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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 10. 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 $e/1Hz = S_v/(2L(2V/\Phi))^2 \approx 2h$, where $2V/\Phi$ is the flux-to-voltage transfer coefficient.

I. INTRODUCTION

Tesche and Clarke computed the optimized noise energy, $e/1Hz = S_v/2L$, 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 $S_v = S_v/(2V/\Phi)^2$ where $S_v$ is the spectral density of the voltage noise across the SQUID, and $2V/\Phi$ is the flux-to-voltage transfer coefficient. For an optimized SQUID, they found $e/1Hz \approx 10kBT(LC)$, where $T$ is the temperature and $C$ is the capacitance of each tunnel junction. The optimization required that $B_c = 2\Phi_0/C_{\Phi_0}$ and $B = 2L\phi/\Phi_0 = 1$, where $\Phi_0$ and $R$ are the critical current and shunt resistance of each junction. The computed value of $e/1Hz$ has been quite successful in predicting the sensitivity of SQUIDs over about 4 decades of noise energy. The most sensitive devices reported so far have noise energies of about $6h$. 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. 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 $2h/\Phi$ at frequency $v$. They find that the SQUID is again optimized when $B_c \approx 1$ and $B \approx 1$, and that the optimum noise energy is $e/1Hz = h$. At non-zero temperatures, it is necessary to design SQUIDs in the limit $k_B T >> 1$ in order to approach quantum-limited sensitivity. For $B_c \approx 1$, this restriction implies a critical current density much greater than $10^4 A cm^{-2}$ at 4K.

In this paper, we report measurements on dc SQUIDs that approach the quantum limit. The highest performance achieved so far is $e/1Hz < 2h$ 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-thick Cu (0.02% Cu) 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 of the dc SQUID assuming that the limiting noise is determined by zero point current fluctuations in each shunt resistor, with a spectral density $2h/\Phi$ at frequency $v$. They find that the SQUID is again optimized when $B_c \approx 1$ and $B \approx 1$, and that the optimum noise energy is $e/1Hz = h$. At non-zero temperatures, it is necessary to design SQUIDs in the limit $k_B T >> 1$ in order to approach quantum-limited sensitivity. For $B_c \approx 1$, this restriction implies a critical current density much greater than $10^4 A cm^{-2}$ at 4K.

In this paper, we report measurements on dc SQUIDs that approach the quantum limit. The highest performance achieved so far is $e/1Hz < 2h$ when the measured $1/f$ noise has been subtracted.

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Figure 1: Current-voltage characteristic of dc SQUID. Inset shows SQUID configuration.
The current-voltage characteristic of our best SQUID at temperatures near 1K. The measurement frequency is being increased to 1 MHz, to avoid the need to correct for 1/f noise. 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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REFERENCES

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