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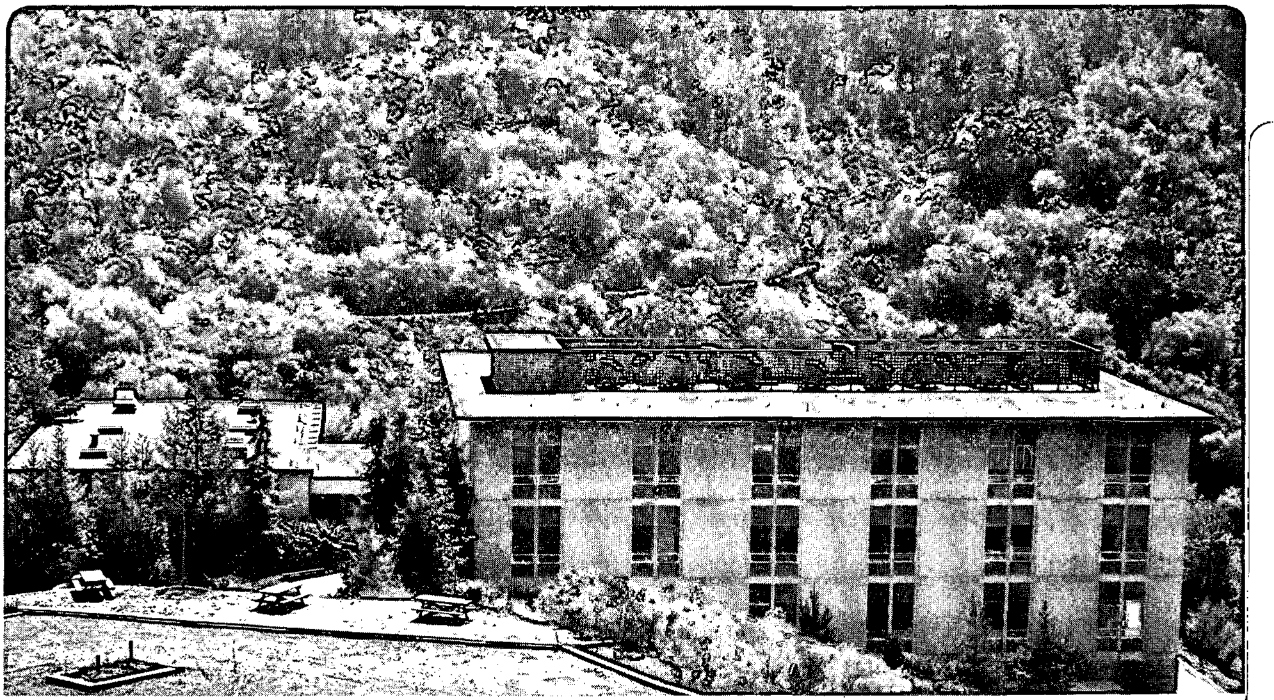

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Abstract

We describe an improved interconnect technology for the fabrication of multiturn flux transformers from $YBa_2Cu_3O_{7-x}$-$SrTiO_3$-$YBa_2Cu_3O_{7-x}$ multilayers. The essential improvements are reductions in the thicknesses of the trilayer films, typically to 100 nm, 250 nm and 250 nm respectively, and in the deposition rate, to 0.07 nm/laser pulse. This process yields crossovers in which the critical current density in the upper $YBa_2Cu_3O_{7-x}$ film at 77K is (2-3) x 10^6 A cm^{-2}. *In situ* trilayers exhibited 1/f flux noise levels at 1Hz below the measurement sensitivity of $15\mu\Phi_0$ $Hz^{-1/2}$, where Φ_0 is the flux quantum. However, the flux noise of trilayers in which each layer had been patterned was significantly higher. The best flip-chip magnetometer had a white noise of 40 fT $Hz^{-1/2}$, increasing to 340 fT $Hz^{-1/2}$ at 1Hz; the corresponding flux noise levels were 9 $\mu\Phi_0$ $Hz^{-1/2}$ and 75 $\mu\Phi_0$ $Hz^{-1/2}$, respectively.

Short Title: Optimizing $YBa_2Cu_3O_{7-x}$ Flux Transformers

Classification numbers: 0755, 6855, 7270

1. Introduction

To exploit the high magnetic flux sensitivity of high transition temperature (T_c) Superconducting QUantum Interference Devices (SQUIDs) in measurements of magnetic field, one has to increase the effective area of the device. Considerable progress has been made with magnetometers that involve only a single $YBa_2Cu_3O_{7-x}$ (YBCO) film. For example, Zhang, *et al.* [1] have used rf SQUIDs with large area washers as sensitive magnetometers, while Koelle *et al.* [2] have developed magnetometers in which a dc SQUID is directly coupled to a single loop patterned in the same film. The performance of the first device was further improved by means of a flux focusser [1], and of the second by coupling it to a larger, single loop flux transformer deposited on a separate substrate [3]. To make further progress, however, particularly with the relatively small area magnetometers needed for biomagnetic measurements, it seems inevitable that one must use a planar flux transformer involving a multiturn input coil coupled to the SQUID. The inductance of this coil can then be matched to that of the pick-up loop to ensure optimum flux transfer. Such transformers require multilayer structures involving both crossovers and vias, and have been operated at 77K by a number of groups [4-9]. However, these patterned, multilayer films can produce significant levels of low-frequency 1/f noise [10, 11] arising from the thermally activated hopping of vortices trapped in the films (f is frequency). In this report, we describe our recent progress in improving our YBCO multilayer technology and fabricating flux transformers with lower 1/f noise.

2. Single films and trilayers

Since the 1/f noise of YBCO films decreases dramatically as their crystalline quality is improved [12], we first made systematic efforts to improve the quality of both our single-layer YBCO films and multilayer YBCO-$SrTiO_3$-YBCO films. We deposited our films *in situ* on (100) $SrTiO_3$ substrates, buffered with about 10 nm of $SrTiO_3$, using a pulsed KrF excimer laser. This substrate material replaces the MgO substrates we had used previously, and we believe the better lattice match to YBCO improved the quality of our films. We also made a substantial improvement in the film quality by reducing the laser power and thus the deposition rate from the 0.2 nm/pulse we had used in the past [4] to 0.07 nm/pulse. For single YBCO films 100-120 nm thick deposited with our optimized process, we measure $T_c = 89 - 90K$ and a critical current density j_c (77K) of (3-5) x 10^6 A cm^{-2}. For trilayers with a lower YBCO film of the same thickness, a 250-300 nm $SrTiO_3$ film and a 250-300 nm upper YBCO film we measure $T_c = 89K$ for the upper film. X-ray diffraction measurements indicate a high degree of c-axis orientation for both YBCO films and of (100) orientation for the $SrTiO_3$ film. We also measured the flux noise of trilayers by coupling them to a high-T_c dc SQUID in a flip-chip arrangement. The SQUID, immersed in liquid nitrogen, was operated in a flux-locked loop with a bias reversal scheme to reduce l/f noise due to critical current fluctuations. The dewar was surrounded with three mu-metal shields. Figure 1 shows that the trilayer did not increase the l/f noise of the SQUID above its rms value of $S_\Phi^{1/2}$ (1Hz) = 15 $\mu\Phi_0$ $Hz^{-1/2}$; here, $\Phi_0 \equiv h/2e$ is the flux quantum. This low value represents a considerable improvement over that for our earlier trilayers (0.2 nm / pulse, 300 nm for the lower YBCO film, 400 nm each for the $SrTiO_3$ and upper YBCO films), in which the noise of the upper YBCO film at 1Hz was always above $100\mu\Phi_0$ $Hz^{-1/2}$. We ascribe this decrease in noise to an improvement in the crystalline quality of all three layers.

3. Crossovers and vias

The noise of our *in situ* trilayers is in principle low enough to enable us to make quiet flux transformers. However, for this purpose, one must pattern each film in the multilayer separately, exposing each film to photolithographic processing and producing edges over which subsequent films must grow with a high degree of crystallinity if low noise is to be maintained. To study the properties of the various transformer components we fabricated test samples that enable us to make independent measurements of the lower and upper YBCO films, the crossovers where the two films pass over each other, the vias connecting them through the insulating layer, and the insulation itself. We patterned both YBCO films with photolithography and wet etching in 0.05% HNO_3; in addition, the patterned lower YBCO film was etched for 5-6 sec in a 1% solution of Br in methanol before subsequent depositions. We cut windows for the vias in the $SrTiO_3$ insulator using an Ar ion mill at a 60° angle of incidence. The milling process also removed all of the lower YBCO film in the window area, leaving only a beveled edge with which to make contact to the upper YBCO film.

With the film thicknesses listed above, we found j_c (77K) for the upper film remained at (2-3) x 10^6 A cm^{-2} even when it crossed the edges of the lower YBCO strip. This is a dramatic improvement over our earlier crossovers using thicker YBCO and $SrTiO_3$ films, apparently because the thinner lower YBCO film presents a more shallow edge to the subsequent insulator and YBCO layers. The vias, however, had much lower critical current densities. For a via 30 μm wide and a lower YBCO thickness of 100 nm the critical current I_c at 77K was typically 15 mA, corresponding to j_c (77K) $\approx 5 \times 10^5$ A cm^{-2}. This value of critical current is entirely adequate for flux transformers. The resistivity of the $SrTiO_3$ measured between the upper and lower YBCO films over an area of 20 μm x 100 μm was typically 10^8 Ω cm or higher, at 77K.

To investigate our crossovers and vias further, we performed scanning electron microscopy (SEM) and atomic force microscopy (AFM). From the SEM images we found that the edge of the wet-etched YBCO film can make an angle with the substrate as high as 90°. The Br etch rounds the edge, producing a slope of about 45° for film thicknesses below 150 nm. For thicker YBCO films, however, only the upper part of the edge is rounded, so that subsequent layers grow over a steep edge, presumably producing grain boundaries and disorder [13]. Figure 2 is an SEM image of a stripe patterned in an upper YBCO film grown over the patterned edge of a 100 nm YBCO film covered with a 300 nm $SrTiO_3$ film. The upper film grows relatively smoothly over the edge and on both the $SrTiO_3$ film and the YBCO-$SrTiO_3$ bilayer (the YBCO is deposited first, followed by the $SrTiO_3$). However, we note several rather large particles, 100-150 nm high; although they do not seem to affect the electrical properties of the crossovers, they are potential sources of low-frequency noise.

Figure 3 shows an AFM image of part of a completed via. The angled ion milling produces a nicely beveled edge, with a slope of 7°-10°, over which the upper YBCO film grows quite smoothly. The large particles at the upper edge of the via are caused by redeposition of ablated material during ion milling of the window, and we believe that they inhibit the epitaxial growth of YBCO in the upper layer. However, we can easily remove them by rotating the sample by 90° about an axis normal to the film surface immediately after cutting the via and ion milling for 1min.

4. Flux transformers

Using the procedures outlined above, we fabricated a series of flux transformers with either 10 or 16-turn input coils and pickup loop areas of either 68 or 81 mm^2. Both the input coil and pickup loop were patterned in the lower YBCO film, with linewidths of 7μm and 1mm, respectively. The width of the crossover, patterned in the upper YBCO film, was 50μm. Of the 8 transformers we made, 7 operated at 77K. However, 4 of the 8 transformers, including the one that failed to operate, were fabricated before we learned to remove the redeposited material near the via mentioned above. Additionally, we fabricated one transformer with an open pickup loop, and measured T_c (R = 0) = 89.5K and I_c (77K) = 20 mA; we believe the latter was limited by the via at the inner turn.

To make magnetometers, we coupled each transformer in turn to a dc SQUID in a flip-chip arrangement. The SQUID was patterned in a 300 nm-thick YBCO film deposited on a 24° $SrTiO_3$ bicrystal, and has inner and outer dimensions of 25μm and 500μm [10]. Figure 4 shows the magnetic field noise $S_B^{1/2}(f)$ of our best magnetometer with a 16-turn input coil and a pickup loop area of 81 mm^2. This device had a magnetic field gain [6] of 70, yielding $S_B^{1/2} = 40$ fT $Hz^{-1/2}$ in the white noise region [14] and $S_B^{1/2}$ (1 Hz) = 340 fT $Hz^{-1/2}$. The latter value represents an improvement of a factor of 5 over our best multiturn flux transformer reported previously [10], measured with the same SQUID. Nevertheless, the rms flux noise at 1Hz is $75\mu\Phi_0$ $Hz^{-1/2}$, a factor of 5 above the noise of the bare SQUID. However, we note that more typical values for the rms flux noise of our magnetometers are 110 to 130 $\mu\Phi_0$ $Hz^{-1/2}$ at 1 Hz. Thus, despite their excellent electrical transport properties, the flux transformers still dominate the low-frequency resolution of the magnetometers.

To investigate the origin of the flux noise, on some of the flux transformers we patterned an *ex situ* trilayer on a small portion of the pickup loop and a $SrTiO_3$-YBCO bilayer inside the pickup loop, either of which we could position directly over the high-T_c SQUID. Although the results are not conclusive, we found that in most cases the *ex situ* trilayers were the noisiest part of the multilayer structure. However, we cannot rule out the possibility that the vias also contribute to the magnetometer noise. We have also found that moving the multilayer parts a few tens of micrometers further away from the SQUID hole causes the rms flux noise to decrease faster than the magnetic field gain. This indicates that the dominant source of noise is the direct coupling of moving vortices in the flux transformer to the SQUID [11]. This finding is in contrast with the earlier result [11] in which "indirect noise", that is noise currents in the transformer generated by vortex motion in the transformer films, was the dominant source. In the present experiments, the flux transformer is much closer to the SQUID (about 3-10 μm separation) than in ref. [11], and the direct noise is consequently enhanced relative to the indirect noise.

5. Concluding remarks

We have improved our interconnect technology by reducing both the deposition rate and the thicknesses of the YBCO and $SrTiO_3$ films. These changes have resulted in substantial increases in the critical currents of crossovers and flux transformers. The flux noise of *in situ* trilayers is also much lower, but the flux noise of our best transformer, although much lower at 1Hz than in our earlier transformers, is still 5 times higher than the noise of our typical dc SQUIDs operated with bias reversal. We believe that the flux noise arises in the crossover and possibly in the via of the flux transformer. Thus, we must make further improvements in the fabrication process if the multiturn flux transformers are to achieve the low-frequency performance of our single layer magnetometers [2, 3].

Acknowledgments

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[14] We note that the white flux noise in Fig. 4 is higher than that in Fig. 1, for reasons that are not clear.

Figure Captions

Figure 1 Spectral density of magnetic flux noise, $S_\Phi(f)$, vs. frequency for an optimized *in situ* YBCO-$SrTiO_3$-YBCO trilayer. The dashed line shows the flux noise spectral density of the high-T_c SQUID alone.

Figure 2 SEM image of a strip patterned in the upper YBCO film (top part of figure) crossing the edge of the lower YBCO film which is covered with $SrTiO_3$ (lower part of figure). Dark region in central portion of figure is the edge of the upper YBCO film.

Figure 3 AFM image of the upper YBCO strip running over the beveled edge of a via cut by Ar ion milling (top portion of figure). Lower left portion of figure is $SrTiO_3$ film with beveled edge lying on top of lower YBCO film, the edge of which is visible. Lower right region is ion milled $SrTiO_3$ substrate.

Figure 4 Rms magnetic field noise, $S_B^{1/2}(f)$, and spectral density of flux noise, $S_\Phi(f)$, vs. frequency for 16-turn flux transformer coupled to a 40 pH dc SQUID. The dashed line indicates the flux noise spectral density of the bare SQUID.

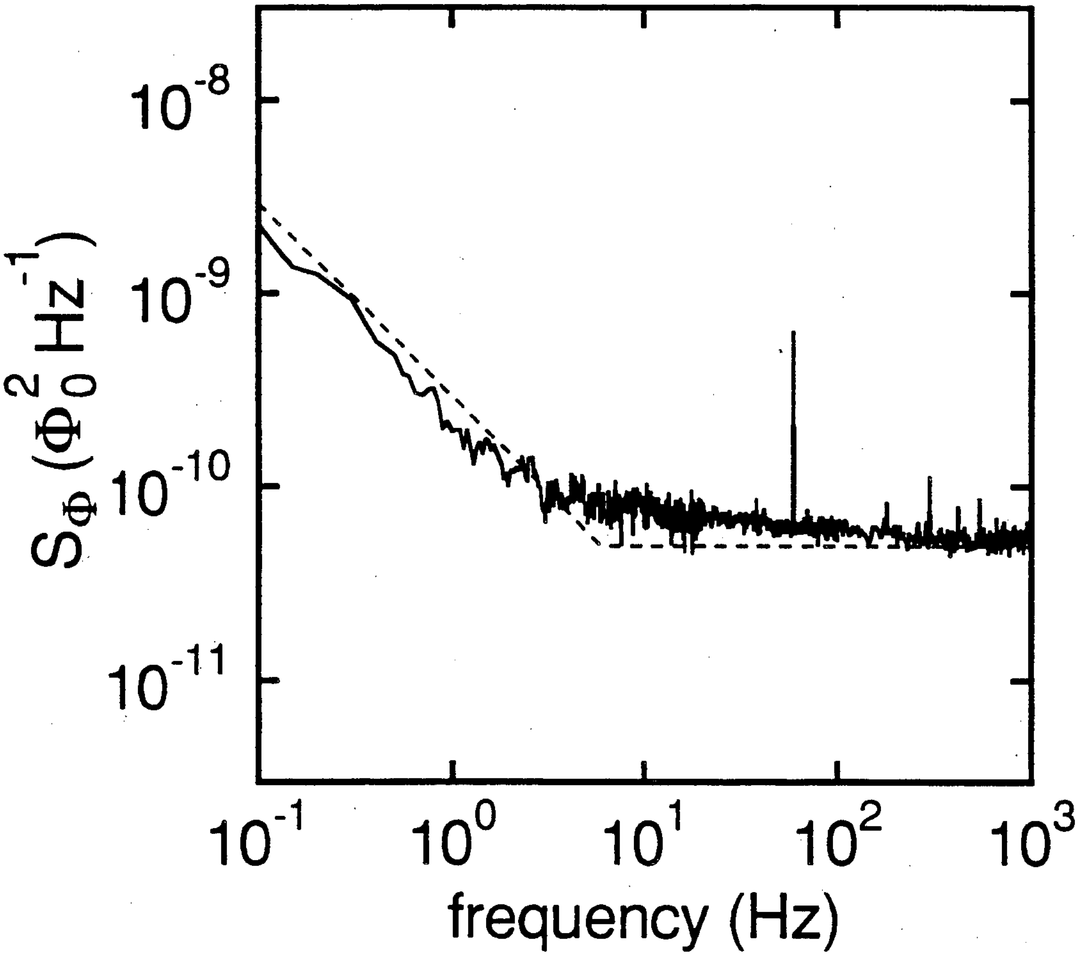

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Fig. 1

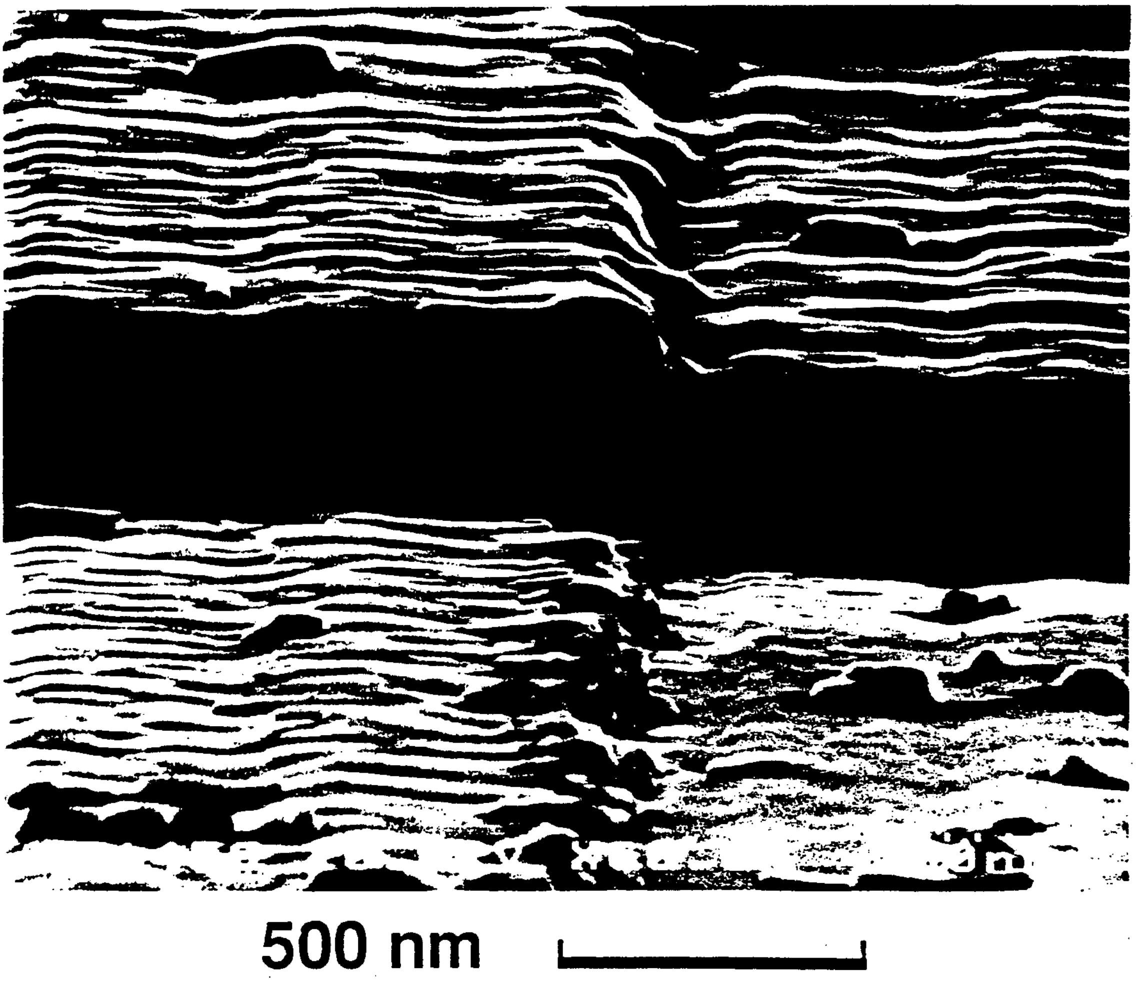

Fig. 2

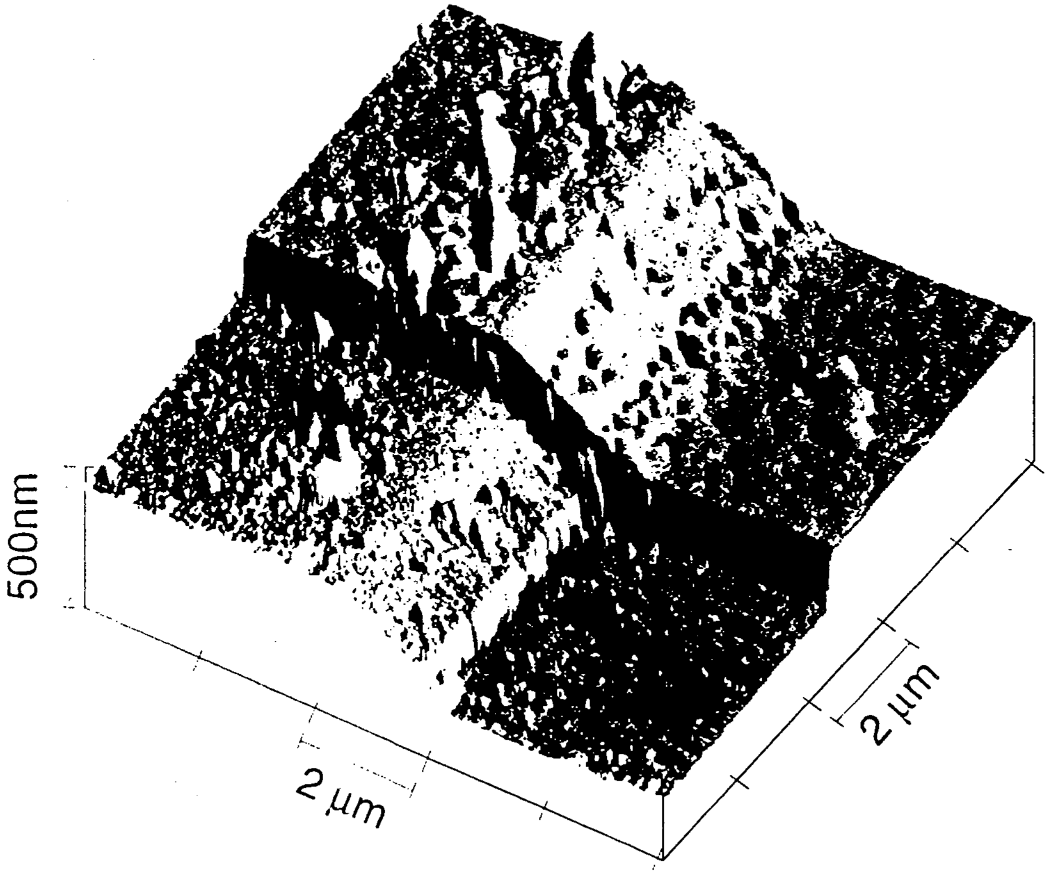

Fig. 3

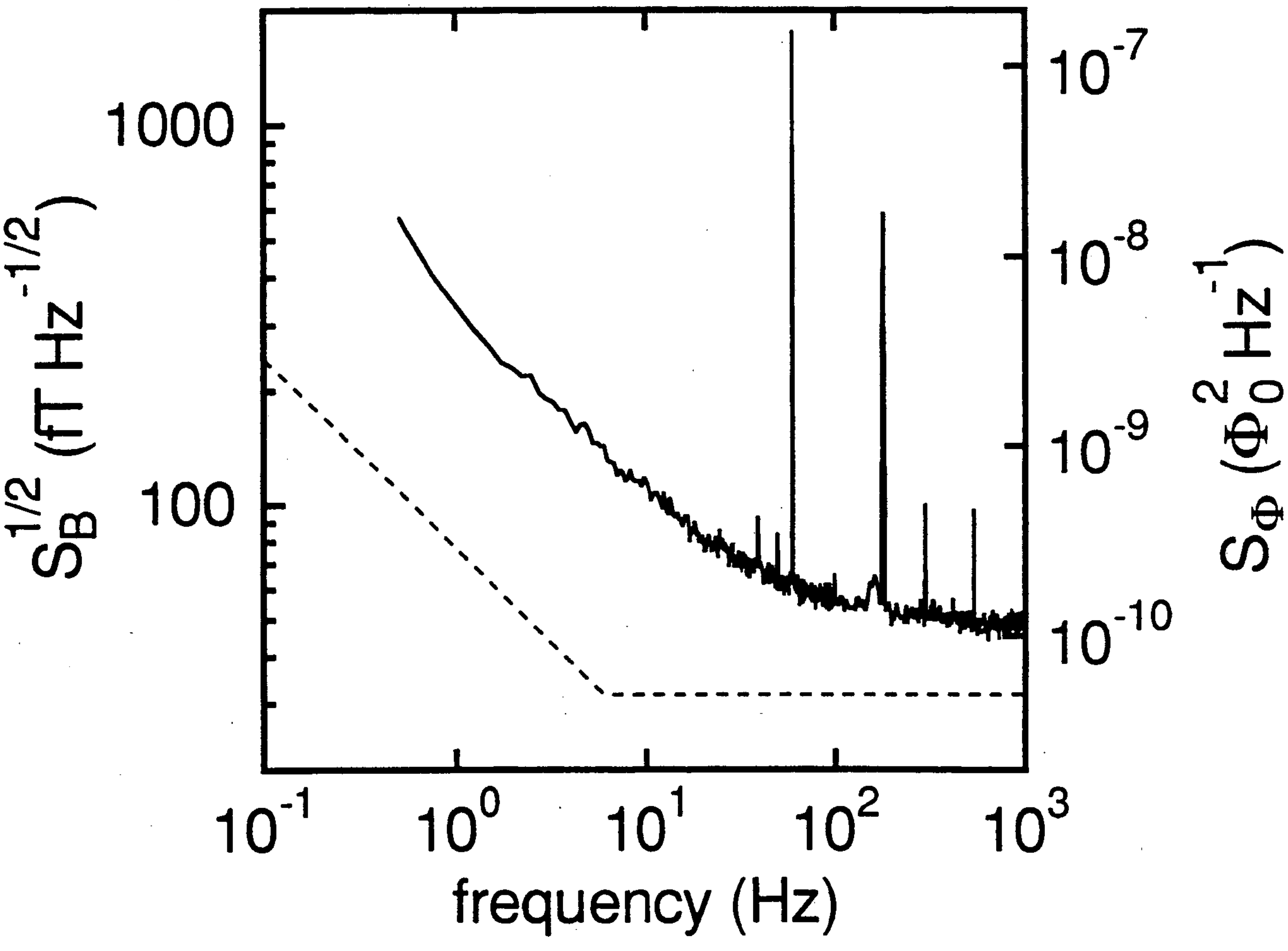

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Fig. 4

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