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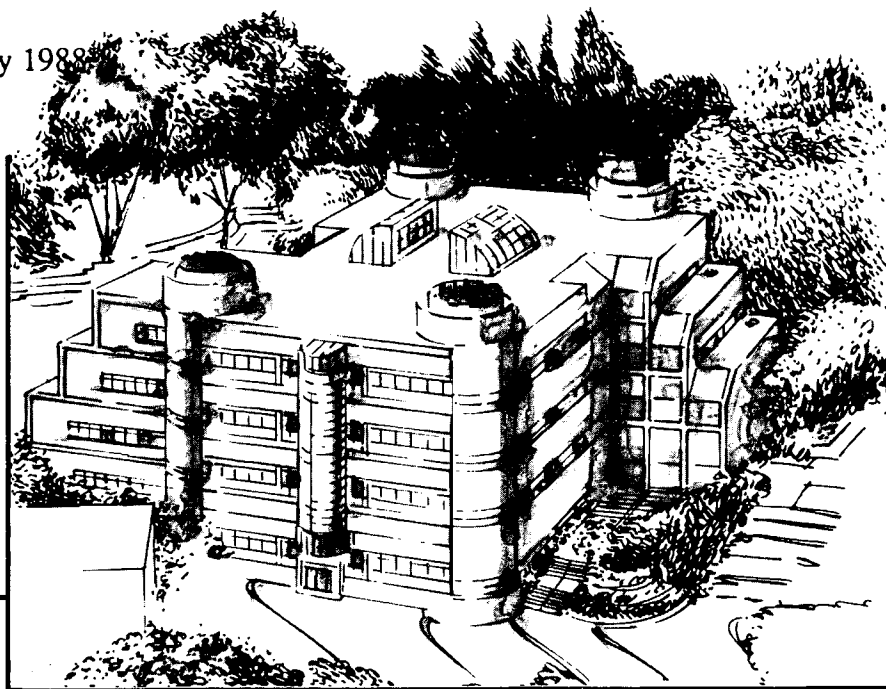
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DISCLAIMER

MAGNETIC FLUX NOISE IN THIN-FILM RINGS OF $YBa_2Cu_3O_{7-\delta}$

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ABSTRACT

The low-frequency magnetic flux noise in thin-film rings of

$YBa_2Cu_3O_{7-\delta}$ (YBCO) is measured over the temperature range 1.3 to 125K

by means of a dc Superconducting QUantum Interference Device (SQUID)

maintained at liquid helium temperatures. Below the transition

temperature T_c of the YBCO, the spectral density of the noise scales as

1/f, where f is the frequency, and generally increases with increasing

temperature. The magnitude of the noise depends strongly on the

microstructure of the film, and is lowest for a sample which is

predominantly oriented with its c-axis perpendicular to the substrate.

These results imply that SQUIDs and flux transformers of YBCO must be

fabricated from highly-oriented films to produce good resolution at low

frequencies.

Thin-film dc Superconducting QUantum Interference Devices (SQUIDs) fabricated from classic superconductors such as Nb and Pb have been operated routinely as measuring instruments for many years.[1] At 4.2K, the flux noise energy of a typical device with an inductance, L, of the order of 100 pH is $\varepsilon(f) = S_\Phi(f)/2L = (1-5)10^{-32}$ JHz^{-1} at frequencies above the 1/f noise region, where $S_\Phi(f)$ is the spectral density of the flux noise at a frequency f. At low frequencies, most of these SQUIDs exhibit 1/f noise[1] with a noise energy $\varepsilon(f) \lesssim 10^{-30}/(f/1$ Hz) JHz^{-1}. This performance is adequate for many practical applications. Over the last year, a number of authors[2-5] have fabricated dc SQUIDs from films of $YBa_2Cu_3O_{7-\delta}$ (YBCO), and operated them at temperatures up to 77K. However, relatively few noise measurements have been reported, and only over a limited temperature range. Koch et al.[2] reported $S_\Phi(100Hz) \approx 10^{-6}\Phi_0^2$ Hz^{-1} at 40K, a value limited by voltage noise in the preamplifier; with the quoted loop inductance of 80 pH, this flux noise corresponds to $\varepsilon \approx 3 \times 10^{-26}$ JHz^{-1}. Subsequently, devices of this kind have shown a noise energy at 40K of about 3×10^{-30} JHz^{-1} at 1 kHz, increasing as 1/f at lower frequencies.[6] At 77K, the noise energy again varied as 1/f at low frequencies, with a value of about 2×10^{-25} JHz^{-1} at 1 Hz. Thus, although the resolution of these devices is good at frequencies above the 1/f region, the 1/f noise is much larger than in classic SQUIDs at 4.2K, and is potentially a limitation on the usefulness of high-T_c SQUIDs for low-frequency applications in, for example, geophysics and biomagnetism.

In this Letter we report a systematic study of the magnetic flux noise in thin-film loops of YBCO with various microstructures over the temperature range from 1.3K to 125K. The measured noise sets a lower

bound on the flux noise to be expected from SQUIDs of comparable

geometries fabricated from similar materials. It is also hoped that

these measurements will shed light on the physical origin of the noise,

and enable one to reduce its magnitude.

The experimental configuration is sketched in Fig. 1. A Nb-PbIn

SQUID in a square washer configuration on a sapphire substrate is

attached to a sapphire plate. This plate is clamped to the flange of a

vacuum can immersed in liquid ^{4}He, so that the temperature of the SQUID

is close to that of the bath. A film of YBCO approximately 200 nm

thick with the same dimensions as the SQUID loop is fabricated on a

SrTiO$_3$ chip that is then mounted on a larger Si plate. The Si plate is

attached to a fiberglass mount that has weak thermal coupling to the

sapphire plate. We use a heater on the reverse side of the Si plate to

raise the temperature of the sample   as high as 125K without

disturbing the operation of the SQUID. A platinum resistance

thermometer measures the temperature of the plate. A small modulation

and feedback coil enables one to operate the SQUID in a flux-locked

loop, with a typical bandwidth of a few kHz. The SQUID and YBCO loop

are magnetically shielded by a Pb can, and the cryostat is surrounded

by a mu-metal cylinder to minimize the magnetic field in which the

sample is cooled.

We have studied three films of YBCO, the properties of which are

summarized in Table I. Samples 1 and 2 were coevaporated onto SrTiO$_3$

substrates at ambient temperature in flowing O$_2$, and subsequently

annealed as described in detail previously.[7] Sample 3 was cosputtered

in 0.7 m torr of Ar and 0.1 m torr of O$_2$ at ambient temperature, and

annealed similarly. The films were patterned photolithographically and

etched in dilute nitric acid. X-ray studies showed that sample 1 was mostly polycrystalline with some a- and c-axis oriented grains; its low transition temperature of about 47K was probably due to underannealing. Sample 2 had mixed a- and c-axis orientation, while sample 3 was predominantly c-axis oriented. These latter two films should be typical of the current state-of-the-art in postannealed YBCO films.

We determined the mutual inductance $M = \alpha(LL_\ell)^{1/2}$ between the SQUID and the loop of inductance L_ℓ from the modulation depth ΔI_c of the critical current of the SQUID. Here, α is the coupling coefficient and ΔI_c is the difference between the maximum and minimum critical currents observed when one varies the flux applied to the SQUID. The dependence of ΔI_c on temperature for sample 3 is shown in Fig. 2. Above the transition temperature, T_c, the SQUID is unshielded by the YBCO loop, and we estimate $\beta = 2LI_o/\Phi_o \approx 2$, where $L \approx 400$ pH, $I_o \approx 5$ µA is the critical current per junction, and $\Phi_o \equiv h/2e$ is the flux quantum. Below T_c, the SQUID inductance is reduced to $L' = L(1 - \alpha^2)$ by the screening action of the YBCO loop, and ΔI_c is correspondingly increased. We estimate L' from Fig. 4 of ref. 8, and hence deduce the value of α, which ranged from 0.6 to 0.7. The spectral density of the flux noise in the loop is given by $S_\phi(f) = S_\phi{}^s(f)/\alpha^2$, where $S_\phi{}^s(f)$ is the noise observed in the SQUID.

Figure 3 shows $S_\phi(f)$ for sample 1 at three temperatures. At 4.2K $S_\phi(f)$ varies approximately as $1/f$ over the measured frequency range, with a value of 9×10^{-7} Φ_o^2 Hz^{-1} at 1 Hz. The excess noise of the loop becomes comparable with the white noise of the SQUID at about 1 kHz. When the temperature was increased to 44K, the noise power increased by a factor of about 600. At 80K (well above the transition temperature

of this sample) the measured noise corresponded to the intrinsic noise
of the SQUID, with no discernible contribution from the YBCO loop.

In Figure 4 we plot the spectral density of the noise at 1 Hz vs.
temperature for the three samples of Table I. The spectral density of
the noise in the SQUID has been subtracted. At low temperatures, the
noise power scales as 1/f and increases with increasing temperature.
Just below T_c (which we define as the temperature at which the
inductive screening of the SQUID by the YBCO film vanishes), the noise
increases steeply with temperature. Just above T_c, the noise drops
very rapidly with increasing temperature, and its spectral density is
no longer 1/f; the detailed behavior of each sample is different. For
example, for sample 1 above T_c we observed a knee frequency in some
spectra, below which the noise was white and above which it was
approximately 1/f. At point A this knee frequency was near 10 Hz, at
point B it was near 100 Hz, and at point C the noise was white over the
bandwidth of the measurement. The white noise observed in samples 1
and 3 over a range of temperature indicated by dashed lines was so
large that we could not maintain the SQUID in flux-locked operation.
At sufficiently high temperatures, the noise from the YBCO is below the
noise of the SQUID. We note that although the peak noise magnitudes
are not very different for all three films, the magnitudes at
temperatures well below the peaks decrease substantially as the film
quality improves progressively from sample 1 to sample 3. Furthermore,
the data indicate a weaker temperature dependence for sample 3 in this
temperature range.

We tentatively ascribe the noise to the motion of flux quanta or
possibly bundles of flux quanta in the film. Similar sources of flux

noise (of much lower magnitude) have been suggested[9] for Nb-based dc SQUIDs, and it is possible but not a foregone conclusion that the underlying mechanism is the same for YBCO and Nb. If one assumes a distribution of times τ_i for the flux hopping process, one expects to find a 1/f power spectrum from the superposition of Lorentzian spectra in the usual way.[10] As the temperature is increased, one expects the hopping frequency to increase, as more processes with higher activation energies move into the range of measured frequencies. Indeed, for sample 1 we see knee frequencies at points A and B, while at C the characteristic frequencies (~ $1/\tau_i$) have presumably shifted to values greater than 1kHz, producing a white power spectrum in the measured frequency range. From the temperature dependence of the noise at low temperatures, we estimate the activation temperatures to be no greater than 2K for samples 1 and 2 and of the order of 10K for sample 3.

We estimate the flux noise energy for our best film, sample 3, assuming an inductance of 400 pH. We find $\epsilon(1 \text{ Hz}) \approx 1 \times 10^{-27}$ JHz^{-1} in the vicinity of 77K, the boiling point of liquid N_2, and $\epsilon(1 \text{ Hz}) \approx 7 \times 10^{-29}$ JHz^{-1} at 28K, the boiling point of liquid Ne. Although these 1/f noise values are substantially higher than those obtained in Nb-based devices at 4.2K, nonetheless the value at 28K would be adequate for many applications of SQUIDs.

In summary, we have shown that the low-frequency flux noise in YBCO loops has a 1/f spectral density and increases rapidly with temperature. The noise decreases markedly as the degree of crystallographic orientation of the films is improved, and is lowest for a highly oriented c-axis film. There is, of course, no reason to believe that the lowest noise reported here cannot be improved upon: We

expect further reductions in noise as the film quality is improved. These measurements imply that very high quality films of YBCO are required to yield reasonably low levels of 1/f noise in dc or rf SQUIDs; furthermore, coils and flux transformers coupled to the SQUIDs should also have the best possible microstructural properties.

Table I. Properties of three YBCO samples.

Sample #	SrTiO$_3$ orientation	YBCO orientation	T$_c$ K	J$_c$(4.2K)[a] A/cm^2
1	18° from <100>	polycrystalline	47	—
2	<100>	mixed a- and c-axis	85	2×10^4
3	<100>	> 90% c-axis	85	5×10^6

[a] From magnetization measurements prior to patterning.

REFERENCES

1. For example, see J. Clarke, Physics Today 39, 36 (1986).

2. R. H. Koch, C. P. Umbach, G. J. Clark, P. Chaudhari, and R. B. Laibowitz, Appl. Phys. Lett. 51, 200 (1987).

3. H. Nakane, Y. Tarutani, T. Nishino, H. Yamada, and U. Kawabe, Jap. J. Appl. Phys. 26, L1925 (1987).

4. B. Häuser, M. Diegel, and H. Rogalla, Appl. Phys. Lett. 52, 844 (1988).

5. P. Chaudhari, J. Mannhart, D. Dimos, C. C. Tsuei, J. Chi, M. M. Oprysko, and M. Scheuermann, Phys. Rev. Lett. 60, 1653 (1988).

6. R. H. Koch, private communication.

7. M. Naito, R. H. Hammond, B. Oh, M. R. Hahn, J. W. P. Hsu, P. Rosenthal, A. F. Marshall, M. R. Beasley, T. H. Geballe, and A. Kapatulnik, J. Mat. Res. 2, 713 (1987).

8. C. D. Tesche and J. Clarke, J. Low Temp. Phys. 29, 301 (1977).

9. 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).

10. A. Van der Ziel, Physica 16, 359 (1950).

FIGURE CAPTIONS

Fig. 1 Experimental configuration: (a) perspective view of YBCO film, SQUID and coil, and (b) side view showing mounting arrangement. A is the SQUID substrate, B is the sapphire plate, C is the modulation and feedback coil, D is the $SrTiO_3$ substrate, E is the silicon plate, F is the heater, and G is the thermometer.

Fig. 2 Normalized modulation depth of the critical current of the SQUID, $\Delta I_c(T)/\Delta I_c(4.2K)$, vs. temperature for sample 3.

Fig. 3 Power spectra of observed flux noise for sample 1 at 3 different temperatures. At 80K, the spectrum is that of the SQUID, divided by α^2.

Fig. 4 Spectral density of flux noise at 1 Hz vs. temperature for 3 samples: squares, sample 1; triangles, sample 2; circles, sample 3. The spectral density of the SQUID noise has been subtracted. Solid symbols imply that the spectral density is 1/f at 1Hz, open symbols that it is white or nearly white. Downward arrows above T_c indicate upper limits on the noise from the sample loops.
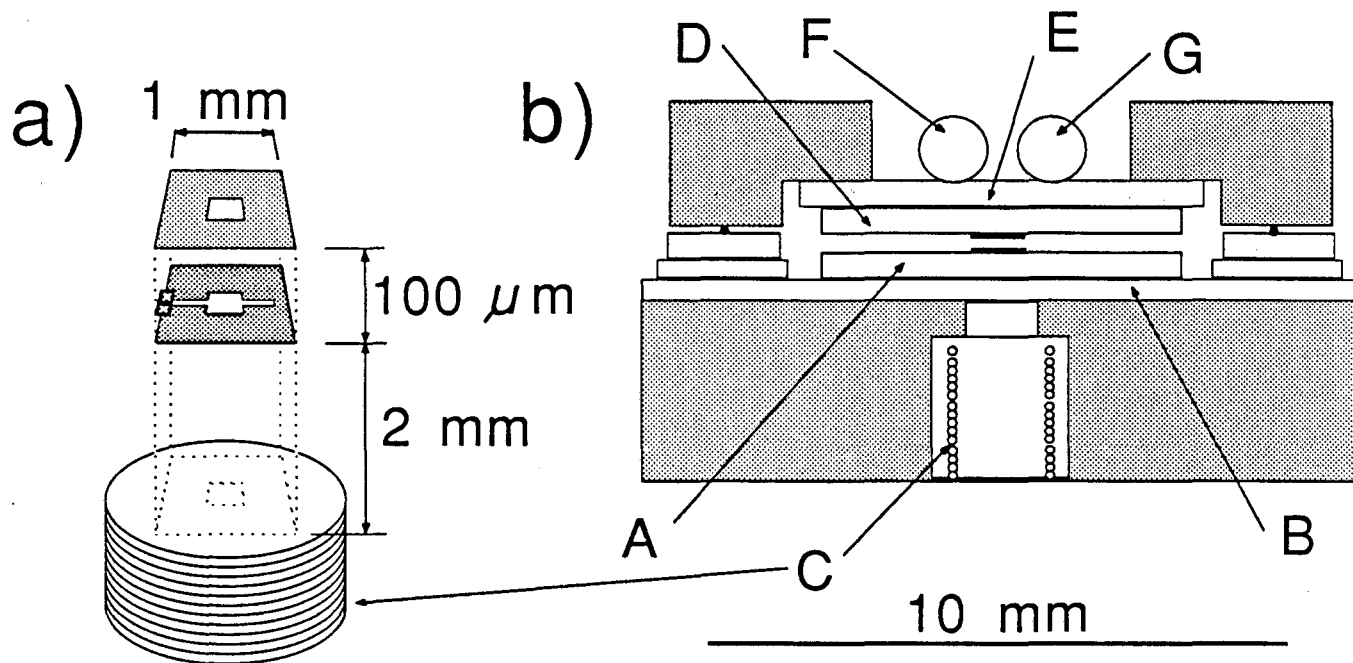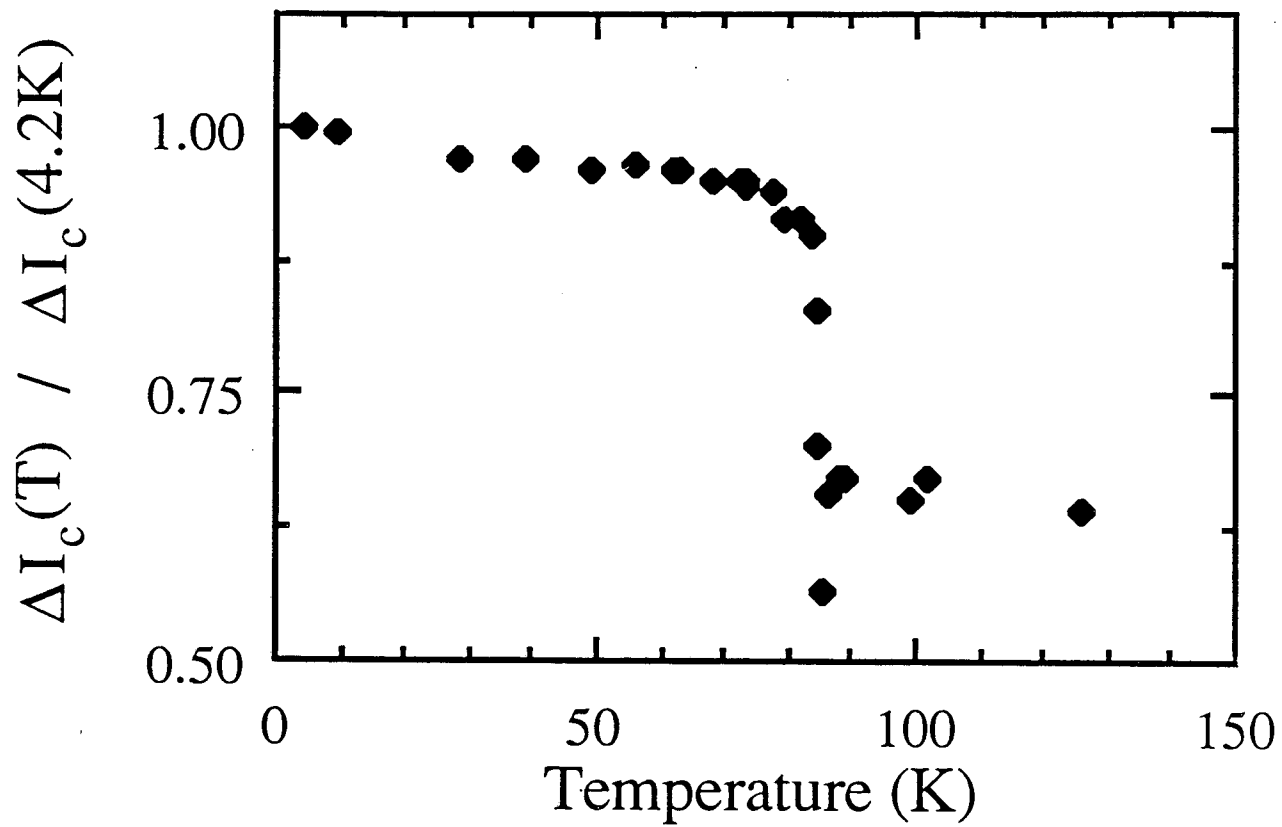
a)

1 mm

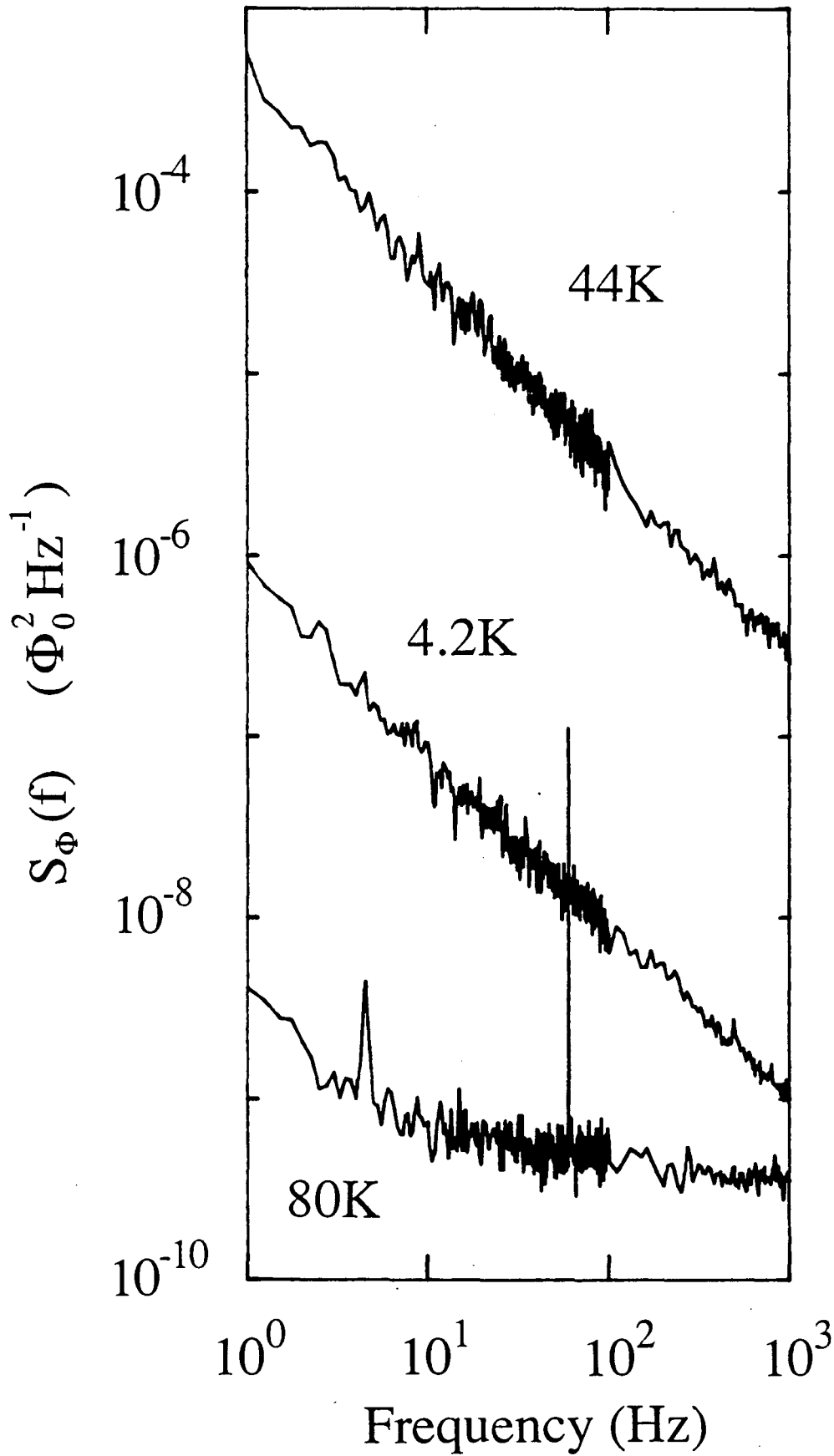100 μm

2 mm

b)

D   F   E   G

A   C   B

10 mm

Figure 1

11

Figure 2

Figure 3

Figure 4