Selection of the Best Proper DC-SQUIDs in a Multi-SQUID Configuration

I. Avci, R. Akram, A. Bozbey, M. Tepe, and D. Abukay

***Abstract*—We have carried out experimental investigation of multi-DC-SQUID magnetometer configuration fabricated on $YBa_2Cu_3O_{7-\delta}$ thin films onto 24 degree $SrTiO_3$ bicrystal substrates by directly coupling the pick-up loop to DC-SQUIDs. The layout of the magnetometer pick-up loop was chosen as a square washer configuration by maximizing loop effective area and minimizing loop inductance. We have used Dc-Magnetron Sputtering technique for deposition of the films and chemical etching process for patterning the Josephson junctions having 4 μm widths. The use of multi-SQUID configuration is related to the selection of the best proper junctions for SQUID to improve the chip sensitivity with selectivity option of choosing the squid junctions rather than multichannel operation. Selection of the best junctions compared to each other depending on the junction critical currents and noise levels caused by the fabrication process and placements of the junctions on the grain boundary enable having an increased output signal of the DC-SQUID.**

***Index Terms*—Bicrystal Josephson junctions, HTS DC-SQUIDs, multi-SQUID configuration.**

I. Introduction

In the fabrication of high temperature superconducting quantum interference devices (SQUIDs) on $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films, some different fabrication technologies have been used for realization of different types of SQUIDs for needed applications [1]–[3]. For high-T_c DC-SQUIDs, fabricating bicrystal junctions by the epitaxial growth of YBCO thin film on bicrystal substrates (i.e., $SrTiO_3$), is relatively the best choice among the other techniques (i.e., step-edge, ramp-edge, SNS, etc.) because of the exhibition of high reproducibility and consistent characteristics of the bicrystal junctions [4]. In bicrystal technology, there have been relatively many limiting factors for designing the SQUIDs in different geometries and fabricating them onto different places of thin films. For eliminating some unwanted effects coming from the grain boundary of the bicrystal substrates, many improvements have been reported related with the improvement of thin film quality along the grain boundary [5]–[7]. Particularly on different substrates, obtaining similar Josephson junctions for bicrystal DC-SQUIDs are still depend on the fabrication process and film-grain boundary structure.

In our study, we used multi-SQUID configuration to investigate the selectivity option of an individual SQUIDs to reduce some limitations caused by the variation of thin film and junction properties coming from the fabrication process and grain boundary of the substrate. This configuration, in which the DC-SQUIDs are connected to the same pick-up loop and lying on the grain boundary with different characteristics, allows us to select the best proper SQUID in terms of noise and output signal values rather than the multichannel operations.

II. Experimental Results and Discussion

We prepared 200 nm thick $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films by dc inverted cylindrical magnetron sputtering (ICMS) system on 24-degree bicrystal $SrTiO_3$ (STO) substrates (purchased from MaTecK GmbH-Juelich). The growth process was optimized with respect to deposition parameters. We controlled the film growth parameters by modifying the target surface and plasma conditions as well as the deposition rate. Resulting films have good quality with respect to its structural and electrical properties (i.e., highly c-axis oriented, 4–5 nm surface roughness and 91 K T_c with 1 K transition sharpness) as needed for good quality Josephson junctions and DC-SQUIDs.

YBCO thin films were patterned by standard photolitography and chemical etching. The device layouts were prepared as single SQUID and array-like multi-SQUID configuration of directly coupled magnetometer design as shown in Fig. 1(a). The outer dimensions of magnetometers were chosen as 9 mm $\times$ 9 mm leaving narrow edges of 10 mm $\times$ 10 mm STO substrates to decrease the edge effects and increase the effective area of the pick-up loop.

A square hole placed at the center of the pick-up loop having one edge of 3 mm. The SQUIDs were designed to have inductances, Ls $\sim$ 85 pH and Lp $\sim$ 5.1 nH, effective area, $A_{eff} \sim 0.42\ mm^2$ and pick-up loop area, $Ap \sim 30\ mm^2$. The Josephson junctions of SQUIDs were patterned as 4 μm widths and 10 μm long onto bicrystal line of STO, having 4 μm line-spacing in the SQUID hole. The strip lines of the SQUID loop was chosen as 10 μm-wide and 70 μm-long. The devices were characterized by low noise electronics inside two-layer μ-metal shield and non-magnetic liquid nitrogen dewar by directly immersing the SQUIDs into the liquid nitrogen bath.

The critical temperatures of the junctions were measured as 88–89 K after from the chemical etching. This difference in

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I. Avci is with the Department of Physics, Izmir Institute of Technology, 35436-Urla Izmir, Turkey, and also with Ege University, 35100-Bornova Izmir, Turkey (e-mail: ilbeyiavci@iyte.edu.tr).

R. Akram and D. Abukay are with the Department of Physics, Izmir Institute of Technology, 35436-Urla Izmir, Turkey.

A. Bozbey is with the Department of Electrical and Electronics Engineering, Bilkent University, 0680-Bilkent, Ankara, Turkey.

M. Tepe is with the Department of Physics, Ege University, 35100-Bornova Izmir, Turkey.

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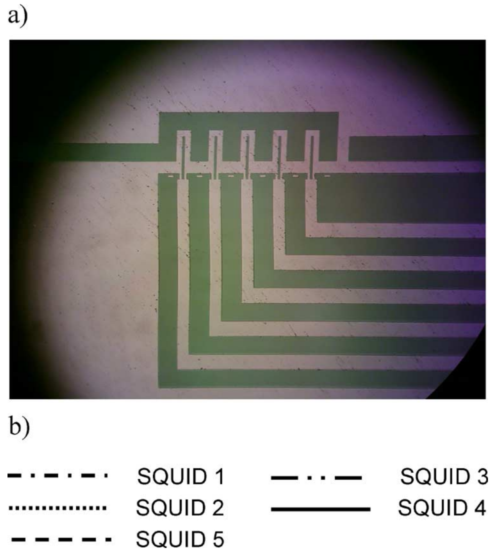

Fig. 1. (a) Layout of the multi-SQUID configuration. (b) Legends describe the five individual SQUIDs placed into the multi-SQUID configuration. All SQUIDs have 4 $\mu\mathrm{m}$-width junctions placed on grain boundary line having separate electrodes and all SQUIDs were connected to the same pick-up loop.

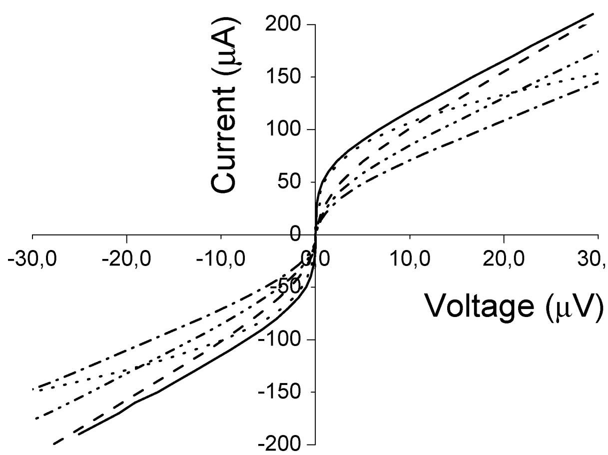

Fig. 2. Current-voltage measurements of individual DC-SQUIDs in multi-SQUID device. $\mathrm{I_c}$ values were varied between 8 to 40 $\mu\mathrm{A}$.

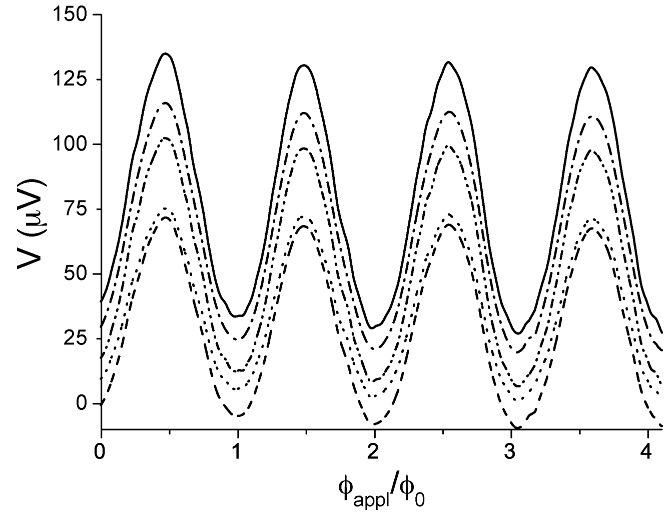

Fig. 3. Output signals of the individual SQUIDs. Solid line represents the best proper SQUID. The values have 4 times magnification by the readout electronics. SQUIDs were modulated by integrated on chip coil by applying 20 Hz ac signal.

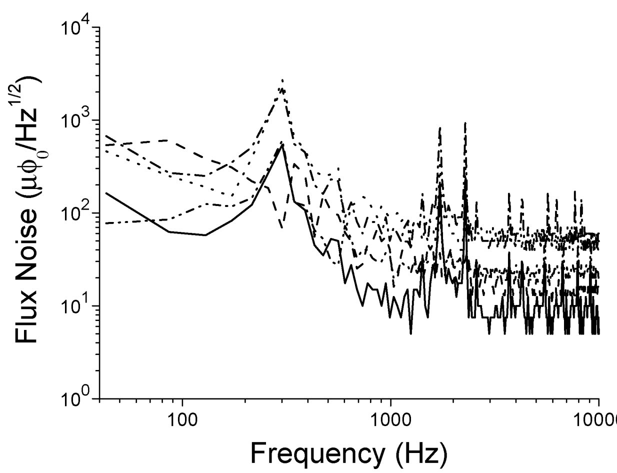

Fig. 4. Noise responses of individual DC-SQUIDs. Solid line represents the noise spectrum of SQUID 4 which has the lowest white noise value compared to other devices in multi-SQUID configuration.

$\mathrm{T_c}$ between original film and patterned junctions caused by the edge effects resulted by chemical etching process.

I-V characteristics of individual DC-SQUIDs were measured by low noise electronics having integrated current source. Critical currents of the junctions, determined at 77 K, varied from 8 to 40 $\mu\mathrm{A}$ as shown in Fig. 2.

Here, the difference in $\mathrm{I_c}$ values are caused by the effect of etching process and placement of the junctions onto the grain boundary line.

The individual SQUID signals are shown in Fig. 3. V-Φ measurements were made by FLL electronics inside the μ-metal shield and the SQUIDs were modulated by on-chip integrated coil. Peak-to-peak voltage modulations $(\mathrm{V_{spp}})$ of SQUIDs are in the range of 75–100 $\mu\mathrm{V}$ with 4 times amplification by readout electronics. Here SQUID-4, described as solid line, has largest $\mathrm{V_{spp}}$ as well as critical current value.

Flux noise spectrums of the individual SQUIDs were analysed by high frequency spectrum analyser and results are shown in Fig. 4. Because of the limitation of spectrum analyser used in this study, low noise spectrums below 40 Hz are not shown here.

As seen from Fig. 4, SQUID-4 shows the lowest white noise level compared to others. Here SQUID-1, which with the lowest critical current and $\mathrm{V_{spp}}$, has maximum white noise value among the other SQUIDs.

There were some noise contributions to the flux noise scheme at 300 Hz and around 1 KHz even in the two-layer mu-metal shield. These noises are coming up from the measurement environment and spectrum analyser itself but the mains noises were filtered by using the preamplifier's high-pass filter.

Bias current dependence of the $\mathrm{V_{spp}}$ signals were determined either for single DC-SQUID and individual device in multi-SQUID as shown in Fig. 5.

The $\mathrm{V_{spp}}$ of single SQUID shows characteristic bias current dependence; however, there is a second peak for an individual

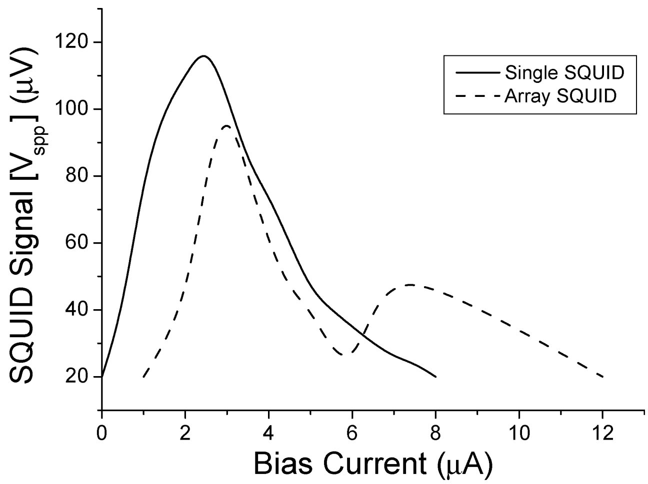

Fig. 5. Bias current dependence of the single SQUID chip and individual SQUID in multi-SQUID configuration. Here in the multi-SQUID configuration, individual SQUID's bias current vs. V_{spp} dependence shows second peak in contrast to the single chip (represented by a solid line). The reason of this second peak may be caused by inductive coupling and crosstalk of other SQUIDs placed in multi-SQUID configuration.

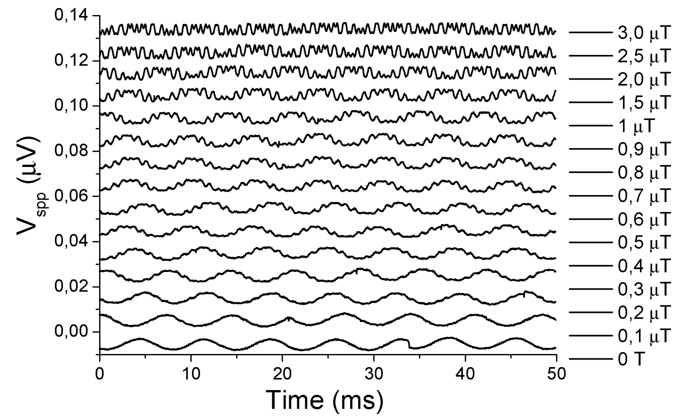

Fig. 6. DC-SQUID response to applied field. [V_{PP} (1 kHz) ac signal applied to a wire lying 1 cm distance under the SQUID]. Here the SQUID were used as a sensor to scan a wire lying under the device.

device in multi-SQUID. This second peak can be caused by inductive coupling and crosstalk of other SQUIDs. This behavior is under investigation for further research and reports.

We selected SQUID-4 from the multi-SQUID configuration for sensing the magnetic field of a Cu wire having 0.1 mm diameter, lying 1 cm below the device, by applying 1 kHz and different peak-to-peak ac voltages to the wire.

Resulting generated magnetic fields values and SQUID response to these fields coming from the wire are shown in the Fig. 6. Just above 0.1 μT, SQUID becomes sensitive to the wire and above 2.0 μT the SQUID signal driven by the feedback coil are suppressed by the wire signal as seen from the graph.

SQUID-4, described as solid line in the figures, has the most proper junctions among the others in multi-SQUID configuration by means of its relatively high I_cR_n value, high output signal and low white noise value. Therefore, in an array-like multi-device configuration, these SQUIDs can be easily chosen for proper application with required properties.

III. Conclusion

In this multi-SQUID configuration, the SQUIDs were characterized individually and compared with each other depending on the differences in characteristics. The use of such configuration is related to the selection of the best proper junctions for SQUID rather than multichannel operation. Selection of the best junction compared to each other depending on the junction critical currents, SQUID voltage modulation and noise levels caused by the fabrication process and placements of the junctions on the grain boundary enable having a reduced noise level of the DC-SQUID. In this study, chemically etched 4 μm width junctions showed different characteristics in the SQUIDs placed on single chip and one of them was chosen as having the best results for SQUID output and field sensitivity. By this method, any SQUID in the array-like configuration can be selected for using them in different applications depending on the needed device properties.

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