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Effects of microwave radiation on the noise in high- T_c YBa₂Cu₃O₇ dc SQUID magnetometer

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Abstract

With a properly fabricated low-noise SQUID, we have studied the effects of microwave radiation on the noise behavior. Under an ac bias, with increasing microwave power, the critical current and the voltage modulation depth $\Delta V = \Phi_0 V_\phi / \pi$ decrease, but the SQUID resistance R_s increases, suggesting a dynamical interaction between the charge carriers and the electromagnetic wave. Furthermore, the microwave radiation modifies drastically the functional dependence of S_ϕ and ΔV on ac bias current. © 2000 Elsevier Science Ltd. All rights reserved.

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SQUIDS based on high-temperature superconductors are extremely sensitive magnetic field detectors [1–5]. By measuring the field strength, the field gradient, or the susceptibility, which can be originated from either the direct or the induced magnetic field source, many physical properties and biological signals [6] can be determined. Such detectors are commercially available because of the cheap cooling with liquid nitrogen. During the measurements, the sensitivity of converting the magnetic flux to output voltage depends on the noise level, which can be reduced by proper fabrication processes. However, to do so one must clarify the characteristic features of SQUIDS that are relevant to noise.

We are interested in the flux noise S_ϕ . It is well known [7] that if the condition $L \leq \Phi_0^2 / k_B T$ is violated, the thermal noise can be so large that the SQUID operation becomes unreliable, where L is the inductance of the SQUID. Furthermore, the increase of thermal noise will degrade the voltage-to-flux transfer function V_ϕ , resulting in a large flux noise through the relation $S_\phi^{1/2} = S_V^{1/2} / V_\phi$, where S_V is the voltage noise [8]. In Ref. [8] the theoretical study on V_ϕ suggests a maximum value of L around 200 pH.

In this paper we investigate the noise in a dc directly coupled SQUID magnetometer of washer type under microwave irradiation. Under an ac bias, with increasing microwave power, the critical current and the voltage modulation depth $\Delta V = \Phi_0 V_\phi / \pi$ decrease, but the SQUID resistance R_s increases, suggesting a dynamical interaction between the charge carriers and the electromagnetic wave. Furthermore, the microwave radiation modifies drastically the functional dependence of S_ϕ and ΔV on ac bias current.

In designing SQUID there are three constraints for the parameters of SQUID set out by Tesche and Clarke [9]. The first is that the junction coupling energy should be greater than the thermal energy, $I_c \Phi_0 / 2\pi \geq 5k_B T$. For our experiment at 77 K, the critical current I_c is required to be

Fig. 1. The geometry of the junctions of the SQUID magnetometer coupled to the pickup washer.

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Fig. 2. The configuration of the flux-locked-loop (FLL).

greater than $16.68 \mu\text{A}$, which can be achieved by good film deposition technology. The second requirement for optimum SQUID performance is $\beta_L \equiv 2L_s I_c / \Phi_0 \sim 1$, where L_s is the SQUID inductance. In our case this criterion is satisfied at $L_s \leq 60 \text{ pH}$. The last constraint is to ensure the nonhysteretic characteristics with the condition $\beta_C \equiv 2\pi I_c R_s^2 C / \Phi_0 \leq 1$, where R_s is the SQUID resistance and C is the SQUID capacitance. Therefore, one can reduce the thermal flux noise by making R_s as large as possible, because the thermal noise S_ϕ is proportional to $L_s(2k_B T/R_s)/[1 + (R_s/I_c V_\phi)^2]$, so long as C is kept small enough to satisfy the condition on β_C . This can be easily realized with the present technology, which yields a value of less than 10 fF for a capacitance on planer grain boundary junction.

The SQUID to be investigated here is a directly coupled bicrystal magnetometer of washer type. It has the advantage of allowing the independent adjustment of L_s and R_s without disturbing the other optimization condition $I_c \Phi_0 / 2\pi \cong 5k_B T$. The double junction SQUID magnetometer is fabricated from a 300-nm thick YBCO film on a $1 \times 1 \text{ cm}^2$ SrTiO₂ bicrystal substrate with a 24° misorientation angle. The structure was patterned by ion beam etching technology and the normal metallization was done by ion beam sputtering of Ag/Au after ion beam cleaning through a photoresist liftoff method. The total inductance, which consists of L_s and the circuit contribution, has a value about 50 pH , and R_s is about 2.5 Ohm . Fig. 1 shows the detailed structure of the coupling between the pickup washer and the body of the bare SQUID.

The voltage spectral density S_V and the flux noise S_ϕ are measured with a spectrum analyzer (Stanford Research system, model FFT 760) attached to a commercial SQUID controller. The SQUID is operated in the flux-locked-loop (FLL) mode with a commercial ac flux modulation at 77 K . The configuration of the FLL is shown in Fig. 2. The circuit design of FLL reduces the low-frequency noise arising from the critical current fluctuation of the Josephson junction. In commercial SQUIDS fabricated from high-quality films, it is known [10] that the critical current is the main source of noise. If we assume that the dc SQUID has two symmetric

junctions, then the SQUID voltage noise can be expressed as [11–13]

$$S_V = (1/2)[(V - IR_d)^2 + (LI_c V_\phi)^2](S_c/I_c^2), \quad (1)$$

where V is the voltage across the SQUID at the bias current I , $V_\phi = dV/d\Phi$, and R_d the dynamic resistance of the SQUID. S_c represents the power spectrum of the critical current fluctuations. In the square bracket, the first term is the “in phase” voltage noise, and the second term is a flux noise arising from the “out of phase” critical current fluctuation. Operating the SQUID in the FLL mode will suppress the “in phase” contribution, and in the bias current reverse mode will suppress the “out of phase” contribution.

The operation in the FLL is achieved by a read-out electronic system, which uses a positive flux feedback to lock the SQUID sensor, and the measured magnetic flux is amplified by the electronic system. Under the condition of locking, the noise at 15 Hz was measured with both dc bias and 3125-Hz ac bias. From the results shown in Fig. 3, we see that the ac bias noise is about four times smaller than the dc noise. All of our measurements were then performed with ac bias. The SQUID system is screened with two layers of Mu-metal and a high- T_c superconducting Bi₂Sr₂Ca₂Cu₃O_y cylinder shield.

Microwave radiation of 9 GHz was led to the junctions of SQUID through a dipole antenna. As the microwave power increases, we have observed a decrease of both I_c and the voltage modulation depth $\Delta V \equiv V_\phi \Phi_0 / \pi$ as shown in Fig. 4. However, as seen from Fig. 5, the quantity $(1 + \beta_L)\Delta V/I_c$ increases with the microwave power. Enpuku et al. [8] have proposed an analytical formula

$$V_\phi = 4I_c R_s [1 - 3.57(k_B T L)^{1/2} / \Phi_0] / [\Phi_0 (1 + \beta_L)], \quad (2)$$

according to which our experimental results imply an enhancement of R_s by microwave radiation. One possible reason of such behavior is the sample heating arising from microwave, which increases R_s faster than $T^{1/2}$. To check this conjecture, we have turned off the microwave radiation and repeated the experiment at various temperatures. In this

Fig. 3. Noise as a function of bias current for dc bias (upper curve) and for ac bias (lower curve).

Fig. 4. The critical current I_c and the voltage modulation depth ΔV as functions of microwave power measured at 77 K.

Fig. 5. The value of $\Delta V(1 + \beta_L)/I_c$ as a function of the microwave power.

Fig. 6. The ratio of the effective noise temperature T_n to the sample temperature T , where T_n is determined by fitting Eq. (2) to measured data.

Fig. 7. The flux noise $S_\phi^{1/2}$ and ΔV as a function of ac bias current under microwave radiation at the power level 9 dbm. The insert shows the voltage noise $S_V^{1/2}$. The noises are measured at 1.5 kHz.

case, we found that $(1 + \beta_L)\Delta V/I_c$ decreases monotonically with increasing temperature. In using Eq. (2) to fit experimental data, it is commonly accepted that the true temperature in Eq. (2) should be replaced by an “effective noise temperature T_n ”, and T_n/T derived from our fitting is shown in Fig. 6, which yields $T_n/T = 1.75$ with a fluctuation of less than 1%. Our conclusion is that the increase of R_s by microwave radiation is caused by the dynamical interaction between the charge carriers and the electromagnetic wave, the theoretical details of which interaction remain to be explained.

In the absence of microwave radiation, the noise S_ϕ as a function of dc bias current exhibits a broad minimum, and the corresponding ΔV has a broad maximum. The effect of microwave radiation is shown in Fig. 7, where the noise is measured at 1.5 kHz. The broad maximum of ΔV splits into two peaks, with two corresponding minima of $S_\phi^{1/2}$. With reducing frequency, there is little qualitative change of the noise curve, although its magnitude is enhanced. The voltage noise S_V is shown by the insert in Fig. 7, which is also modified strongly by microwave radiation. Our conjecture that the results in Fig. 7 are related to the formation of Shapiro steps [14] is a subject for further investigation.

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