Ed., pp. 424-431. W. W. Webb, "Superconducting Quantum Magnetometers," *IEEE Trans. Magn.*, Vol. MAG-8, pp. 51-60, March 1972. J. E. Zimmerman, P. Thiene, and J. T. Warding, "Design and Operation of Stable RF-Biased Superconducting Point-Contact Quantum Devices, and a Note on the Properties of Perfectly Clean Metal Contacts," *J. Appl. Phys.*, vol. 41, pp. 1572-1580, 1970. J. M. Goodkind and D. L. Stofa, "The Superconducting Magnetic Flux Detector," *Rev. Sci. Instr.*, vol. 41, pp. 799-807, 1970. R. P. Giffard, R. A. Webb, and J. C. Wheatley, "Principles and Methods of Low-Frequency Electric and Magnetic Measurements Using an RF-Biased Point-Contact Superconducting Device," *J. Low Temp. Phys.*, vol. 6, pp. 533-610, 1972. J. E. Zimmerman, "Josephson Effect Devices and Low-Frequency Field Sensing," *Cryogenics*, vol. 12, pp. 19-31, 1972.

5. J. E. Nordman, "Thin-Film Josephson Junctions Using Getter-Sputtered Niobium," *J. Appl. Phys.*, vol. 40, pp. 2111-2115, 1969.
 L. J. Maillen and D. B. Sullivan, "Fabrication of Tunnel Junctions on Niobium Films," *J. Appl. Phys.*, vol. 40, pp. 2115-2117, 1969.
 M. Graftig and T. White, "Preparation of Josephson Junctions by Plasma Oxidation of Nb," *J. Appl. Phys.*, vol. 42, pp. 2144-2147, 1971.
 K. Schwidtal, "Dc and Ac Josephson Effect in Sputtered Nb-NbO₂-Pb Junctions," *J. Appl. Phys.*, vol. 43, pp. 202-204, 1972.
 P. E. Hansma, "A New Method of Fabricating Niobium-Oxide Barrier Josephson Junctions," *J. Appl. Phys.*, vol. 45, pp. 1472-1473, 1974.
6. D. E. McCumber, "Effect of AC Impedance on DC Voltage-Current Characteristics of Superconductor Weak-Link Junctions," *J. Appl. Phys.*, vol. 39, pp. 1113-1118, 1968.
7. S. Letzter and K. Webster, "Noise in Amplifiers," *IEEE Spectrum*, Vol. 7, pp. 67-75, August 1970.
8. A more detailed account of the noise limitations will be published subsequently.

-NOTICE-

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.