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A DC SQUID using natural grain boundaries in BSCCO

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We report the first low-noise thin film BSCCO 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 from devices fabricated from YBCO and TBCCO films (see refs. [1–4]), operating at 77 K. The weak links used vary from natural grain boundaries through "engineered" bi-crystal grain boundaries to step-edge junctions, performance being essentially independent of the weak link type. Little work on similar BSCCO devices has been reported, with SQUID operation mainly observed at low temperatures [5]. Face et al. [6] previously reported detailed noise measurements for a BSCCO SQUID operating at up to 75 K, with energy sensitivity $\epsilon(100\ \mathrm{Hz})=2.7\times10^{-25}$ J/Hz. The BSCCO SQUID presented here worked in liquid nitrogen with considerably lower noise levels, $\epsilon(10\ \mathrm{Hz})=6\times10^{-27}$ J/Hz, comparable with those achieved with natural grain boundary YBCO and TBCCO SQUIDs. The SQUID was fabricated from a thin film predominantly of the high-T_c ($=105$ K) phase (2223 material) of the BSCCO system.

2. Thin film deposition and device fabrication

The Pb-doped BSCCO film was produced ex-situ [7]. Single target DC triode sputtering onto (100) MgO substrates yielded a deposit with thickness around 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 h 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. $T_{c\,\mathrm{zero}}$ was measured resistively as 107 K also being confirmed by an inductive transition measurement, showing an onset at around 110 K [8].

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. An inductive characterisation after patterning indicated no detectable suppression of T_c, in agreement with observations to be published elsewhere [9]. Electrical contact between the film and four Ag wires was made with Ag paint onto evaporated Ag bonding pads.

3. SQUID operation and performance

The SQUID was cooled by direct immersion in liquid nitrogen inside a two-layer mu-metal shield with a single layer lid. The ambient field inside the shield was less than 30 nT. Leads to the SQUID were filtered using low pass R–C networks with roll-off above 1 MHz. A 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 was around 1–2 $\mathrm{nV(Hz)}^{1/2}$. External field modulation was applied perpendicular to the SQUID thin film either through a Helmholtz coil geometry or through a multi-turn pancake coil closely coupled to the SQUID loop, the latter being used to apply AC modulation signals for use in the lock-in amplifier detection mode.

The measured I–V characteristic has been fitted to a noise-rounded RSJ model [10]. A one-parameter fit is shown in fig. 1 which suggests that a critical current i_c of 8 μA is noise rounded (due to thermally activated phase-slips) so that at $T=77$ K no zero voltage supercurrent step is visible in the I–V curves. Nevertheless, the device works as a conventional DC SQUID when biased into the finite voltage regime. The i_cR_n product is only ~4 μV. For a DC SQUID the expected voltage modulation ΔV is of order $R_n\Delta i_c$ or $R_n\Phi_0/L$, whichever is the smaller, where Δi_c 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 $\Delta i_c < 4$ μA, so both limits predict $\Delta V < 2$ μV, in reasonable agreement with the experimental value of 0.6 μV. The observed field periodicity corresponds to an area approximately twice that of the patterned hole. This discrepancy may arise from flux focussing by the superconducting electrodes or to the film being rather more granular around the perimeter of the patterned hole in it.

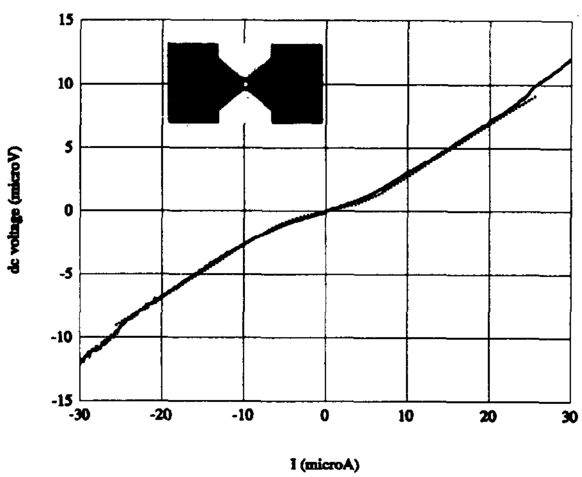

Fig. 1. I–V characteristic of BSCCO SQUID for $n\Phi_0$ applied flux. Calculated I–V curve (shown dotted) for $\gamma=\Phi_0 i_c/\pi k_B T=3.5$ and $i_c=8$ μA, according to ref. [10]. The SQUID pattern is shown as an inset.

The SQUID also exhibits other periodic modulations in larger applied fields, particularly a dominant one with $\Delta B \sim 20$ μT, for which ΔV is as large as 6 μV. We attribute these to internal loops in the region of the weak link bridges. Note that a Fourier transform of the response to applied field over a wide range shows no periodicities between 100 nT and 10 μT, and some 200 oscillations of the former periodicity can be seen without detectable envelope modulation caused by the response of smaller, naturally occurring, loops.

4. Discussion

Except for the hypothetical case of a SQUID incorporating very low capacitance Josephson junctions which can in principle be quantum noise-limited at any temperature [11], most real HTS devices will be limited by thermal noise to an energy sensitivity per unit bandwidth in the white noise regime of

$$\delta E > 8kTL/R_n \sim 10^{-29}\ \mathrm{J/Hz}\,.$$

In practical DC SQUIDs two sources of noise must be considered and can sometimes be separately measured. The first arises from flux noise in the SQUID ring, associated with thermally activated motion of trapped flux in the superconducting film. The second arises predominantly from Nyquist noise across the junction shunt resistors. The first appears at the input to the SQUID whereas the second appears only at the output terminals. Since the transfer function of the SQUID ($\mathrm{d}V/\mathrm{d}\Phi$) is strongly flux dependent, the first source of noise should vary with a strong Φ_0 periodicity in the applied flux, whereas the second should be applied flux independent, except insofar as the bias point of the SQUID varies with Φ_x. Figure 2 demonstrates the dominance of flux noise at 1

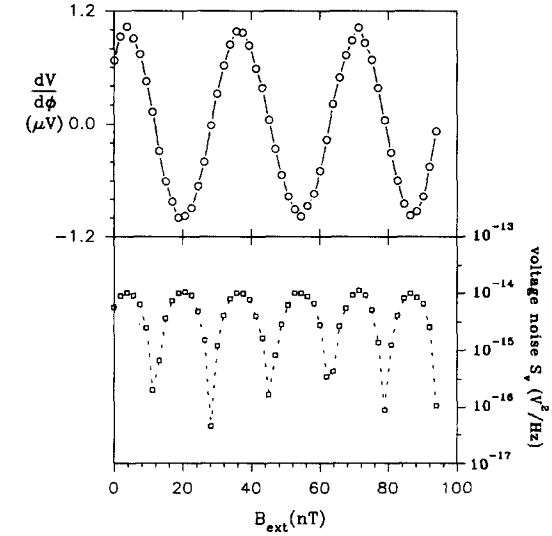

Fig. 2. The dominance of flux noise for our BSCCO SQUID at 1 Hz and 77 K is demonstrated in the following figures. (a) Transfer function ($dV/d\Phi$) as a function of the applied flux Φ_x in units of Φ_0. (b) Power spectral density of voltage noise at the SQUID voltage output terminals as a function of Φ_x, measured simultaneously with (a), showing a modulation which is characteristic of flux noise.

Hz, since the voltage noise spectral density is strongly periodic in applied flux, following closely the periodic response of $dV/d\Phi$. The observed flux noise is very strongly frequency dependent for $f < 10$ Hz. At 10 Hz, the effective flux noise has fallen dramatically, to around $9\times10^{-4}\,\Phi_0/(\mathrm{Hz})^{1/2}$.

When our SQUID is maintained in a stable ambient field the noise appearing at the voltage terminals is only greater than the detector noise (referred to these voltage terminals) for frequencies less than about 10 Hz. A plot of the output voltage remains substantially drift-free over many minutes though occasionally, particularly after the SQUID was transferred from its storage dewar to the experimental cryostat the output voltage level is seen to undergo sudden transitions to other levels. Transitions in the reverse sense sometimes follow. This is an example of "telegraph noise" seen in other HTS SQUID devices [12] and attributed to the reversible stochastic movement of trapped flux lines within the thin film, somewhere close to the sensitive SQUID ring.

The BSCCO 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 suggest that there is nothing intrinsically worse in the performance of grain boundary weak links present in the BSCCO (2223) system, compared with other work-horse superconductors. We intend to apply these prototype directly coupled SQUIDs to non-invasive measurement of corrosion currents. Further work is planned to integrate the SQUID with various input coil configurations.

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