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Properties of rf-SQUIDs Fabricated from Epitaxial $YBa_2Cu_3O_7$ Films

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Abstract. Radio-frequency (rf) SQUIDs were evaluated with weak links in epitaxial $YBa_2Cu_3O_7$ films created by either local ion-implantation or step-edges in the substrate. It is shown that such weak links permit one to fabricate rf-SQUIDs with low 1/f noise. The step-edge SQUIDs show a promise of reproducible I_c control.

1. Introduction

The purpose of this work was to evaluate the performance of $YBa_2Cu_3O_7$ (YBCO) thin-film rf-SQUIDs with engineered and controllable weak-link microbridges. First reports on thin film YBCO one-hole rf-SQUIDs described results obtained with post-annealed, polycrystalline or textured films (Betts et al. 1989a, Daly et al. 1989b). These SQUIDs utilized the natural grain boundary (GB) junctions present in microbridges (30 and 10 μm wide) and exhibited temperatures of operation, T_{op}, up to 55 and 65K, respectively. The low-frequency 1/f noise was high, 10^{-3} to 10^{-2} $\Phi_0 Hz^{-1/2}$ at 10 Hz. The authors attributed it to random fluxoid motion at grain boundaries. Similar results were obtained in this laboratory with textured YBCO SQUID microbridges 0.5 to 10 μm wide (Tinchev 1990a).

Weak links engineered in epitaxial, GB-free YBCO films hold the promise of controllable properties and lower 1/f noise. Recently, Simon et al. (1990b) demonstrated operating rf-SQUIDs with weak links fabricated by several different means in epitaxial, *in-situ* grown YBCO . A narrow disordered stripe across a patterned microbridge was created by local in-diffusion of Al, a sharp step-edge in the substrate or by focussed ion-beam irradiation. In each case, the film's J_c was locally reduced by two or three orders of magnitude and, consequently, rf-SQUIDs operating between 4.2 and 60K were obtained.

We have been investigating similar rf-SQUIDs with step-edge weak links, and with links which were locally ion implanted. One of us (G.C.) experimented earlier with this approach to weak link formation (Shao et al. 1990c).

2. Fabrication and Measurements

Epitaxial, c-axis oriented YBCO films were *in-situ* deposited on (100) $SrTiO_3$ substrates by pulsed laser deposition (PLD) and magnetron sputtering. Film thicknesses were 100 and 200 nm. One-hole SQUID structures were patterned by optical lithography and Ar ion-beam etching (Lehmann et al. 1990d). Chemical etching in diluted H_3PO_4 or in EDTA (Shokoohi et al. 1989c) has also been used.

The examined SQUID microbridges were 10 μm long and nominally 2 μm wide. The one-hole rf-SQUID structure consisted of a 1.4 x 1.4 mm^2 flux

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concentrator with a central hole of $100x100^2$ μm corresponding to an inductance of approximately 150 pH. The SQUID was loosely coupled to a 40-turn, 1 μH tank-circuit coil (coupling coefficient $\alpha < 0.2$). The tank circuit frequency was between 13 and 20 MHz. The SQUID noise was measured between 1 and 10^5 Hz using a HP 3562 spectrum analyser. The dewars used for measurements had a Mumetal or Mumetal and Pb shielding.

3. SQUIDs with Ion-Implanted Microbridges

The rf-SQUID structures were patterned by wet etching from magnetron sputtered, 200 nm thick, epitaxial YBCO films on $SrTiO_3$ having critical temperatures, T_c, of 86 to 89K. The microbridges were locally implanted using 100 KeV Ar-ions. After determining the dependence of the film resistivity upon the dose, the latter was set at $5x10^{12}$ cm^{-2}. The PMMA 950K resist serving as an implantation mask had 100-200 nm wide open slits written by e-beam lithography across the 2 μm wide microbridges. The PMMA was 300 nm thick, sufficient for protection of the underlayer (Biersack 1967). Prior to implantation, no SQUID response could be observed.

The locally implanted rf-SQUIDs exhibited a well-defined, periodic and nearly triangular $V(\Phi)$ response on up to 10 steps of the rf I-V curve. These SQUIDs operated over a wide temperature range, between 4.2 and 60K, in the dissipative or dispersive mode, as defined by the temperature-dependent critical current $I_c(T)$. At 4.2K, the estimated I_c was of the order of 10 μA and the SQUID-parameter β was approximately 3. Noise characteristics were measured over the temperature range of 4.2 to 50K. The lowest white noise voltage level above $f = 3$ Hz corresponded to $2x10^{-4}$ $\Phi_0 Hz^{1/2}$ at 4.2K and $8x10^{-4}$ $\Phi_0 Hz^{1/2}$ at 38K with a crossover to 1/f noise still observed near 3 Hz, as shown in Fig. 1. The presence of strong 50 Hz and harmonic signals in the spectrum and also the much lower intrinsic SQUID noise calculated (Jackel and Buhrman 1975) indicated that our shielding was inadequate.

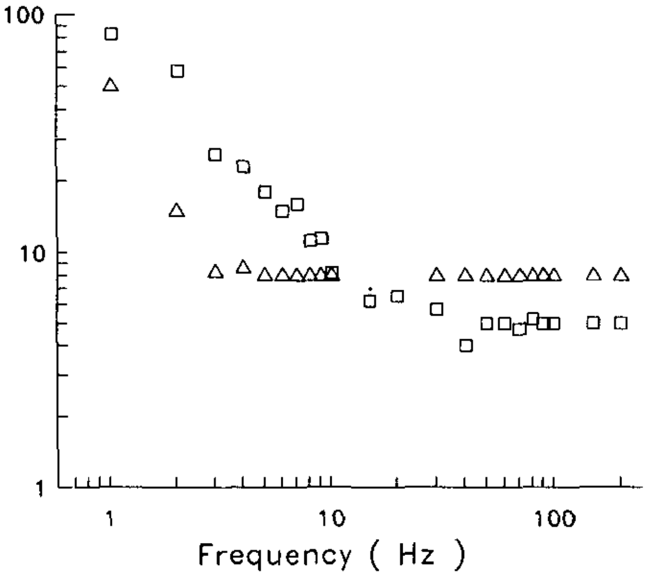

Fig. 1. Low-frequency SQUID noise spectra, in units of $10^{-4}\Phi_0 Hz^{-1/2}$: triangles - ion-beam implanted link (1) at T = 38K, squares - step-edge link (2) at 47K (comparable β's). The 1/f noise in (1) did not change significantly between 30 and 50K.

One of the SQUIDs was thermally cycled 8 times between 4.2 and 300K, with intermittent exposures to moisture, without any change in characteristics.

4. SQUIDs with Step-Edge Microbridges

Steps 20 to 200 nm high were Ar-ion beam milled in $SrTiO_3$ substrates through photolithographically defined Nb masks. Epitaxial YBCO films, 100 nm thick, were subsequently fabricated by PLD and exhibited a $T_c = 87$ to 89K. In such films, the J_c at 77K was typically in the 10^6 A/cm^2 range. The ion-beam patterned SQUID microbridges were 2 μm wide. In the absence of the step-edge, no SQUID response was observed.

At low step heights, h, a well-defined, triangular and periodic $V(\Phi)$ response was observed only over a narrow temperature range near T_c, e.g. 75 to 82K at h = 20 nm, indicating that at lower temperatures the I_c was too high. With the increasing step height, the temperature range of operation broadened and extended down to 4.2K. At h = 70 nm, the range extended from 4.2 to 55K. At 200 nm, the range of periodic response was typically 4.2 to 30K while between 65K and T_c a much stronger nonperiodic response was observed. This nonperiodic response could be tentatively associated with the random array of junctions in the 0.65 mm wide step in the SQUID loop located opposite to the weak link.

The grain boundaries which nucleate at both edges of a step, (where the film orientation changes from c- to a-axis and back), the reduction of film thickness at the step and the I_c anisotropy should contribute to the h-independent I_c reduction. Boundaries and other defects in the a-axis step plane will make I_c to depend upon h. The uniformity of I_c distribution on the chip was high at low step heights: up to 50% of the 16 SQUIDs had nearly identical T_{op} ranges. The spread in T_{op} increased with h, thus confirming the role of random defects and percolation paths in the step.

The best step-edge SQUID sample operated between 20 and 80K in the dissipative and dispersive mode. The inferred low-temperature I_c was of the order of $10\ \mu A$. The 1/f noise was much higher than in SQUIDs with implanted microbridges (Fig. 1) while the white noise level was comparable. At 74K, $\beta = 1$ and $f > 60$ Hz the noise was $5\times10^{-4}\ \Phi_0 \mathrm{Hz}^{-1/2}$. However, even the step-edge SQUIDs exhibited lower 1/f than the bulk (Zhang 1990d) and thin film SQUIDs with grain-boundary junctions.

5. Conclusion

We confirmed that weak links created in epitaxial YBCO films permit one to fabricate rf-SQUIDs with 1/f noise lower than in grain-boundary devices. The step-edge SQUIDs show a promise of reproducible I_c control.

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