Noise, Junction Characteristics, and Magnetic Field Dependencies of Bicrystal Grain Boundary Junction Rf-SQUIDs

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***Abstract*—Bicrystal grain boundary (GB) Josephson junctions and rf-SQUID's were made of 200 nm thick PLD YBCO films on bi-crystal $SrTiO_3$ substrates. The junction characteristics were studied to investigate optimal parameters in the rf-SQUID layout designs and the limits imposed by the technology. The I_c of 3 to 8 μm wide test junctions scaled with the junction widths, showing clear linear RSJ-like I–V characteristics at 77 K. All the junctions showed hysteretic RCSJ-like behavior at very low temperatures. Classical Josephson flux motion type (long junction) nonlinearity in I–V curves of all the junctions was also observed at lower temperatures with systematic dependence on the junction widths. Measurements of the magnetic field dependence of the I_c of the junctions resulted in junction width dependent well-defined Fraunhofer-pattern like characteristics. The obtained characteristics of the junctions led to feasible criteria for the rf-SQUID layouts with desired device characteristics. Rf-SQUID's were made using designs for optimal performance at 77 K while avoiding large superconducting weak links across the substrate GB. Devices with low noise characteristics and junction field sensitivities proper for operation in environmental background magnetic fields were obtained. A nonsystematic spread of optimal working temperature of the SQUID's were also observed which is associated to the spread of the junction parameters caused by the defects at the GB of substrates.**

***Index Terms*—Bicrystal, Josephson junction, magnetic field, noise, rf-SQUID.**

I. Introduction

BI-CRYSTAL substrates have been widely used in bi-crystal grain boundary (GB) Josephson junction (JJ) based devices such as SQUID's [1]–[4]. The straightforward fabrication of high-T_c superconducting GB JJ's using thin films across the bicrystal substrate GB's [3], [4] makes this technologies very attractive among other fabrication technologies. This type of JJ has been widely used in fabrication of dc-SQUID's since the extended GB across the substrate does not impose major limits in the designs [2], [4]–[6]. Though, the applications of the bicrystal GB JJ's in rf-SQUID's are limited by the extended bicrystal GB across the substrate [7], [9]. The quality of the substrate GB as well as the film quality across the GB is also very critical in the use of this type of JJ in rf-SQUID's. This is due to the need to control junction parameters through the fabrication process to obtain proper operation of the rf-SQUID's, such as for the devices in this work [7]. For determining the limits and characteristics of such devices and to find their optimal designs made using the bi-crystal GB technology, better understanding of the characteristics of the used GB JJ's is also very essential.

In this study, we first present results of our investigation on the characteristics of the fabricated bicrystal GB JJ's on bi-crystal $SrTiO_3$ substrates. The junction width, magnetic field, and temperature dependencies of the junction parameters were investigated. Based on above results, we made bi-crystal GB rf-SQUID magnetometers and gradiometers using layout designs to obtain low noise devices with background magnetic field sensitivities proper for use in systems such as for NDE, unshielded MCG, and SQUID microscopy [8]. The temperature dependencies of the characteristics and the field sensitivity of the junctions and the resulting SQUID's are discussed.

II. Sample Preparation and Characterization Setup

Bicrystal GB junctions and rf-SQUID's were made on symmetric 36.8° angled bicrystal $SrTiO_3$ substrates. The samples were made of 200 nm thick Y-Ba-Cu-O films deposited using pulsed laser deposition technique. The device patterns were developed using conventional photolithography technique and low energy IBE process [10]. A Helium dewar based characterization setup with a two layer μ-metal magnetic shield and a temperature stability of better than 0.1 K was used to characterize the samples. Temperatures above 5 K were obtained by elevating the samples above the liquid helium level using the stabilized temperature gradient in the dewar [10]. The junctions were characterized by making contacts of gold wire bonds directly onto the surface of the films resulting in contact resistances in range of a few ohms at low temperatures. The dynamic resistances, dV/dI, of the samples were measured using an approximate 1% modulation of the bias current through the junction in four-probe configuration. A nonmagnetic chip carrier was used to interface the samples to the characterization electronics. The SQUID signals were measured using a conventional tank circuit in combination with a 1 GHz rf-electronics with a white noise level of less than 10 $\mu\Phi_0/\mathrm{Hz}^{0.5}$ for the used frequency range.

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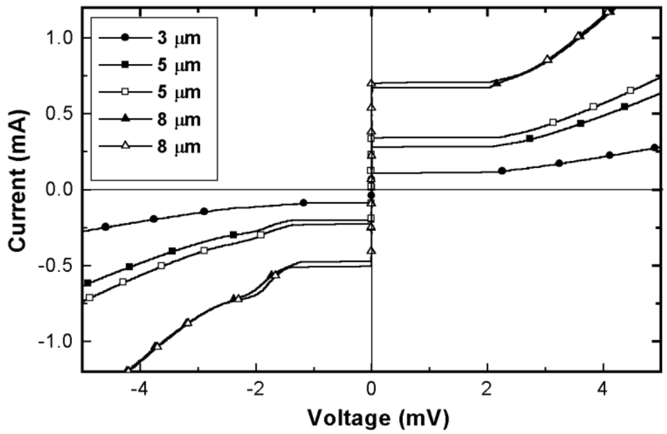

Fig. 1. IV Curves of an array of one 3 μm, two 5 μm, and two 8 μm wide GB junctions on a bicrystal $SrTiO_3$ substrate at 7 K.

III. Bi-Crystal Junction Characteristics

A. I–V Characteristic

All the junctions showed resistively-capacitively-shunted junction (RCSJ) type behavior with hysteretic I–V curves at low temperatures. The I–V characteristics of 3 μm to 8 μm wide junctions on one chip are shown in Fig. 1. The critical current density, J_c, of the junctions ranged within about 20–40 kA/cm^2 at 7 K decreasing as the geometrical junction width, W, decreased. The sheet resistance, ρ_N, of the junctions at 7 K, ranged within about 48–95 nΩ–cm^2 increasing with decrease of W. The hysteretic underdamped (nonzero Steward-McCumber parameter, β_c) behavior of the junctions increased as the temperature decreased below about 40 K, resulting in β_c of about 2.3–2.5 at 7 K. The associated values of the $\beta_c = 4\pi e I_c C R^2/h$ of the junctions led to junction capacitances within the range of 5 to 8.5 μF/cm^2 which is about two times less than typical reported values [11]–[13]. As shown in Fig. 1, I–V curves of the junctions showed nonlinear behavior with deviation from the simple RSJ-model at low temperatures. This is associated with the Josephson flux motion effect happening in junctions with widths of about 4 times larger than the Josephson penetration depth, $\lambda_j = (h/4\pi e J_c \mu_o(2\lambda + d))^{0.5}$[14]. The calculated λ_j, of the junctions at 7 K resulted in W/λ_J of about 2, 4, and 7.8 for the 3, 5, and 8 μm wide junctions respectively. The W/λ_j values were obtained using the geometrical dimensions of the junctions. The obtained W/λ_J ratios are about the reported values for these types of the junctions with similar junction widths [13], [15]. As shown in the figure, the nonlinearity in the I–V curves became prominent as the junction widths increased to 8 μm resulting in W/λ_J well above 4 [14]. The junctions showed clear linear RSJ type I–V characteristics at temperatures higher than about 35 K, 50 K, and 70 K for the 3, 5, and 8 μm wide junctions respectively, corresponding to approximate $W/\lambda_J <\sim 2$ in our samples. The I–V characteristics versus temperature of the 8 μm wide junction and its corresponding dynamic resistance are shown in Fig. 2. The dV/dI versus temperature of the samples was used to determine the clear RSJ-like behavior.

The normal resistance, R_N, of the junctions also scaled inversely with the I_c or width of the junctions, leading to almost similar I_cR_N (or $J_c\rho_N$) values for the junctions on one chip. The R_N of the 3, 5, and 8 μm wide junctions was measured to be about 14, 6, and 2.5 Ω, respectively, leading to I_cR_N in the range of 1.8–2.1 mV at 7 K. This is in the range and slightly higher than the reported values for this type of the junctions [1], [4]. The measured R_N of most of our bicrystal GB junctions showed slight temperature dependence decreasing by maximum of about 5–10%, as the temperature increased from 7 K to their T_c.

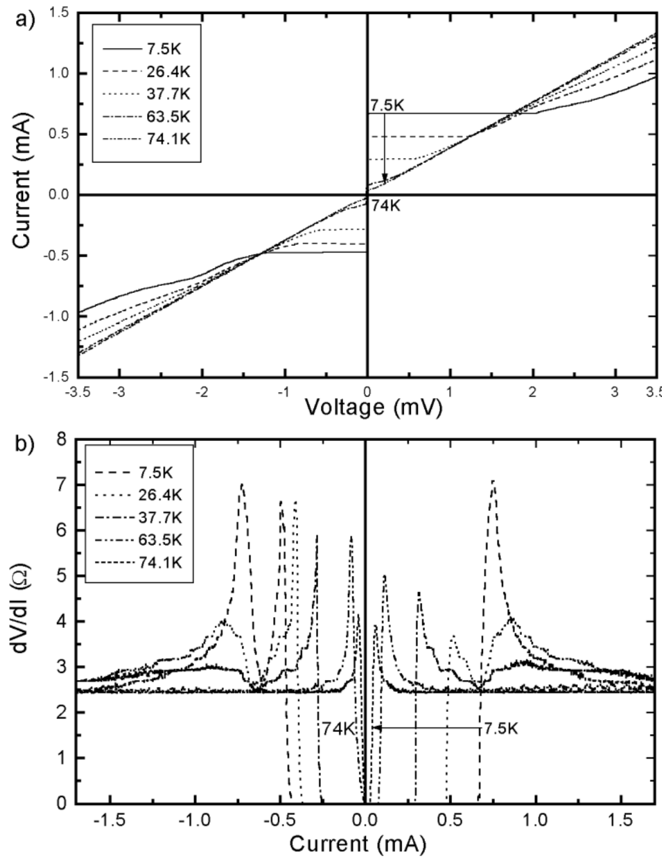

Fig. 2. Temperature dependence of I–V curve and the corresponding dV/dI of a 8 μm wide junction on bicrystal $SrTiO_3$ substrate.

The obtained values for the J_c and ρ_N of our samples are close and slightly better than the typical reported values [11], [13], [16]. While the I_c of the junctions made on one chip decreased as the W decreased, a systematic change of the I_c was not observed. The I_c ratios decreased further than the junction width ratios, which is interpreted to be due to the side defects or slight nonuniformity of the barrier being more effective for smaller W[16]. We associate the defects at our GB junctions to the optically observable imperfection of the substrate GB's deteriorating the film growth at the junctions.

B. Magnetic Field Dependence

The applied magnetic field, B_a, dependence of the I_c of the junctions was used to investigate the physical structural dependent characteristics of the junctions. Investigations of the dependence of the maximum Josephson current on the B_a, provide useful means to make evident spatial variation of J, since these are reflected in peculiar features of the I_c vs. B_a patterns. The

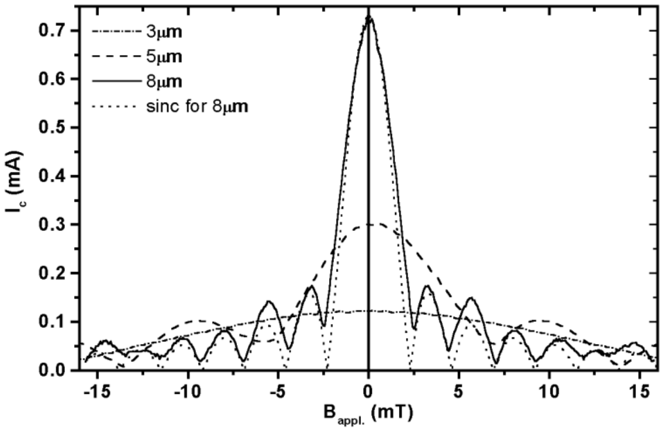

Fig. 3. Magnetic field dependence of I_c of 3–8 μm wide GB junctions on bicrystal $SrTiO_3$ substrates. The classical field dependence of the I_c (sinc function) is shown for the 8 μm wide junction.

I_c versus B_a of the junctions revealed a well-defined Fraunhofer-pattern like behavior scaled with the I_c of the junctions showing proportionality to junction widths. The field dependence of the I_c of three junctions at 7 K is shown in Fig. 3. The measured field dependence of the junctions is very close to the calculated results from the classical field dependence for uniform current through the junctions as shown for the 8 μm wide JJ in Fig. 3. The measured dependence of the field period, ΔB_0 of the junctions, versus W showed $1/W^2$ dependence [17]–[19]. This is mainly associated with the effect of the field focusing factor of the film areas of the patterns, as also verified and previously reported for some of our SEJ's [19]. While the ΔB_0 of the junctions scaled with $1/W^2$ for a magnetic penetration depth, $\lambda \sim 300$ nm, it was larger than the expected values [17]–[19], a systematic and detailed study of which is in progress. The sinc function type form of the field dependence of the I_c and its deep modulation shown in Fig. 3 indicate an almost uniform current distribution through the areas of the junctions. The B_a dependence of I_c of our 3 to 5 μm wide junctions showed approximate short junction behavior down to liquid helium temperature lower than the reported values for similar type of the junctions [13], [18]. The 8 μm wide junction showed a clear short junction characteristic at 35 K and above. Similar field dependence versus temperature was obtained for all the junctions with a slight change of the ΔB_0, associated with temperature dependence of the λ [19], [20].

IV. Bi-Crystal GB Rf-SQUIDs and the Characteristics

Rf-SQUID magnetometers and gradiometers were made on symmetric 36.8° angled bicrystal $SrTiO_3$ substrates. While the Bi-crystal substrates offer very simple fabrication for the mono-layer device structures, the layout designs for typical rf-SQUID's on them are limited by the extension of the grain boundary (GB) across the substrate [9], [10]. The extended GB creates unwanted large superconducting weak links such as in the washer areas of the conventional thin film planar rf-SQUID magnetometer and gradiometer layout designs [9], [10]. Large superconducting weak links across the GB are known to be a source for the $1/f$ type noise in the devices due to the motion of fluxons along the GB [6], [7], [9]. We present results on monolayer bi-crystal substrate rf-SQUID layouts for optimal operation under background earth magnetic field at liquid nitrogen temperature while also avoiding large GB weak links in the patterns.

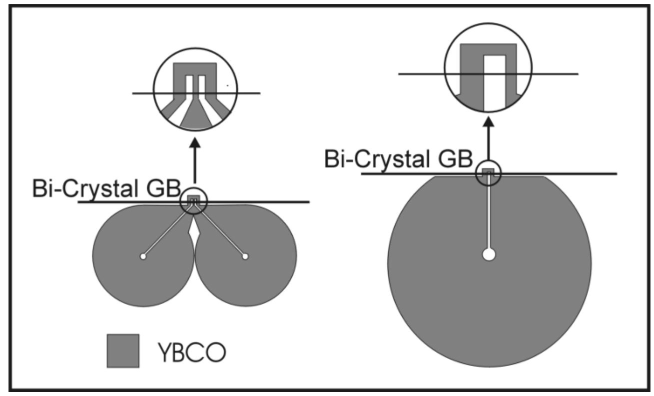

Fig. 4. Asymetric multi-junction rf-SQUID gradiometer and magnetometer layout designs on bicrystal substrates.

A. Rf-SQUID Gradiometer and Magnetometer Designs

Layout designs based on asymmetric multi-junction structures for rf-SQUID magnetometers and gradiometers on bi-crystal substrates are shown in Fig. 4. The gradiometer layout has three junctions in parallel across the GB with the smaller middle junction as the determining JJ. The same design concept is used for the magnetometer design with two parallel junctions containing one determining JJ and a wider dummy junction. SQUID's were made with about 0.8 to 1 μm wide narrow junction, and 2–4 μm wide dummy junctions, resulting up to 4/1 asymmetric junction width ratios. The basics of the rf-SQUID magnetometer design are similar to the well-established typical dc-SQUID designs [2], [5], [6]. The magnetometers had a washer area of 7 mm^2 (3 mm diameter), 200 μm long slit, and 50 μm diameter loop leading to inductance, L, of about 180 pH. The gradiometers had washer areas of 1.7 mm^2 (1.5 mm diameter), 1.5 mm baseline, 1 mm long slit, and 75 μm diameter loop leading to inductance of 590 pH. As shown in the figure, the washer areas of both designs are modified to minimize the length of the slits while avoiding major reduction of the coupling coefficient of the used conventional $L-C$ tank circuits of the SQUIDS.

B. Experimental Results

The noise spectra of a magnetometer and a gradiometer at their optimal operating temperatures are shown in Fig. 5. The $1/f$ type noise of the devices was measured to increase as the temperature was decreased. This increase of the low frequency noise is interpreted to be due to the increase of I_c of the junctions and its associated fluctuations. The optimal working temperature of the SQUID's were scattered from above $\sim$20 K to about T_c of the films while the amplitude of the flux-voltage transfer function, $V_{s\text{-}pp}$, of some devices were too small to allow the noise spectra measurements at any temperature by resulting very high white noise levels [7]. Based on the I_c versus temperature and the effective width of our junctions, with the consideration

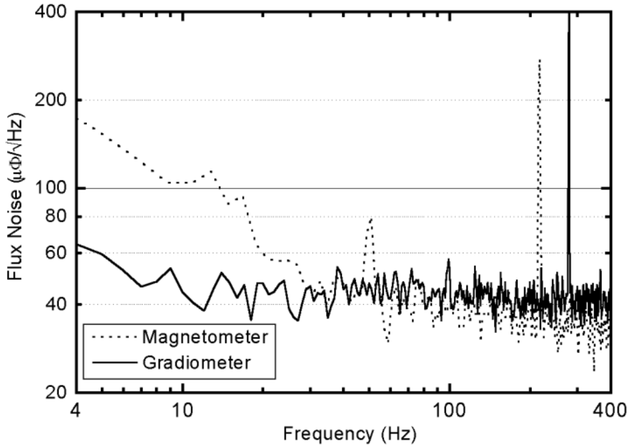

Fig. 5. Noise spectra of bicrystal GB magnetometer and gradiometer designs on bicrystal $SrTiO_3$ substrate at their optimal operating temperatures of 85.4 K and 54.8 K respectively.

of the $\lambda \sim 300$ nm, an approximate optimal working temperature range close to 77 K was expected for our devices. This was based on optimal rf-SQUID parameter $\beta_L = 2\pi L I_c/\Phi_o \cong 1$ for the used layouts and the expected I_c for the smaller and presumably the working junction of the SQUID's. The observed spread and deviation of the optimal working temperature of our devices was mainly interpreted to be due to the spread of I_cs. I–V characterizations of arrays of 3 to 25 serial 3 μm and 5 μm wide junctions showed an spread of I_c parameter of up to about 50% of their mean values. This is while the serial junctions are physically very close to each other, compared to the junctions of an array of SQUID's on one chip. The spread of junction parameters has been the source for difficulties in control of the optimal working temperature of our devices. The spread of junction parameters is interpreted to be mainly caused by optically observable defects at the substrate GB's deteriorating the film growths at the junction areas. The work for obtaining junctions with more controlled parameters is in progress.

Based on the B_a dependence of the I_c of the junctions, a suppression of less than 20% of $V_{s\text{-}pp}$ of zero field cooled SQUID's were expected under a background earth magnetic field, as was also verified by the direct field sensitivity measurements of the devices.

V. Summary and Conclusions

Bi-crystal GB Josephson Junction and rf-SQUID magnetometers and gradiometers were made on symmetric 36.8° angled bicrystal $SrTiO_3$ substrates. Short junction characteristics with clear RSJ-like behavior were obtained for junctions widths up to 8 μm at 77 K. All the characterized junctions showed a well-defined Fraunhofer-pattern like magnetic field dependent I_c, indicating an almost uniform junction barrier, scaling with $1/W^2$, Study of the I–V characteristics and the field sensitivity of various junction arrays led to the criteria for optimal desired junction geometries in the rf-SQUID layout designs. The criteria allowed rf-SQUID layout designs for obtaining low noise devices with optimal working temperature close to 77 K proper for operation under background earth magnetic field. While the layouts resulted in devices with noise characteristics and junction field sensitivities proper for practical applications such as NDE, unshielded MCG, and rf-SQUID microscopes, a relatively large spread of the optimal working temperature for the arrays of the SQUID's were obtained on various chips. This is interpreted to be mainly due to the defects of the substrate GB's leading to variation of the I_c of the junctions of the devices. Further work for better control of the optimal working temperature of the devices through fabrication process is in progress.

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