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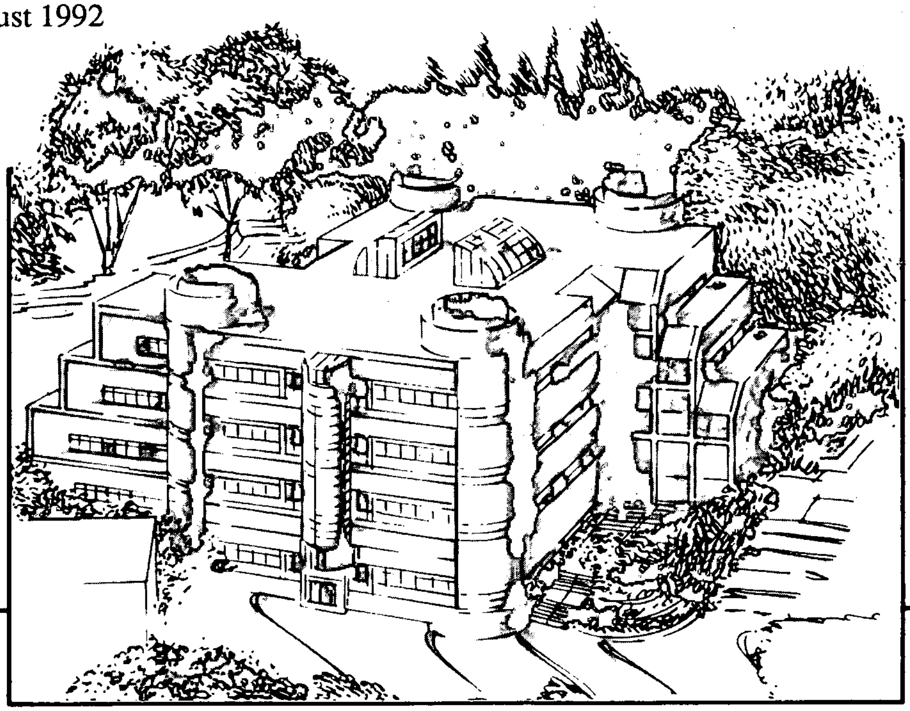

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Abstract--We have fabricated 12 dc SQUIDs by laser depositing $YBa_2Cu_3O_{7-x}$ on a $SrTiO_3$ bicrystal substrate with a misorientation angle of 24°. At 77K all twelve devices had acceptable values of critical current, resistance and voltage modulation produced by an external magnetic field. The white noise energy of one device with an estimated inductance of 41 pH was 1.8×10^{-30} JHz^{-1}. The noise power scaled as l/f at frequencies below about 1kHz, however; by using a bias current reversal scheme we were able to reduce this noise by two orders of magnitude at 1 Hz, to a value of about 1.5×10^{-29} JHz^{-1}. We made a magnetometer by coupling the SQUID to a flux transformer with a 5-turn input coil. The measured magnetic field gain was 60, and the white noise 36fT $Hz^{-1/2}$. However, the transformer produced relatively large levels of l/f flux noise, not reduced by the bias reversal scheme, that limited the noise at 1 Hz to 1.7 pT $Hz^{-1/2}$. A single-layer magnetometer with a single-turn pick up loop is briefly described.

I. INTRODUCTION

There has recently been considerable progress in the development of Superconducting QUantum Interference Devices (SQUIDs) fabricated from thin films of high transition temperature (T_c) superconductors. [1-6] Of particular interest for many applications is the level of l/f noise at low frequencies f. This noise may be inherent to the junctions where it arises from critical current fluctuations, [4, 7, 8] or it may arise from the motion of vortices trapped in the body of the SQUID. [9] It is possible to reduce the contribution of the first mechanism substantially by applying one of several electronic modulation schemes to the dc SQUID, whereas the latter mechanism cannot be reduced in this way. In this paper, we report a study of YBCO SQUIDs deposited on a single bicrystal substrate. We describe the reduction of the low frequency l/f noise by an electronic modulation scheme to a level that is technologically useful. Finally, we describe magnetometers involving both multiturn flux transformers and single-loop devices fabricated in a single layer.

II. FABRICATION

We use a pulsed excimer laser to deposit YBCO films 200 to 300nm thick on 10mm x 10mm (100) $SrTiO_3$ bicrystal substrates with a 24° misorientation angle. [10] Subsequently, we laser deposit an Ag film to a thickness of 100-200nm through a shadow mask over the part of the YBCO film to be used for contact pads. The faint line of YBCO grains along the grain boundary of the substrate allows us to align a mask for photolithographic patterning. We first ion mill the Ag through the photomask and then etch the SQUID in 0.05-0.1% nitric acid. The acid undercuts the photoresist in a controllable way, enabling us to make a bridge 2-4μm wide for the junctions. Finally, we make electrical connections to the SQUIDs by ultrasonic bonding 25μm diameter $A\ell$ wires to the Ag-covered contact pads.

Figure 1 shows the configuration of two types of square-washer SQUIDs; both have inner holes of 25μm x 25μm. The type A washers have an outer dimension of 250μm x 250μm, while the type B were either 250μm x 250μm or 500μm x 500μm. In the type A design, the junctions are placed outside the washer, to maintain a high coupling efficiency to a multiturn input coil. However, the extra inductance associated with the slit reduces the signal available from the SQUID. In the type B design, the junctions are placed at the inner edge of the washer, thereby eliminating the inductance of the slit. On the other hand, the junctions are now in the relatively high magnetic field region produced by

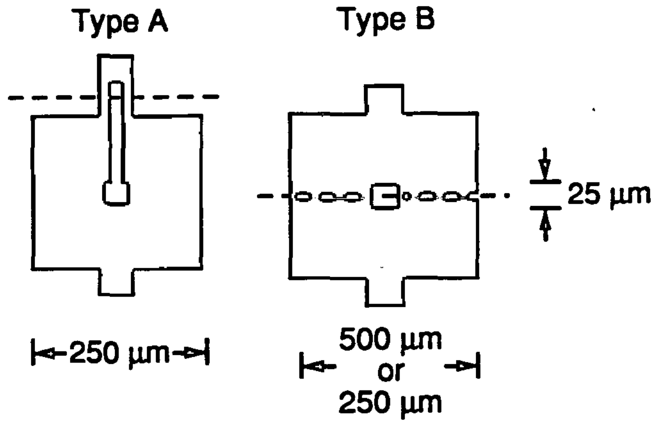

Fig. 1 Two types of YBCO SQUID fabricated on a $SrTiO_3$ bicrystal with grain boundary shown with dashed line. Junction widths were 2-4μm.

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the flux focusing [11] of the SQUID body, which introduces additional single-junction modulation effects in the earth's field. We tested 9 type A SQUIDs and 3 type B SQUIDs on one chip.

III. RESULTS

We first studied the properties of our SQUIDs by cooling them, in the earth's magnetic field, in liquid nitrogen. The current-voltage (I-V) characteristics were close to those expected from the resistively shunted junction model. Figure 2 summarizes the critical currents ($2I_c$), maximized by rotating the probe in the ambient magnetic field, and asymptotic resistances ($R_N/2$) for all 12 SQUIDs on a single chip with nominally identical junction widths of 3µm; I_c and R_N refer to single junctions. Also shown is the maximum peak-to-peak voltage modulation, ΔV, obtained when the magnetic flux is varied at the optimum bias current. The average values of these parameters are $2I_c = 185\mu A$, $R_N/2 = 0.78\Omega$, and $\Delta V = 1.8\mu V$ and $15\mu V$ for type A and type B SQUIDs, respectively. The standard deviation in $2I_c$ corresponds to about ± 30% of the average value and in $R_N/2$ to about ±20% for both type A and type B devices. For the type A devices, the standard deviation in ΔV corresponds to about ±20%. We note, however, that the standard deviation in I_cR_N corresponds to about ±18%, suggesting that some of the scatter in I_0 and R_N may well be due to small variations in the widths of the junctions. An additional variation in I_c may arise from the flux trapped in the junctions. The scatter in $\Delta V/R_N$ is only ±11% in type A and ±9% in type B, implying that the modulation depth in critical current is constant to this level.

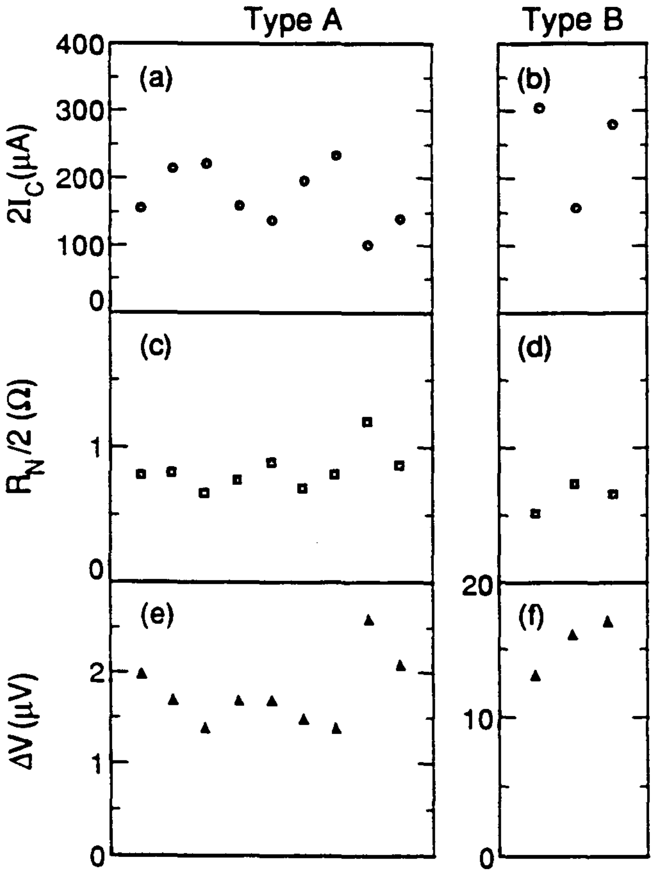

Fig. 2 Critical current (a) and (b), asymptotic resistance (c) and (d), and peak-to-peak voltage modulation, ΔV, (e) and (f) at 77K for 12 SQUIDs on a single bicrystal. Abscissa enumerates the SQUIDs.

All SQUIDs of the same type have remarkably similar effective magnetic flux capture areas. For the type A SQUIDs this was $\Phi_0/0.14\mu T = 1.5 \times 10^{-8} m^2$; neglecting the slit, we expect an effective area [11] A_s of $25\mu m \times 250\mu m = 6.3 \times 10^{-9} m^2$. Thus the slit increases the effective area by a factor of about 2.5. For the type B SQUIDs, the measured effective area for the 250µm washer was $\Phi_0/0.48\mu T = 4.3 \times 10^{-9} m^2$ compared with the predicted value, neglecting the slits, of $6.3 \times 10^{-9} m^2$, while for the 500µm washer the measured value was $\Phi_0/0.32\mu T = 6.5 \times 10^{-9} m^2$ compared with the predicted value of $1.25 \times 10^{-8} m^2$. Thus, for the type B SQUIDs the presence of the slits reduces the effective area by 32% and 48% for the 250µm and 500µm washer, respectively.

For one type B SQUID that we studied in detail, the measured flux-to-voltage transfer coefficient was $dV/d\Phi = (65 \pm 10)\mu V/\Phi_0$. From the measured dimensions of the inner hole, $d^2 = 26\mu m \times 26\mu m$, we estimate an inductance [12] $L = 1.25\mu_0 d = 41pH$. Using the measured asymptotic resistance $R_N = 1.28\Omega$, we expect [13] $dV/d\Phi \approx 65\mu V/\Phi_0$, an agreement that is excellent but undoubtedly fortuitous, given the uncertainties in the parameters. In the case of the type A SQUIDs, however, the transfer coefficients are much smaller, ranging up to $6\mu V/\Phi_0$ in a device with $R_N \approx 2.4\Omega$. Estimating the inductance of the slit as $L_s \approx \mu_0 \ell/2$ for a length $\ell = 152\mu m$ we find $L_s \approx 95pH$ for a total SQUID inductance of about 135 pH. Thus, we would expect $dV/d\Phi \approx 37\mu V/\Phi_0$, considerably larger than the observed transfer coefficient. The reason for the reduced response of the type A SQUIDs is not clear; one explanation is that the inductance associated with the slit is higher than anticipated.

Having determined the parameters of our SQUIDs, we measured the flux noise in one of them at 77K, first using a static current bias and a flux modulation frequency of 100kHz. The flux noise power spectrum, $S_\Phi(f)$, and the noise energy, $\varepsilon(f) \equiv S_\Phi(f)/2L$, are shown as the upper trace of Fig. 3 for the type B SQUID discussed in the paragraph above with an outer dimension of 500µm. At frequencies above 5kHz the spectral density becomes white with a value of $S_\Phi\ (10kHz) = 3.5 \times 10^{-11}\ \Phi_0^2\ Hz^{-1}$, corresponding to $\varepsilon(10kHz) = 1.8 \times 10^{-30}\ JHz^{-1}$. By comparison, using $R_N = 1.3\Omega$ and $L = 41$ pH, we predict [13] $\varepsilon \approx 9k_BTL/R \approx 3 \times 10^{-31}\ JHz^{-1}$, a factor of 6 smaller. Part, although not all, of this discrepancy, may be explained by noise generated in the contact resistance to the SQUID.

Between 0.1Hz and 1kHz, the power spectrum scales closely as 1/f. In an attempt to reduce this noise, we used a bias current reversal scheme. [14] We divide the 100kHz square wave modulation signal from the flux-locked loop using a digital counting circuit to produce a synchronous

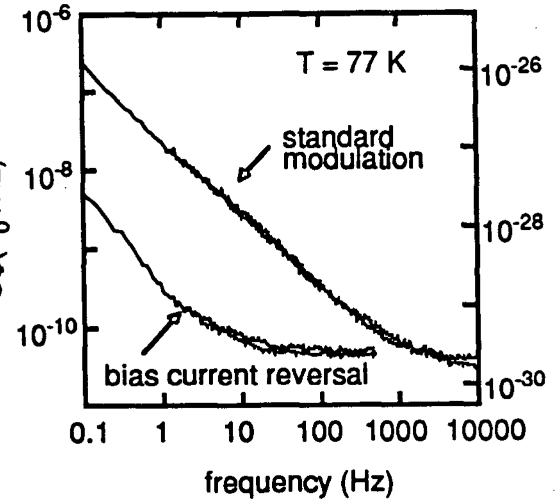

Fig. 3 Flux noise spectral density, $S_\Phi(f)$, and noise energy, $\varepsilon(f)$, for type B SQUID (500μm outer dimension) at 77K. Upper trace is for conventional flux-locked loop with static current bias, lower trace is for bias reversal scheme.

2kHz square wave that reverses the bias current and simultaneously shifts the flux in the SQUID by $\Phi_0/2$. The resultant noise spectral density (lower trace in Fig. 3) is reduced by two orders of magnitude at 1 Hz. This large reduction demonstrates that the 1/f noise in the upper trace of Fig. 3 arises from critical current fluctuations rather than from flux noise. The bias reversal scheme has caused the white noise to increase slightly, to 2.5×10^{-30} JHz^{-1}. The residual noise, $S_\Phi(1\ \text{Hz}) = 2.9 \times 10^{-10}\Phi_0^2\ \text{Hz}^{-1}$, may be due to flux noise within the body of the SQUID, or may represent the limit to which we have thus far been able to suppress the critical current fluctuations. We note that Koch *et al.* [4] have previously reported a similar degree of noise reduction in a bicrystal SQUID; however, the residual noise at 1 Hz in their case was considerably higher than in our devices. At the time of writing, our measured noise energy at 1 Hz, 1.5×10^{-29} JHz^{-1}, is the lowest value we are aware of in a dc SQUID operating at 77K.

IV. MAGNETOMETERS

To make a sensitive magnetometer from our SQUIDs, it is essential to increase the flux capture area with a suitable flux transformer. We have coupled the low noise type B SQUID discussed above (500μm washer) in a flip-chip arrangement to a thin-film flux transformer [6] with a 5-turn input coil and a 10mm pick-up loop with an approximate area of 81mm^2. The estimated inductance of the pick-up loop, L_p = 20nH, greatly exceeds the inductance of the input coil L_i = 1nH. In this limit, the magnetic field gain of the transformer is approximately $(A_p/A_s)\ \alpha(LL_i)^{1/2}/L_p$. The measured gain was about 60, indicating a magnetic coupling coefficient $\alpha \approx 0.5$. The spectral density of the noise is plotted in Fig. 4. At 10kHz the noise of the magnetometer corresponded to approximately 36fT Hz$^{-1/2}$. However, at frequencies below a few kilohertz the noise power scaled as 1/f. The magnitude of this noise was not measurably reduced by our bias reversal

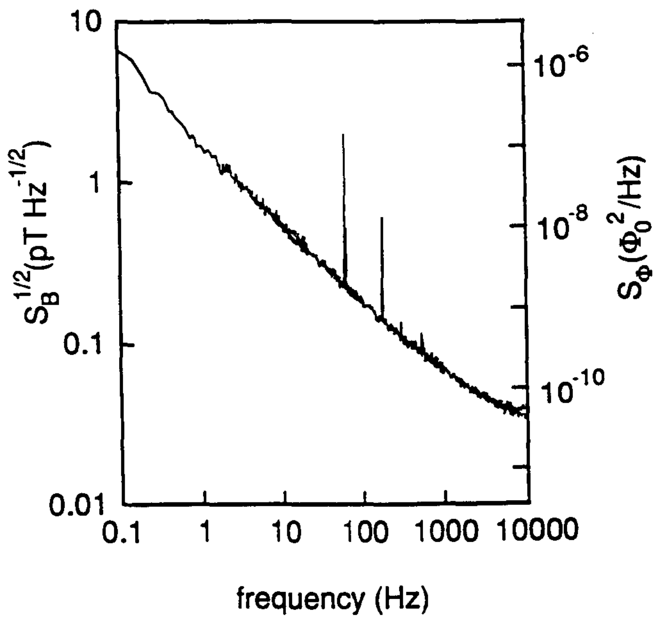

Fig. 4 Rms magnetic field resolution, $S_B^{1/2}(f)$, and flux noise spectral density, $S_\Phi(f)$, vs. frequency for 5-turn flux transformer coupled to the type B SQUID of Fig. 3. Low frequency noise was not reduced by bias reversal scheme.

scheme, indicating that it arose from flux noise in the films of the transformer. The magnetic field noise at 1 Hz was 1.7pT Hz$^{-1/2}$. This high noise level stresses the need to be able to deposit and pattern multilayer films while maintaining very high film quality and concomitantly very low levels of flux noise. We note that the number of turns on the input coil of the flux transformer was below optimum for the size of the pick-up loop. A properly optimized transformer with the same pick-up loop would have had a white noise of approximately 10 fT Hz$^{-1/2}$.

Finally, we have made a simple magnetometer in which a loop of YBCO, deposited and patterned along with the SQUID, is coupled directly to the body of a type A SQUID (Fig. 5). The magnetic field gain of such a device is approximately $(L/L_p)(A_p/A_s)$. Estimating $L_p \approx 15$ nH, $A_p \approx 56$ mm^2, $L = 135$ pH and using the measured value $A_s = 1.5 \times 10^{-2}$ mm^2, we expect a gain of about 34. The measured gain at 77K was only 22, approximately two-thirds of the predicted value. We measured the noise of one device at 77K and found a white noise of 245 fT Hz$^{-1/2}$, corresponding to a flux noise of 38 $\mu\Phi_0$ Hz$^{-1/2}$ which is expected for a type A SQUID. The 1/f noise was unfortunately very high, increasing the magnetic field noise at 1Hz to 9.5 pT Hz$^{-1/2}$, a value which was not reduced by bias current reversal. This level of flux noise in our films is unusually high, and we expect future devices to have much lower noise. Although such a device cannot compete in sensitivity with an optimized multiturn flux transformer, its simplicity is very appealing. The design could be readily adapted to a planar gradiometer that might well have adequate sensitivity for certain applications, for example, non-destructive evaluation.

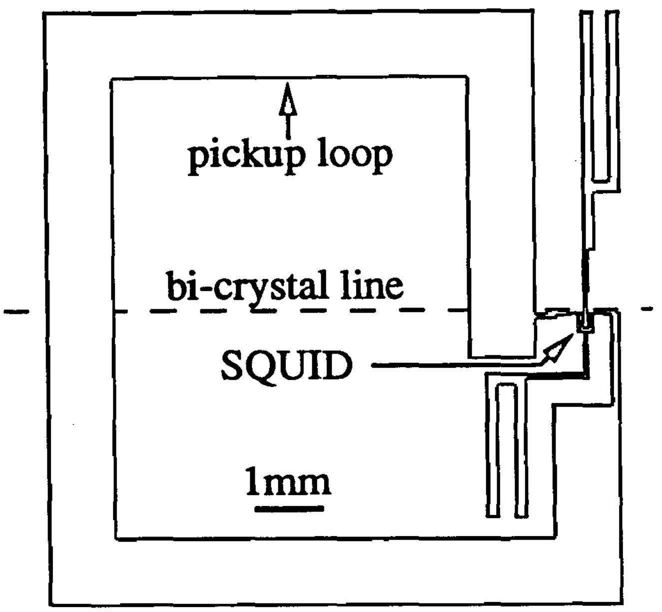

Fig. 5 Configuration of single-turn magnetometer. The pick-up loop connects to the SQUID body on either side of the slit, just below the two junctions. The four vertical lines extending from the SQUID are contact pads.

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