*Journal of Alloys and Compounds, 195* (1993) 703–706
*JALCOM 7562*



# A BSCCO(2223) thin film DC SQUID utilising natural grain boundary weak-links

F J Müller[a,b], J C Gallop[a,b], A D Caplin[b], S Labdi[c] and H Raffy[c]

[a]National Physical Laboratory, Teddington TW11 0LW, UK

[b]Centre for High Temperature Superconductivity, Blackett Laboratory, Imperial College, London SW7 2BZ, UK

[c]Universite Paris-Sud, Laboratoire de Physique des Solides, 91405 Orsay, France

**Abstract**

We report the first low noise thin film BSCCO(2223) SQUID operating at 77 K and above. The natural grain boundary weak links combine with a highly textured film structure to allow noise levels comparable to those achieved in YBCO or TBCCO devices.

## 1. Introduction

A number of groups have described low noise DC SQUID performance in devices fabricated from YBCO and TBCCO films [1-4], operating at 77 K. The weak links that have been used range from natural grain boundaries through 'engineered' bi-crystal grain boundaries to step-edge junctions, although in practice there is no clearly established correlation between the type of junction and the performance that is obtained (perhaps because all approaches yield what are effectively natural grain boundary junctions).

The interest in fabricating a BSCCO SQUID is that the material is more stable against atmospheric corrosion than YBCO, and has not the toxicity of TBCCO; also, the transition temperature $T_c$ of BSCCO(2223) is above 100 K. On the other hand, the well-known weakness of flux-pinning in the BSCCO phases suggests that flux noise in a SQUID fabricated from this material might be too high for the device to be useful. Little work on similar BSCCO devices has been reported, with SQUID operation mainly observed at low temperatures [5]. Face et al. [6] have reported detailed noise measurements for a BSCCO SQUID operating at up to 75 K, with energy sensitivity $\varepsilon(100\ \mathrm{Hz}) = 2.7\times10^{-25}$ J/Hz, four orders of magnitude worse than the best reported YBCO SQUID at 77 K [7]. Our work was intended to determine whether this high noise level is intrinsic to BSCCO, or whether the possibility exists of fabricating low noise devices from this material.

## 2. Thin film deposition and device fabrication

The Pb-doped BSCCO film was produced ex-situ [8]. Single target DC triode sputtering on to (1 0 0) MgO substrates yielded a deposit with thickness of about 830 nm. EDX analysis revealed the film composition to be in the ratio (1.68,0.4):1.95:2.09:3.04 for (Bi,Pb):Sr:Ca:Cu, respectively. The film was subsequently annealed at 858 C for 15 hrs in air with a Pb-doped pellet of the (2223) stoichiometry in close proximity. The film was cooled in air outside the furnace. The volume fraction of high $T_c$ phase was estimated as 92(±3)% from a comparison of the (0 0 14) high $T_c$ phase peak with the (0 0 12) low $T_c$ phase peak in XRD. The films are granular, but strongly textured with the *c*-axis normal to the substrate; the typical grain size is 5 µm.

The film $T_c$(zero) measured resistively was 107 K, being confirmed also by an inductive transition measurement, showing an onset at 110 K [9]. At 77 K, the film has a $J_c$ of 500 A $cm^{-2}$

A DC SQUID pattern was imposed on the film using conventional photolithography and AZ1512 photoresist. This was followed by a wet etch in a saturated solution of EDTA at room temperature for 6 min. The SQUID ring pattern had a hole nominally 130 µm in diameter, with two 'microbridges' on either side, some 20 µm wide, the intention being that one of the small number of grain boundaries crossing each 'microbridge' should act as the weak-links. An inductive characterisation of the patterned film indicated no detectable suppression of $T_c$, in agreement with previous observations [10]. Electrical contact between the film and four Ag wires was made with Ag paint onto evaporated Ag bonding pads.

0925-8388/93/$06.00

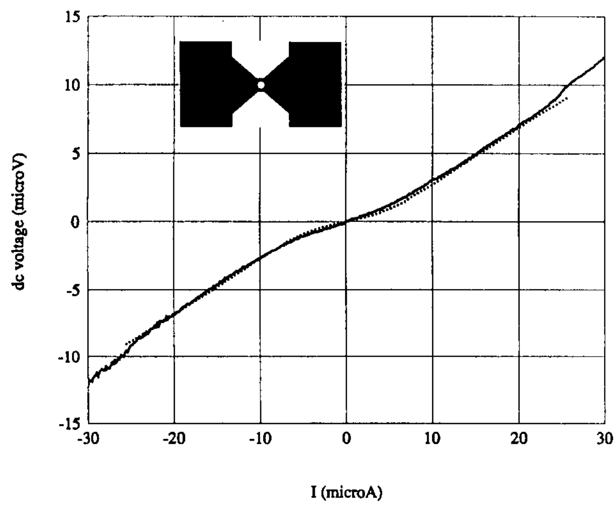


Figure 1 Measured I-V characteristic of SQUID 1 with an integer number of $\Phi_0$ through the ring. The dotted curve is a fit to the Ambegoakar-Halperin model, with $\gamma = \Phi_0 i_c / \pi k_B T$ and $i_c = 4\ \mu A$.
Inset The patterned SQUID ring.

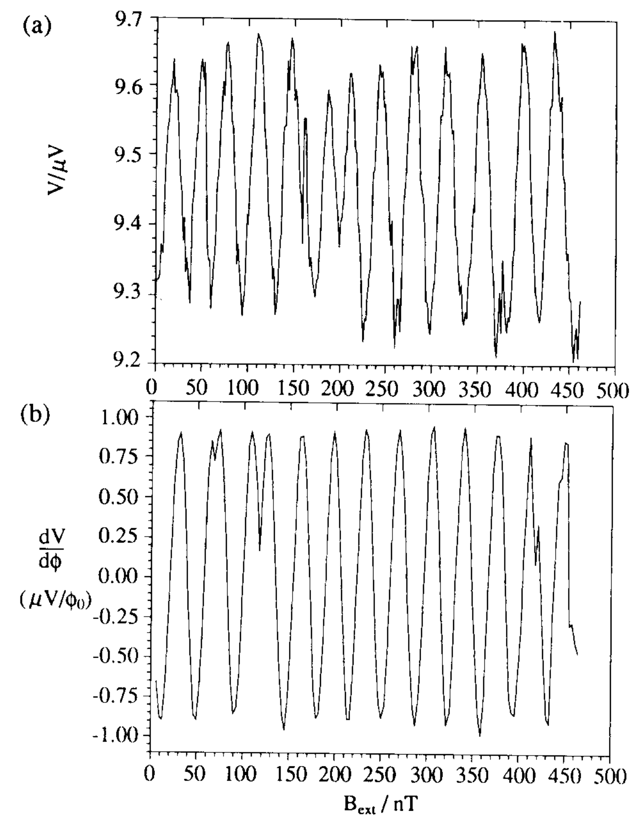


Figure 2. The DC voltage response of SQUID 1 as a function of applied magnetic field, at a bias current of 40 μA.

## 3. SQUID operation and performance

The SQUID was cooled by direct immersion in liquid nitrogen within a 2-layer mu-metal shield with a single layer lid. The residual steady field inside the shield was less than 30 nT, and mains frequency field noise was attenuated by 60 dB or more. Leads to the SQUID were filtered using low pass RC networks with roll-off above 1 MHz. DC bias current was supplied from a battery-derived source, with the voltage leads being connected to either a low noise DC nanovoltmeter (EM Type N11) or through the differentially connected pre-amplifier of a lock-in amplifier. In both cases the limiting voltage noise from the electronics was about 1-2 nV/√Hz. External field modulation was applied perpendicular to the SQUID thin film with either a Helmholtz coil geometry or a multi-turn pancake coil coupled closely to the SQUID loop, the latter being used to apply AC modulation in the lock-in amplifier detection mode.

The measured current-voltage (I-V) characteristic has been fitted to a noise-rounded RSJ model [11]. A one-parameter fit is shown in Figure 1; the fit corresponds to a critical current $i_c$ of 4 μA which is noise rounded by thermally activated phase-slips. The $i_c R_n$ product is ~2 μV. The measured critical current translates to a $J_c$ within the 'microbridges' of ~40 A $cm^{-2}$, a factor of ~10 less than that of the film as a whole.

Although no zero voltage supercurrent step is visible in the I-V curves at 77 K (Figure 1), the device works well as a conventional DC SQUID when biassed into the finite voltage regime. For a DC SQUID the expected voltage modulation $\Delta V$ is of order $i_{cs} R_n$ or $R_n \Phi o / L$, whichever is the less, where $i_{cs}$ is the smaller of the two weak-link critical currents and L is the SQUID ring inductance. For a 130 μm diameter hole in a 1 μm thick film, the ring inductance L is estimated as 470 pH and $i_{cs} < 4\ \mu A$, so both estimates suggest that $\Delta V < 2\ \mu V$, in reasonable agreement with the experimental value of 0.6 μV.

The observed field periodicity (Figure 2) corresponds to an area of 0.061 $mm^2$, approximately twice that of the patterned hole. This enhancement can be understood in terms of flux focussing by the superconducting electrodes, whereby as the external field is increased, screening currents prevent entry of flux into the

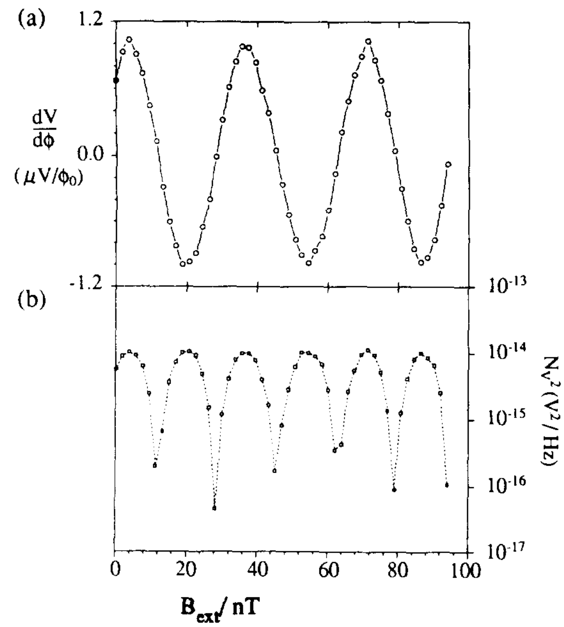


Figure 3 (a) Transfer function ($dV/d\phi$) as a function of the applied field $B_{ext}$.

(b) Power spectral density of voltage noise at the SQUID voltage output terminals as a function of $B_{ext}$, measured simultaneously with (a), showing a modulation correlated with $dV/d\phi$ which is characteristic of flux noise.

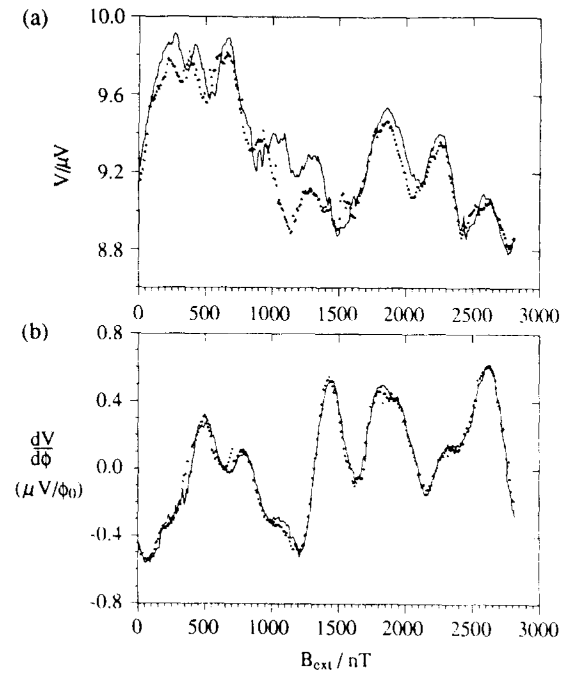


Figure 4 SQUID 2; (a) response and (b) transfer function as functions of applied magnetic field.

electrodes, and so increase the field at the SQUID ring itself. Although the geometry of the ring and electrodes (inset to Figure 1) does not lend itself to exact calculation of this effect, a focussing factor of 2 appears perfectly reasonable.

This SQUID has a response that can be followed for about 200 cycles of the 33 nT period; furthermore, the hysteresis after field excursions of this magnitude was typically a fraction of a flux quantum. However, in larger applied fields, the response is modulated, particularly by a dominant period with $\Delta B \sim 70\ \mu T$ (corresponding to an area of $\sim 30\ \mu m^2$), for which $\Delta V$ is as large as $6\ \mu V$. We attribute this modulation to internal loops within the 'microbridges', and note that the corresponding area is on the order of the grain size.

The noise performance of the SQUIDs was measured using an HP 35660A Signal Analyser. At frequencies above 10 Hz, SQUID noise was found to drop below the instrumentation noise floor.

Figure 3 shows that at 1 Hz, the measured noise depends strongly on applied field, and tracks closely the SQUID transfer function $dV/d\phi$. This correlation shows that the dominant contribution is field noise as against, for example, fluctuations in critical current of the junctions. The major contribution to field noise is likely to be from thermally activated motion of flux trapped in the superconducting ring and the adjacent electrodes.

Translating from voltage noise to flux noise yields figures of $10^{-2}\ \Phi_0^2/Hz$ at 1 Hz, decreasing very rapidly with frequency to about $10^{-6}\ \Phi_0^2/Hz$ at 10 Hz. In terms of energy, these figures correspond to $4\ 10^{-23}$ and $4\ 10^{-27}$ J/ Hz respectively.

A second device, SQUID 2, was fabricated on a different film that was slightly more Bi-rich. At 77 K, the 'microbridge' $i_c$ was $\sim 20\ \mu A$, but the field response was complex (Figure 4), indicating that several different weak-linked areas are contributing simultaneously.

The long-term stability of these devices appears to be excellent too. In the ambient field of 30 nT, typical drift rates are of the order of $10^{-2}\ \Phi_0/min$. After exposure to larger fields of several mT, the response stabilises after a few minutes, although some additional 'telegraph' noise [12] is then visible.

## 4. Discussion

The BSCCO(2223) material has a number of advantages over YBCO (higher $T_c$, greater resistance to atmospheric corrosion) and TBCCO (lower toxicity) which have not yet been exploited in device applications.

Our results show that SQUIDs can be fabricated from this material by straightforward patterning techniques, utilising natural grain boundary weak-links in a granular, but highly textured, thin film.

Although flux is rather poorly pinned in these materials, and the resultant flux noise is high at low frequencies, satisfactory SQUID operation is perfectly feasible at 77 K. The devices are therefore well-suited to applications where simplicity of fabrication and operation outweigh the requirements for the highest sensitivity.

## Acknowledgements

This work has been supported by the UK Science and Engineering Research Council and by the CEC (Twinning Contract No SC1* CT91-0758).

## References

1 R H Koch, W J Gallagher, B Bumble & W Lee, Appl. Phys. Lett. **54** 951 (1989)
2 R Gross, P Chaudhari, M Kawasaki, M B Ketchen & A Gupta, Appl. Phys. Lett. **57** 727 (1990)
3 K Char, M S Colclough, S M Garrison, N Newman & G Zaharchuk, Appl. Phys. Lett. **59** 733 (1991)
4 M S Dilorio, S Yoshizumi, M Maung, K Y Yang, J Zheng & N Q Fan, Nature **354** 513 (1991)
5 M Matsuda, Y Murayama, S Kiryu, N Kasai, S Kashiwaya, M Koyanagi, T Endo & S Kuriki, IEEE Trans. Mag. **27** 3043 (1991)
6 D W Face, J M Graybeal, T P Orlando & D A Rudman, Appl. Phys. Lett. **56** 1493 (1990)
7 G Friedl et al., Appl. Phys. Lett. **60** 3 048 (1992).
8 S Labdi, H Raffy, S Megtert, A Vaures & P Tremblay, J. Less Comm. Met. **164-5** 687 (1990)
9 F J Müller, J C Gallop & A D Caplin, Supercond. Sci. Technol. **4** 616 (1991)
10 F J Müller, J C Gallop, J R Laverty, M A Angadi, A D Caplin, S Labdi & H Raffy, *High $T_c$ Superconducting Thin Films; Proceedings of ICAM 1991* (ed. L Correra, Amsterdam:Elsevier 1992).
11 V Ambegaokar & B I Halperin, Phys. Rev. Lett. **22** 1364 (1969)
12 M J Ferrari, F C Wellstood, J J Kingston & J Clarke, Phys. Rev. Lett. **67** 1346 (1991)