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High T_c bi-epitaxial dc SQUIDs structured by focused ion beam etching from single junctions: β_L optimisation

R.P.J. IJsselsteijn, J.W.M. Hilgenkamp, D. Veldhuis, J. Flokstra, and H. Rogalla.

University of Twente, Department of Applied Physics, P.O. Box 217, 7500 AE Enschede, The Netherlands.

Focused ion beam etching has been used to pattern dc SQUIDs into previously characterised template bi-epitaxial grain boundary junctions. In this way, the screening parameter β_L can be optimised for a chosen temperature (in our case 30 K). Electrical characteristics, including noise measurements, are presented. A minimal white noise level of 22 $\mu\phi_0 \cdot Hz^{-1/2}$ ($1.8 \cdot 10^{-29}$ $J \cdot Hz^{-1}$) has been obtained at 20 K. Using bias current modulation the 1/f noise could be almost completely suppressed down to 1 Hz in the entire temperature range (10-65 K).

1. INTRODUCTION

Template grain boundary junctions typically show a spread in J_c of a factor 10. Because of this spread in J_c, dc SQUIDs based on this kind of grain boundary may not show a good match of the critical current I_0 of the separate junctions and the SQUID inductance L_{SQ}. Lowest expected white noise levels, thus optimal energy sensitivity, of the dc SQUID are expected for a value of the screening parameter $\beta_L = 2I_0 \cdot L_{SQ}/\phi_0$ equal to one according to Tesche and Clarke [1]. A second problem for these SQUIDs concerning voltage modulation and noise levels might be the thermally activated phase slippage (TAPS) across the grain boundary, causing a small voltage drop across the junction for temperatures below T_c (the critical temperature of the electrodes), down to T^* (minimum temperature at which this voltage drop is observed).

2. EXPERIMENTAL

Template grain boundary junctions were prepared using (100) oriented MgO substrates, a 10 nm thick CeO_2 template layer structured by CaO lift-off and an $YBa_2Cu_3O_7$ toplayer of 100 nm [2]. Dc SQUIDs were patterned in these characterised junctions using a 25 kV Focused Ion Beam (FIB) equiped with a Ga liquid metal ion source. SQUID hole and slit dimensions (determining the main part of the SQUID inductance [3-5]) were adjusted to obtain $\beta_L = 1$ at 30 K. Figure 1 shows a schematic topview of the resulting dc SQUID presented in this paper. Light parts are the original junction and $YBa_2Cu_3O_7$ electrode. The darker parts are etched away using the FIB. Alignment problems of the ion beam caused a small asymmetry of the junctions. Etching depths are 200 nm. The slit is structured using minimal ion beam diameter (50 nm), resulting in a FWHM line width of 200 nm. The lines defining the washer (marked a) and the SQUID hole are etched using an ion beam spot size of 130 nm. The resulting SQUID inductance is 70 pH, with $L_{slit} = 15$ pH and $L_{hole} = 55$ pH.

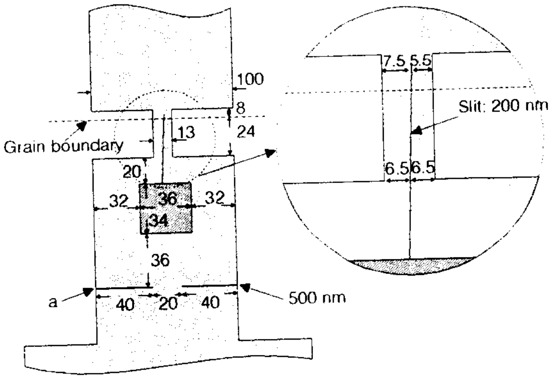

Figure 1: Schematic topview of the dc SQUID described in the paper. Sizes are in microns, unless noted otherwise.

Electrical characterisation including noise measurements were performed in a variable temperature He gas flow cryostat. From the inside outwards, the sample was shielded from external noise sources by a BiSrCaCuO, a mu-metal and an Al can. Magnetics fields perpendicular to the substrate surface were applied using a coil mounted around the sample inside the BiSrCaCuO can.

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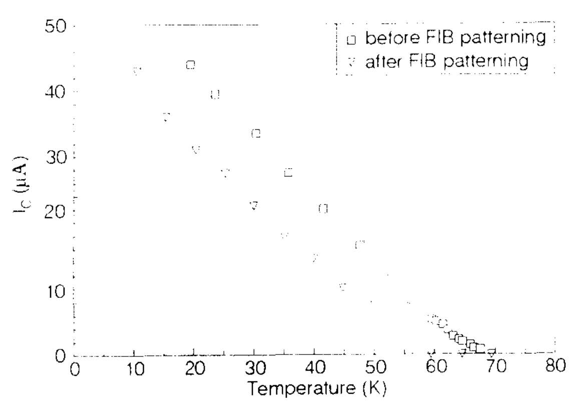

Figure 2: The critical current of the original junction (before patterning) and of the dc SQUID (after patterning) as a function of the temperature.

3. RESULTS AND DISCUSSION

Figure 2 shows the critical current of the original junction before patterning and the total critical current of the dc SQUID after patterning by the FIB. A reduction in T^* of about 10 K is observed. No change in the critical temperature of the $YBa_2Cu_3O_7$ electrodes is observed. The normal resistance $R_{n,sq}$ of the dc SQUID increased to 4.2 Ω as compared to R_{nj}= 3.3 Ω of the original junction (both determined at 20 K). Because of the decrease of T^* and the increase of R_n of 27%, as compared to the decrease of the total junction width of 2%, it is concluded that the grain boundary is damaged by the Ga ions during aligning and structuring of the sample.

Applying a small varying magnetic field, IV curves and voltage modulation of the SQUID were measured as a function of temperature. Sinusoidal voltage modulation was observed up to 72 K, about 15 K above T^* of the SQUID. At 10 K a maximum voltage modulation of 72 μV and a flux to voltage transfer $dV/d\phi$ of 230 $\mu V/\phi_o$ were obtained.

$\beta_{L,meas}$ as determined from the IV curves using $I_{mod}/I_c=\beta_{L,meas}/(1+\beta_{L,meas})$ was compared with $\beta_{L,calc}$ as determined from the critical current and the calculated SQUID inductance. Here I_{mod} is the minimal current at which voltage modulation is observed, and I_c the total critical current of the SQUID. For temperatures below 40 K $\beta_{L,meas}$ is larger than expected from the critical current and the calculated SQUID inductance. This difference can not be explained by a correction for the excess current present in this junction (maximum value 6 μA at 35 K and below) or the kinetic inductance of the junction striplines and slit which is estimated to be about 10% of the slit inductance.

Temperature dependent noise measurements (1 Hz - 1 kHz) have been obtained in a flux locked loop, both for dc and ac current bias at maximum voltage modulation. For dc current bias the noise powerspectrum in general consists of a 1/f part for frequencies up to $\nu_{1/f}$ and a white noise level at higher frequencies. For increasing temperature $\nu_{1/f}$ decreases. By applying ac current biasing the 1/f noise could be suppressed considerably over the entire temperature range. Figure 3 shows the flux noise as a function of temperature at 1 Hz and the white noise level, both for dc and ac current biasing. For temperatures of 40 K and higher the 1/f noise could be totally suppressed indicating that asymmetric critical current fluctuations are the main reason for the 1/f noise at these temperatures. A minimum value of 40 $\mu\phi_o\cdot Hz^{-1/2}$ at 1 Hz and 40 K is obtained. The white noise level is slighly increased by ac current biasing, and shows a broad minimum around 20 K for dc biasing. A minimum white noise level of 22 $\mu\phi_o\cdot Hz^{-1/2}$ ($1.8\cdot10^{-29}$ $J\cdot Hz^{-1}$) at 20 K is obtained.

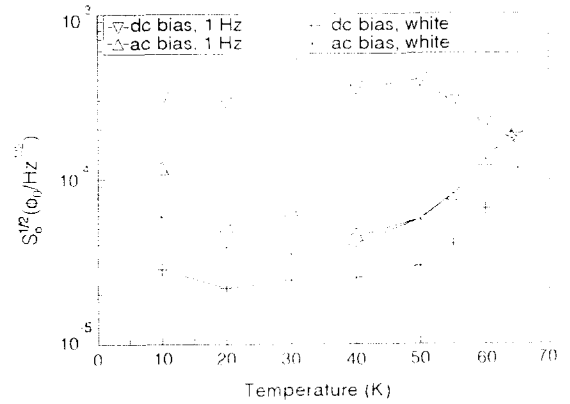

Figure 3: Flux noise as a function of temperature at 1 Hz (1/f noise) and the white noise level both for dc and ac current biasing.

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