1/f Noise Characteristics of SEJ Y-Ba-Cu-O rf-SQUIDs on $LaAlO_3$ Substrate and the Step Structure, Film, and Temperature Dependence

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Abstract—**Step edge junction (SEJ) rf-SQUID magnetometers and gradiometers were fabricated using PLD Y-Ba-Cu-O films on $LaAlO_3$(100) and $SrTiO_3$(100) substrates. Effects of different step structure and the film properties on the yield, optimal operating temperature, and the 1/f noise of the SQUIDs were investigated. The step structure was controlled using various IBE processes. The devices on $LaAlO_3$ showed higher sensitivity to the step structure compared to those on $SrTiO_3$. This was due to re-deposition of substrate material at the steps prepared using the conventional IBE process resulting in a very low yield of unstable SQUIDs. High yield of low 1/f noise stable SQUIDs was obtained on $LaAlO_3$ substrates with sharp steps prepared using an optimized IBE process. A typical 1/f noise corner frequency of about 10Hz at 77K with two major temperature dependencies was obtained. The temperature dependencies of the 1/f noise could be correlated to the junction and the film of washer area of the SQUIDs. The white noise of our devices showed a dependency mainly on the amplitude of the flux to voltage transfer function signal. The operating temperature range of the SQUIDs could be controlled by the step structure and narrowed when the optimal operating temperature range was increased. All the measured junctions of our devices on the modified steps showed RSJ type behavior with a moderate decrease of the R_N versus temperature.**

Index Terms—**superconductivity, rf-SQUID, YBCO, 1/f noise**

I. Introduction

Among the known technologies used to make Josephson junctions (JJ) for High-Tc devices such as rf-SQUIDs, the step edge junctions (SEJs) are favorable from the fabrication point of view [1]-[2]. While the SEJs provide very high flexibility in the layout designs, they also have relative simple fabrication process e.g. when compared to the ramp type junctions, and low cost when compared to the bi-crystal grain boundary junctions. The SEJs are also shown to provide lower critical current (I_c) JJs in the micron size dimensions easing the fabrication process by avoiding the need to very small dimensions in devices where small I_c of junction ($I_{c\text{-}j}$) is required. This is in particular for the typical high-T_c rf-SQUID layout designs where a very small $I_{c\text{-}j}$ in the range of a few μA is required at 77K [1], [3]-[4].

There have been many efforts to obtain high yield of stable low noise SEJ rf-SQUIDs [1], [4]. While the SEJ based devices are very attractive with respect to the design flexibility and the fabrication, the control of its parameters is known to remain challenging due to the nature of such grain boundary (GB) JJs [1], [5]. This is interpreted to be mainly due to the difficulty in obtaining the desired step structure. This is while the quality of both the step and the superconducting films are essential for high yield of low noise devices such as rf-SQUIDs.

The effects of the step structure and the superconducting film on the noise, operating temperature range, as well as the yield and stability of the SEJ rf-SQUIDs were investigated. Operating temperature range of the SQUIDs was investigated using the amplitude of the flux-voltage transfer function signal, $V_{s\text{-}pp}$. The focus of this work is on the reduction of the 1/f type noise, yield, and control of the operating temperature range of the SQUIDs without further oxygen treatment. Here we present the results on the SEJ rf-SQUID magnetometers and gradiometers on substrates with steps prepared using developed IBE processes and covered with Y-Ba-Cu-O film structures to obtain high yield of stable low noise devices with optimal operating temperature of 77K.

II. Sample Preparation and Experimental Setup

SQUID magnetometers and gradiometers were made using Y-Ba-Cu-O film deposited on $LaAlO_3$(100) and $SrTiO_3$(100) substrates. The Y-Ba-Cu-O films were deposited by the pulsed laser deposition technique using KrF Excimer laser and were patterned using either wet chemical etching in 0.25% dilute phosphoric acid, or low energy argon IBE process. The step structures were made onto the substrates using argon IBE process with the beam energy ranges of 250-600 eV and the beam intensities of 0.125-0.5 mA/cm^2. A typical 60 nm thick e-gun evaporated gold layer was deposited on the substrate prior to the step etching process to obtain clean edges at the steps [4]. The magnetometers were made using a layout with a 3.5 mm diameter washer and a loop size of 150•150 μm^2 giving an inductance of 225 pH. The gradiometers were made using layouts with washer areas with 1.5 mm diameter, loop areas of 75•75 μm^2 and a baseline of 1.5 mm.

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The SQUIDs were characterized using either a liquid nitrogen (LN) based system for stable temperature measurements at 77K or, a liquid helium (LH) based system for measurements at various temperatures down to 4.3 K. The LN based set-up with a 3 layer μ-metal shield was used to measure very low frequency noise spectra of the samples at 77K with the combination of a coplanar resonator as well as the conventional L-C tank circuits matched for a resonating frequency of about 900 MHz [6]. The LH based setup with two layers of μ-metal shield had a temperature stability of about 0.1 K allowing noise measurements down to a few Hz. The junction of the SQUIDs could be characterized by opening their magnetic field concentrating washer area using a micro-scriber.

III. Effects of the IBE process on the SEJ structure and the yield

The IBE process is one of the key parameters in obtaining high quality SEJs. The sensitivity of the junction properties to the IBE process is found to differ strongly from one substrate material to another mainly due to re-deposition of materials at the steps during the IBE. This re-deposition is observed to be much higher for $LaAlO_3$ substrate compared to that on the $SrTiO_3$ substrate. The re-deposited material is interpreted to be mainly composed of substrate material [4]. The re-deposition is observed to be the highest when a normal incident ion beam is used to develop the steps. A 270 nm deep step structure etched using 500 eV normal incident argon ion beam is shown in figure 1a. The re-deposited material at the step is observed for all the steps developed using normal incident IBE process. A clean sharp step made using an optimized developed IBE process is given in figure 1b obtained as explained in the following.

As shown in the figure 1a the re-deposition can clearly be seen on the side wall of the step (at the broken edge) with a thickness of less than about 100 nm and a height of a few hundred nm extended above the edge of the step. This re-deposition, in particular on the sidewalls of the steps, is interpreted to be the main cause for the very low yield of stable SQUIDs on such steps. Using a conventional 45° angled rotating ion beam, the re-deposition of the material could be avoided. But due to the rotating angled ion beam, shallow ramped type steps were obtained resulting in junctions with relatively high I_c and hence high optimal operating temperature for the SQUIDs close to the T_c of the films. The increase of the step depth lowered the working temperature range of the SQUIDs but led to low quality film on the ramp at the bottom of the steps resulting in very low yield and high noise devices.

As shown in the figure 1b, very sharp clean steps could be obtained using a developed "Combinational IBE" (CIBE) process where different IBE process steps were used. This was achieved by using a relatively high energy stationary 40° angled IB along the step edge to reach the approximate desired step height, and then use of lower energy rotating 45° angled IB to get surface modified steps. By use of high quality Y-Ba-Cu-O films on the CIBE steps, high yield of stable low noise SQUIDs on $LaAlO_3$ substrates were obtained [4]. The optimal operating temperature of the SQUIDs could be tuned to 77 K by control of the step height as explained in the followings.

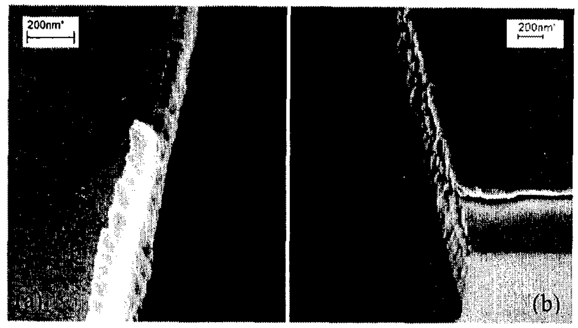

Fig. 1. SEM pictures of step structures on $LaAlO_3$ substrates; a) etched using normal incident ion beam (left), b) etched using "Combinational IBE" process (right).

IV. The SQUID characteristics and the temperature dependence

A. The step structure dependence

Effects of different step structures on the $V_{s\text{-}pp}$ and the I-V characteristics of the junctions of the SQUIDs were investigated. Three major step structures were reproducibly made namely the sharp ramp type, smooth ramp type, and the sharp steep CIBE step structures. The JJs on both the sharp and smooth ramp type steps had relatively high I_c. The CIBE steps favorably provided very low $I_{c\text{-}j}$ compared to that of the ramp type steps. This allowed reproducible fabrication of the rf-SQUIDs with desired operating temperature ranges using a few micron wide bridges and 200 nm thick films.

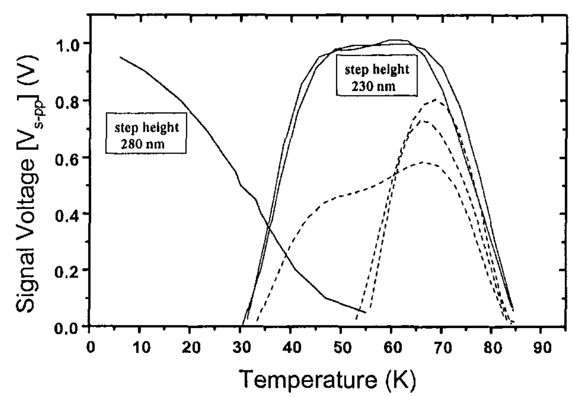

Fig. 2. $V_{s\text{-}pp}$ vs. T of 3 μm wide junction SQUIDs gradiometers (solid lines) and Magnetometers (dashed lines all with 280nm step hight) made of 200 nm thick Y-Ba-Cu-O films on $LaAlO_3$ substrates with CIBE steps.

While the I_c of the JJs made on the ramp type junctions were not considerably controllable by the depth of the trench, the I_c of the junctions on the CIBE steps were found to be strongly sensitive to the step height. As shown in Fig. 2, for a film thickness of about 200 nm, the $I_{c\text{-}j}$s were found to decrease as the step height increased from about less than 200 nm to about 300 nm, the investigated range. This step height dependence of the $I_{c\text{-}j}$ allowed the controlled shift of the operating temperature range of the SQUIDs to the desired temperature window [4].

B. *Effects of the superconducting film properties*

The I_{c-j} of the CIBE SEJs and consequently the operating temperature range of the SQUIDs was also found to be dependent on the film thickness. The I_{c-j} of the SQUIDs increased with increase of the film thickness for the investigated range of 120 nm up to 300 nm. This with the observed increase of the I_{c-j} by the increase of the junction width led to the proportionality of the I_{cj} with the geometric junction area [4]. While the I-V characteristics of junctions on one chip showed the dependence of the I_{cj} on the junction area, the I_cs of junctions with the same geometries varied considerably from one chip to another showing high sensitivity to the growth of the films.

The V_{s-pp} of a SQUID array of eight on a 1 cm^2 $LaAlO_3$ is shown in Fig. 3. While the operating temperature range of the neighbor SQUIDs were close to each other, it changed systematically from one side of the substrate to the other end and narrowed as the temperature range increased. This is interpreted to be due to the very slight non-uniformity of the film thickness and/or film properties across the substrates. The narrowing of the operating temperature range at higher temperatures is associated to the sharp variation of the I_{c-j} versus temperature in particular close to the T_c.

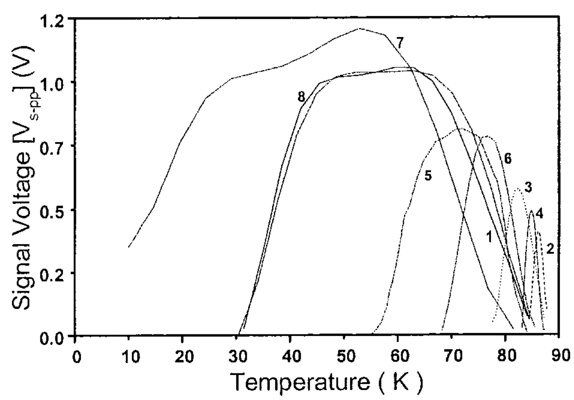

Fig. 3. Operating temperature range of an rf-SQUID gradiometer array on a 1 cm^2 $LaAlO_3$ substrate with CIBE-steps. The SQUIDs numbers 3-6 are in the middle of the substrate.

C. *The I-V Characteristics and Temperature Dependence*

To characterize the junctions of the SQUIDs, the washer areas of the rf-SQUIDs were opened and the I-V curves of the junctions were measured down to LH temperature. While the junctions on non-optimized steps showed randomly mixed RSJ and non-RSJ behavior, the junction of the low 1/f noise SQUIDs made on substrates with CIBE steps showed RSJ type behavior reproducibly. The I-V curve for one of such low noise rf-SQUID with 3 µm wide bridge is shown in figure 4a. The measured I_c of an array of junctions, made of similar film quality on the same CIBE steps, scaled with the junction widths of 3 to 8 µm on one chip. The field dependence of the junction array also indicated an effective junction area scaled with the junction widths [3].

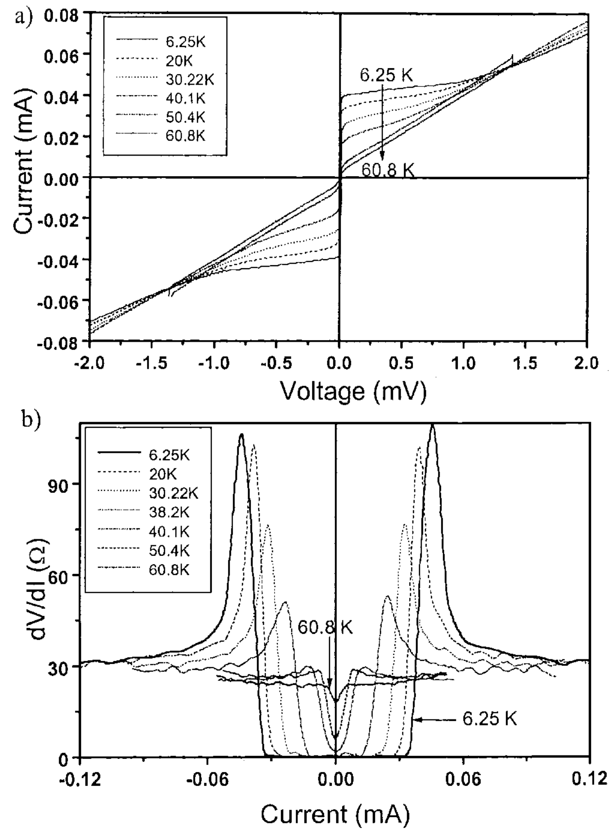

Fig. 4. a) I-V curve and, b) dV/dR versus temperature of the junction of a rf-SQUID magnetometer made on $LaAlO_3$ substrate with CIBE-steps.

R_N of the junctions was also measured to decrease slightly as the temperature increased. The I-V curve of a SQUID junction is shown in figure 4a with its corresponding dV/dR in figure 4b. While a single junction I-V characteristic is shown in the figure for one of the devices, many SQUID junctions showed serial multi-junction (typically four junctions) behavior with I_c of the two weakest junctions close to each other. More detailed study and analysis on the I-V characteristics of such SQUID junctions are presented elsewhere [3].

V. 1/F NOISE AND THE TEMPERATURE DEPENDENCE

Two temperature dependencies for the low frequency 1/f type noise are observed for the SQUIDs made on the CIBE steps. One type of 1/f noise was found to decrease as the temperature was increased and the 2nd type decreasing as the temperature was decreased. The change in the temperature caused a change in the white noise level determined by the V_{s-pp}. The change in the white noise at different operating temperature range of the above SQUIDs was not linked to the 1/f noise behavior. The noise spectra of a sample with the first type characteristics is given in Fig. 5, showing increase of the 1/f noise as the temperature is decreased. This increase of the low frequency noise is interpreted to be due to the increase of the I_{c-j} and its associated fluctuations. This type of noise characteristics is mostly observed in the SQUIDs with very smooth and precipitate free films but having minor structural defects right at the step edge [4].

The second type of the 1/f noise increased with the temperature. The source for this noise is interpreted to be due to the flux hopping mechanism in the film of the washer area of the SQUIDs close to the loop [4]. The increase of the noise at high temperatures is associated with the increase of the thermal energy for the fluxons as well as decrease of the barrier heights. This noise characteristic is mostly observed in the samples made of the films with relatively high density of precipitates and is found to increase as the density of the precipitates in the film increased [4].

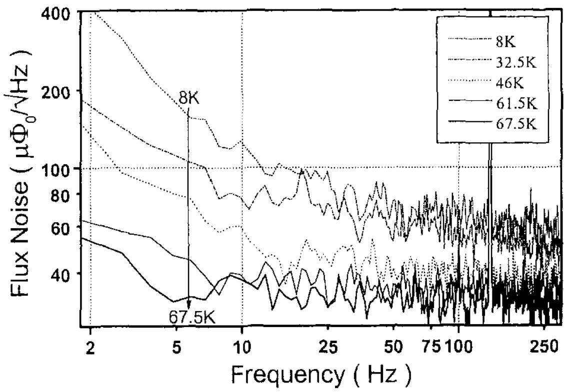

Fig. 5. Temperature dependence of noise spectra of a rf-SQUID gradiometer made of 200 nm thick Y-Ba-Cu-O film on $LaAlO_3$ substrate.

None of the above low frequency noise behavior was observed for SQUIDs with high quality films on the CIBE steps while the white noise level was mainly determined by the $V_{s\text{-}pp}$. The noise spectra of a SQUID made of high quality film grown on a $LaAlO_3$ substrate with clean sharp CIBE steps is shown in Fig. 6. Similar SQUIDs have been integrated in a second order 9-channel SQUID gradiometer system working over many thermal cycles and for about one year to date [7]. The noise spectra of the samples was measured with both conventional L-C tank circuit and superconducting coplanar resonators [6]. While the white noise level of the SQUIDs could be decreased by about four times when using the coplanar resonators, a relatively higher low frequency noise revealed in the noise spectra, the determining source of which is under further investigation.

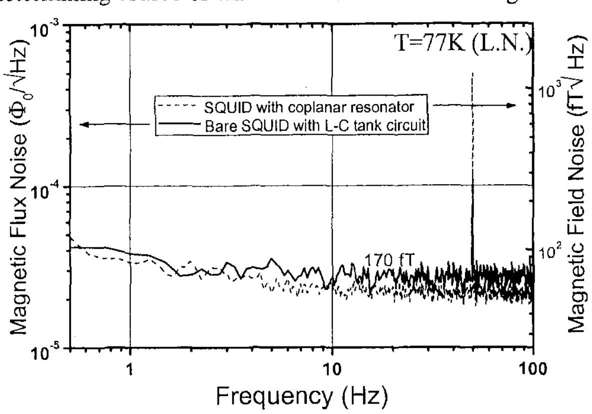

Fig. 6. Noise spectra of low 1/f noise rf-SQUID magnetometer measured with conventional L-C tank circuit and superconducting coplanar resonator. The field sensitivity of the bare SQUID at white noise level is 170 $fT/\sqrt{Hz}$.

VI. SUMMARY AND CONCLUSIONS

Effects of the step structure and the film characteristics on the noise and operating temperature range of the SEJ rf-SQUID magnetometers and gradiometers were investigated. For normal incident IBE process, a re-deposition of substrate material was formed at the edges as well as on the sidewalls of the step. This re-deposition was dependent on the substrate materials being the most for the $LaAlO_3$. The re-deposited material at the edges is interpreted to be the main source for very low yield and high 1/f noise SQUIDs. Using a developed Combinational IBE process, sharp steep steps could be made. By control of the height of the CIBE-steps made using the Combinational IBE process, the operating temperature range of the SQUIDs could be tuned to the desired liquid nitrogen temperature.

The low frequency 1/f type noise of the SQUIDs made on the CIBE-steps could be classified into two major categories. One type of the 1/f noise increased as the temperature decreased. This was associated to the noise in the junction caused by the $I_{c\text{-}j}$ fluctuations. The second type of the 1/f noise spectra was found to increase as the temperature increased and was associated to the flux hopping mechanism in the film. The latter type of the noise was found in films with relatively high density of precipitates while the former was mostly observed in samples with smooth film surfaces but defects at the edge of the steps. High yield of low 1/f noise rf-SQUIDs was achieved using high quality films on the CIBE-steps on $LaAlO_3(100)$. The I-V curves of the junctions of the SQUIDs showed RSJ type behavior with field dependency as for uniform junctions. The white noise level of the SQUIDs was mainly following the trend of the $V_{s\text{-}pp}$ increasing as the voltage signal decreased.

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