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Publication Date
1975-04-01

Submitted to Applied Physics Letters

LBL-3797
Preprint c.1

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Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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A thin-film dc SQUID with low noise and drift*

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ABSTRACT

We describe the fabrication and operation of thin film dc SQUIDs of cylindrical geometry that make use of shunted Nb-NbO_x-Pb tunnel junctions. A typical noise power spectrum is shown. At frequencies between 2×10^{-2}Hz and the electronic roll-off frequency, the flux resolution is $3.5\times10^{-5}\phi_o/\sqrt{Hz}$, corresponding to a magnetic field resolution of $10^{-10}G/\sqrt{Hz}$. This resolution appears to be set by intrinsic sensor noise. Below 2×10^{-2}Hz, the spectrum is approximately 1/f. A 20hr plot of SQUID output as a function of time demonstrates an average drift of less than $2\times10^{-5}\phi_o$/hr.

We have constructed and tested a thin film dc SQUID[1] that makes use of two resistively shunted Nb-NbO$_x$-Pb tunnel junctions.[2] These junctions are very robust: our SQUIDs can be thermally cycled repeatedly, and stored at room temperature indefinitely. The weak temperature dependence of the critical current allows the SQUID to be operated at any temperature below about 6K. Above 2×10^{-2}Hz, the SQUID typically has a flux resolution of $4\times10^{-5}\phi_o/\sqrt{Hz}$, corresponding to a magnetic field resolution of about $10^{-10}G/\sqrt{Hz}$. Below 10^{-2}Hz, the noise power spectrum varies as 1/f. The average long-term drift is less than $2\times10^{-5}\phi_o$/hr. The 1/f noise and long-term drift are lower than any values reported previously.

The SQUID is shown schematically in Fig. 1. A 10mm wide band of lead (+5% indium) is evaporated around a 20mm long, 3mm o.d. quartz tube. A gold film is evaporated and two parallel 150μm wide niobium strips are dc sputtered, as shown. The niobium strips make superconducting contacts to the lead band and low resistance contacts to the gold. After thermally oxidizing the niobium, a T of lead (+5% indium) is evaporated to form two tunnel junctions, each shunted by part of the gold film. The crossbar of the T is 75μm wide, so that each junction has an area of about $10^{-2}mm^2$. A slit is scribed through the lead band between the niobium strips after which the whole device is coated with a thin layer of Duco cement. Finally, a lead ground plane (not shown in Fig. 1) is evaporated over the front surface of the SQUID, leaving the lower ends of the niobium strips and lead T exposed. The ground plane minimizes the inductance of the various metal films, and reduces flux leakage through the slit in the lead band. Fine copper wires are attached to the end of the lead T and to the end of one of the niobium strips with indium contacts.

Typical values for various SQUID parameters are as follows: SQUID inductance $L_s \approx 1\mathrm{nH}$; capacitance per junction $C \approx 200\mathrm{pF}$; parallel resistance of the two shunts $R_s \approx 0.4\Omega$; total critical current for the two junctions $I_c \approx 5\mu\mathrm{A}$. The hysteresis parameter[3] for each junction $\beta_c = 4\pi I_c R_s^2 C/\phi_o \lesssim 1$ so that the current-voltage characteristics are non-hysteretic. The SQUID is biased with a dc current $I_o > I_c$ at a voltage of 1 to 2μV. When the applied flux is changed from an integral to a half-integral number of flux quanta the voltage change is about 0.5μV.

A 100kHz current passing through a coil inside the quartz tube modulates the flux in the SQUID with a peak-to-peak amplitude $\lesssim \phi_o$. The 100kHz signal developed across the junctions is amplified at 4.2K by a tank circuit having a Q of about 300. The amplitude of the 100kHz signal across the tank circuit is periodic in the quasistatic flux in the SQUID. The tank circuit is connected to a room temperature FET amplifier that has a noise temperature of about 1K. The amplified 100kHz signal is lock-in detected, integrated, and fed back as a current via a resistor into the coil inside the quartz tube to cancel any change in the applied flux. The output voltage appearing across the series resistor is thus proportional to the flux applied to the SQUID. The dynamic range of the closed loop system is $\sim 10^6$, and the maximum slewing rate that we have achieved is $\sim 10^5 \phi_o/\mathrm{sec}$.

Noise and drift measurements are made with the SQUID enclosed in a 76mm long 6.4mm i.d. superconducting tube. This shield attenuates changes in external magnetic field by a factor of at least 10^{11}. The shielded SQUID and the tank circuit are mounted in a vacuum can which is immersed in liquid helium.

Figure 2 shows a typical noise power spectrum for one of our SQUIDs at 4.2K. The spectrum is nearly white from the high frequency roll-off of the feedback circuit (100Hz in this case) down to about 2×10^{-2}Hz where 1/f noise becomes significant. The rms flux noise over this frequency range is $\sim3.5\times10^{-5}\phi_o/\sqrt{\mathrm{Hz}}$ corresponding to a magnetic field resolution of $10^{-10}\mathrm{G}/\sqrt{\mathrm{Hz}}$. Our best resolution was $2\times10^{-5}\phi_o/\sqrt{\mathrm{Hz}}$ measured with the SQUID at 2K. The resolution is limited by inherent noise in the SQUID rather than by noise in the preamplifier. The signal developed by the SQUID is approximately $1\mu\mathrm{V}/\phi_o$. If we assume that the theory of Likharev and Semenov for noise in Josephson junctions[4] is applicable, the thermal noise in the junctions in a bandwidth B is given by $\overline{V_N^2}=4kTR_sB[1+(1/2)(I_c/I_o)^2]/[1-(I_c/I_o)^2]$. At 4.2K with $(I_c/I_o)^2\approx0.5$ we find $\sqrt{\overline{V_N^2}}\approx2\times10^{-11}\mathrm{V}/\sqrt{\mathrm{Hz}}$. Thus the predicted thermal noise limited resolution is $2\times10^{-5}\phi_o/\sqrt{\mathrm{Hz}}$. The observed resolution of our SQUIDs is not more than a factor of 2 above the estimated thermal noise limit. Given the various uncertainties in the calculation, this factor may not be significant, although it is possible that the effective temperature seen by the SQUID is somewhat above the bath temperature. In the presence of a magnetic field greater than ~1G the noise increases somewhat due to microphonic effects.

The output of the SQUID exhibits a magnetic field related temperature sensitivity[5] of $\sim0.6\phi_o\mathrm{G}^{-1}\mathrm{K}^{-1}$ at 4.2K. We believe this effect to be caused primarily by the reversible movement of flux lines pinned in the SQUID shield. Temperature drifts in an unregulated helium bath associated with changes in atmospheric pressure and hydrostatic head are typically 1mK/hr or less. Thus if the SQUID and its shield are cooled in the earth's field, drifts on the order of $3\times10^{-4}\phi_o$/hr are to be expected. Consequently, in order to obtain low long-term drift, one must either regulate the temperature of the SQUID or cool down the shield in a suitably low magnetic field.

We achieve temperature regulation in the following way. The temperature of the SQUID is measured with a carbon resistance thermometer. The thermometer is in an ac bridge circuit, the output of which is detected, amplified, and fed back to a mechanical transducer that controls the blow-off rate of the helium gas from the bath. This system stabilizes the SQUID temperature to within ±50μK indefinitely. Figure 3 shows the output over a 20 hour period of a temperature regulated SQUID whose temperature sensitivity was $0.1\phi_o$/K. The bandwidth is 0 Hz to 0.25Hz. The average drift is less than $2\times10^{-5}\phi_o$/hr. The gradual upward trend evident over most of the trace is believed to be due to small changes in the capacitance of the cable connecting the tank circuit to the FET preamplifier as the helium level falls.

The temperature sensitivity of the SQUID output is reduced by cooling the SQUID and its shield in an applied axial field that opposes the earth's field. The applied field during cooldown is adjusted to minimize the temperature dependence. In general, the total axial field is not quite zero when the temperature dependence is a minimum. A temperature dependence as low as $5\times10^{-3}\phi_o$/K over a 50mK range can be readily achieved in this manner.

In practice the lowest drift we have observed with an unregulated helium bath is again about $2\times10^{-5}\phi_o$/hr.

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[*] Work supported by the U.S.E.R.D.A.

[†] IBM Postdoctoral Fellow.

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3. W. C. Stewart, Appl. Phys. Letters 12, 277 (1968); D. E. McCumber, J. Appl. Phys. 39, 3113 (1968).
4. K. K. Likharev and V. K. Semenov, JETP Letters 15, 442 (1972).
5. In an earlier version of the SQUID [reported in the Proceedings of the Applied Superconductivity Conference, IEEE Transactions on Magnetics, MAG-11, 724 (1965)], the temperature dependence in the presence of a magnetic field was much higher. This higher dependence was caused by the broad superconducting transition of the InBi solder used to attach the leads.

Figure Captions

Fig. 1. Cylindrical dc SQUID with tank circuit and modulation coil.

Fig. 2. Noise power spectrum of a SQUID.

Fig. 3. SQUID output vs time.

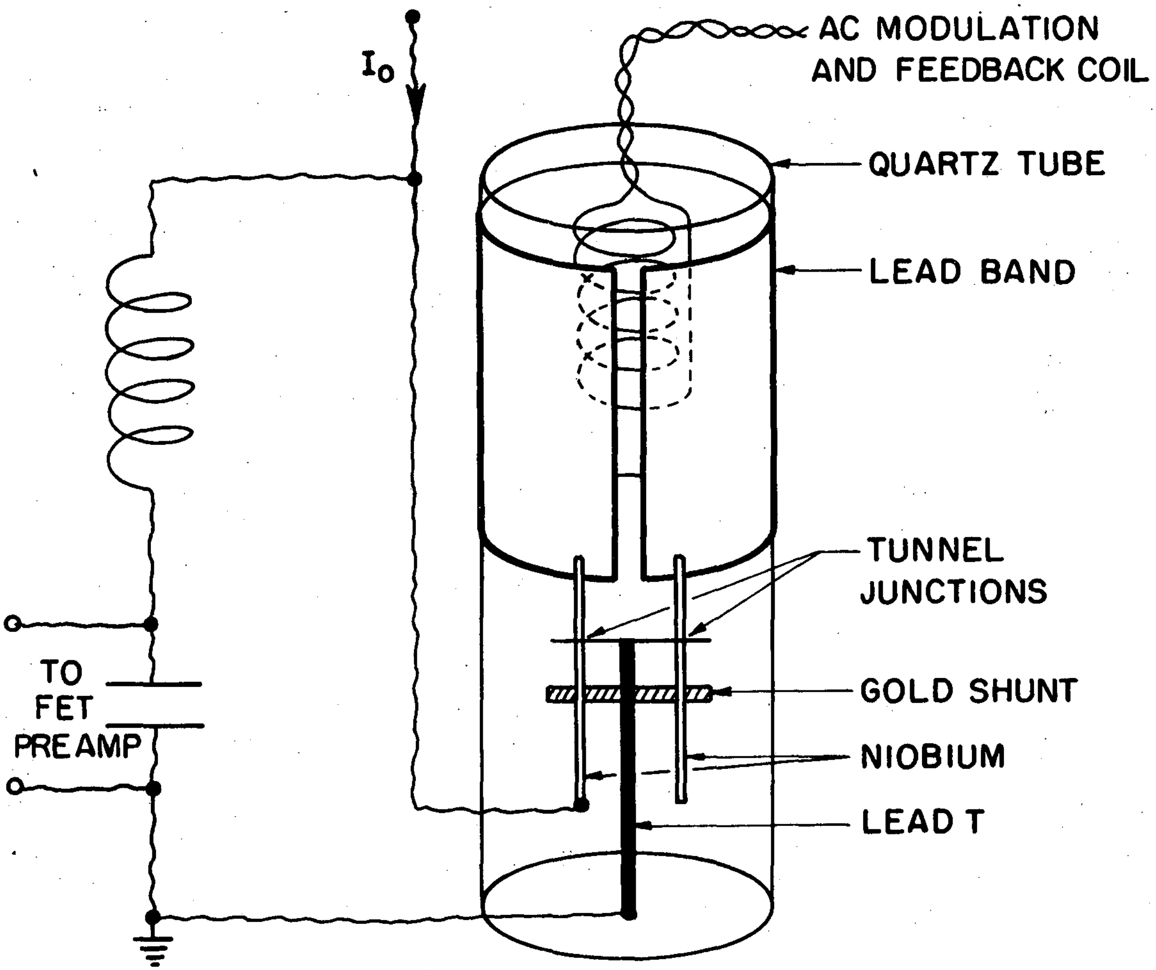

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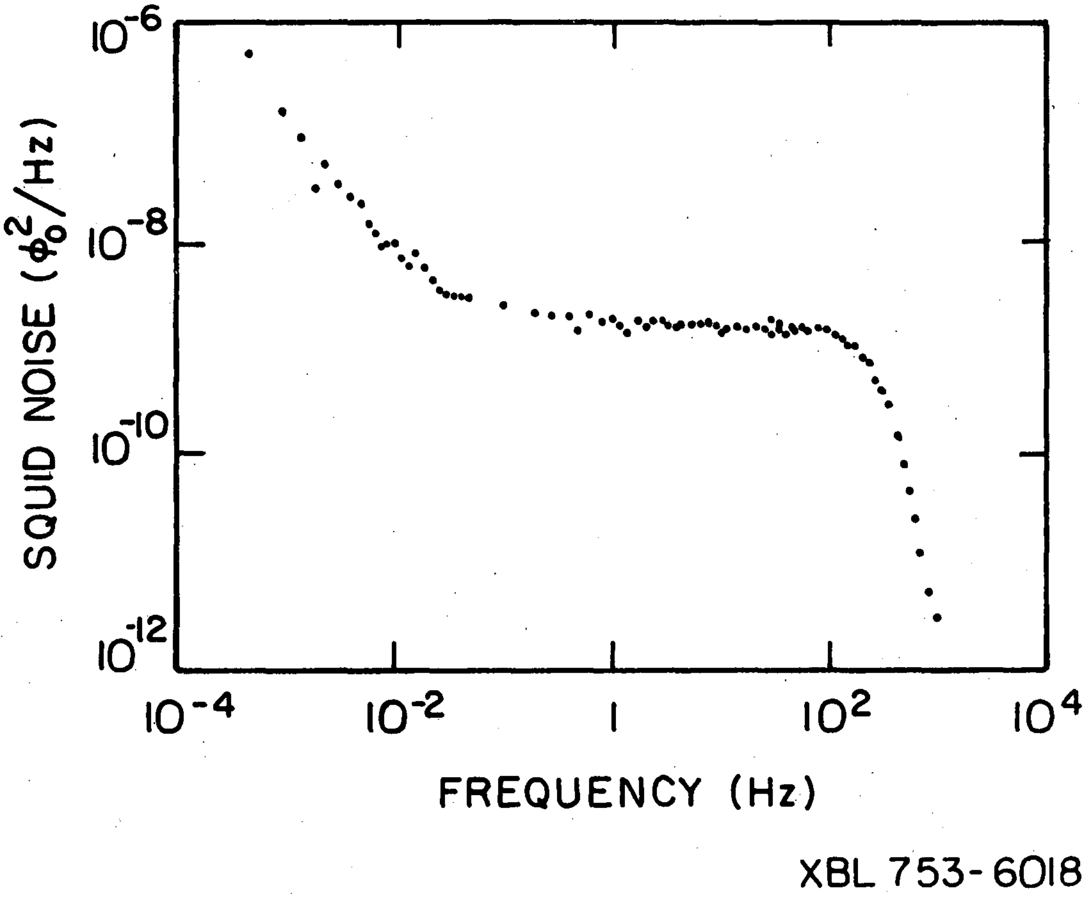
Fig. 1


10^{-6}
10^{-8}
10^{-10}
10^{-12}
SQUID NOISE (ϕ_0^2/Hz)
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10^{-2}
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10^{2}
10^{4}
FREQUENCY (Hz)
XBL 753-6018

Fig. 2

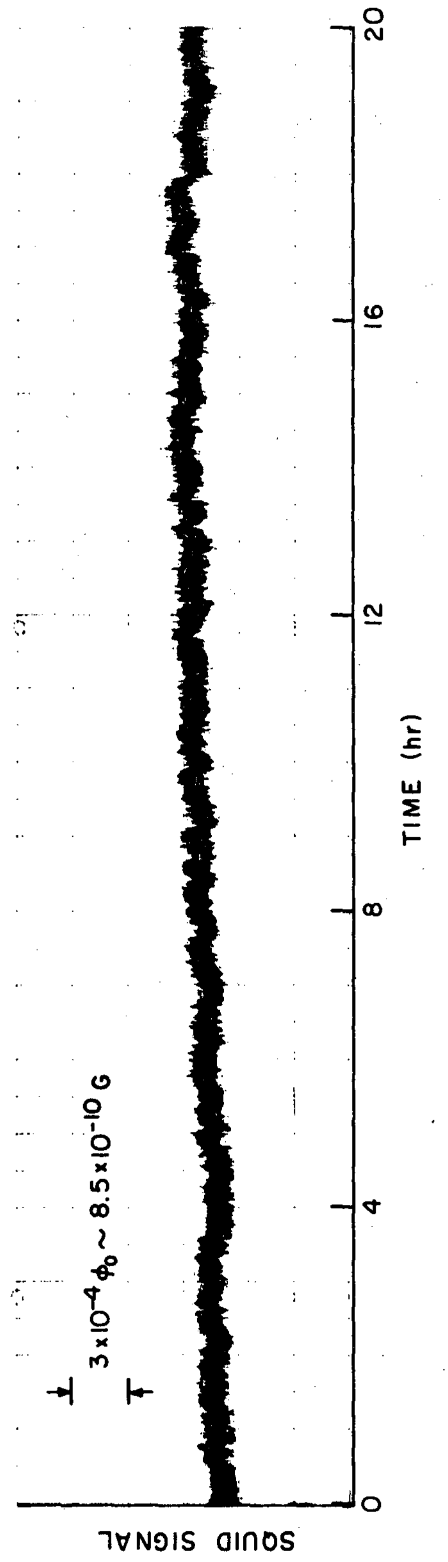

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Fig. 3

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