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Abstract

We have constructed and tested high-T_C magnetometers by coupling a high-T_C thin-film Superconducting QUantum Interference Device (SQUID) to two different high-T_C thin-film flux transformers. The SQUID was made from $Tl_2CaBa_2Cu_2O_{8+y}$ films grown on MgO, with junctions consisting of native grain boundaries. The flux transformers were made from $YBa_2Cu_3O_{7-x}$, and each had 10-turn input coils and a single-turn pickup loop. The first transformer, which was patterned with a combination of shadow masks and photolithography, yielded a magnetic field gain of about -7.5, functioned up to 79 K, and gave a magnetic field sensitivity B_N (10 Hz) ≈ 3.1 pT $Hz^{-1/2}$ at 38 K. The second transformer, which was patterned entirely by photolithography, yielded a gain of about -8.7, functioned up to 25 K, and had a sensitivity B_N (10 Hz) ≈ 3.5 pT $Hz^{-1/2}$ at 4.2 K. In both cases, the limiting noise arose in the SQUID.

Introduction

Although Superconducting QUantum Interference Devices (SQUIDs) are extremely sensitive detectors of changes in magnetic flux, planar SQUIDs made from thin films of superconductor are generally not very sensitive to changes in magnetic field. This is because the field sensitivity of the SQUID is

$$B_N^{(S)}(f) = S_\Phi^{1/2}(f) / \eta A_S, \qquad (1)$$

where $S_\Phi^{1/2}(f)$ is the spectral density of the flux noise, A_S is the geometric area of the hole in the SQUID, and η is the flux focussing factor[1] that depends on the geometry of the device. Thus, ηA_S is the effective pickup area of the SQUID, defined as the flux coupled per unit applied magnetic field. The inductance of a square hole of side d in a large film is given approximately by[2] $L = 1.25\mu_0 d$. For use as a SQUID there is an upper bound on L imposed by the requirement that thermal fluctuations in the flux be much less than $\Phi_0/2$, where $\Phi_0 = h/2e$ is the flux quantum. As a result, the inner dimensions of most high-T_C thin-film SQUIDs[3] are not much more than 50×50 μm^2. To achieve useful sensitivities to magnetic field, all such devices require a superconducting flux transformer[4].

A flux transformer consists of a pickup coil of inductance L_p connected to an input coil of inductance L_i which is inductively coupled to the SQUID of inductance L (see Fig. 1). The pickup coil often consists of a single turn, while the input coil usually has many turns. Any magnetic flux, Φ, applied to the pickup coil induces a supercurrent in the transformer and hence a flux in the SQUID given by

$$\Phi^{(S)} = -\frac{M_i}{L_i + L_p}\Phi, \qquad (2)$$

where $M_i = \alpha(L_i L)^{1/2}$ is the mutual inductance between the input coil and the SQUID, and α is the associated coupling coefficient. The minus sign arises because on the transformers we fabricated we chose the winding of the input coil to be such that in a uniform applied field the flux coupled to the SQUID by the flux transformer is of *opposite sign* to that linking the SQUID directly. This gives us an unequivocal signal that the flux transformer is functioning.

We can express the magnetic field gain, G, of the flux transformer as the ratio of the magnetometer effective area, A_M, to the SQUID effective area, ηA_S:

$$G = \frac{A_M}{\eta A_S} = 1 - \frac{A_p}{\eta A_S}\frac{\alpha(L_i L)^{1/2}}{L_i + L_p}. \qquad (3)$$

Here, A_p is the area of the pickup loop. Assuming that the flux transformer itself contributes no noise, we can write the magnetic field sensitivity of the magnetometer as

$$B_N(f) = B_N^{(S)}(f) / |G|. \qquad (4)$$

We note that when the flux transformer is functioning and well coupled to the SQUID the second term in Eq. 3 dominates and the measured gain is negative.

The dc SQUID

The dc SQUID we used was fabricated by Superconductor Technologies, Inc. by wet etching a 500 nm thick film of $Tl_2CaBa_2Cu_2O_{8+y}$ (TCBCO) grown on a MgO substrate by laser ablation and post annealing[5]. Before the film was patterned, the transition temperature, determined by magnetic susceptibility, was 103.4 K. The inner hole of the SQUID is a 20×80 μm^2 rectangle, and has two small bridges a few microns wide which contain native grain boundary weak-links (Fig. 2). At liquid nitrogen temperatures the noise rounded critical current of the SQUID was 1-2 μA, and the dynamic resistance about 3.8 Ω. The application of a magnetic field to the bare SQUID modulated the critical current with a period corresponding to an effective pickup area of 4.4×10^4 μm^2. This area is about 27 times greater than the geometrical area of the loop; we attribute this large flux focussing factor to the large rectangles of superconductor used to provide contacts to the SQUID.

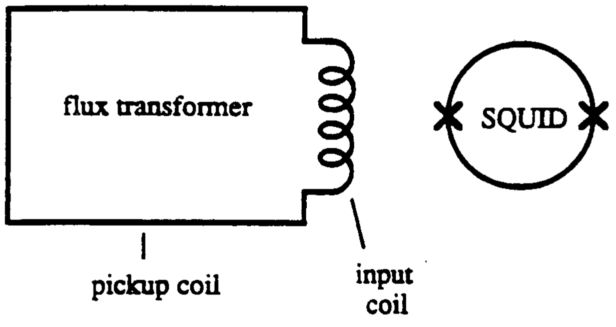

Figure 1. Schematic of a flux transformer coupled to a SQUID.

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To measure its noise as a function of temperature, we mounted the SQUID on a probe that we could position at a variable height above the surface of liquid helium in a dewar. The end of the probe was surrounded with a thin tube of CO-NETIC brand high-μ metallic foil, a solid copper can, and a further layer of μ-metal, and the cryostat was operated inside an rf shielded room. At low frequencies, this arrangement screened external magnetic fields by a factor of 100. The SQUID was operated in a flux-locked loop, with a flux modulation frequency of 100 kHz. The voltage across the SQUID was amplified by a cooled transformer of turns ratio 1:15 wound from copper wire.

A representative flux noise power spectrum of the SQUID at 55 K is shown in Fig. 3. The two noise spikes are due to external noise sources, and demonstrate that the shielding is somewhat inadequate. At low frequencies (< 10 Hz), the noise power is steeper than 1/f (where f is the frequency), and probably arises from a number of sources including external noise and drifts in temperature and ambient magnetic field during the period of the measurement. At 10 Hz, the rms noise is $S_\Phi^{1/2}$ (10 Hz) ~ $7.0 \times 10^{-4}\ \Phi_0\ Hz^{-1/2}$, while in the white noise region the noise drops to $S_\Phi^{1/2}$ (100 Hz) ~ $4.5 \times 10^{-4}\ \Phi_0\ Hz^{-1/2}$. The latter flux noise corresponds to a magnetic field sensitivity of about 21 pT $Hz^{-1/2}$. These noise levels are appreciably higher than those for the quietest TCBCO SQUID yet reported[6].

Flux Transformers

We have successfully coupled the SQUID to two $YBa_2Cu_3O_{7-x}$ (YBCO) flux transformers, each with a 10-turn input coil. Each transformer was deposited on a 12.5×12.5×0.75 mm^3 MgO substrate. The first, which we refer to as the "large" transformer, had an input coil of 1×1 mm^2, while the second, the "small" transformer, had an input coil of 250×250 μm^2. The relevant parameters of the two transformers are listed in Tab. 1. The multiturn geometry of the transformers necessitated the use of multilayer technologies that have been described elsewhere[7]. The first layer is a strip, or "crossunder", of YBCO that eventually connects the innermost turn of the spiral input coil to one side of the pickup loop. The second layer is $SrTiO_3$ which insulates the crossunder from the turns of the input coil. The third layer is YBCO, which is patterned to form both the input coil and the pickup loop; it is essential that this layer makes a superconducting contact to each end of the YBCO crossunder. In the case of the large transformer, the first two layers were patterned with shadow masks and the third was patterned photolithographically[8]. For the small transformer, all three layers were patterned photolithographically[9].

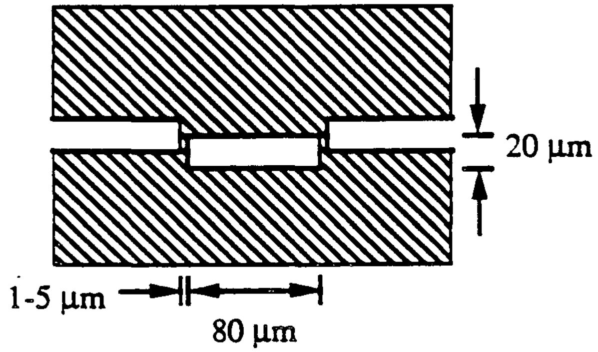

Figure 2. Schematic of SQUID design drawn roughly to scale. The shaded areas are superconductor (which extends beyond the edges of the drawing), the clear areas have been etched away. The SQUID loop is the central rectangle, weak links are formed by native grain boundaries in the narrow bridges on either side.

Magnetometers

We coupled each flux transformer in turn to the SQUID by pressing the two chips together face-to-face in a flip-chip arrangement. A thin (~ 3 μm) sheet of mylar was placed between the two chips to provide electrical insulation and to prevent scratching, and the two chips were tied together and secured to the probe with nylon twine. By observing the two chips through a microscope with bright transmitted light, we were able to align the centers of the input coil and the SQUID to within 20 μm.

In Fig. 4 we show the measured low frequency gain of our two magnetometers vs. temperature. From Eq. 3, using the estimated values of L_i and L_p, we used the measured gains to estimate the coefficient α. The maximum gains of the large and small transformers at 4.2 K were -7.5 and -8.7, respectively, and the corresponding values of α were 0.23 and 0.21. The large transformer operated at temperatures up to 79 K, while the small one operated up to only 25 K. It should be noted here, however, that inaccuracies in the calibration of the coil with which we apply the magnetic field to the transformer may have caused us to overestimate the above gains by as much as 30%.

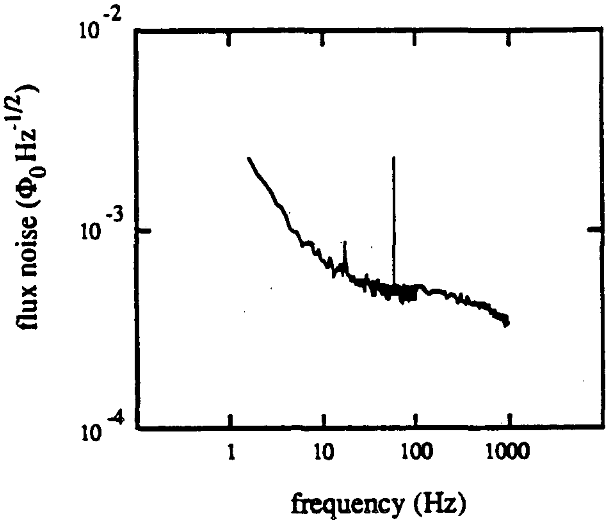

Figure 3. Flux noise, $S_\Phi^{1/2}$ (f), of the SQUID without a flux transformer. The data were taken at T = 55 K. The measured bandwidth of the flux-locked SQUID was ~ 1 kHz.

Table 1. Flux Transformer Parameters

Parameter	Small Transformer	Large Transformer
Number of Turns on Input Coil	10	10
Linewidth of Input Coil	~5 μm†	20 μm
Input Coil Inductance (L_i)*	~50 nH	~75 nH
Pickup Coil Inductance (L_p)*	~20 nH	~20 nH
Area of Pickup Coil (A_p)	81 mm^2	70 mm^2

†The lines were set on a 10 μm pitch.
*Estimate based on geometry of the uncoupled coils.

The failure of the small transformer to operate at zero frequency above 25 K is somewhat puzzling, particularly in view of measurements[9] of the transport properties of a second small transformer made by the same process. In this transformer we opened the pickup loop and found that the resistive transition, as measured by a transport current with a voltage resolution of 5 μV, was about 85 K. However, those measurements are not capable of detecting a resistance smaller than 5 mΩ. While the first small transformer did not operate above 25 K at zero frequency, at 26 K it did display a gain for alternating fields with the low frequency rolloff occurring at about 1 kHz. From this frequency and the estimated inductance of the transformer we deduce a series resistance of about 0.4 mΩ, a value too small to have been observed in transport measurements. Since the transformer has a normal state resistance of about 600 Ω at 90 K, this small resistance is probably due to a highly localized failure. Thus, we believe the integrity of most of the transformer was maintained to a very much higher temperature than 25 K. The fact that the transformer exhibited large gain demonstrates that the turns of the input coil were indeed electrically isolated from the crossunder.

In Fig. 5 we show the measured power spectra of the magnetic field sensitivity of the two magnetometers. The increase in the magnitude of the spikes compared with those in Fig. 3 indicates the higher sensitivity to environmental noise. The noise levels with the large transformer at 38 K were about 3.1 pT Hz$^{-1/2}$ at 10 Hz and 0.34 pT Hz$^{-1/2}$ at 1 kHz. The magnetometer with the small transformer at 4.2 K exhibited very similar values, about 3.5 pT Hz$^{-1/2}$ at 10 Hz and 0.35 pT Hz$^{-1/2}$ at 1 kHz. In both cases, the magnetic field sensitivity was limited by the flux noise in the SQUID. Separate measurements[10] on the large transformer at 60 K with a Nb/PbIn SQUID yielded a magnetic field sensitivity of 0.3 pT Hz$^{-1/2}$ at 10 Hz that was determined to be limited by intrinsic noise in the flux transformer. Thus, a quieter high-T_C SQUID would give an improvement in the magnetic field sensitivity. At this point, we have no measurements with a low-T_C SQUID coupled to the small transformer.

Concluding Remarks

We have successfully constructed two high-T_C magnetometers by coupling high-T_C flux transformers with multiturn input coils to a high-T_C dc SQUID. The large transformer was operated successfully at temperatures up to 79 K, while the small transformer ceased to operate at 25 K, due to a localized failure in its structure. The coupling coefficients between the input coils and the SQUID, in the range 0.2 - 0.25, are lower than desirable and imply that the two chips need to be brought closer together. A reduced spacing would enhance the gain and hence the magnetic field resolution in two ways, one by increasing α, and the other by reducing the inductance L_i of the input coil by means of screening (see Eq. 3). The measured gains of the large and small transformers were about -7.5 and -8.7, respectively. We note that these values would have been larger if the body of the SQUID had been narrower and, thus, the flux focussing factor η smaller; however, the overall magnetic field sensitivity of the transformers would not have been very different. The magnetic field noise levels measured in the large transformer at 38 K and in the small transformer at 4.2 K were virtually the same, about 3 pT Hz$^{-1/2}$ at 10 Hz and 0.35 pT Hz$^{-1/2}$ at 1 kHz.

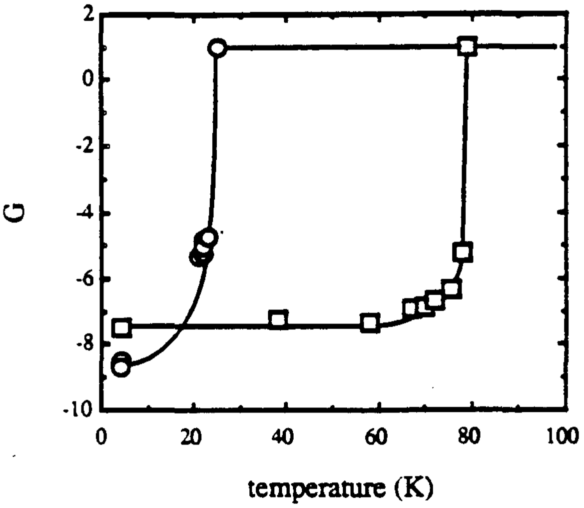

Figure 4. Measured gain, G, of magnetometers (ratio of the magnetometer effective area to the SQUID effective area) vs. temperature. Circles are for the small flux transformer, squares are for the large transformer. The solid lines are guides for the eye. Note that when the flux transformer is operating, the gain is negative because of the sense of the input coil.

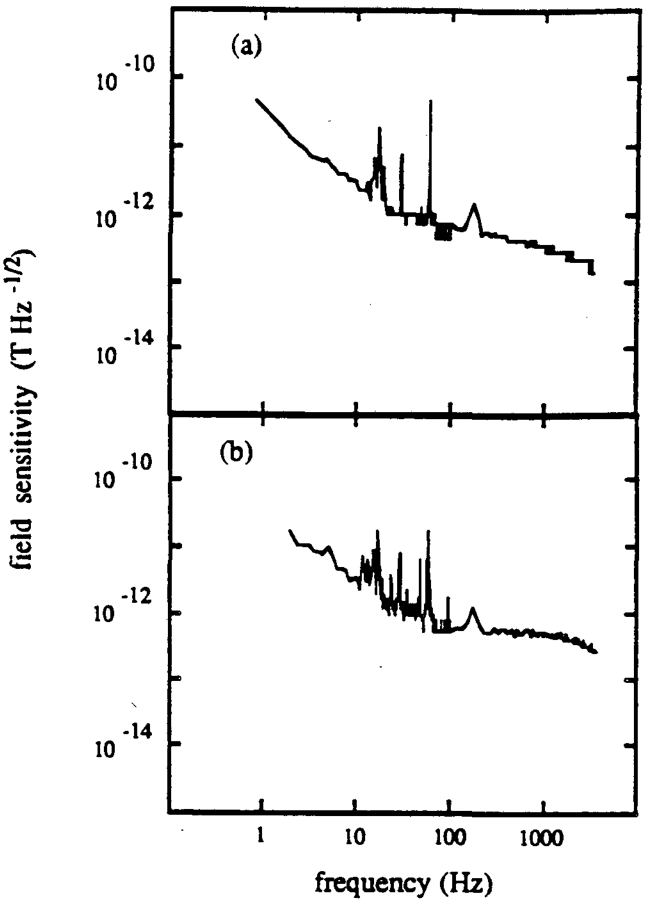

Figure 5. Field sensitivities $B_N(f)$ of the magnetometer with (a) large flux transformer at 38 K and (b) small transformer at 4.2 K. The measured flux-locked bandwidths were ~ 3.5 kHz and 3.8 kHz respectively.

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