Reduction of $1/f$ noise in high-T_c dc superconducting quantum interference devices cooled in an ambient magnetic field

E. Dantsker, S. Tanaka, P.-Å. Nilsson,[a] R. Kleiner,[b] and John Clarke
Department of Physics, University of California, Berkeley, California 94720
and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Received 6 August 1996; accepted for publication 20 October 1996)

The spectral density $S_\Phi(f)$ of the low-frequency $1/f$ noise of high transition temperature dc superconducting quantum interference devices (SQUIDs) with narrow linewidths was independent of B_0, the magnetic field in which they were cooled, up to a threshold value, about 33 μT in the best case. Above this threshold, which is associated with the entry of flux vortices into the film, the noise increased rapidly. By contrast, for large square washer SQUIDs, $S_\Phi(f)$ scaled linearly with B_0. Estimates indicate that the $1/f$ flux noise produced by the pickup loop of a directly coupled magnetometer is negligible. © *1996 American Institute of Physics.* [S0003-6951(96)01552-5]

Over the past two years, there have been substantial improvements in the performance of dc superconducting quantum interference devices (SQUIDs) fabricated from both single-layer films[1] and multilayers[2,3] of $YBa_2Cu_3O_{7-x}$ (YBCO). The most sensitive magnetometers have achieved magnetic field noise levels below 10 fT Hz$^{-1/2}$ at frequencies above the $1/f$ regime,[2,3] and below 30 fT Hz$^{-1/2}$ at 1 Hz.[1,2] These low levels of noise, however, were achieved with the device surrounded by magnetic shielding that reduced the ambient magnetic field to below 1 μT. For a number of practical applications, for example, geophysics, it is necessary to operate the magnetometers in the Earth's magnetic field, ~50 μT at our location. In an earlier study on SQUIDs involving large area washers, Miklich *et al.*[4] found that the $1/f$ flux noise at low frequencies f increased substantially when the SQUIDs were cooled in static magnetic fields comparable to that of the Earth. The spectral density of the flux noise, $S_\Phi(f)$, scaled linearly with magnetic field B_0. This noise is attributed to the thermally activated hopping of vortices among pinning sites in the YBCO film.[5] Comparable increases in $1/f$ noise with magnetic field were reported by Glyantsev *et al.*[6] Recently, however, Schmidt *et al.*[7] reported the operation of high-T_c dc SQUID magnetometers in the Earth's field without an increase in low-frequency noise, but gave no details of the design. Faley *et al.*[18] presented data showing little increase in the flux noise at 1 Hz, more than 50 $\mu\Phi_0$ Hz$^{-1/2}$, at fields up to 100 μT, and ascribed this behavior to the geometry of their ramp-type junctions (Φ_0 is the flux quantum).

In this letter, we examine the effects of SQUID geometry on the increase of $1/f$ flux noise in an ambient magnetic field, and show that by appropriate design this increase can be eliminated for fields up to a certain value. In the SQUIDs we studied previously,[4] the body was of large size (250×250 μm^2) to facilitate coupling to the multiturn input coil of a flux transformer.[9] As a result, when the SQUID is cooled in a magnetic field perpendicular to its plane, flux vortices enter the material. However, if one reduces the outer dimension of the washer so that the inner hole is surrounded by a strip of film of width w, one expects that it is energetically unfavorable for flux to enter for values of B_0 below $\pi\Phi_0/4w^2$.[10] Thus, one expects no increase in $1/f$ noise due to vortex motion for fields below this threshold value.

To test this hypothesis, we fabricated dc SQUIDs from 150 nm thick YBCO films that were laser deposited on $SrTiO_3$ bicrystal substrates with a 24° angle of in-plane misorientation. Typically, we patterned 10–15 SQUIDs with 1–2 μm wide junctions on each 10×10 mm^2 chip using conventional photolithography and Ar ion milling at liquid nitrogen temperatures. For noise measurements, the SQUIDs were immersed in liquid nitrogen in a Dewar surrounded by a triple mu-metal shield. The SQUIDs were cooled in a static magnetic field (perpendicular to the chip) provided by a cooled solenoid powered by an acid battery; in some measurements we used a cylindrical shield of YBCO on a YSZ tube,[11] placed inside the solenoid and cooled with the SQUID, to stabilize the field. The SQUID was flux modulated at 100 kHz and the bias current was reversed at 2 kHz to eliminate $1/f$ noise from fluctuations in the critical current of the grain boundary junctions.[12] The critical current was not measurably reduced by static fields up to 60 μT.

We first examined the dependence of $S_\Phi^{1/2}$ (1 Hz) on the magnetic field for the five large-area devices listed in Table I. The geometry of devices 4 and 5 is shown in the inset in Fig. 1. The square washer had a width $D=500$ μm, the width and length l of the slit were 4 and 100 μm, respectively, and the estimated inductance L was 40 pH. In the case of devices 1–3, the slit length was increased to 250 μm and the estimated inductance to 80 pH; the bicrystal boundary was outside the SQUID washer, and the slit extended beyond this boundary. We see from Table I that the flux noise at 1 Hz increases very substantially in a magnetic field over the value at nominally zero field. Figure 1 shows that $S_\Phi^{1/2}(f)$ scales approximately as $1/f^{1/2}$ below about 300 Hz. This behavior is similar to our earlier observations on devices of comparable dimensions.[14]

After measuring the noise in device 5, we repatterned it to remove the material outside the dotted lines in the inset of Fig. 1, reducing the width D to 30 μm. As we see in Fig. 1 and Table I (device 5*), the noise at 24 μT is dramatically

[a]Current address: IMC, P.O. Box 1084, S-164, 21 Kista, Sweden.
[b]Current address: Physikalishes Institut III, Universität Erlangen, D-91058 Erlangen, Germany.

TABLE I. Flux noise of six SQUIDs measured at 1 Hz for three values of magnetic field. The spectral density of the noise at 1 Hz is approximately white at zero field, and for 1–5 scales as 1/*f* at the higher fields. *D* is the outer width of the SQUID washer, *l* the length of the slit, and *L* the estimated inductance.

Device No.	D (μm)	l (μm)	L (pH)	$S_\Phi^{1/2}$ (1 Hz) ($\mu\Phi_0$ Hz$^{-1/2}$) 0 μT	24 μT	61 μT
1	500	250	80	31	220	330
2	500	250	80	24	240	380
3	500	250	80	16	250	400
4	500	100	40	33	120	⋯
5	500	100	40	5	130	180
5*	30	100	40	8	11	170

reduced, by more than two orders of magnitude in power. In Fig. 1, we note that the noise is approximately white at frequencies down to 10 Hz and increases only slowly at frequencies down to 0.5 Hz. At 61 μT, however, the noise at 1 Hz is not significantly different from that in the original device. This reduction in 1/*f* noise at the lower field is a graphic illustration of the role of the SQUID configuration.

Subsequently, we investigated the noise in a series of SQUIDs (inset Fig. 2) with values of D ranging from 12 to 30 μm and linewidths w ranging from 4 to 13 μm; in some cases, the SQUIDs were coupled to a 1×4 mm^2 pickup loop to form a small area directly coupled magnetometer (inset Fig. 3). The length of the slit was adjusted to keep the estimated inductance of the SQUID loop at 40 *p*H. The behavior of three devices of each kind, made on the same chip, is shown in Figs. 2 and 3. In Fig. 2, we see that $S_\Phi^{1/2}$ (1 Hz) for two devices with $D=30$ μm ($w=13$ μm) is constant up to $B_0\approx20$ μT, above which the noise increases steeply with magnetic field. We interpret the magnetic field at which the noise abruptly increases as the threshold for vortex entry when the SQUID is cooled. For the third device with $D=20$ μm ($w=8$ μm), $S_\Phi^{1/2}$ (1 Hz) is constant up to about 26 μT. The threshold values of B_0 estimated from $\pi\Phi_0/4w^2$ for $w=13$ and 8 μm are 10 and 25 μT, respectively. Figure 3 shows $S_\Phi^{1/2}$ (1 Hz) for the trio of directly coupled magnetometers. For $D=30$ μm, the noise increases at about 20 μT, as before, while for the two devices with $D=12$ μm ($w=4$ μm), the threshold is at about 33 μT, comparable with the value obtained with $D=20$ μm (Fig. 2).

The fact that the threshold field does not increase as expected for smaller values of w likely reflects variations in the quality of the films and, in particular, of the nature of their edges. As a further illustration of possible materials issues, we note that in two out of the nine devices studied, with $D=12$ and 20 μm, S_Φ (1 Hz) increased linearly with B_0; however, for the latter device S_Φ (1 Hz) was still two orders of magnitude lower than that for devices 1–5 in Table I.

We now turn to a discussion of the implications of these results for directly coupled magnetometers (inset, Fig. 3). To keep the inductance of the pickup loop low, the width of the film is typically 1 mm or more so that vortices penetrate even for relatively low cooling fields. We begin by estimating the contribution of these vortices to the 1/*f* noise. We assume that the pickup loop is square, with outer and inner dimensions d_1 and d_2 and an inductance L_p. The loop is coupled to the SQUID via a mutual inductance $\alpha_d L$, where α_d is the fraction of the SQUID inductance to which a current in the pickup loop couples. We define $S_r(f)$ as the average spectral density of the radial motion of a vortex in the film, and $\mathcal{N}$ ($\propto B_0$) as the number of uncorrelated vortices per unit area, which we take to be uniform. Since the closed superconducting loop conserves flux, the vortex motion induces a current noise and hence a flux noise in the SQUID. Following the model calculation for this ''indirect noise,''[13] we find the spectral density of this flux noise to be

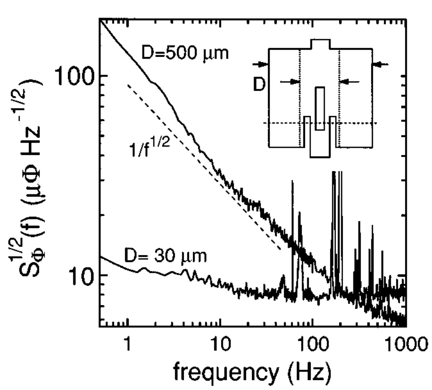

FIG. 1. $S_\Phi^{1/2}(f)$ for the SQUID shown inset cooled in field of 24 μT: upper trace for $D=500$ μm (device 5), lower trace after washer has been reduced to width $D=30$ μm indicated by dotted lines (device 5*). Inset is not to scale, slit length is 100 μm, dashed line indicates bicrystal boundary. Spikes on traces are due to 60 Hz and its harmonics and to microphonic noise.

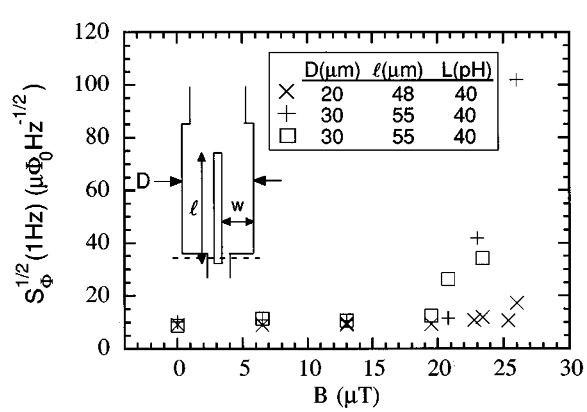

FIG. 2. $S_\Phi^{1/2}$ (1 Hz) vs cooling field for three SQUIDs with configuration shown in the inset.

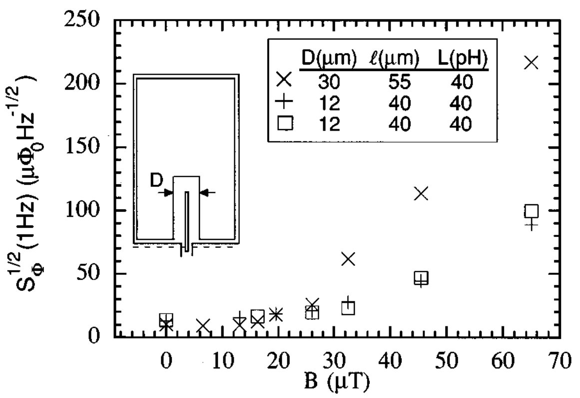

FIG. 3. $S_\Phi^{1/2}$ (1 Hz) vs cooling field for three directly coupled magnetometers with configuration shown in the inset.

$$S_\Phi(f) \approx 4\mathcal{N} S_r(f)\Phi_0^2\alpha_d^2 L^2(d_1+d_2)/L_p^2(d_1-d_2). \quad (1)$$

We now make an order-of-magnitude estimate for this noise. In Ref. 13 it is shown that $4\mathcal{N} S_r(f)\Phi_0^2 \approx S_\Phi^U(f)$, where $S_\Phi^U(f)$ is the spectral density of the flux noise produced by an unpatterned, laser-deposited film as measured by a low-T_c SQUID placed directly over it. For representative YBCO films at 77 K we have found that S_Φ^U (1 Hz)$\lesssim 10$ $-9\Phi02$ Hz-1 for $B_0 = 50$ μT.[5] We take as typical values for a directly coupled magnetometer $\alpha_d \approx 1$, $L \approx 20$ pH, $L_p \approx 5$ nH, $d_1 \approx 10$ mm, and $d_2 \approx 2$ mm. Inserting these values into Eq. (1), we find S_Φ (1 Hz)$\approx 10^{-4} S_\Phi^U$ (1 Hz) $\lesssim 10^{-13}\Phi_0^2$ Hz^{-1}. This spectral density is three orders of magnitude less than that of our SQUIDs (Figs. 1–3) at magnetic fields below the threshold for flux entry. We thus conclude that the 1/f noise contribution of the pickup loop is entirely negligible, even though the film is penetrated by vortices.

It is worthy of note that if one makes the pickup loop larger, the contribution of the 1/f noise in the loop to the magnetic field noise becomes even smaller. To convert Eq. (1) into a magnetic field spectral density, $S_B(f)$, we divide by $A_{\mathrm{eff}}^2(f)$, where $A_{\mathrm{eff}} = \alpha_d L(d_1+d_2)^2/4L_p$ is the effective area of the magnetometer. We find that $S_B(f)$ scales as $1/(d_1+d_2)^3(d_1-d_2)$. Thus, the contribution of the 1/f noise generated by the loop to the magnetic field noise falls rapidly as we increase the size of the pickup loop.

In conclusion, we have shown that the 1/f flux noise of dc SQUIDs cooled in a magnetic field can be dramatically lowered by reducing the linewidth of the device. In seven out of nine narrow linewidth devices that we studied, the noise at 1 Hz remained nearly constant for fields up to a threshold, and increased rapidly as the field was increased beyond this point (Figs. 2 and 3). Although the order-of-magnitude estimate for the threshold field, $\pi\Phi_0/4w^2$, was in reasonably good agreement with the experiment for $w = 13$ μm, the expected increase was not observed for $w = 4$ μm. Furthermore, in two out of the nine devices, the 1/f noise increased linearly with magnetic field. It is very likely that variations in the quality of the thin films, particularly at the edges, are responsible for these sample-to-sample variations, and that improvements in processing techniques may well increase the threshold for flux entry, as in the experiments of Sun *et al.*[14] on magnetic hysteresis. Further work on these issues is clearly indicated. In particular, the threshold field for our devices with the narrowest linewidths was below the Earth's magnetic field in our location, although the 1/f noise at 50 μT (Fig. 3) was still substantially below that for large area devices in the same field. Obviously, it would be highly desirable to increase the threshold field by a factor of at least two or three. In the case of single-layer, directly coupled magnetometers, it is straightforward to make the SQUID with a narrow linewidths; the 1/f noise of the pickup loop is negligible for typical devices because of the large mismatch between the inductances of the loop and the SQUID. For a large washer SQUID inductively coupled to the multiturn input coil of a flux transformer, on the other hand, it seems inevitable that the magnetic field will penetrate the washer and that the 1/f noise will increase with magnetic field. A viable alternative multilayer device may be the fractional-turn SQUID,[15,16] since all of the linewidths can, in principle, be made very narrow.

Note added in proof: Subsequently, by improving the quality of the edges of the films, we achieved a threshold field of 130 μT for a SQUID with a linewidth of 4 μm. This is somewhat higher than the predicted threshold of 100 μT.

We are indebted to John Clem, Tom Lee, and Tim Shaw for helpful discussions and to John Clem for communicating his unpublished results. 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] R. Cantor, L. P. Lee, M. Teepe, V. Vinetskiy, and J. Longo, IEEE Trans. Appl. Supercond. **5**, 2927 (1995).
[2] E. Dantsker, F. Ludwig, R. Kleiner, J. Clarke, M. Teepe, L. P. Lee, N. McN. Alford, and T. Button, Appl. Phys. Lett. **67**, 725 (1995).
[3] D. Drung, F. Ludwig, W. Müller, U. Steinhoff, L. Trahms, H. Koch, Y. Q. Shen, M. B. Jensen, P. Vase, T. Holst, T. Freltov, and G. Curio, Appl. Phys. Lett. **68**, 1421 (1996).
[4] A. H. Miklich, D. Koelle, T. J. Shaw, F. Ludwig, D. T. Nemeth, E. Dantsker, J. Clarke, N. McN. Alford, T. W. Button, and M. S. Colclough, Appl. Phys. Lett. **64**, 3494 (1994).
[5] M. J. Ferrari, M. Johnson, F. C. Wellstood, J. J. Kingston, T. J. Shaw, and J. Clarke, J. Low Temp. Phys. **94**, 15 (1994).
[6] V. N. Glyantsev, Y. Tavrin, W. Zander, J. Schubert, and M. Siegel, Semicond. Sci. Technol. **9**, A105 (1996).
[7] J. M. Schmidt, L. P. Lee, A. Matlashov, M. Teepe, V. Vinetskiy, R. Cantor, and M. S. DiIorio, Proceedings of Biomag 96, Santa Fe, NM, February 16–21, 1996.
[8] M. I. Faley, U. Poppe, K. Urbana, H. Hilgenkamp, H. Hennes, W. Aarwink, J. Flokstra, and H. Rogalla, Appl. Phys. Lett. **67**, 2087 (1995).
[9] M. B. Ketchen and J. M. Jaycox, Appl. Phys. Lett. **40**, 736 (1982).
[10] J. R. Clem (private communication).
[11] T. W. Button, N. McN. Alford, F. Wellhofer, T. C. Shields, J. S. Abell, and M. Day, IEEE Trans. Magn. **27**, 1434 (1991).
[12] R. H. Koch, J. Clarke, W. M. Goubau, J. M. Martinis, C. M. Pegrum, and D. J. Van Harlingen, J. Low Temp. Phys. **51**, 207 (1983).
[13] M. J. Ferrari, J. J. Kingston, F. C. Wellstood, and J. Clarke, Appl. Phys. Lett. **58**, 1106 (1991).
[14] J. Z. Sun, W. J. Gallagher, and R. H. Koch, Phys. Rev. B **50**, 664 (1994).
[15] F. Ludwig, E. Dantsker, R. Kleiner, D. Koelle, J. Clarke, S. Knappe, D. Drung, H. Koch, N. McN. Alford, and T. W. Button, Appl. Phys. Lett. **66**, 1418 (1995).
[16] D. Reimer, M. Schilling, S. Knappe, and D. Drung, IEEE Trans. Appl. Supercond. **5**, 2342 (1995).