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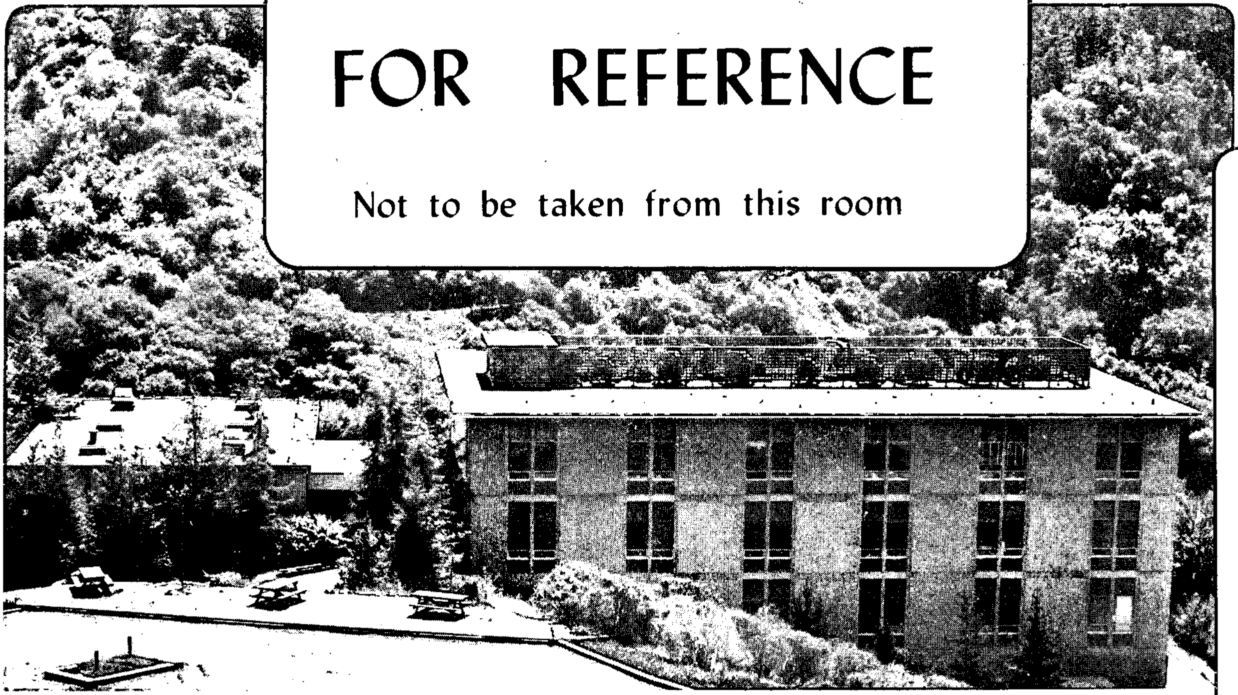

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# Thin-Film High Temperature Superconducting Flux Transformers Coupled to SQUIDs

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**Abstract.** Using photolithographic patterning and laser deposition, we have constructed a sensitive thin-film SQUID magnetometer from $YBa_2Cu_3O_{7-x}$ (YBCO). The device consists of a flux transformer, deposited on one substrate, which is coupled to a thin-film YBCO SQUID, made with bi-epitaxial junctions, deposited on another substrate. At 77K, the magnetometer has attained a sensitivity of $1.8 pTHz^{-1/2}$ at 1Hz, and has been used to measure the magnetic signal from the human heart.

## 1. Introduction

The development of a thin-film superconducting microelectronics technology using high transition temperature ($T_c$) superconductors requires the ability to produce just five basic circuit components. These are: (1) thin-film wires, (2) superconducting contacts or connections between wires, (3) superconducting to normal metal contacts, (4) multilayer wiring or crossovers, and (5) Josephson weak links or tunnel junctions. It is somewhat remarkable that this is all that is required to produce almost any superconducting circuit of interest, provided that all the components can be reliably constructed on the same substrate.

For a variety of reasons, our investigation of circuit construction techniques utilizing YBCO has focussed on the development of magnetometers based on the Superconducting Quantum Interference Device (SQUID). Most importantly, the magnetometers utilize all five of the basic components, but require only a small total number of components. In addition, because the SQUID can be utilized to measure current, voltage or flux, the circuit itself can provide a sensitive measure of the integrity of the circuit. Finally, a sensitive 77K magnetometer may be useful in a number of applications and may well find early commercialization.

## 2. YBCO Flux Transformers

A flux transformer is a closed superconducting circuit consisting of a relatively large area pickup coil connected to a smaller area multiturn input coil. Application of a magnetic field to the pickup coil induces a screening current which flows through the input coil, thereby coupling flux into the SQUID. For maximum sensitivity to magnetic field, the pickup coil should be a single loop which is made as large as possible, the input coil should be the same size as the SQUID, and the number of turns on the input coil should give the input and pickup coil the same inductance. The main difficulty in making a flux transformer is that a thin-film superconducting connection must be made to the inner turn of the input coil, see Fig. 1(a). This connecting line must not electrically short circuit the turns, and thus crossovers are needed.

In our initial development of flux transformers we used *in situ* pulsed laser deposition of $SrTiO_3$ insulating layers and the YBCO films.[1] We patterned the transformers using shadow masks for the first two layers, followed by photolithography on the last layer. The advantages of the shadow masks are that they are simple to use, no chemicals are required to do the patterning, and the masks produce smoothly sloping edge profiles which are easily covered by layers deposited subsequently. This work was quite successful in that we constructed flux transformers which operated up to 77K.[1] However, it is difficult to extend the use of shadow masks to make small features, complex patterns, or patterns which would require unsupported masks.

The shortcomings of shadow masking have lead us to develop more general techniques which use photolithography and etching to define the layers.[2] The input coil of a photolithographically patterned flux transformer is shown in Fig. 1(a). The size of the input coil was chosen to fit a typical high $T_c$ SQUID; it is about 250μm on a side, and has 5 turns of 10μm linewidth and an inductance of approximately 5nH. The pickup coil is approximately 10mm on a side, and has an effective pickup area of about $81mm^2$ and an inductance of about 20nH.

To build the flux transformer we first deposit 300nm of YBCO onto a (100) MgO substrate.[2] We use photolithography and a weak nitric acid etch to form the contact line which connects to the inner turn of the input coil. The resist is stripped with ethanol and the surface of the YBCO is etched clean using a bromine in methanol solution. We deposit a 400nm layer of $SrTiO_3$; this thickness is required to prevent shorts arising from the sharp edge remaining after etching the first YBCO layer. The substrate is covered with a layer of photoresist about 2μm thick, which is then developed to open two small windows for contacts to the connecting line. We use an Ar ion beam to etch through the $SrTiO_3$ to expose the surface of the YBCO in the two contact regions. The etching is done at an angle of $30^o$ to the surface using beam parameters of approximately $0.5mAcm^{-2}$ and 600V. This produces a shallow, $8^o$ sloped $SrTiO_3$ edge on one side of the windows. Finally, we deposit 400nm of YBCO and pattern it to form the pickup loop and the turns of the coil using photolithography and a weak acid etch.

The shallow slope of the $SrTiO_3$ edge produced by ion milling at $30^o$ yields contact structures which can support critical current densities as high as $10^6Acm^{-2}$ at 77K (referred to the cross-sectional area of the thin-film wires making the contacts).[2] The completed flux transformer has a critical current of about 2mA at 77K, corresponding to a critical current density of $10^5Acm^{-2}$ in the turns of the coil.

We believe that this reduced critical current density is due to portions of the last YBCO layer which cross $SrTiO_3$ deposited over a lower YBCO edge.

## 3. Bi-epitaxial Junction SQUIDs

At present, there are no techniques for producing Josephson tunnel junctions in YBCO with hysteretic current-voltage characteristics. Nonetheless, significant advances have been made in the construction of non-hysteretic Josephson junctions. In particular, Char *et al.* [3] have used "seed layers" of MgO to grow YBCO with different orientations on a sapphire substrate. The technique allows 45°, "bi-epitaxial" grain boundary junctions to be placed anywhere on a substrate using photolithography.

The SQUIDs are formed by first using standard *in situ* pulsed laser deposition to deposit a 3 to 10nm layer of MgO on an r-plane sapphire substrate. The MgO is patterned photolithographically and ion beam etched to leave MgO on a region of the substrate. A 10 to 100nm layer of $SrTiO_3$ is then laser deposited, followed by a 300nm layer of c-axis oriented YBCO. The $SrTiO_3$ grows with one orientation on the MgO and with its axes rotated by 45° about the c-axis on the sapphire. The YBCO replicates the orientation of the underlying $SrTiO_3$, giving rise to 45° grain boundary junctions where the two regions meet. The YBCO layer is patterned using photolithography and an acid etch to form the SQUID.

Figure 1b shows a completed SQUID which has outside and inside dimensions of 250μm and 25μm, respectively, and an inductance of approximately 100pH. The SQUID used in the following measurements operates up to about 83K. At 77K, the device showed a heavily noise rounded current-voltage characteristic, with a critical current of about 1μA and a dynamic resistance of 2Ω.

## 4. All High-Tc Magnetometer

To form a magnetometer,[4] the SQUID chip was covered with a 3μm thick sheet of mylar and the flux transformer chip was pressed against it, face-to-face. The SQUID was visually aligned with the input coil of the flux transformer to achieve good coupling. We find that the flux transformer typically increases the magnetic field response of the SQUID by a factor of from 40 to 80, the variation probably arising from small differences in the spacing or alignment between the SQUID and input coil.

We determined the magnetic field sensitivity by measuring the performance of the system when operated in a flux-locked loop and surrounded by a mu-metal shield. At frequencies, f, below 50Hz, we find low frequency noise with a 1/f power spectral density. At 77K the rms noise magnitude is typically about $10^{-3}\Phi_0 Hz^{-1/2}$ at 1Hz, where $\Phi_0$ is the flux quantum. With a magnetometer gain of 83, this yields a magnetic field sensitivity of about $1.8 pTHz^{-1/2}$ at 1 Hz. The low frequency noise depends only weakly on temperature; the sensitivity is approximately $1 pTHz^{-1/2}$ at both 4.2K and 68K. [4]

We had earlier measured the noise in flux transformers (made with shadow masks) using a low noise, low $T_C$ SQUID.[5] Noise arising from the motion of vortices in the input coil of the flux transformer was readily observed and greatly dominated any noise from the SQUID itself. In the present arrangement, however, the noise (expressed as flux units in the SQUID) was the same whether or not the flux transformer was attached, provided the system was magnetically well-shielded. Thus the sensitivity of this high $T_C$ magnetometer is dominated by the noise arising in the SQUID. This difference occurs, first, because the noise power at 1Hz in the high $T_C$ SQUID is 4 orders of magnitude higher than in the low $T_C$ SQUID, and second, because the geometry of the present flux transformer results in significantly less noise coupled into the SQUID.

This magnetic field sensitivity is sufficient for some applications. As an example, we have used our magnetometer to obtain magnetocardiograms from human subjects. To shield against external noise sources, we surrounded the subject with two concentric cylinders of Hypernom which provided a low frequency magnetic field attenuation of about 300. The shields were placed in a Cu and steel plate shielded room to minimize rf interference, and the SQUID output was bandpass filtered to the range of 2Hz to 50Hz. In the absence of a subject, the noise level of the SQUID in this range was identical to that found in a well-shielded environment, with the exception of a few small peaks from external sources.

The SQUID and flux transformer were immersed in liquid nitrogen kept in a thin-walled glass dewar. The magnetometer was rigidly held by a support with the pickup coil at a distance of 10mm to 20mm from the subject's chest, and oriented with the plane of the pickup coil parallel to the surface of the chest. To prevent spurious magnetic signals, we removed all metallic objects from the subject, who was in a standing position leaning against a backrest to minimize motion.

Figure 2 shows a magnetocardiogram taken with the magnetometer. The signal is consistent with the expected magnetic signal from the human heart;[6] the large peaks were found to be synchronous with the subject's pulse and to correspond to the main stroke or QRS part of the heartbeat. While the magnetic signal is well-resolved, noise is still evident in the traces. Most of this arises from 60Hz powerline interference and the low frequency noise from the SQUID. For clinical use, another order of magnitude increase in the sensitivity would be preferable. We believe that such an increased sensitivity will be readily achievable, for example, by increasing the size of the pickup coil to 25mm and using a matched and well-coupled input coil. In addition, an understanding of the low frequency noise and how it is affected by the fabrication technique may well lead to devices with better performance.

We note in concluding that very recently, using a 7-layer process, L. Lee *et al.* [7] have succeeded in constructing an integrated magnetometer, i.e. with the SQUID and flux transformer on the same chip. The device functions as a magnetometer, but at the time of writing the performance was still being evaluated.

## 5. Acknowledgements

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## References

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## Figure Captions

FIG. 1. (a) 5-turn input coil of a photolithographically patterned YBCO flux transformer; (b) YBCO dc SQUID with bi-epitaxial junctions. Arrow points to side of one junction formed at boundary between YBCO grown on MgO seed layer (light, upper portion of photograph) and YBCO grown without seed layer (darker, lower portion of photograph).

FIG. 2. Magnetocardiogram from a healthy adult male subject. The magnetometer was positioned 10 to 20 cm from the subject's chest, below the rib cage and slightly to the left of center.

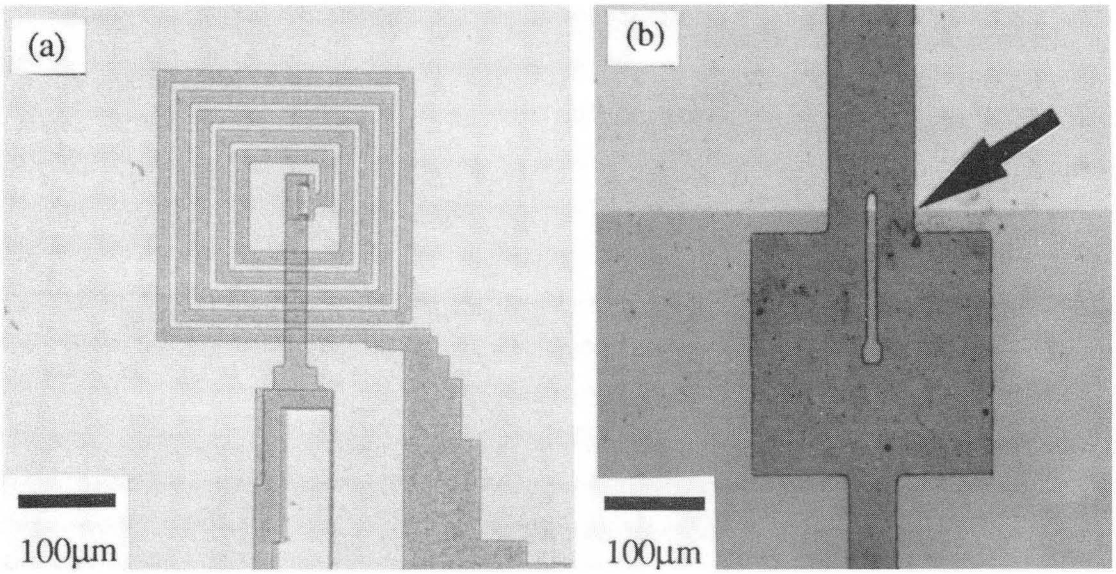

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Figure 1

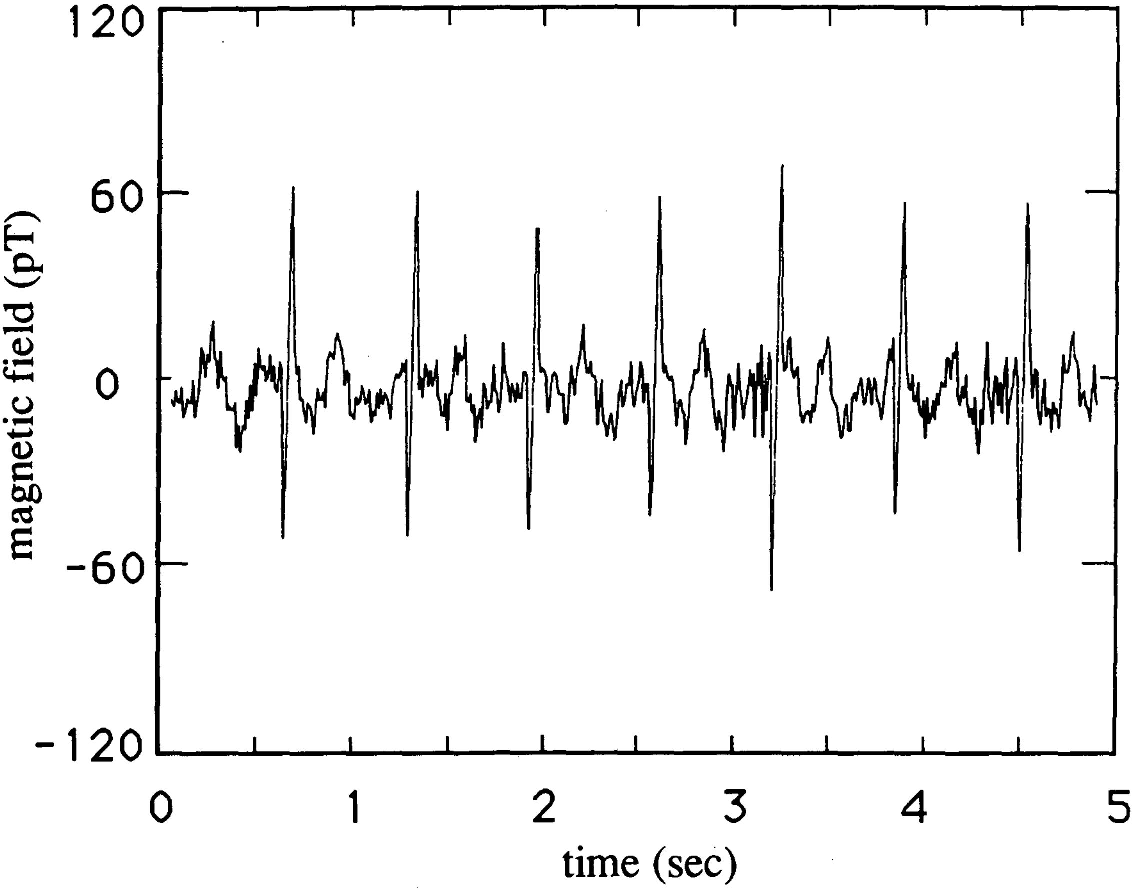

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Figure 2

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