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DC SQUID NEAR THE QUANTUM NOISE LIMIT

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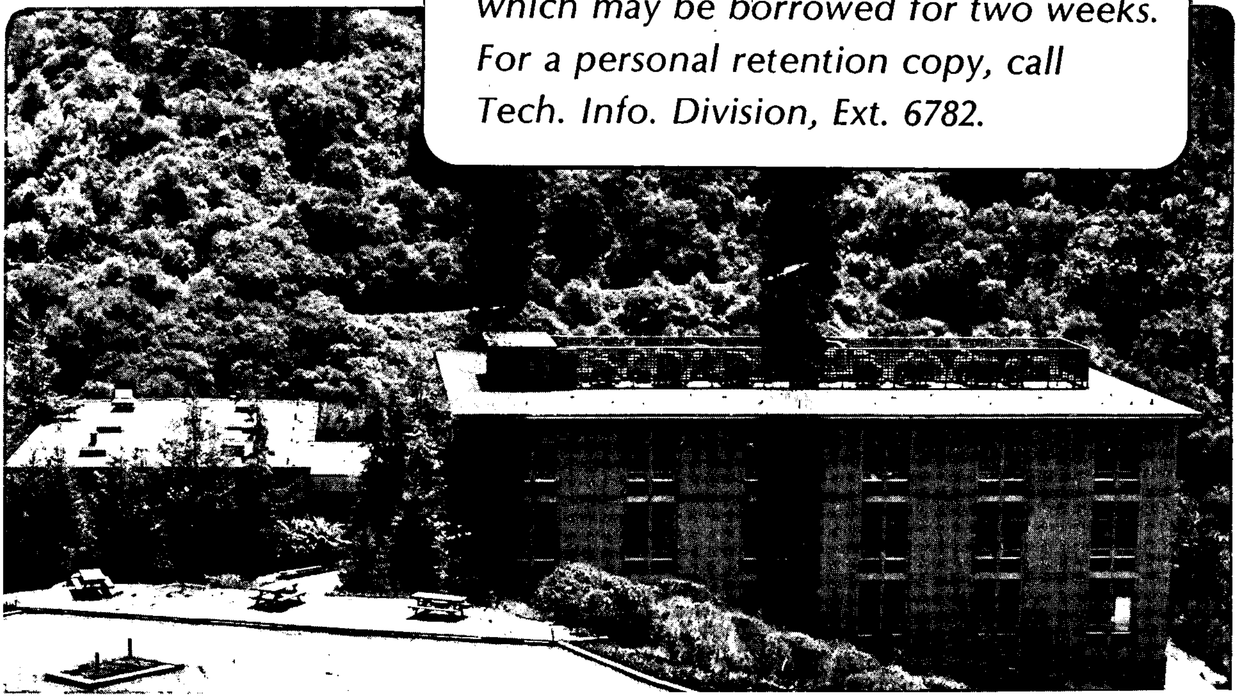

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DC SQUID NEAR THE QUANTUM NOISE LIMIT

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A series of dc SQUIDs has been fabricated in an attempt to obtain quantum-limited sensitivity. Typically, the SQUID inductance, L, is 2 pH, the capacitance and critical current of each tunnel junction are 0.5 pF and 0.5 mA, and the shunt resistance for each junction is 1Ω. The measured spectral density of the voltage noise S_V contains a 1/f component that extends typically to 100 kHz or higher. When the 1/f component is subtracted out, the best energy sensitivity achieved to date is $\varepsilon/1\text{Hz} = S_V/2L(\partial V/\partial \Phi)^2 \lesssim 2\hbar$, where $\partial V/\partial \Phi$ is the transfer coefficient.

I. INTRODUCTION

Tesche and Clarke[1] computed the optimized noise energy, $\varepsilon/1\text{Hz} = S_\Phi/2L$, of the dc SQUID in the thermal limit in which the noise is assumed to originate from Nyquist current noise in the resistances shunting the junctions; here, L is the SQUID inductance, and $S_\Phi = S_V/(\partial V/\partial \Phi)^2$ where S_V is the spectral density of the voltage noise across the SQUID, and $\partial V/\partial \Phi$ is the flux-to-voltage transfer coefficient. For an optimized SQUID, they found $\varepsilon/1\text{Hz} \approx 10k_BT(LC)^{1/2}$, where T is the temperature and C is the capacitance of each tunnel junction. The optimization required that $\beta_c \equiv 2\pi R^2CI_o/\Phi_o \lesssim 1$, and $\beta \equiv 2LI_o/\Phi_o \approx 1$, where I_o and R are the critical current and shunt resistance of each junction. The computed value of $\varepsilon/1\text{Hz}$ has been quite successful in predicting the sensitivity of SQUIDs over about 4 decades of noise energy[2]. The most sensitive devices reported[3-5] so far have noise energies of about $6\hbar$. As T, L, and/or C are reduced, quantum corrections to the noise generated in the shunts becomes important, and eventually the SQUID is expected to become quantum limited. Koch et al[6] have computed the limiting energy sensitivity of the dc SQUID assuming that the limiting noise at T=0 is determined by zero point current fluctuations in each shunt resistor, with a spectral density $2h\nu/R$ at frequency ν. They find that the SQUID is again optimized when $\beta_c \lesssim 1$ and $\beta=1$, and that the optimum noise energy is $\varepsilon/1\text{Hz} \approx \hbar$. At non-zero temperatures, it is necessary to design SQUIDs in the limit $\kappa \equiv eI_oR/k_BT >> 1$ in order to approach quantum-limited sensitivity. For $\beta_c \lesssim 1$, this restriction implies a critical current density much greater than 10^4 Acm^{-2} at 4K.

In this paper, we report measurements on dc SQUIDs that approach the quantum limit. The highest performance achieved so far is $\varepsilon/1\text{Hz} \lesssim 2\hbar$ when the measured 1/f noise has been subtracted.

II. EXPERIMENT

We have fabricated dc SQUIDs designed to approach the quantum limit in the liquid He^4 temperature range. The configuration of the SQUID is shown in the inset of Figure 1. The resistive shunt consists of a 10 μm-wide by 60 nm-thick Cu (3wt.% Al) strip. The lower electrode is a 250 nm-thick Pb (20 wt.% In) film patterned by photolithographic liftoff. The junctions, 2 μm in diameter and spaced 30 μm

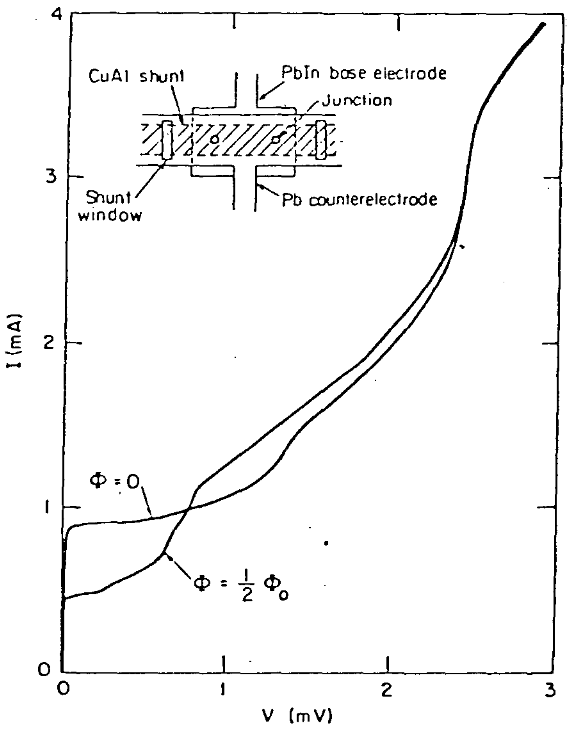

Figure 1 : Current-voltage characteristic of dc SQUID. Inset shows SQUID configuration.

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*Present address: Department of Physics, University of Illinois, Urbana, IL apart, are defined by windows in an SiO insulating layer; additional windows over the resistive strip set the shunt lengths at 5 μm. After the photoresist pattern for the upper electrode is formed, the PbIn base electrode is sputter cleaned in an Ar rf glow discharge and thermally-oxidized in O_2. The counter-electrode, a 400 nm-thick Pb film, completes the SQUID loop and provides a ground plane that reduces the inductances of the resistive shunts. The SQUID inductance is about 2pH. For our PbIn-In_2O_3-Pb tunnel junctions, we estimate the capacitance to be 0.5pF. Hence, for an optimized SQUID ($\beta=\beta_c=1$), we require R=1.1Ω and I_o=0.5 mA, corresponding to a critical current density of 10^4 Acm^{-2}.

The SQUID is connected across three cooled LC resonant circuits (typically at 30, 100, and 300 kHz) that amplify the voltage noise before coupling it to a low-noise room-temperature preamplifier. The noise is then mixed down to low frequencies (<100 Hz) and its power spectrum is obtained on a computer. By measuring the noise at several frequencies, we can determine any 1/f contribution to the noise that may be present. We measure the transfer function by modulating the flux through the SQUID with an amplitude of $\Phi_o/1000$, and lock-in detecting the resulting output voltage.

The current-voltage characteristic of our best SQUID to date is shown in Figure 1. For this SQUID, $\beta \approx 1.1$, and the critical current modulates to approximately 1/2 its maximum value. The structure in the I-V characteristic near $V \approx 0.8$ mV results from the excitation by the Josephson frequency of the LC resonant circuit formed by the SQUID inductance and the junction capacitances. Transfer functions of up to 6.5 mV/Φ_o at 4.2K and 22 mV/Φ_o at 3.4K have been obtained for this SQUID. In Figure 2, we plot the energy resolution ε/1Hz vs. 1/f for several frequencies and temperatures. At 4.2K, the noise extrapolates to a white noise level of 2.6ħ, corresponding to a flux resolution $S_\Phi^{1/2} = 2\times10^{-8}\Phi_o/\sqrt{Hz}$. This result is in excellent agreement with the predictions of our model[6]. The 1/f noise level is $(3.1\times10^5 Hz/f)$ħ, giving a 1/f crossover frequency of 120 kHz. At 3.4K, the white noise drops to 1.7ħ and the 1/f crossover moves out to 140 kHz. At lower temperatures, this particular SQUID becomes hysteretic because the critical current increases.

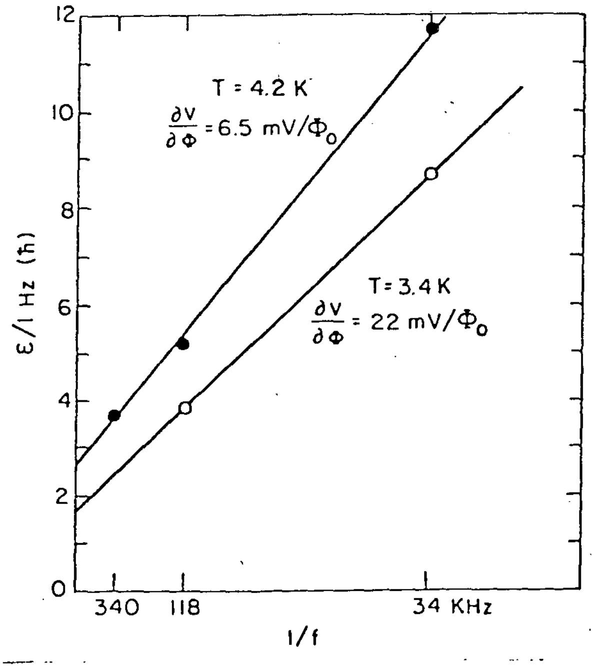

Figure 2 : ε/1Hz as a function of frequency for SQUID of Fig. 1.

Further experiments are underway on other SQUIDs in an attempt to achieve a higher sensitivity at temperatures near 1K. The measurement frequency is being increased to 1 MHz, to avoid the need to correct for 1/f noise.

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