Title
High-T{sub c} Thin-Film Microelectronics

Permalink
https://escholarship.org/uc/item/3sz6q52r

Authors
Clarke, J.
Quan, D.
Ferrari, M.J.
et al.

Publication Date
1990-11-01

LBL-29794

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Materials & Chemical Sciences Division

Presented at the International Symposium on
Superconductivity (ISS'90), Sendai, Japan,
November 7–9, 1990, and to be published in
the Proceedings

High-T_c Thin-Film Microelectronics

J. Clarke, D. Quan, M.J. Ferrari, A.H. Miklich, J.J. Kingston,
F.C. Wellstood, and M.S. Colclough

November 1990

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-29794

High-T_C Thin-Film Microelectronics

John Clarke, Du Quan, M.J. Ferrari, A.H. Miklich, J.J. Kingston,
and F.C. Wellstood

Department of Physics,
University of California, Berkeley

and

Materials Sciences Division,
Lawrence Berkeley Laboratory
University of California,
Berkeley, CA 94720, U.S.A.

M.S. Colclough,
Conductus, Inc.,
969 West Maude Avenue,
Sunnyvale, CA, 94086, U.S.A.

This work was supported by Conductus, Inc., the California Competitive Technology Program and by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under contract number DE-AC03-76SF00098.

High-T_c Thin-Film Microelectronics

John Clarke, Du Quan, M.J. Ferrari, J.J. Kingston, A.H. Miklich, and
F.C. Wellstood,
Department of Physics, University of California, Berkeley
and
Materials Sciences Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720, U.S.A.
M.S. Colclough, Conductus, Inc., 969 West Maude Avenue,
Sunnyvale, CA, 94086, U.S.A.

ABSTRACT

A complete microelectronics technology based on high-transition temperature superconducting thin films requires two key components: a reproducible Josephson weak link and a multilayer process for interconnects. Although many kinds of weak link have been studied, none is yet satisfactory for circuits involving more than a few elements. On the other hand, a viable interconnect technology has been developed in which two $YBa_2Cu_3O_{7-x}$ films may be either electrically isolated or connected via a superconducting contact. The junctions and interconnect technology have been used to produce magnetometers involving a flux transformer with a multiturn input coil coupled to a dc Superconducting QUantum Interference Device.

KEY WORDS: Junction, interconnect, SQUID, flux transformer

INTRODUCTION

In the four years since the discovery of the high transition temperature (T_c) oxide superconductors [1], there has been remarkable progress in the technology for fabricating thin films of these materials, particularly in the case of $YBa_2Cu_3O_{7-x}$ (YBCO). However, the ability to produce good single layer films is far from being sufficient to enable one to construct electronic circuits. A complete superconducting microelectronic technology also requires Josephson junctions [2] and interconnects; the latter involve superconducting contacts and electrically insulated crossovers between two superconducting layers. In this paper we briefly review the status of junctions and interconnects, and discuss their application to magnetometers based on dc Superconducting QUantum Interference Devices (SQUIDs) [3]. Needless to say, in such a brief review, we have been able to touch on only a fraction of all the work that has been published.

JOSEPHSON JUNCTIONS

The development of a controllable junction process remains the single greatest challenge for the creation of a successful high-T_c microelectronics technology. At this point, no well-defined Josephson tunnel junction - that is, with a current-voltage (I-V) characteristic exhibiting both a discontinuous switching to a well-defined energy gap and a high subgap resistance - has been fabricated from the liquid nitrogen temperature superconductors. On the other hand, a variety of structures with nonhysteretic I-V characteristics have been investigated, and we briefly describe the main types.

Grain boundary junctions. The first thin film junctions were formed from naturally occurring grain boundaries [4]. The junctions can be obtained by patterning a microbridge, typically a few micrometers in width and length, in a film of YBCO, $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) or $Tl_2CaBa_2Cu_2O_{8+z}$ (TCBCO) with grain sizes of the order of 1µm. Suitable c-axis oriented YBCO films may be grown, for example, on (100) MgO substrates where the lattice mismatch is relatively large. Although the a- and b-axes have a preferential alignment along the cubic axis of the substrate, some grains are rotated by 45°; the fraction of such grains can be controlled by the growth conditions [5, 6]. The 45° grain boundaries so formed provide a region of lowered critical current density, and thus form one or more junctions in the microbridge. Junctions with relatively low critical current density ($\lesssim 10^5$ A cm^{-2}) can exhibit [5] almost ideal resistively shunted junction (RSJ) behavior [7], while those with higher critical current densities exhibit behavior consistent with flux flow and flux creep [5]. The nature of the junction remains elusive; the boundary layer between the weak links may be normal, semiconducting, insulating (albeit with a linear quasiparticle resistance) or superconducting with a reduced energy gap.

Grain boundary junctions on bicrystals. A more controlled grain boundary junction has been devised by Dimos *et al.* [8]. In this technique, a $SrTiO_3$ substrate is cut and fused together to form a bicrystal with a misorientation that can be chosen at will, and the microbridge is deposited across the interface. Thus, the grains on the two sides of the boundary have a predictable relative orientation θ, and the critical current has a relatively reproducible dependence on θ. As with naturally occurring grain boundary junctions, the I-V characteristics for lower critical currents are close to the predictions of the RSJ model.

Step-edge microbridges. Simon *et al.* [9] have fabricated microbridges by etching a sharp step in the substrate and depositing a film across the step with a thickness less than the step height. The important feature of this process is the formation of a sharp step edge so that the length of the junction is made as short as possible. Once again, the details of the junction structure are not entirely clear, but transmission electron microscopy suggests that a grain boundary is formed at the step edge. These junctions exhibit a supercurrent at and above 77K, and have I_oR products of several millivolts at 4.2K (I_o is the critical current and R the resistance).

Other "weakened" structures. Various other techniques have been devised to weaken the superconductivity over a restricted length. In one process [10], a YBCO film is deposited over a thin Al stripe which "poisons" the superconductor and yields a weak link structure. In another method [11], one focuses high energy ions on to a microbridge [12] or uses an electron-beam lithographically patterned mask to define the area exposed to an unfocussed ion beam [13]. It is likely that the irradiation destroys the superconductivity in most of the film, leaving narrow superconducting filaments connecting the banks of unirradiated film. In yet another technique [14], controlled electrical pulses were applied to a microbridge at 77K, producing a weakened region that, again, possibly consisted of narrow superconducting threads.

Normal metal bridges. Schwarz and coworkers [15] fabricated superconductor-normal metal-superconductor (SNS) junctions by depositing a strip of Au across a narrow slit (~100nm) in a YBCO film. Provided there is a good proximity effect between the YBCO and the gold, one would expect a substantial supercurrent for bridges as long as $10\xi_N$ or more, where $\xi_N = \hbar v_F/2\pi k_B T \sim 15$ nm at 77K is the decay length [16] (v_F is the Fermi velocity). In fact, a supercurrent was observed, but only up to about 16K, implying that the Josephson coupling energy was extremely small. Subsequently, other measurements [17] have shown that the proximity effect is extremely weak along the direction of the c-axis, so that the weak coupling is not surprising.

Planar junctions. Rogers *et al.* [18] fabricated planar YBCO-PrBCO-YBCO junctions in which the PrBCO layer, typically 50nm thick, is nonsuperconducting. The YBCO films were c-axis oriented, and some junctions supported a supercurrent at temperatures as high as 65K. This type of junction has much to commend it, since the normal layer can have a much higher resistance than a noble metal, and the structure takes advantage of the natural epitaxy of the materials. However, it is now clear that c-axis oriented films yield a very weak proximity effect [17], and it is quite likely that the observed supercurrent arose from YBCO filaments extending through the normal layer.

Edge junctions. The first high-T_c edge junctions were made by Laibowitz *et al.* [19]. A film of c-axis oriented YBCO is deposited, followed by an insulating layer which is not necessarily epitaxial. The films are patterned into a narrow line, part of which is removed with an ion mill to leave an edge. After an "oxyfluoridation" process, a second film of YBCO is deposited and makes contact to the edge of the first film. Some of these edge junctions support supercurrents, although the yield is low. However, as with the PrBCO barriers, it is likely that the supercurrents were carried by YBCO filaments rather than by tunneling through a barrier. A variant on this technique has been made by Gao *et al.* [20], who deposited a PrBCO film followed by a YBCO counterelectrode over the tapered edge of the first YBCO film. All three films were c-axis oriented, so that supercurrent flowed along the ab-axes of the YBCO films. The yield was high, and for a PrBCO thickness of 6nm, the I_0R product was as high as 8mV at 4.2K.

$BaKBiO_3$ junctions. Before leaving the subject of junctions, we mention briefly the results obtained by Dynes and coworkers [21] on the isotropic material $BaKBiO_3$, which has T_c ~30K. By pressing a single crystal against a thin film, they achieved a classic quasiparticle tunneling curve as well as a Josephson current. Thus, one may be able to make thin film tunnel junctions with hysteretic behavior using this material.

In concluding this section, we note that although much useful information has been gained from the study of grain boundary junctions, the lack of control of their properties and location makes them unsuitable for use in circuits. Grain boundaries made deliberately on bicrystals or step edges offer a reasonable degree of reproducibility, and are of interest for circuits requiring a few junctions, but are not extendible to more complicated circuits. The structures that are weakened by poisoning, irradiation or electrical pulsing tend to be rather extended in the direction of current flow, possibly leading to a nonsinusoidal current-phase relation. Again, they may be useful for circuits with a few junctions, but are unlikely to find their way into complex circuits. The SNS junctions deserve further study now that a-axis films are available and one could hope for a stronger proximity effect. These junctions could, in principle, become reasonably reproducible, but the low I_0R product arising from the low resistivity of the metal is likely to be a drawback in most applications. However, one obtains a higher resistance using PrBCO barriers, and, in configurations such as edge junctions in which the current flows along the a-axis, there is a good chance that a successful technology will emerge. Finally, if one can fabricate $BaKBiO_3$ thin film junctions, these may be attractive for computer elements operated at (say) 15K in a closed-cycle refrigerator.

INTERCONNECTS

We turn now to a discussion of interconnects, which involve superconducting connections and electrical isolation between superconducting layers. To minimize interdiffusion between layers, it is probably essential that such films be deposited using *in situ* techniques, and YBCO is at present the superconductor of choice. The constraints on the insulating layer are demanding, and include (i) epitaxial or highly oriented growth on both the substrate and on YBCO; (ii) low interdiffusion and chemical reactivity with the substrate and YBCO at temperatures as high as 750°C; (iii) good coverage of and adhesion to YBCO and the substrate, particularly at edges and irregularities; (iv) the ability to support the growth of high quality YBCO films; and (v) high resistivity ρ at temperatures below T_c. The obvious choices for the insulator are much the same as for substrates: $SrTiO_3$, MgO, YSZ or $LaAlO_3$.

Kingston *et al.* [22] demonstrated a successful crossover technology using laser ablated films on MgO substrates, with $SrTiO_3$ as the insulator. The nominal substrate temperatures during deposition were 730°C and 690°C for YBCO and $SrTiO_3$, respectively, with an O_2 pressure of 190 mTorr in both cases. The films were patterned with stainless steel or etched Si shadow masks pressed against the substrate. The vacuum chamber was opened between depositions to allow the targets and masks to be changed. The first layer was an H-shaped YBCO film, and the second was a $SrTiO_3$ film, typically 0.4nm thick, that covered the crossbar of the H. The upper YBCO film consisted of two strips perpendicular to the crossbar. Figures 1(b) and (c) show the resistance R vs. temperature T for the lower and upper YBCO films; for comparison, Fig. 1(a) shows R vs. T for a single layer YBCO film. We see that the transition temperature and width are not significantly degraded in the trilayer. Figure 1(d) shows R vs. T measured between the two YBCO films, through the $SrTiO_3$

layer. The resistance at 77K, $\sim 10^8 \Omega$, corresponds to a resistivity of 4 x $10^9 \Omega$cm. This value is much higher than that needed for most applications. The excellent electrical characteristics of the crossover are due to the fact that each film grows epitaxially, as demonstrated by high resolution transmission electron microscopy [23]. To investigate the properties of superconducting contacts, the same workers also fabricated cross-strips of YBCO with no intervening insulating layer. Despite the need to expose the first film to the atmosphere to change masks, there was no difficulty in obtaining contacts with high critical currents.

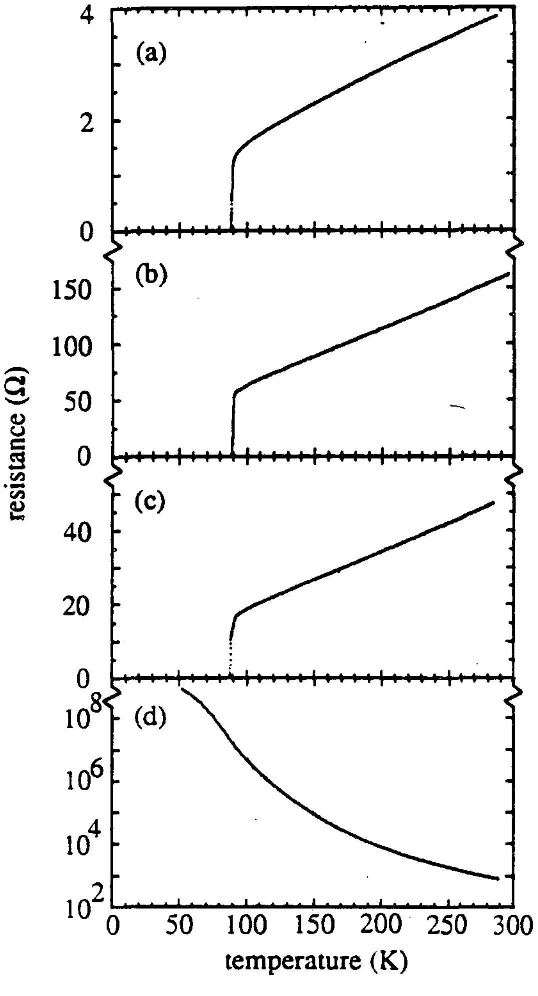

Fig. 1. Resistance (R) vs. temperature for (a) single-layer YBCO film deposited on MgO; (b) lower YBCO film of trilayer; (c) upper YBCO film of trilayer; (d) SrTiO3 insulating layer measured between the upper and lower YBCO films [22].

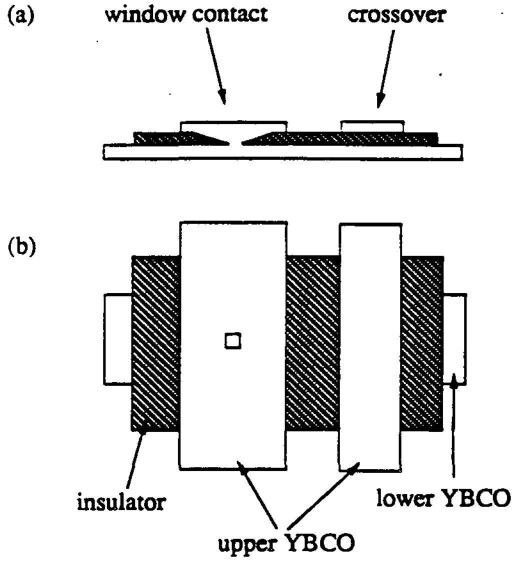

Fig. 2. (a) Cross-sectional view and (b) top view of window contact (left) and crossover (right) [24].

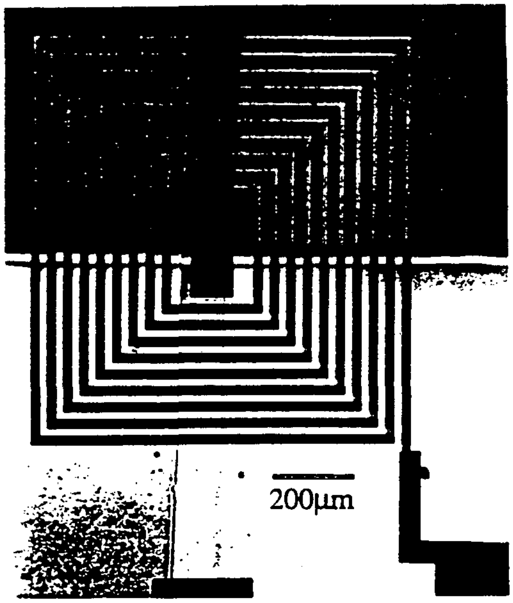

Fig. 3. Photograph of 10-turn coil; first two layers were patterned with shadow masks, upper layer patterned photolithographically [34].

Although shadow masks may be satisfactory for small numbers of devices with not-too-narrow linewidths, it is clear that a process in which each layer is patterned photolithographically is preferable for most applications. A suitable process has been developed by Kingston *et al.* [24]. There are two particular problems to be overcome when one replaces shadow masks with photolithographic patterning. First, while a shadow mask produces a line with rounded edges, photolithography followed by an etch tends to yield sharp edges that are more difficult to insulate. Second, exposure of YBCO films to photoresist leaves a layer of contamination that often prevents the epitaxial growth of subsequent layers. Both problems can be ameliorated by etching the surface in a 2% solution of Br in methanol. Figure 2 shows a window contact and an insulating crossover. After the first YBCO film is patterned, it is etched in the Br solution prior to the deposition of the $SrTiO_3$ layer. The window in the $SrTiO_3$ is patterned by means of an ion mill and a resist mask. An important consideration is the need to bevel the edges of the insulator to support the epitaxial growth of the upper YBCO film. The bevel was obtained by exposing the resist somewhat out-of-focus and subsequently ion-milling the sample. No Br etch is used prior to the deposition of the upper YBCO film; the ion mill apparently leaves a sufficiently clean, albeit somewhat damaged, YBCO surface. The crossover is made by a similar process to that used for the contact, with the omission of the patterning of the window.

It is evident that the basic technology for interconnects now exists. However, for some applications, the dielectric constant of $SrTiO_3$ may be far too high and other insulators may be required; to this end, Kingston *et al.* [25] have produced satisfactory crossovers using YSZ.

DC SQUIDS

Using the junction and interconnect technology described above, a number of groups have begun to produce more complicated structures. The first of these was a dc SQUID, made by Koch *et al.* [4] from YBCO, which relied on grain boundary junctions. The device was in the form of a square washer with an inner hole of side $d \approx 50\mu m$ with an estimated inductance $L = 1.25\mu_o d \approx 60pH$. Subsequently, numerous other workers [26] have described grain boundary SQUIDs made from YBCO, and similar devices made from TCBCO [27, 28] and BSCCO [29] have also been reported. Recently, SQUIDs with more controlled junctions have been fabricated, notably grain boundary junctions on bicrystals [30] and edge junctions [19, 20]. Although it is not possible to review the properties of all these devices here, they do share one common feature, namely a high level of 1/f noise at low frequencies. The conventional figure of merit is the intrinsic noise energy per unit bandwidth $\varepsilon(f) = S_\Phi(f)/2L$, where $S_\Phi(f)$ is the spectral density of the flux noise. The quietest YBCO SQUID reported appears to be that of Gross *et al.*, [30] which had an estimated inductance of 60pH. At 77K, the noise energy was about 1.2×10^{-28} JHz^{-1} at 10Hz, improving approximately as 1/f to about 1.2×10^{-30} JHz^{-1} at 10kHz. The latter noise energy is the best yet reported for a SQUID at 77K and is close to the value predicted for the white noise $\varepsilon \approx 9k_BTL/R$ [31], where R is the resistance of each junction. However, at 77K, a TCBCO SQUID [27] with an estimated inductance of 80 pH was quieter at low frequencies, with a noise energy of about 5×10^{-29} JHz^{-1} at 10Hz; the noise energy fell off more slowly than 1/f, reaching about 10^{-29} JHz^{-1} at 1kHz.

At frequencies above 100 Hz, the noise energy obtained in the best devices is better than that in some commercially available Nb rf SQUIDs operated at 4.2K. However, the high level of 1/f noise remains a serious limitation at lower frequencies. Koch and coworkers have reported that this noise is not reduced by standard double modulation techniques [32], yet it appears not to arise from the motion of flux lines in the body of the SQUID. It is to be hoped that greater insight into this problem will be gained in the near future.

FLUX TRANSFORMERS AND MAGNETOMETERS

Although, as we have seen, progress has been made with thin film dc SQUIDs, it is important to realize that these devices are not particularly sensitive as magnetometers. The reason is simple: the need for low inductance reduces the area of the hole in the SQUID to typically $2500\mu m^2$. Even with a flux focussing factor of (say) 5, a flux noise $S_\Phi^{1/2}(1Hz)$ of 10^{-4} Φ_o $Hz^{-1/2}$ corresponds to a magnetic field sensitivity of 16 pT $Hz^{-1/2}$, a value that is not competitive with flux gate magnetometers. Thus, to achieve a high magnetic field sensitivity, it is essential to couple the SQUID to a superconducting flux transformer. These transformers consist of a multiturn input coil with inductance L_i, tightly coupled to the SQUID, connected to a pickup loop with a much larger area and inductance $L_p \approx L_i$. A single-turn input coil, for example that described by Oh *et al.*, [33] yields only a modest improvement in magnetic field sensitivity because L_p and L_i are not matched.

Multiple-turn coils and flux transformers have been made and tested by Wellstood and coworkers [34-36, 24], using their interconnect technology described above. In the early coils [34], the first two layers were patterned with shadow masks and the third layer with photolithography and an Ar ion mill etch. A photograph of a completed coil is shown in Fig. 3. The first layer was a YBCO strip, about 100µm wide, stretching from one side of the chip to the other. The second layer, $SrTiO_3$, covered approximately 2mm of the length of the YBCO strip. The entire chip was then covered with YBCO, which was subsequently patterned to produce either a 10-turn or a 19-turn coil. In the patterning process, parts of the YBCO strip between the turns of the coil were removed so that the turns were not shorted; however, a portion of this strip provided a superconducting connection between the pickup coil and the innermost turn of the input coil. The coil was approximately 1mm across, and the best sample had a transition temperature of 82K and a critical current at 77K of 1.4mA, corresponding to a critical current density of 2×10^4 Acm^{-2} in the turns of the coil. Subsequently, Kingston *et al.* [24] fabricated smaller coils 0.25mm across, in which all three layers were patterned photolithographically in the configuration of Fig. 4(a). A window contact was made between the first YBCO layer and the innermost turn of the coil, and between the outer end of the first YBCO film and one end of the YBCO pickup loop. A photograph of a completed coil appears in Fig. 5. The best of these microfabricated coils had a transition temperature of 87K and a critical current of 135µA at 82K (5µV measurement criterion).

Both large and small coils have been integrated into flux transformers by patterning the last layer to contain a 10 x 10mm^2 pickup loop as well as the input coil [see Fig. 4(b)]. The performance of the flux transformers was tested by coupling the input coil to a SQUID. In the first measurements, a

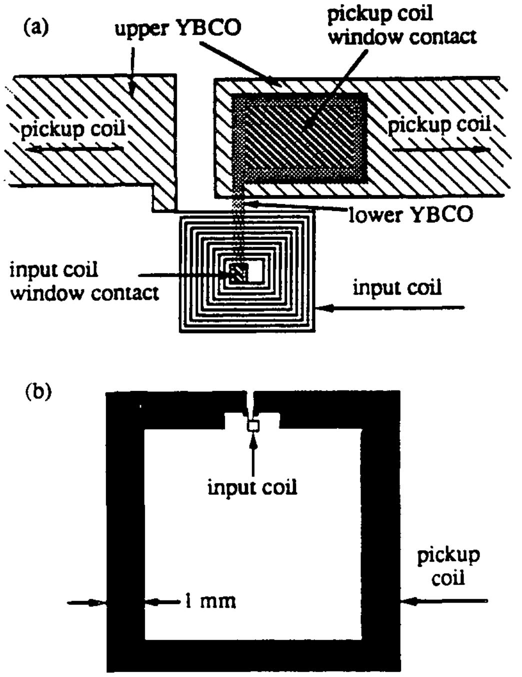

Fig. 4. Flux transformer: configurations of (a) input coil and connections to pickup loop, and (b) pickup loop (not to scale) [24].

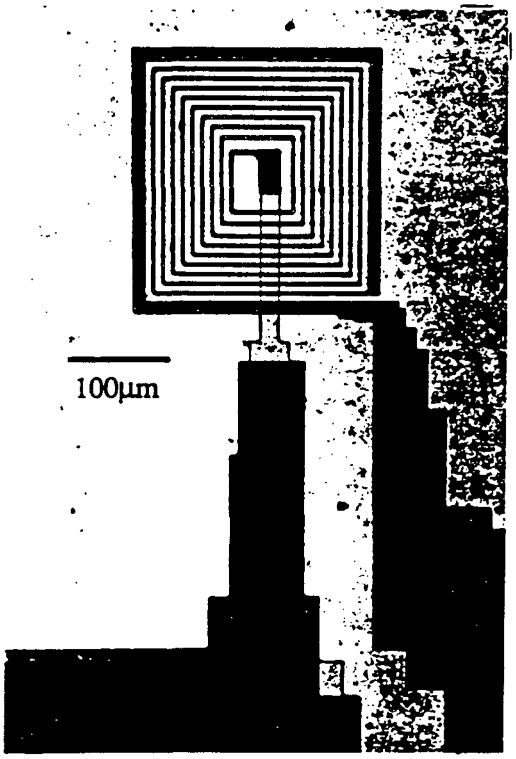

Fig. 5. Photograph of 10-turn input coil patterned as in Fig. 4(a) [24].

large transformer was coupled to a Nb-based SQUID [35, 36]. The magnetic field response was enhanced over that of the bare SQUID by a factor of 9.5. The noise was limited by 1/f noise in the transformer; the measured noise referred to the pickup loop was 0.9pT $Hz^{-1/2}$ at 1Hz and 60K.

Subsequently, both the large and small transformers were coupled to a TCBCO SQUID [28]. The large transformer had a gain of 7.5 and operated at temperatures up to 79K. The small transformer had a gain of 8.7 and ceased to operate at 25K. However, above 25K, it was found that the transformer contained a small resistance (~0.4 mΩ) which probably arose from a localized defect. The measured field sensitivities are shown in Fig. 6. In each case, external noise was observed, indicating that shielding of external magnetic field fluctuations was inadequate. The magnetic field sensitivities with the large transformer at 38K and the small transformer at 4.2K were very similar, about 3pT $Hz^{-1/2}$ at 10Hz and 0.35pT $Hz^{-1/2}$ at 1kHz. In both cases, the sensitivity was limited by noise in the SQUID; a quieter high-T_c SQUID should produce an improvement in the magnetic field sensitivity. If such an improvement can indeed be achieved, high-T_c magnetometers may well find their way into applications within one or two years.

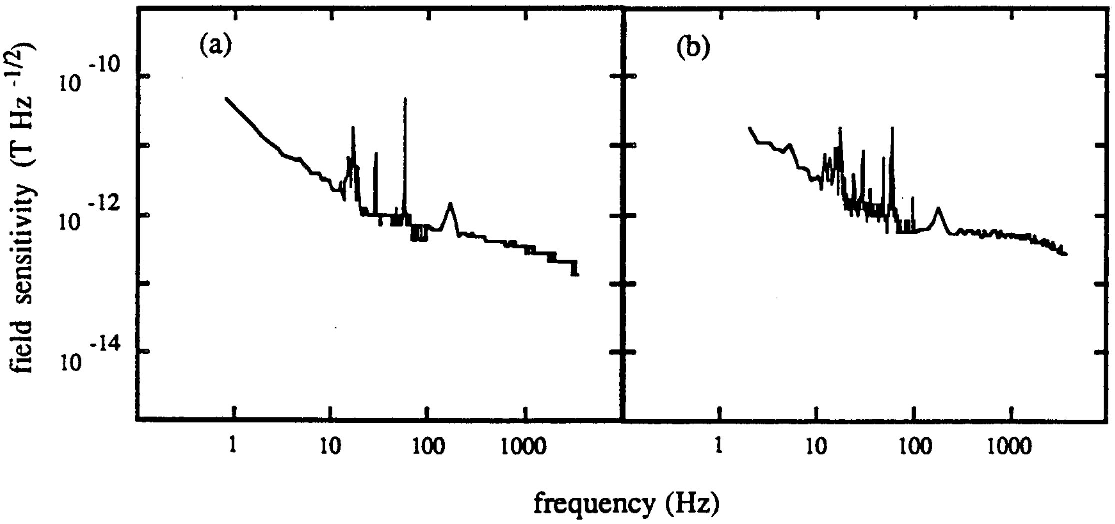

Fig.6 Field sensitivities B_N (f) of the magnetometer with (a) large flux transformer at 38 K and (b) small transformer at 4.2 K. The measured flux-locked bandwidths were ~ 3.5 kHz and 3.8 kHz respectively [28].

ACKNOWLEDGMENTS

We thank A.H. Cardona, L.C. Bourne, W.L. Olson and M.M. Eddy of Superconductor Technologies, Inc. for providing the TCBCO SQUID used in our own work. A.H.M. thanks the Hertz Foundation for a fellowship. The work was supported by Conductus, Inc., the California Competitive Technology Program and by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under contract number DE-AC03-76SF00098.

REFERENCES

1. Bednorz JG, Muller KA (1986) Z Phys.B 64: 189
2. Josephson BD (1962) Phys.Lett.1: 251
3. For a review, see, for example, Clarke J (1989) In: Weinstock H, Nisenoff M (eds) Superconducting Electronics. Springer-Verlag, Berlin, p 87
4. Koch RH, Umbach CP, Clark RJ, Chaudhari P, Laibowitz RB (1987) Appl.Phys. Lett.51: 200
5. Russek SE, Lathrop DK, Moeckly BH, Buhrman RA, Shin DH, Silcox J (1990) Appl.Phys.Lett.57: 1155
6. Newman N, private communication

7. McCumber DE (1968) J.Appl.Phys.39: 3113; Stewart WC (1968) Appl.Phys.Lett.12: 277
8. Dimos D, Chaudhari P, Mannhart J, LeGoues FK (1988) Phys.Rev.Lett.61: 219
9. Daly KP, Dozier WD, Burch JF, Coons SB, Hu R, Platt CE, Simon RW (unpublished)
10. Simon RW, Burch JF, Daly KP, Dozier WD, Hu R, Lee AE, Luine JA, Manasevit HM, Platt CE, Schwarzbek SM, St.John D, Wire MS, Zani MJ (1990) Proceedings of the Conference on the Science and Technology of Thin Film Superconductors, Denver, April 1990
11. White AE, Short KT, Dynes RC, Leir AFJ, Anzlowar M, Baldwin KW, Polakos PA, Fulton TA, Dunkleberger LN (1988) Appl.Phys.Lett.53: 1010
12. Zani MJ, Luine JA, Simon RW, Davidheiser RA (unpublished)
13. Cui G, Zhang Y, Hermann K, Buchal Ch, Schubert J, Zander W. Braginski AE, Heiden C (1990) LT-19 Satellite Conference on High Temperature Superconductors, Cambridge, England, August 1990
14. Robbes D. Miklich AH, Kingston JJ, Lerch Ph, Wellstood FC, Clarke J (1990) Appl.Phys.Lett.56: 2240
15. Schwarz DB, Mankiewich PM, Howard RE, Jackel LD, Straughn BL, Burhart EG, Dayem AH (1989) IEEE Trans.Magn.MAG-25: 1298
16. Clarke J (1969) Proc.Roy.Soc.A 208: 447
17. See, for example, Akoh H, Camerlingo C, Takata S (1990) Appl.Phys.Lett.56: 1487; Lee M, Lew D, Eom CB, Geballe TH, Beasley MR (1990) Appl.Phys.Lett.57: 1152
18. Rogers CT, Inam A, Hegde MS, Dutta B, Wu XD, Venkatesan T (1989) Appl.Phys.Lett.55: 2032
19. Laibowitz RB, Koch RH, Gupta A, Koren G, Gallagher WJ, Foglietti V, Oh B, Viggiano JM (1990) Appl.Phys.Lett.56: 686
20. Gao J, Aarnink WAM, Gerritsma GJ, Veldhuis D, Rogalla H (1990) Proceedings of the Applied Superconductivity Conference, Snowmass, Colorado, Sept. 24-28, 1990 (to be published)
21. Dynes RC (1990) Proceedings of LT-19, Brighton, England, August 1990
22. Kingston JJ, Wellstood FC, Lerch Ph, Miklich AH, Clarke J (1990) Appl.Phys.Lett.56: 189
23. Tidjani ME, Gronsky R, Kingston JJ, Wellstood FC, Clarke J (1990) (unpublished)
24. Kingston JJ, Wellstood FC, Du Q, Clarke J (1990) Proceedings of the Applied Superconductivity Conference, Snowmass, Colorado, Sept. 24-28, 1990 (to be published)
25. Kingston JJ, Wellstood FC, Clarke J (unpublished)
26. See, for example, Nakane H, Tarutani Y, Nishino T, Yamada H, Kawabe U (1987) Jap.J.Appl.Phys.26: L1925; Häuser B, Diegel M, Rogalla H (1988) Appl.Phys.Lett.52: 844; Katoh Y, Asahi M, Asano H, Michikami O (1988) Jap.J.Appl.Phys.27: L1110; Takeuchi I, Tsai JS, Tsuge H, Matsukara N (1988) Jap.J. Appl.Phys.27: 2265; Golovashkin AI, Gudkov AL, Krasnosvobadtsev SI, Kuzmin LS, Likharev KK, Maslennikov YV, Pashkin YA, Pechen EV, Snigirev OV (1989) IEEE Trans.Magn.MAG-25: 943; Irie A, Sashara H, Yamashita T, Kurosawa H, Yamane H, Hirai T (1990) Proceedings of the Applied Superconductivity Conference, Snowmass, Colorado, Sept. 24-28, 1990 (to be published)
27. Koch RH, Gallagher WJ, Bumble B, Lee WY (1989) Appl.Phys.Lett.54: 951; Foglietti V, Koch RH, Gallagher WJ, Oh B, Bumble B, Lee WY (1989) Appl.Phys.Lett.54: 2259
28. Miklich AH, Wellstood FC, Kingston JJ, Clarke J, Colclough MS, Cardona AH, Bourne LC, Olson WL, Eddy MM (1990) Proceedings of the Applied Superconductivity Conference, Snowmass, Colorado, September 24-28, 1990 (to be published)
29. Face DW, Graybeal JM, Orlando TP, Rudman DA (1990) Appl.Phys.Lett.56: 1493
30. Gross R. Chaudhari P, Kawasaki M, Ketchen MB, Gupta A (1990) Appl.Phys.Lett.57: 727
31. Tesche CD, Clarke J (1977) J.Low Temp.Phys.29: 301
32. Koch RH, private communication
33. Oh B, Koch RH, Gallagher WJ, Foglietti V, Koren G, Gupta A, Lee WY (1990) Appl.Phys.Lett.56: 2575
34. Wellstood FC, Kingston JJ, Clarke J (1990) Appl.Phys.Lett.56: 2336
35. Wellstood FC, Kingston JJ, Ferrari MJ, Clarke J (in press) Appl.Phys.Lett.
36. Ferrari MJ, Kingston JJ, Wellstood FC, Clarke J (1990) (unpublished)