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# Suppression of Magnetic Flux Noise in $YBa_2Cu_3O_{7-x}$ Flux Transformers

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Abstract. We have constructed hybrid magnetometers by coupling a flux transformer of $YBa_2Cu_3O_{7-x}$ to a Nb-PbIn SQUID. The low frequency (1/f) noise is dominated by fluctuations in the supercurrent circulating in the transformer, driven by vortex motion. The application of a small static magnetic field induces a supercurrent that reversibly suppresses the noise, in quantitative agreement with a model of thermally activated vortex hopping between symmetrical pairs of pinning sites. A persistent current can be used to reduce the low frequency noise power of high-$T_c$ flux transformers by at least one order of magnitude.

## 1. Introduction

Although the SQUID is a sensitive detector of magnetic flux, its small size implies a relatively poor magnetic field sensitivity, a deficiency generally overcome by the use of a flux transformer.[1] The need for a flux transformer is particularly acute in the case of SQUIDs fabricated from high transition temperature ($T_c$) superconductors such as $YBa_2Cu_3O_{7-x}$ (YBCO) since these devices operate at higher temperatures than conventional SQUIDs, and therefore have smaller inductances. To our knowledge, complete YBCO thin-film magnetometers consisting of a grain boundary dc SQUID and a multilayer flux transformer have been successfully operated by two groups, Miklich *et al.*[2] and Oh *et al.*,[3] who reported field sensitivities of 0.6 pT $Hz^{-1/2}$ and 12 pT $Hz^{-1/2}$, respectively, at 10 Hz and 77 K. The sensitivity in both cases was limited by the 1/f noise of the SQUID (f is frequency).

High-$T_c$ magnetometers are attractive for applications such as magnetocardiography and magnetoencephalography because they require much less thermal shielding than their low-$T_c$ counterparts, allowing pickup loops to be brought closer to the subject and thereby improving spatial resolution. At present, however, the 1/f noise of high-$T_c$ SQUIDs is too high for the more demanding of these applications. One might seek means to reduce this low frequency noise in order to produce a sensitive all-high-$T_c$ magnetometer. Alternatively, one might construct a hybrid magnetometer combining a low-$T_c$ SQUID, with its low 1/f noise, and a high-$T_c$ flux transformer, which provides high resolution; this is the approach we describe in this paper. In either case, noise from the flux transformer itself will become significant, and it is important to understand its origin and to find ways to reduce it.

## 2. Noise Mechanisms

We have investigated the noise in YBCO flux transformers by coupling them to a Nb-PbIn SQUID, as shown schematically in Fig. 1. Wellstood *et al.*[4] have described the design and fabrication of the flux transformers. The motion of vortices in a transformer causes variations in the flux $\Phi$ through the SQUID to which its input coil is coupled. Consider an ensemble of vortices, the position r of each one of which fluctuates with an average spectral density $\langle S_r(f,T,I)\rangle$, which may depend on the temperature T and the time-averaged circulating current I in the transformer. If there are $n_v$ uncorrelated vortices per unit area of the transformer, the power spectrum of the flux noise in the SQUID is

$$S_\Phi(f,T,I) = n_v \int_A dA \, \langle S_r(f,T,I)\rangle \left(\frac{\partial\Phi}{\partial r}\right)^2 , \qquad (1)$$

where the integral is taken over the area A of the transformer. When $\langle S_r(f,T,I)\rangle$ is independent of position, Eq. 1 becomes

$$S_\Phi(f,T,I) = \eta n_v \Phi_0^2 \langle S_r(f,T,I)\rangle , \qquad (2)$$

where $\Phi_0$ is the flux quantum and $\eta$ is a dimensionless geometrical parameter.

Evaluating the parameter $\eta$ in Eq. (2) requires knowledge of the transfer function $\partial\Phi/\partial r$, which we now discuss for two coupling mechanisms, one of which involves currents circulating in the transformer (indirect noise) and one of which does not (direct noise). We first consider indirect noise. The magnetic field lines produced by a vortex close around the transformer line in which it is pinned, preferentially around the nearer edge. If the vortex were displaced the entire distance w from one edge of the line to the other, the flux which it applies to the transformer would change by one flux quantum. A small displacement $\delta r$ across the line produces, in a linear approximation, an applied flux change $\Phi_0\delta r/w$. Because the transformer is a closed superconducting circuit, a current $\delta I_i = \Phi_0\delta r/w(L_i+L_p)$ flows to oppose this flux, where $L_i \approx 75$ nH and $L_p \approx 20$ nH are the estimated inductances of the input coil and pickup loop, respectively. This current produces a flux in the SQUID, and we immediately obtain

$$\frac{\partial\Phi}{\partial r} = \frac{\Phi_0\alpha\sqrt{LL_i}}{w(L_i+L_p)} , \qquad (3)$$

where $L = 0.44$ nH is the SQUID inductance and $\alpha \approx 0.5$ is the coefficient of inductive coupling between the input coil and the SQUID. Thus for the case of indirect noise,

$$\eta^{(in)} = \frac{\alpha^2 LL_i}{(L_i+L_p)^2}\left(\frac{\ell_i}{w_i} + \frac{\ell_{cr}}{w_{cr}} + \frac{\ell_p}{w_p}\right) \approx 1.2 , \qquad (4)$$

where $\ell_i$, $\ell_{cr}$, and $\ell_p$ are the lengths of the input coil, crossunder, and pickup loop, respectively, and $w_i$, $w_{cr}$, and $w_p$ are their widths. Most of the indirect noise is due to the input coil because of the large ratio $\ell_i/w_i \approx 1200$, as compared to $\ell_{cr}/w_{cr} \approx 30$ and $\ell_p/w_p \approx 40$.

Vortex motion also produces flux noise in the SQUID even in the absence of a closed superconducting path around the transformer, by a mechanism we call direct noise. Consider an unpatterned YBCO film in place of the transformer input coil in our apparatus. A vortex in this film couples a fraction of its flux directly into the SQUID, and this fraction varies with position. The relevant coordinate r is now the radial distance of the vortex from the center of the SQUID, not position across the transformer line as in the case of indirect noise; the approximate radial symmetry of the SQUID implies that azimuthal vortex motion produces little noise.

The direct-noise transfer function $\partial\Phi/\partial r$ is difficult to calculate exactly for our experimental geometry because of the distortion of the vortex field by the body of the SQUID and by the lines of the transformer. Approximate calculations of $\eta$ have been made by Ferrari *et al.*,[5] and are summarized in Table I. Note that the indirect noise is only about a factor of three less than the direct noise from an unpatterned film. On the other hand, the direct noise from the input coil is much less, because most of the field lines from a vortex in a given turn close around that turn and do not couple into the SQUID. We are therefore justified in neglecting correlations between the direct and indirect contributions.

## 3. Noise Measurements

We measured the low-frequency noise produced by two similarly fabricated[4] YBCO flux transformers, T1 and T2. Each transformer was supported on a thermally isolated hot stage[6] with its 10-turn input coil approximately 100 μm from a Nb-PbIn SQUID maintained at 4.2 K; the temperature of the transformer could be raised above its transition temperature. Mu-metal and superconducting Pb shields surround the apparatus, which was cooled in a field $B < 1$ μT. The measured noise power spectra scaled approximately as $1/f$, as shown in Fig. 2(a). Figure 3(a) indicates that the magnitude of the noise and its temperature dependence were similar for both transformers. The transition temperatures of T1 and T2 were 77 K and 59 K, respectively; however, above 62 K other Nb components of the apparatus became normal, preventing us from making meaningful noise measurements.

To test the mechanism of noise generation, we made a cut through the pickup loop of T2 which prevented the flow of screening current. Figure 3(b) illustrates the order-of-magnitude decrease observed in the noise power. According to Table I, this is consistent with noise in the intact transformer being dominated by indirect noise, while in the cut transformer only direct noise from the crossunder is significant. Next we moved the 1 mm strip of part of the pickup loop over the SQUID. Figure 3(b) shows that the noise from this wide portion of the film ("unpatterned film" geometry) is larger than that from the intact transformer by approximately a factor of three, as Table I predicts.

## 4. Suppression of Noise by a Supercurrent

A Nb magnetic field coil operated in a persistent current mode allowed us to apply a small static magnetic field ($< 10^{-5}$ T) to the flux transformer, inducing a circulating current I. This current reversibly suppressed the noise power at low frequencies by an order of magnitude, as shown in Fig. 2. We have shown[7] that only indirect noise is significantly suppressed, so the direct noise background is subtracted from the data plotted in Fig. 4.

The reduction of indirect noise by current can be explained by our model[6,7] for 1/f noise in YBCO, based on the work of Dutta *et al.*[8] This model postulates an ensemble of thermally activated bistable processes such as the one depicted in the inset to Fig. 2(a). A vortex hops between two pinning sites separated by a distance $\ell$. The temperature-dependent activation energy for hopping out of either site is U(T); we define $U_0 = U(0)$. Our model depends on two-level systems which are symmetric in the absence of the current, as would be the case, for example, if similar defects were present at each pinning site. The current, which we assume to be uniformly distributed across the line, exerts a Lorentz force $F = I\Phi_0/w$ on each vortex. The inset to Fig. 2(a) shows that this force introduces a misalignment $\Delta U = F\ell \cos\theta$ between the minima of the pinning potential, where $\theta$ is the angle between the Lorentz force and the vortex trajectory. Increasing current decreases the probability that the vortex will be activated out of site 2, reducing the indirect noise. Direct noise will not be significantly affected because it originates primarily in the crossunder, where the noisiest (radial) processes involve vortices moving perpendicular to the Lorentz force. The lifetimes of states 1 and 2 are

$$\tau_1(T,I) = 2\tau_0 \exp[U_0\beta - \delta] \tag{5a}$$

$$\tau_2(T,I) = 2\tau_0 \exp[U_0\beta + \delta] \;, \tag{5b}$$

where the attempt time $2\tau_0$ and $\beta(T) = U(T)/U_0k_BT$ are assumed to be the same for all processes in the ensemble, and $\delta = I\Phi_0\ell \cos\theta/2wk_BT$. For consistency with Ref. 6, we choose $U(T)/U_0 = 1-(T/T_c)^4$ and $\tau_0 = 10^{-11}$ s; our results are relatively insensitive to these parameters.

The spectral density for a single hopping process is given by[9]

$$S_r(f,T,I) = \frac{4\,(\ell\,\cos\theta)^2}{(\tau_1+\tau_2)[(\tau_1^{-1}+\tau_2^{-1})^2 + (2\pi f)^2]} \;. \tag{6}$$

To solve Eq. (1) we need the spectral density averaged over angle and energy in the ensemble:

$$<S_r(f,T,I)> = \frac{1}{\pi n_v A}\int_0^{\pi} d\theta \int_0^{\infty} dU_0\, D(U_0)\, S_r(f,T,I) \;, \tag{7}$$

where $D(U_0)\,dU_0$ is the number of processes with zero-temperature activation energies between $U_0$ and $U_0+dU_0$. Two functions remain to be specified, $D(U_0)$ and the hopping distance $\ell$. We have shown[7] that for I = 0, Eqs. (1), (3), and (7) can be inverted to yield $D(U_0)$ from $S_\Phi(f,T,0)$, as shown in the inset to Fig. 2(b). We assume that the minima in the inset to Fig. 2(a) are parabolic, so the hopping distance is given by $\ell = (8U_0/k_0)^{1/2}$, where the spring constant $k_0$ is the only significant adjustable parameter in our model.

We obtain the best fit to our data with $k_0 = 6 \times 10^{-5}$ N/m, as shown in Fig. 4. This gives a hopping distance for the processes contributing to the measured noise which increases from 13 nm at 4.2 K to 53 nm at 52 K.[7] Integrating $D(U_0)$ gives a number density of vortices $n_v$ which can be expressed as an effective field $B_{eff} = n_v\Phi_0 \approx 40$ µT.[7] Accounting for processes outside the experimental energy range may increase $B_{eff}$, but it is already much greater than the field B in which the transformer was cooled, implying that there is another mechanism for generating vortices in the film, such as the freezing-in of vortex-antivortex pairs as the film is cooled below $T_c$.

## 5. Discussion

The dominant source of noise in our hybrid magnetometer is the fluctuation of the screening current in the YBCO flux transformer, caused by vortex motion in the input coil. Inducing a dc current in the transformer significantly reduces its noise; for example, the field sensitivity of the magnetometer [Fig. 2(a)] improves from 0.22 pT $Hz^{-1/2}$ at 10 Hz to 0.08 pT $Hz^{-1/2}$ when we induce a current of 2 mA. Nevertheless, this latter figure is almost an order of magnitude above the limit set by the noise in our Nb-PbIn SQUID. Further improvements could be effected by designing a transformer with a narrower crossunder, thereby reducing the direct noise which dominates for $I > 0.7$ mA, or by fabricating the transformer from higher-quality YBCO films, the noise in which has been observed[10] to approach that in our SQUID. The optimization of future magnetometers with YBCO flux transformers will presumably rely on such intrinsically quiet films, as well as a geometry chosen to minimize both direct and indirect noise, and the suppression of indirect noise by a supercurrent. We note that the existence of a large number of mobile vortices despite the small ambient field ($B << B_{eff}$), which we have observed in YBCO, could also explain 1/f flux noise in low-$T_c$ SQUIDs.[11]

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TABLE I. Estimates of flux noise parameter $\eta$ defined in Eq. (2). Values for an unpatterned film, and for the input coil and crossunder of a flux transformer, are direct noise. Direct noise from pickup loop is negligible because of its distance from the SQUID. Total indirect noise from all transformer components is given by Eq. (4). Noise also shown as a fraction of $\eta^{(u)}$, the value for an unpatterned film.

| Noise source | $\eta$ | $\eta / \eta^{(u)}$ |
|---|---|---|
| Unpatterned film | 3.9 | 1 |
| Input coil | 0.0015 | 0.00038 |
| Crossunder | 0.11 | 0.03 |
| Indirect | 1.2 | 0.31 |

## Figure Captions

Fig. 1. YBCO flux transformer. (a) Pickup loop formed by wide lines, input coil centered on bottom edge, insulating $SrTiO_3$ layer indicated by dashed box. (b) Enlargement of input coil: $SrTiO_3$ is shaded region, crossunder is vertical strip connected to center of coil. (c) Cross section of input coil coupled to SQUID.

Fig. 2. (a) Total noise power vs. frequency for transformer T1 at 39 K. Upper solid curve: initial spectrum ($I = 0$); lower solid curve: application of $I = 2$ mA; dashed curve: subsequent return to $I = 0$. Spike is 60 Hz pickup. Flattening at high frequencies caused by Johnson noise from normal metal in apparatus. Inset: Schematic of pinning potential for single hopping process with $I = 0$ and with $I > 0$. Vortex hops distance $\ell$ between pinning sites 1 and 2. (b) Spectra for $I = 0$ with spectrum for $I = 2$ mA subtracted. Line indicates 1/f scaling. Inset: Distribution of activation energies from zero-current noise.

Fig. 3. Total noise power vs. temperature in ambient field. (a) Both transformers. (b) Transformer T2 after being scribed open (open symbols) and after SQUID has been moved beneath a 1-mm-wide line of pickup loop (solid symbols). For purposes of comparison, linear least-squares fit made to T2 data in (a) is replotted in (b) multiplied by 0.09 (lower line) and by 3 (upper line), indicating noise expected from the configurations represented by the open and solid symbols, respectively, according to Table I.

Fig. 4. Noise power $S_\Phi(1\ \mathrm{Hz})$ vs. current in transformer T1 for six temperatures. Points are experimental data, from which the least noise measured at each temperature has been subtracted to remove background. Curves are prediction of Eqs. (1) and (7) with indirect noise transfer function from Eq. (3).

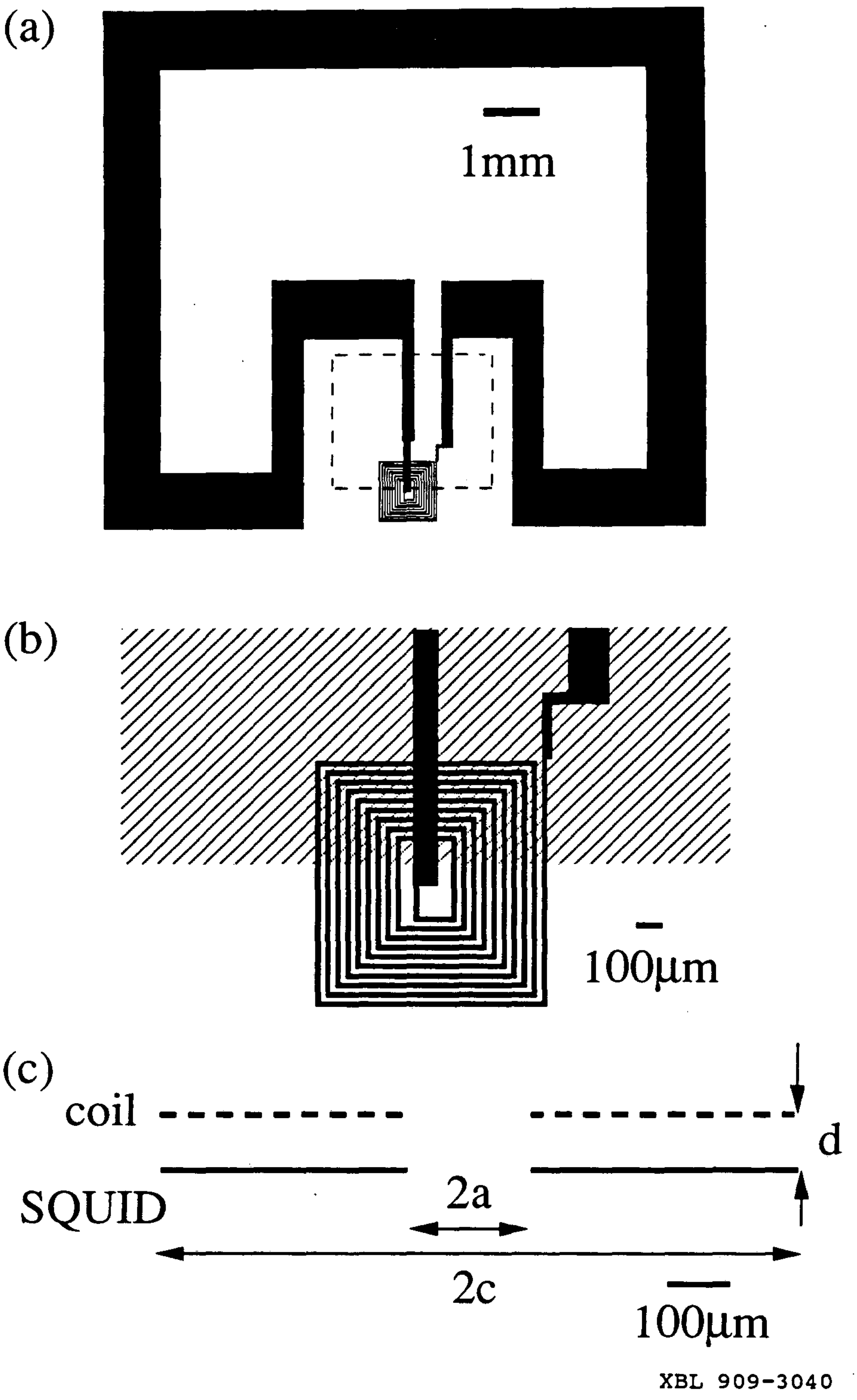

Fig. 1

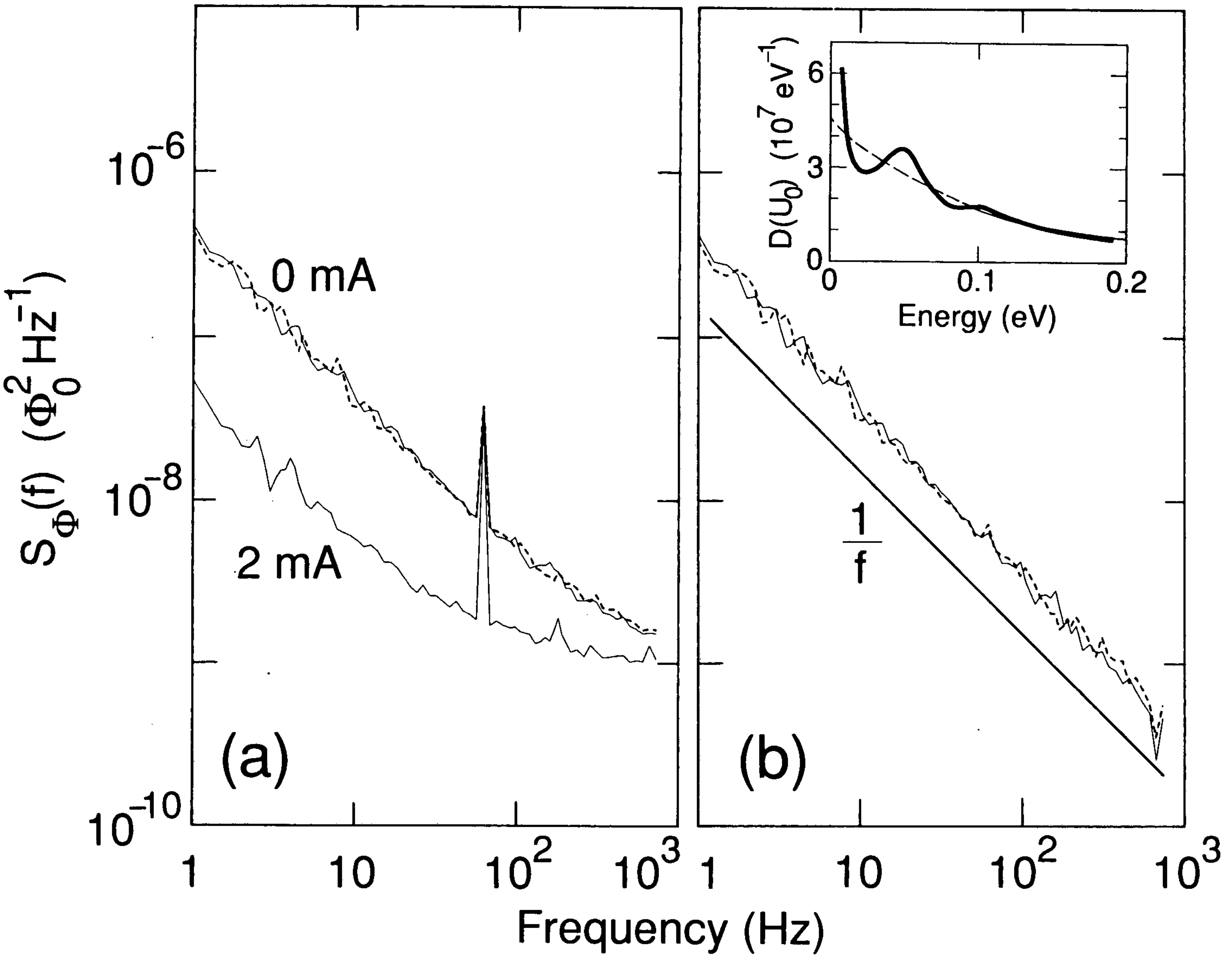

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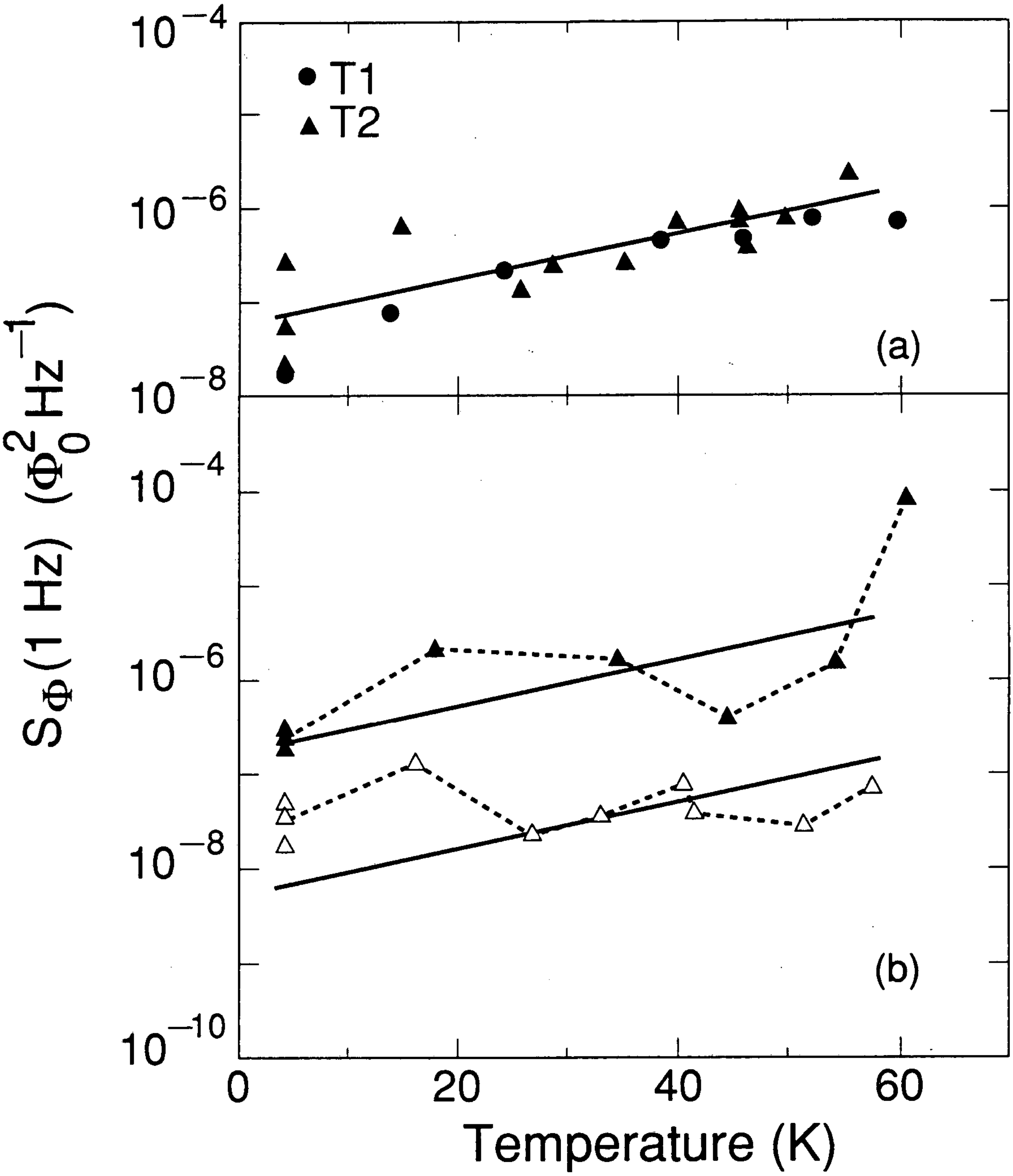
Fig. 2



$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
● T1
▲ T2
(a)
(b)
$S_\Phi(1\ \mathrm{Hz})\ (\Phi_0^2\mathrm{Hz}^{-1})$
0
20
40
60
Temperature (K)
XBL 909-5745

Fig. 3

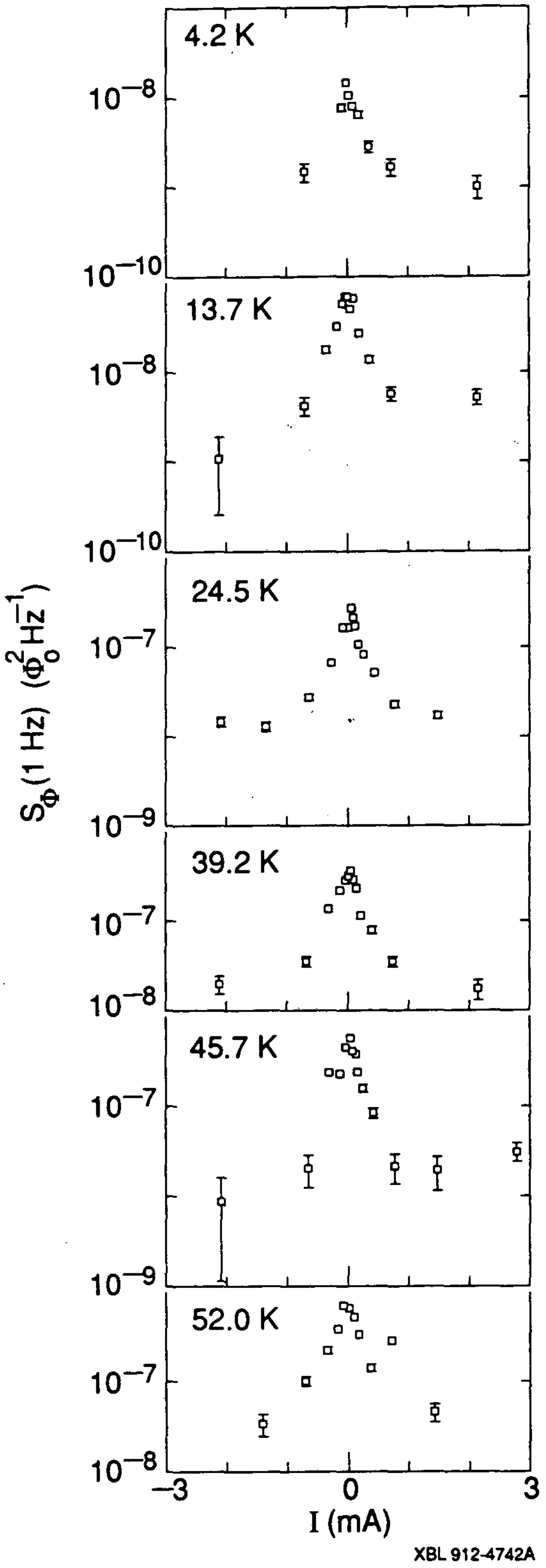

4.2 K
13.7 K
24.5 K
39.2 K
45.7 K
52.0 K
$10^{-8}$
$10^{-10}$
$10^{-8}$
$10^{-10}$
$10^{-7}$
$10^{-9}$
$10^{-7}$
$10^{-8}$
$10^{-7}$
$10^{-9}$
$10^{-7}$
$10^{-8}$
$S_\Phi(1\ Hz)\ (\Phi_o^2 Hz^{-1})$
−3
0
3
I (mA)
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Fig. 4

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