

YBa₂Cu₃O_{7-x} Josephson Junctions on Bicrystal Al₂O₃ and SrTiO₃ Substrates*

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Abstract—Bicrystal grain-boundary junctions (bi-GBJs) have been reproducibly fabricated on SrTiO₃ (STO) and r-plane Al₂O₃ (sapphire) bicrystal substrates. Sapphire bicrystals are candidates for high-frequency applications due to their low dielectric constant and loss tangent. The sapphire bi-GBJs demonstrated resistively shunted junction (RSJ)-like current voltage characteristics, with junction parameters comparable to the STO bi-GBJs and critical current densities $J_c \sim 10^5$ A/cm². Independent control of junction resistance (R_N) was demonstrated with the use of Au shunt layers. In addition, overlayers such as Au or STO may act to passivate the GBJs and improve long term stability.

I. INTRODUCTION

We present preliminary results of a study of bicrystal grain-boundary Josephson junctions (bi-GBJ) suitable for high frequency applications such as programmable voltage standards and THz mixers. After verifying small spreads in critical currents (I_C) in bi-GBJs on SrTiO₃ (STO), we fabricated high quality junctions on sapphire bicrystals, and demonstrated independent control of the junction resistance (R_N) on both STO and sapphire bicrystals. We believe this is the first published study of YBCO Josephson junctions on sapphire bicrystals.

A particular advantage of bicrystal grain-boundary junctions is their controllable and reproducible fabrication, resulting in higher yields and narrower junction parameter spreads than seen in other high- T_C junctions [1,2]. Because of the narrower spreads, bi-GBJs lend themselves to applications such as series arrays. However, to utilize bi-GBJs for high frequency applications such as digital to analog converters (DAC), programmable voltage standards and THz mixers, we need a bicrystal substrate with low dielectric constant and low loss tangent.

We have studied Josephson junctions on bicrystal substrates of r-plane (1012) sapphire with a misorientation angles of 24°. Sapphire's low dielectric constant ($\epsilon \sim 9$), low loss tangent ($\tan \delta < 10^{-7}$), and good infrared (IR) transmission make it a useful substrate for high frequency applications. Other high frequency compatible bicrystal substrates, such as MgO and NdGaO₃ (NGO), have been investigated for GBJs with resulting junction parameter spreads greater than that of GBJs on STO bicrystals [3-6]. In the case of NGO, the reduced junction performance is

attributed to the localized strain on the YBCO film at the grain boundary due to the anisotropic thermal expansion resulting from its orthorhombic structure [4,6]. The hexagonal crystal structure of sapphire and the related anisotropy could cause reduced performance in the sapphire bicrystal as well.

The applications listed above each have different junction parameter requirements. DAC applications require tight parameter spreads, and junctions with high critical currents ($I_C > 1$ mA) and characteristic voltages ($I_C R_N$) matched to the applied frequency [7]. Conversely, high-frequency mixer applications demand R_N matching to the antenna impedance, typically 50 Ω , with the largest possible $I_C R_N$ products. Both applications require the ability to control the junction resistance (R_N) independent of junction critical current (I_C). In our previous work with superconductor-normal metal-superconductor Josephson junctions (SNS JJs) we have shown that a specific junction resistance is attainable by using a Au shunt layer on the YBCO [8]. We report on the results of applying this technique to bi-GBJs.

Aging and annealing effects are important because the grain boundary is exposed to the environment unless it is deliberately covered in a separate deposition step. Ozone annealing has been shown to improve the junction characteristics [9,10], but the annealing effects are temporary, since the oxygen diffuses readily through the grain boundary. We observed situations where long term junction stability was poor and discuss possible solutions to address this problem.

II. EXPERIMENTAL

A. Fabrication Overview

We studied commercially purchased [001] tilt STO bicrystals with misorientation angles of 24° and 36.8°, and sapphire bicrystals with 24°. Using KrF pulsed laser deposition (PLD), a c-axis oriented YBCO film 100 nm thick was deposited onto the bicrystals at 760° C and 106 Pa (800 mTorr) O₂ pressure at a rate of 1.2 nm/sec. The J_c at 87 K of these YBCO films was typically $> 2 \times 10^5$ A/cm² for both STO and sapphire bicrystal substrates, indicating high quality YBCO. Where an insulating passivation layer was used over the YBCO it consisted of a 100 nm thick STO layer that was laser ablated *in situ* at 745° C and 53 Pa (400 mT) O₂ pressure. Where a normal metal shunt layer was used, it consisted of a dc sputtered Au film of various thicknesses (20 nm-80 nm) deposited *in situ* at 100° C. All GBJs were fabricated by patterning microbridges into the YBCO layer using standard photolithography and Ar⁺ ion beam etching. Fig. 1 is a micrograph of the junction layout

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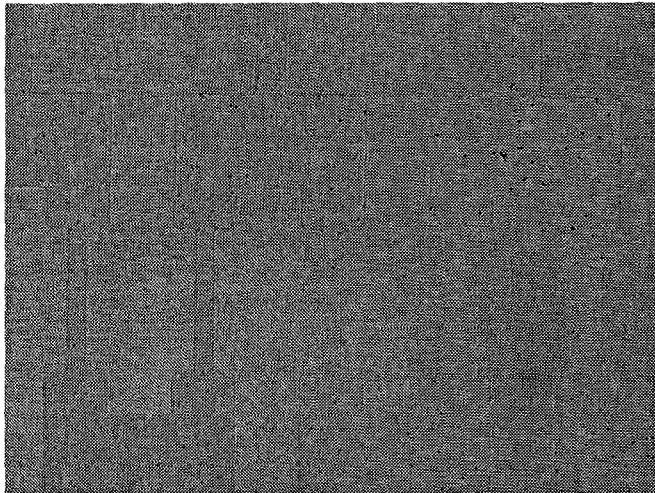


Fig. 1. Micrograph of YBCO microbridges across a sapphire bicrystal grain boundary.

across the grain boundary. Each sample consists of 14 junctions total, with 7 junctions each of nominal $4\mu\text{m}$ and $8\mu\text{m}$ widths.

Because of chemical reactivity, a buffer layer is required to grow YBCO on sapphire. For this study we chose CeO_2 as the buffer layer. A CeO_2 layer with multiple orientations results in highly strained, de-oxygenated YBCO film growth which is only partially recoverable through oxygen annealing. The 20 nm thick CeO_2 buffer layer was deposited at 830°C in 80 Pa (600 mT) O_2 , at a 1 Hz pulse rate. Epitaxial, single orientation growth of all CeO_2 and YBCO layers was confirmed with x-ray diffraction (XRD) analysis.

B. Measurements

The YBCO bicrystal GBJs used in this study were patterned into $40\mu\text{m}$ long microbridges spanning the bicrystal grain boundary and having 7 junctions each of $4\mu\text{m}$ and $8\mu\text{m}$ widths. Temperature dependent resistance measurements, $R(T)$, were made using a four-point probe configuration. The temperature was monitored and controlled by a thermometer attached to the cold stage near the sample mount location. The probe was low-pass filtered and all measurements were carried out in a magnetically shielded liquid helium dewar. All electrical measurements were made with a battery-driven current-bias source filtered through preamplifiers. Microwave radiation was fed to the junctions via an antenna mounted on the probe.

III. RESULTS AND DISCUSSION

The current-voltage characteristics (I-Vs) of a typical $8.0\mu\text{m}$ wide Au-shunted YBCO bi-GBJ on a sapphire bicrystal are shown in Fig. 2a. The I-V curves follow the shape of the resistively shunted junction model [11] for temperatures from 4 K to 77 K. No flux flow behavior was observed in the I-V curves. The normal state resistance in this junction is dominated by the Au shunt, and is

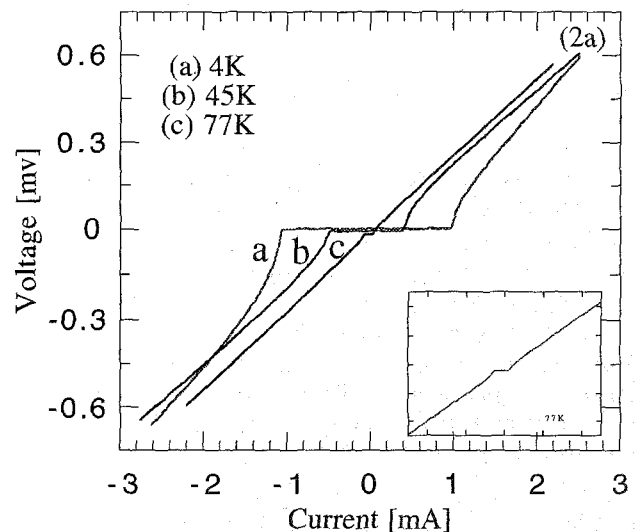


Fig. 2a Current-voltage characteristics of YBCO grain-boundary junction on 24° sapphire substrate at (a) 4K, (b) 45K, and (c) 77K. Inset shows 77K I-V curve.

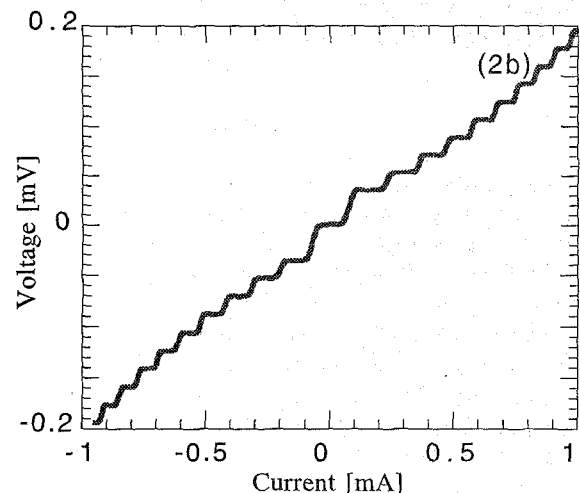


Fig. 2b. Current voltage steps of YBCO bi-GBJ on sapphire when exposed to 9.12 GHz microwaves at 45K.

temperature independent. When a sapphire bi-GBJ was irradiated at 9.12 GHz it demonstrated microwave-induced Shapiro steps at fixed voltages as shown in Fig. 2b, and the amplitude of the step size modulates with increasing rf power as predicted by the Josephson effect.

Typical STO and sapphire bi-GBJs parameters are summarized in Table I. The bi-GBJs in this study consisted of either uncapped YBCO, YBCO capped with a Au shunt layer, or YBCO capped with STO. The critical current density (J_c) of the junctions is obtained by dividing the critical current (I_c) by the cross sectional area of the YBCO microbridge. The STO bi-GBJs had values of J_c smaller for 36.8° than for 24° misorientation angle, as reported in other studies [12,13]. Since our intended application for these

TABLE I. SUMMARY OF JUNCTION PARAMETERS

	Sample #	A (~ 4 μ m)	B (~ 4 μ m)	C (~ 4 μ m)	C (~ 8 μ m)	D (~ 4 μ m)
	Substrate	STO 24°	STO 24°	Sapphire 24°		Sapphire 24°
Temp.	Shunt layer	none	25nm	35 nm	35nm	70 nm
4K	Jc (A/cm ²)	0.7x10 ⁵ ±14%	2.5x10 ⁵ ±23%	0.8x10 ⁵ ±43%	0.7x10 ⁵ ±23%	2.6x10 ⁵ ±54%
	IcRn (avg.) mV	3.0	1.1	0.6	0.3	0.5
	Rn (avg.) Ω	9.3	1.2	0.5	0.3	0.2
45K	Jc (A/cm ²)	0.3x10 ⁵ ±16%	2.4x10 ⁵ ±33%	0.4x10 ⁵ ±38%	0.3x10 ⁵ ±15%	0.5x10 ⁵ ±68%
	IcRn (avg.) mV	0.9	0.7	0.2	0.1	0.1
	Rn (avg.) Ω	6.7	0.8	0.5	0.3	0.2
77K	Jc (A/cm ²)	0.5x10 ⁴ ±28%	4.0x10 ⁴ ±35%	0.5x10 ⁴ ±42%	0.3x10 ⁴ ±27%	0.8x10 ⁴ ±68%
	IcRn (avg.) mV	0.2	0.1	0.01	0.01	0.01
	Rn (avg.) Ω	6.9	0.8	0.5	0.3	0.2

junctions requires large I_c , we used 24° bicrystals for the majority of devices in this study. For the same misorientation angle the J_c was several times larger for the Au capped STO junctions (sample #B) than that of the uncapped STO junctions (sample #A). Prior studies have shown that the J_c can be increased by up to an order of magnitude by altering the film deposition conditions [4,14]. The variation in J_c observed here for the STO junctions may be related to minor differences in each bicrystal's YBCO deposition conditions. It may also be that the presence of the Au layer acts to passivate the GBJ, thereby improving the J_c . The STO bicrystal I_cR_n values are around 1-3 mV at 4 K, which are usable for many applications.

The two sapphire bicrystals were capped with an Au shunt layer of different thicknesses. This reduced the I_cR_n to values < 0.5 mV at 4 K. Fig. 3 shows the I_cR_n as a function of temperature for the 24° STO bi-GBJs and the sapphire bi-GBJs. For sapphire bi-GBJs, the I_cR_n product was about 20 to 30 times smaller at 77 K than at 4 K as compared to only a factor of 10 reduction for the 24° STO junctions. However, at 4 K the sapphire bi-GBJs had critical

current densities in the range of $J_c \sim 10^5$ A/cm² comparable to the STO bi-GBJs.

We have demonstrated the large critical current requirement ($I_c > 1$ mA) of the programmable voltage standard with the wider junctions (>8 μ m) on the sapphire bicrystals. The characteristic voltage (I_cR_n) can be matched to the required frequency by tuning the junction resistance (R_n) independent of the I_c . We deposited an *in situ* Au resistive shunt layer on the YBCO on several STO and sapphire bicrystals. For the 24° STO bicrystal, the Au shunt layer reduced the R_n by an order of magnitude as compared to the unshunted bicrystal (2.0 Ω to 0.2 Ω). This expected behavior confirms that the normal current flow is indeed shunted through the Au layer across the grain boundary, as previously demonstrated for SNS junctions across the step edge [8]. For the 24° sapphire bicrystal, the junction resistance was equivalent to that of the STO bicrystal with equal Au thickness. More notably, the R_n varied inversely with the thickness of the Au layer deposited. Thus we can provide independent, tunable junction resistance control by varying the thickness of the Au shunt layers. With this technique, the sapphire bi-GBJs demonstrated the characteristic voltages (40 μ V) necessary for voltage standard operation in the frequency range of 20 GHz at 60K.

In contrast to the requirements discussed above, the high frequency mixer application requires junction resistances of 50 Ω for impedance matching. For this application we omit the Au layer, use narrow junctions and operate at low temperatures. For example, junctions similar to those obtained on sample A in Table I could be fabricated with 0.7 μ m width using e-beam lithography. This would result in a 50 Ω junction with an I_cR_n of 3 mV which corresponds to a maximum frequency of 1.5 THz.

Although the Au layers on the sapphire bicrystals were mainly intended as resistive shunt layers, we observed that after several months the I_c of an uncapped STO bi-GBJ decreased by 50% while its R_n increased considerably. In contrast, the Au shunted bi-GBJs showed no change in the junction characteristics over time. Also, the Au capped bicrystals in this study had greater yields when compared to uncapped bicrystals. In this situation it may be that the Au cap layer acts to passivate the YBCO, limiting the effects of

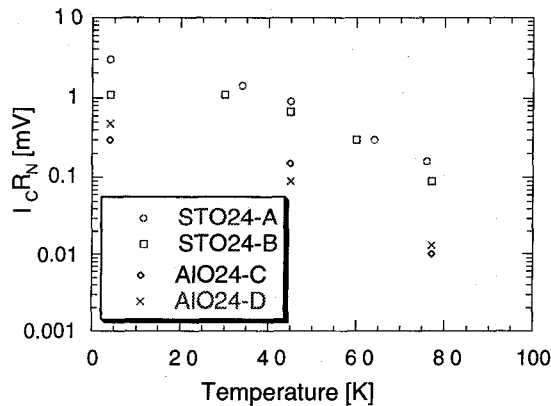


Fig. 3. Typical characteristic voltage for STO and sapphire bi-GBJs at various temperatures.

degradation at the grain boundary. The ease of fabrication where a single layer film is both shunt and passivation has obvious attractions.

Dielectric materials are typically used as passivation layers. In this study, a set of junctions on a 36° STO bicrystal were fabricated with an epitaxial STO cap layer, deposited *in situ* immediately following the YBCO deposition. This STO-capped bicrystal had the tightest J_c parameter spreads yet reported, $\pm 10\%$ over the entire temperature range of 4 K - 77 K. It is possible that the dielectric STO-cap layer has passivated the YBCO GBJ and, if so, indicates that oxygen depletion of GBJs may be controlled through the use of passivation layers. The observation that passivation of YBCO results in significantly tighter parameter spreads provides strong incentive for further study on the use of passivation layers for junction parameter control.

The on-chip spreads of J_c that we initially observed for 36° STO bicrystals were as tight as $\pm 12\%$ which strongly motivated our interest in GBJs for series array applications. However, subsequent 24° STO bicrystals fabricated for this study have demonstrated the more typically reported parameter spreads of $\pm 20\%$ [2,3], which are still adequate for many applications. The sapphire GBJs studied here show on-chip spreads of J_c that are roughly a factor of 2 larger than for the STO bicrystals, as listed in Table I. The junction properties are strongly influenced by the particulars of the grain boundaries [10] and the inherently greater inhomogeneity of the grain boundary for non-cubic bicrystals (such as sapphire) may lead to greater variations than observed on the cubic bicrystal substrates (such as STO). Similar reports of greater junction spreads have been noted for other non-cubic bicrystal substrates [4,6]. Further experiments with unshunted sapphire bicrystal junctions are planned to investigate the source of the large spreads in J_c for the sapphire bicrystals.

IV. CONCLUSIONS

Grain-boundary YBCO junctions on r-plane sapphire bicrystal substrates demonstrate Josephson behavior from 4K to 77K. The electrical transport properties of these junctions are comparable to that of similar junctions on STO, but with greater parameter spreads. It has been demonstrated that a Au shunt layer can be used to tune the junction resistance to a specific application requirement resulting in junctions with large I_c and small R_N . Overlayers of STO and Au may passivate the GBJs, thereby improving the junction

parameters and the long term stabilities. With their low dielectric constant and loss, sapphire bicrystals are good candidates for high frequency applications of Josephson junctions.

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