High-T_c super conducting quantum interference devices with slots or holes: Low 1/*f* noise in ambient magnetic fields

E. Dantsker, S. Tanaka, and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and
Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Received 27 December 1996; accepted for publication 10 February 1997)

High-transition temperature dc superconducting quantum interference devices (SQUIDs) have been fabricated with arrays of slots or holes patterned in the $186\times204\ \mu m^2$ washers. In two designs, with seven slots or 248 holes, the linewidth of the remaining $YBa_2Cu_3O_{7-x}$ film was 4 μm. These devices exhibited virtually no increase in their low-frequency noise when they were cooled in static magnetic fields up to a certain threshold, above 100 μT in the best case. Furthermore, the mutual inductance between these devices and a seven-turn, spiral coil was at least 85% of that for a solid SQUID with the same outer dimensions. © *1997 American Institute of Physics.*
[S0003-6951(97)04715-3]

A long-standing issue in the performance of high-transition temperature (T_c) dc superconducting quantum interference devices (SQUIDs) has been the increase in $1/f$ noise at low frequencies f when they are cooled and operated in an ambient magnetic-field B_0.[1,2] The noise arises from the thermally activated hopping of flux vortices created in the device during cooling. This excess noise has been a serious limitation for SQUID magnetometers required to operate in the earth's magnetic field with high sensitivity at low frequencies, for example, in geophysical measurements. In a previous publication,[3] we showed that the excess noise could be largely eliminated for single-layer, thin-film SQUIDs and magnetometers by reducing the linewidth of the SQUID body. According to a prediction by Clem,[4] a superconducting film of width w cooled in a perpendicular magnetic field will exclude magnetic flux for fields below a threshold value $\pi\Phi_0/4w^2$. In our experiments, we found very little increase in the low-frequency noise for fields below a threshold value B_T, and a rapid increase with field at higher values as flux enters the superconductor.

For a pickup loop of given size, one can achieve a higher magnetic-field sensitivity by means of a superconducting flux transformer in which one connects the loop to a multi-turn input coil that is inductively coupled to a square washer SQUID with a relatively small central hole.[5] In such SQUIDs, however, the threshold for flux entry is very low, and there is inevitably a substantial increase in low-frequency noise in the earth's magnetic field, about 50 μT at our location.

In this letter, we demonstrate that the excess noise in square washer SQUIDs can be eliminated when they are cooled in ambient fields as high as 100 μT, without materially reducing the coupling efficiency to a multiturn coil, by means of holes or slots of appropriate design. Moats have been used in the past[6–8] to reduce the density of flux vortices trapped in superconducting digital circuits cooled in relatively weak magnetic fields, up to 4 μT.[8] However, these designs were not intended to exclude flux from devices cooled in fields as large as that of the earth.

The guiding principle in our design is to maintain a narrow linewidth for the $YBa_2Cu_3O_{7-x}$ (YBCO) film: we chose a value of 4 μm, for which the predicted entry field is 100 μT. Four designs are shown in Fig. 1, together with the configuration of a ''solid'' SQUID in Fig. 1(a); all five devices have outer dimensions of $186\times204\ \mu m^2$. Figure 1(b) shows a configuration in which eight slots, each 8 μm wide, separate nine YBCO strips, each 4 μm wide. The innermost slit is 4 μm wide and 100 μm long. One can alternatively regard this structure as eight pickup loops of a directly coupled magnetometer connected in parallel to a single SQUID. Figure 1(c) shows our second design in which 248 holes, each $8\times8\ \mu$m, divide the square washer into a grid of 4 μm wide lines. In Figs. 1(d) and 1(e), we have reduced the number of slots to 5 and the number of holes to 125, respectively, leaving a superconducting band 40 μm wide around three sides of the devices.

Using pulsed laser ablation, we deposited a 150 nm thick film of YBCO on a $10\times10\ mm^2$ $SrTiO_3$ bicrystal with an in-plane misorientation angle of 24°. We patterned a series of SQUIDs using photolithography and argon ion milling at normal incidence. The bridges across the bicrystal boundary forming the junctions were approximately 1 μm wide. The

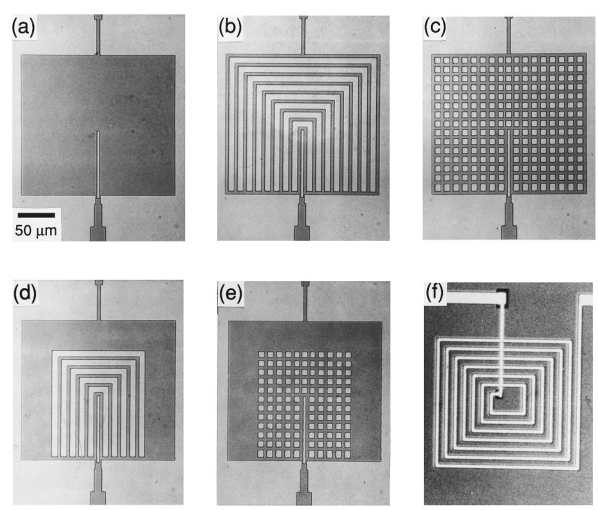

FIG. 1. Photographs of the photomasks for (a) a solid, thin-film SQUID, and for a SQUID with (b) eight slots, (c) 248 holes, (d) five slots, and (e) 125 holes. The outer dimensions of each device are $186\times204\ \mu$m; (f) shows a seven-turn coil that was coupled to the designs in (a)–(c) in a flip–chip arrangement.

TABLE I. Critical current I_0 and resistance R per junction for SQUIDs with configurations of Fig. 1; A_{eff} is the effective area and M_i the mutual inductance to a seven-turn coil. In the first column, letters in parentheses refer to Fig. 1.

SQUID	I_0 (μA)	R (Ω)	A_{eff} (10^{-3} mm^2)	M_i (pH)
1 solid (a)	19	3.8	5.01	148
2 eight slots (b)	40	2.0	5.45	125
3 eight slots (b)	35	2.0	5.58	⋯
4 248 holes (c)	18	2.6	5.95	129
5 five slots (d)	21	2.0	6.81	⋯
6 125 holes (e)	12	3.4	6.18	⋯
7 125 holes (e)	60	2.2	6.67	⋯

critical current and resistance per junction are listed in Table I for each of the seven SQUIDs for which we measured the noise. We estimate the inductance of the solid SQUID [Fig. 1(a)] to be 40 pH. The inductance of the devices containing holes is likely to be comparable. The inductance of the devices with slots are more difficult to calculate; we estimate the inductance of the innermost loop to be 90 pH, a value that is reduced by the parallel inductances of the remaining loops.

We measured the flux noise of these SQUIDs cooled in liquid nitrogen in the presence of a magnetic-field B_0, perpendicular to their plane, generated by a solenoid, powered by a lead–acid battery. To reduce the earth's field and its fluctuations, the solenoid was surrounded by a cold cryoperm shield and the dewar by a triple mu–metal shield. We operated the SQUID in a flux–locked loop with 100 kHz flux modulation and a 2 kHz bias current reversal scheme to eliminate the $1/f$ noise due to critical current fluctuations.

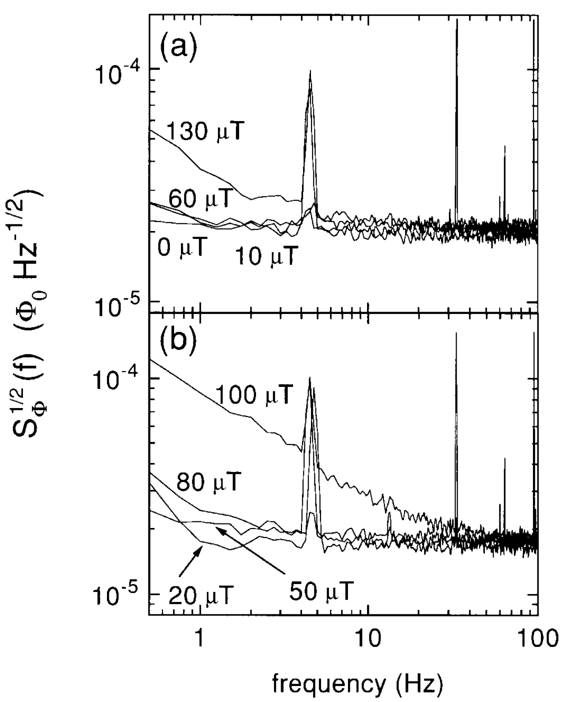

FIG. 2. Flux noise $S_\Phi^{1/2}(f)$ vs frequency for (a) eight-slot SQUID (2) and (b) 248 hole SQUID (4), each cooled in four values of magnetic field. A 60 Hz spike is visible; the spike at approximately 4.5 Hz was due to an external source of unknown origin.

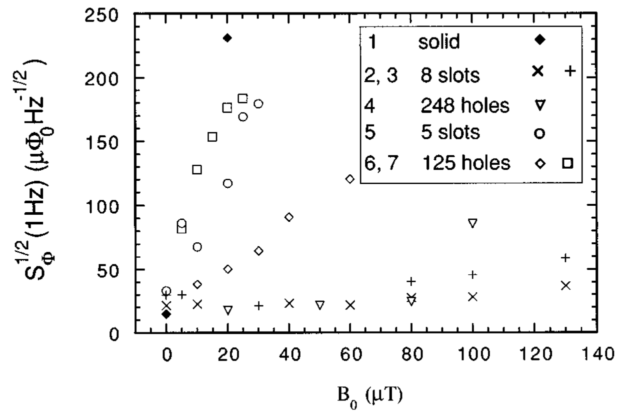

FIG. 3. Noise at 1 Hz, $S_\Phi^{1/2}(f)$ vs cooling field B_0 for the seven devices listed in Table I.

Figure 2 shows the rms flux noise $S_\Phi^{1/2}(f)$ for SQUIDs with (a) eight slots [Fig. 1(b)] and (b) 248 holes [Fig. 1(c)], each cooled in four different magnetic fields. In Fig. 2(a), there is no increase in the magnitude of the noise for fields up to 60 μT. At 130 μT, however, the noise at 1 Hz has increased, by a factor of about 2, indicating that flux entered the YBCO film at a value between 60 and 130 μT. In Fig. 2(b), the low-frequency noise in unchanged for cooling fields up to 80 μT. At 100 μT, the noise below about 50 Hz increases substantially, by a factor of about 5 at 1 Hz, and $S_\Phi^{1/2}(f)$ scales approximately as $1/f^{1/2}$ in this frequency range. In this case, flux evidently entered the YBCO film at a value between 80 and 100 μT. We note that, in both cases, the white noise remains constant for all values of magnetic field, an observation consistent with the fact that the critical current of the SQUIDs did not change significantly.

Figure 3 shows the flux noise at 1 Hz, $S_\Phi^{1/2}$ (1 Hz), versus cooling field B_0 for all seven SQUIDs. For the solid SQUID, $S_\Phi^{1/2}$ (1 Hz) increases rapidly with B_0 to a value of 230 $\mu\Phi_0$ Hz$^{-1/2}$ at 20 μT. For the device with five slots and one of the devices with 125 holes, the noise increase is similar to that of the solid SQUID, suggesting that flux vortices enter the outer band of YBCO. The second device with 125 holes, however, is markedly less noisy, although $S_\Phi^{1/2}$ (1 Hz) increases linearly with B_0; we have no explanation for this unusual dependence. This difference in behavior between two nominally identical devices implies that the quality of the films, most likely at the edges,[9] remains a variable factor. For the devices with eight slots and 248 holes, the noise remains markedly lower as B_0 is increased. The best SQUID, one with eight slots, exhibits no significant increase in $S_\Phi^{1/2}$ (1 Hz) for values of B_0 up to above 100 μT. At 130 μT, the noise has increased slightly, by less than a factor of 2 above the zero-field value, suggesting that flux entry occurred somewhat below this cooling field. This threshold field appears to be a little above the predicted value of 100 μT. For the second SQUID with eight slots, there is a modest increase in the noise at 80 μT. Once again, the fact that flux entry occurs at a lower field than its nominally identical companion suggests a materials dependence. For the SQUID with 248 holes, flux entry occurred between 80 and 100 μT. The value of B_T is lower than that of the better of the two devices with slots: this may be a materials issue, but we note that the result is consistent with the fact that the largest linewidth of the YBCO film, at each intersection of two lines, is $4\sqrt{2}\ \mu$m. For the SQUID with slots, there is only a small number of such wider regions.

We sometimes observed random telegraph signals (RTS) resulting from the hopping of a single flux vortex. We could generally eliminate the RTS by raising the temperature of the SQUID, which was in a hermetically sealed capsule equipped with a heater, above T_c and lowering it again; this procedure took about 5 min. As an example, the number of times we observed RTS after cooling SQUID 3 varied from about 1 out of 10 for fields up to 80 μT to about 9 out of 10 at 150 μT.

We now discuss the effective area A_{eff}, defined as the flux quantum Φ_0 divided by the applied magnetic field required to produce one flux quantum in each SQUID configuration. These values are summarized in Table I. In all cases, the presence of holes or slots increases A_{eff} over the value for the solid washer. For the two 125 hole SQUIDs (6 and 7), there is a surprisingly large difference between the two values of A_{eff}, the device with the larger A_{eff} producing the higher noise in Fig. 3. Table I also shows the mutual inductance M_i between three SQUIDs and a seven-turn input coil [Fig. 1(f)], fabricated from a thin film of CuAu on a separate substrate. The coil was coupled to each SQUID in turn with a 3 μm mylar foil separating the two chips. We see that the presence of slots or holes reduces M_i only modestly compared with the solid SQUID, by about 16% or 13%, respectively.

We turn now to the possible noise contribution of a multiturn flux transformer. There are two sources of such noise:[10] ''direct noise,'' in which the motion of vortices in the input coil couples flux noise directly into the SQUID, and ''indirect noise,'' in which vortex motion in both the input coil and pickup loop generates a noise current in the flux transformer and, thus, a noise flux in the SQUID. In principle, one should be able to eliminate both contributions merely by making all of the linewidths in the transformer sufficiently small, say 4 μm or less. However, it is often desirable to increase the linewidth of the pickup loop substantially in order to reduce its inductance and thereby increase the sensitivity of the magnetometer. In that case, it is straightforward to show that the spectral density of the flux noise coupled into the SQUID due to flux motion in the pickup loop is[10]

$$S_\Phi(f) \approx S_\Phi^u(f)(\ell_p/w_p)/16n^2. \tag{1}$$

Here, $S_\Phi^u(f)$ is the spectral density of an unpatterned film, ℓ_p and w_p are the perimeter and linewidth of the pickup loop, and n is the number of turns on the input coil. We have assumed ideal coupling between the SQUID and input coil and that the inductances of the input coil and pickup loop are equal. Taking S_Φ^u (1 Hz)$\lesssim 10^{-9}\ \Phi_0^2\ \mathrm{Hz}^{-1}$ (Ref. 11), $\ell_p=40$ mm, $w_p=1$ mm, and $n=16$, we find S_Φ (1 Hz) $\lesssim 10^{-11}\Phi_0^2\ \mathrm{Hz}^{-1}$. This value is certainly below the lowest spectral densities we have observed in our SQUIDs, and we conclude that the flux transformer should not add significantly to the noise of the magnetometer.

In summary, we have shown that holes or slots of appropriate configuration substantially reduce the magnitude of the $1/f$ noise in large-area SQUIDs cooled in an ambient magnetic field. Although it appears that the quality of the thin YBCO films, most likely at the edges, still plays a role in determining the properties of these devices, it is noteworthy that all three devices uniformly penetrated with holes or slots exhibited no excess noise at 50 μT. We emphasize that the key factor in the design of these SQUIDs is the narrow linewidths of the YBCO films; the size of the slots or holes is likely to be unimportant provided the remaining YBCO is sufficiently narrow. The effective area of the various devices with holes or slots is always higher than that of the solid device. The coupling efficiency of a spiral coil to the devices with seven slots and 248 holes was not greatly reduced compared with the solid SQUID. This result implies that one should be able to avoid a significant increase in the $1/f$ noise of magnetometers, based on flux transformers with multiturn input coil coupled to large washer SQUIDs, when they are cooled in the earth's magnetic field. We note, however, that if one were to rotate the magnetometer in the field, currents induced in the flux transformer might be sufficient to drive vortices into the film, thus, generating $1/f$ noise. It is likely that this problem could be avoided with a flux dam;[12] otherwise, one would have to momentarily raise the temperature of the device above T_c.

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

[1] A. H. Miklich, D. Koelle, T. J. Shaw, F. Ludwig, D. T. Nemeth, E. Dantsker, John Clarke, Neil McN. Alford, Tim W. Button, and M. S. Colclough, Appl. Phys. Lett. **64**, 3494 (1994).
[2] V. N. Glyantsev, Y. Tavrin, W. Zander, J. Schubert, and M. Siegel, Supercond. Sci. Technol. **9**, A105 (1996).
[3] E. Dantsker, S. Tanaka, P.-Å. Nilsson, R. Kleiner, and J. Clarke, Appl. Phys. Lett. **69**, 4099 (1996).
[4] J. R. Clem (private communication).
[5] M. B. Ketchen and J. M. Jaycox, Appl. Phys. Lett. **40**, 736 (1982).
[6] M. B. Ketchen, D. J. Herell, and C. J. Anderson, J. Appl. Phys. **57**, 2550 (1985).
[7] S. Bermon and T. Gheewala, IEEE Trans. Magn. **MAG-19**, 1160 (1983).
[8] M. Jeffrey, T. Van Duzer, J. R. Kirtley, and M. B. Ketchen, Appl. Phys. Lett. **67**, 1769 (1995).
[9] J. Z. Sun, W. J. Gallagher, and R. H. Koch, Phys. Rev. B **50**, 13 664 (1994).
[10] M. J. Ferrari, J. J. Kingston, F. C. Wellstood, and J. Clarke, Appl. Phys. Lett. **58**, 1106 (1991).
[11] M. J. Ferrari, M. Johnson, F. C. Wellstood, J. J. Kingston, T. J. Shaw, and J. Clarke, J. Low Temp. Phys. **94**, 15 (1994).
[12] R. H. Koch, J. Z. Sun, V. Foglietti, and W. J. Gallagher, Appl. Phys. Lett. **67**, 709 (1995).