Characterization and Dynamics of [100]-Tilted Y-B-C-O Bicrystal Junctions on $\mathrm{Nd-Ga-O_3}$

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***Abstract*—We report on the fabrication technique and electrical properties of Basal Plane Tilted $\mathrm{YBa_2Cu_3O_{7-x}}$ (YBCO) superconducting bicrystal Josephson Junctions (BTJ). In order to form the grain boundary in BTJ we apply an inclination of the (001) YBCO basal planes around the direction of {100} YBCO in contrast to the common In-Plane Tilted bicrystal Josephson Junctions (ITJ) where misorientation of the crystallographic axes in the ab-plane of YBCO has been used. Symmetric and asymmetric junctions were fabricated on bicrystal $\mathrm{NdGaO_3}$ substrates 13–28° tilted from (110) $\mathrm{NdGaO_3}$. DC and RF properties of the BTJ were investigates at temperatures 4.2–77 K, in magnetic fields up to 100 G, and under influence of electromagnetic radiation of 56 GHz frequency. The experimental dependences of critical current and Shapiro steps from RF current fit the Resistive Shunted model of Josephson junctions (RSJ-model). At $\mathrm{T = 77\ K}$ the BTJ reveal critical current density $\mathrm{j_C = 0.2 - 0.5\ MA/cm^2}$ and characteristic voltage $\mathrm{V_C = I_C R_N = 0.6 - 0.9\ mV}$, that makes the junctions promising candidate for practical electronic devices.**

***Index Terms*—Basal plane inclination, bicrystal junction, Josephson effect, metal-oxide superconductor.**

I. Introduction

According to the theoretical models of Josephson junctions [1]–[5] the critical frequency f_C of the junction is designated by the characteristic voltage $V_C = I_C R_N$ (I_C—critical current, R_N—normal resistance of the junction) through Josephson equation $f_C = 2\mathrm{e}V_C/\mathrm{h}$ and defined by an order parameter Δ of the superconductors forming the junction. Thus for $\mathrm{YBa_2Cu_3O_{7-x}}$ (YBCO) with high critical temperature $T_C = 90$ K the amplitude of superconducting order parameter is $\Delta_0/\mathrm{e} \approx 20$ mV, and V_C would be expected to reach few millivolts at liquid nitrogen temperature (77 K). However, experimentally obtained values of V_C do not exceed 300 μV even for well developed In-Plane Tilted bicrystal Josephson Junctions (ITJ), where YBCO films are (001)-oriented on both sides of the grain boundary but a and b axes are rotated around [001] YBCO (Fig. 1(a)) [5], [6]. Recently, significant increase in V_C (up to 1 mV) have been reported in Basal Plane Tilted bicrystal Josephson Junctions (BTJ) [7]–[10], where the (001) YBCO planes are symmetrically misoriented by angles $\alpha = \beta$ by rotation around [100] YBCO (Fig. 1(b)). However, due to an extra conductivity channel through the possible superconducting shorts with the sizes larger than the coherence length of YBCO, high values of V_C, obtained from dc measurements (I_C and R_N), may not correspond to the dynamic characteristics of the junction like Josephson oscillations, superconducting current-phase relation, high frequency impedance and so on [5], [11].

Unfortunately, the considerable anisotropy of the electrical properties of the tilted YBCO epitaxial films may result in problems for Josephson devices based on the BTJ. In order to reduce the effect of anisotropy we suggest Asymmetric Basal Plane Tilted bicrystal Josephson junctions (ABTJ), where $\alpha \neq \beta$, $\beta = 0$ (Fig. 1(b)). In this case the YBCO film on one side from the grain boundary is (001)-oriented and has no significant electrical anisotropy in the ab-plane. Note that V_C is usually small in asymmetric ITJ.

In this paper we present our results on DC and RF properties of BTJ and ABTJ fabricated on $\mathrm{NdGaO_3}$ (NGO) substrates—material with small dielectric losses at millimeter wavelengths [12]. Electrophysical and dynamic (microwave) properties of the symmetric and asymmetric junction have been studied and compared with ordinary ITJ junctions on NGO substrates with the similar values of misorientation angles.

II. Fabrication

NGO bicrystal substrates for all types of junctions have been fabricated by the same technique and have bicrystal boundaries of the same quality [12]. Misorientation angles $\alpha + \beta$ are varied from 13° to 28°. (110) NGO substrates have been used as deposition template for 150 nm thick (001) YBCO films. We applied dc sputtering of YBCO target at high oxygen pressure or laser ablation at substrate temperature 780–800°C to obtain critical temperatures of epitaxial YBCO films $\mathrm{T_c = 87 - 89\ K}$. Josephson junctions namely YBCO thin film microbridges of 4 μm width and 10 μm length were patterned across the bicrystal boundary by photolithography, RF plasma etching in argon and wet chemical etching in 0.5% ethanol solution of $\mathrm{Br_2}$ [13]. IV-curves of the junctions were measured in the temperature range of $4.2\ \mathrm{K} < T < 77\ \mathrm{K}$, magnetic fields up to $B \leq 100$ G, and under influence of monochromatic microwave radiation of $f_e = 56$ GHz frequency.

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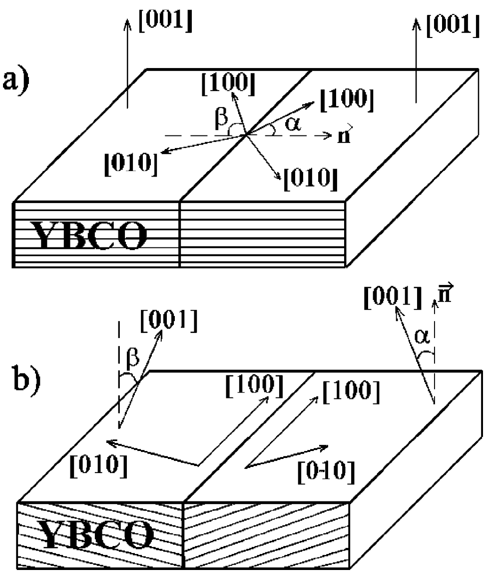

Fig. 1. Types of bicrystal junctions: a) inplane tilted bicrystal junction (ITJ); b) basal plane tilted bicrystal junction (BTJ). α and β are misorientation angles. $\alpha = 0, \beta \neq 0$ for asymmetric junctions.

III. Experimental Results and Discussion

The morphology of the YBCO film deposited on tilted substrate depends on the inclination angle [14]. Fig. 2(a) shows an AFM 3D-image of YBCO film deposited on ABTJ substrate with $\beta = 0$, $\alpha = 13^{\circ}$. A cross section view indicates a difference in the surface morphology compared with (001)-oriented films on (110) NGO substrates: the elongated step-like features can be observed, while the edges of the steps are oriented along the substrate rotation axis [001] NGO (Fig. 2(b)). For small tilted angles the thin film is very smooth (roughness less than 3 nm) and the step height is close to the YBCO c lattice parameter. If the inclination angle exceeds 3–5° the step height increases rapidly and becomes much greater (7–10 nm) than the initial step size on the substrate surface (0.5–1 nm) [14].

Parameters of the three types of bicrystal junctions (ITJ, BTJ, ABTJ) obtained from DC measurements of the I-V curves at $T = 4.2$ K and 78 K are presented in Table I. As it follows from the Table I the values of critical current density $j_C = (2-5) \cdot 10^5\ \mathrm{A/cm^2}$ and characteristic voltage $V_C = 0.6 - 0.9\ \mathrm{mV}$ of the BTJ at 78 K are much higher (by factor of 10) than ones of the ITJ.

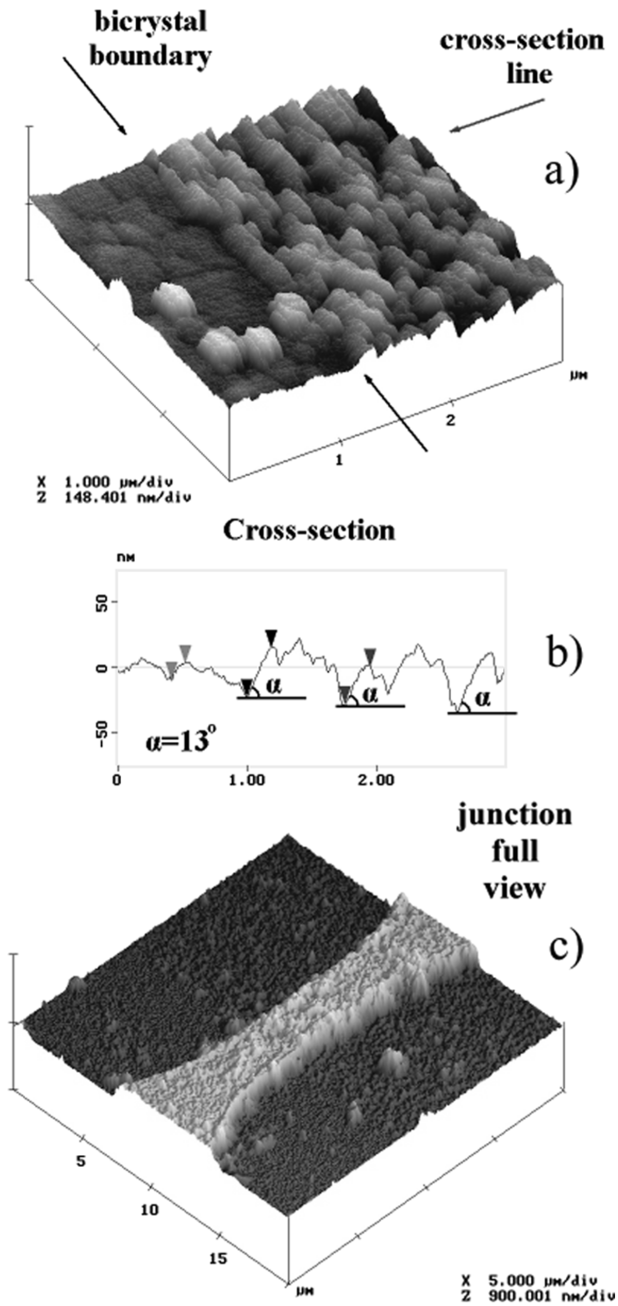

Fig. 2. Three-dimensional AFM view for the ABTJ boundary a), crossection b) and 3-D AFM of the YBCO bridge crossing bicrystal boundary c).

A. I-V Curves

The I-V curves of the BTJ shown on Fig. 3 are hyperbolic-like dependences typical for the RSJ model of a Josephson junction. Two channels of current transport are presented, namely, quasiparticle current V/R_N and superconducting current $I_S(\varphi) = I_C \sin\varphi$, where φ is a phase difference between two superconducting electrodes [1], [15]. Large values of excess current, which are typically about 50% of I_C at $V > 3\ \mathrm{mV}$, may indicate on the existence of an additional channel of direct (non tunnel) conductivity or other current transport mechanism [5]. Note that ABTJ and BTJ with misorientation angle 13° reveal I-V curves different from hyperbolic form and typical for viscous flow of vortices [1], [15]. At $T = 4.2$ K the rise of excess current is observed and the junctions have higher V_C (up to 10 mV) although their utilization in practical systems is difficult because of the significant deviation from RSJ model.

B. Critical Current

Typical $I_C(T)$ dependence of BTJ is shown on Fig. 4. Its shape is rather linear and differs from the theoretically predicted one for tunnel junctions of s-superconductors (SIS) [1], where saturation is observed at $T < 0.5\,T_C$.

In the SIS tunnel junctions the current transport through high-energy Andreev states ($\varepsilon_{\mathrm{conv}} \sim \Delta$) is realized. In contrast, linear dependence of $I_C(T)$ has been previously observed in the junctions with direct conductivity, where within wide

TABLE I
DC PARAMETERS OF BICRYSTAL JUNCTIONS

Type	α+β	№	T = 78 K			T = 4 K		
			I_C, mA	R_N, Ω	V_C, mV	I_C, mA	R_N, Ω	V_C, mV
ITJ	24°	J1	0.03	0.9	0.03	1.6	0.9	1.4
		J2	0.05	2.1	0.1	1.7	1.9	3.2
		J3	0.06	0.5	0.03	3.7	0.6	2.2
ITJ	28°	J1	0.02	4.4	0.09	0.56	4.6	2.6
		J2	0.01	4.0	0.04	0.63	4.1	2.6
		J3	0.01	2.8	0.03	0.85	3.2	2.7
BTJ	22°	J1	1.25	0.5	0.62	-	-	-
		J2	1.5	0.6	0.9	11	0.6	6.6
		J3	1.5	0.4	0.6	10	0.6	6.0
BTJ	28°	J1	0.11	2.5	0.28	-	-	-
		J2	0.24	1.3	0.31	-	-	-
		J3	0.075	4.5	0.34	-	-	-
ABTJ	21°	J1	2.6	0.3	0.78	-	-	-
		J2	1.71	0.4	0.68	-	-	-
		J3	1.5	0.4	0.6	-	-	-
ABTJ	28°	J1	0.49	1.6	0.80	4.0	0.7	2.8
		J2	0.26	1.0	0.26	4.1	0.5	2.1
		J3	0.1	1.9	0.19	2.2	1.8	4.0

α+β = misorientation angle, I_C= critical current, R_N=normal resistance, V_C =characteristic voltage, J1-J3 – junction number on sample.

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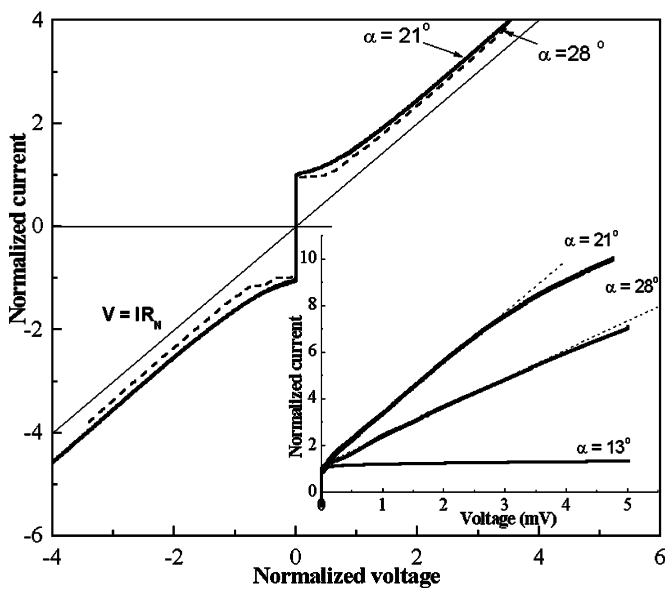

Fig. 3. Normalized (V/V_c and I/I_c) I-V curves for ABTJ ($\beta = 0$) for two misorientation angles $\alpha = 21°$ (solid curve) and 28° (dashed). The reduction of excess current clearly observed with increasing angles. I-V curves for the same junctions for large voltage scale are shown on inset.

temperature range superconducting current transport is determined by low-energy Andreev states ($\varepsilon_{\rm MGS} \ll \Delta$) [1]. In ITJ $d_{x^2-y^2}$-type of superconducting order parameter symmetry presumes both $\varepsilon_{\rm conv}$ and $\varepsilon_{\rm MGS}$ states contributing to current transport at low temperatures. However, at high temperatures the influence of the $\varepsilon_{\rm MGS}$ is drastically reduced. Low-energy states do not appear in BTJ if either a or b crystallographic axis in YBCO is parallel to the grain boundary (no in-plane tilting) [2]–[5]. Hence the significant difference in V_C between ITJ and BTJ at $T = 78$ K can be explained by the $d_{x^2-y^2}$-wave symmetry of the superconducting order parameter Δ in ITJ electrodes. In ITJ the $a - b$ planes are rotated around c-axis of YBCO resulting in smaller Δ along the direction perpendicular to the grain boundary. The suppression of the order parameter may as well occur in the vicinity of the grain boundary interface due to contact phenomenon [3] (Fig. 5).

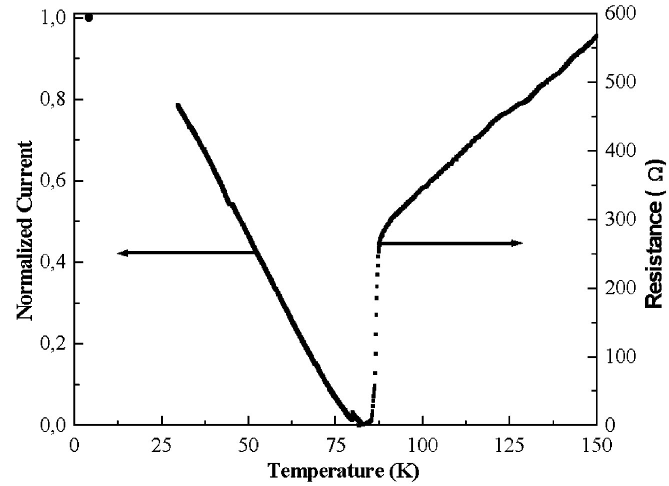

Fig. 4. Temperature dependences of the BTJ resistance and critical current. Almost linear $\rm I_c(T)$ dependence is clear observed.

V_C is decreased more than three times (Table I) when increasing the misorientation angle from 21° to 28°. Such behavior is in a good agreement with a theory [16], where large values of $\Delta/\rm E_F$ ($\rm E_F$ is the Fermi energy) typical for YBCO and significant Fermi surface anisotropy are taken into account. These two factors lead to dispersion in momenta of incident electrons and reflecting holes at the grain boundary and, as a result, the coherence of multiple Andreev reflection is broken and superconducting current is depressed. At the same time there is a certain critical misorientation angle according to [16], at which critical current is reduced almost to zero. Such strong dependence, however, may be decorated by boundary faceting. Note, that the reduction of $\rm V_C$ with increasing $(\alpha + \beta)$ has also been observed in ITJ (see Table I and [5]).

Dependences of the critical current vs. magnetic field $I_C(B)$ are presented in Fig. 6. The maximum of the $I_C(B)$ is observed at $B = 0$. However, $I_C(B)$ dependence is different from the Fraunhofer-type and moreover, asymmetrical. The latter is typical for distributed Josephson junctions [1], [15]. Actually, the Josephson penetration depth of magnetic field for $j_C = 3 \cdot 10^5\ \rm A/cm^2$ is $\lambda_J = 0.5\ \mu\rm m$, which is significantly smaller than the junction width $w = 4\ \mu\rm m$. Thus, we may consider our junctions as distributed ones at liquid nitrogen temperature.

C. Shapiro Steps

In order to determine the junctions dynamical parameters we have measured the IV-curves under the influence of monochromatic radiation of millimeter wavelengths, typically $I_{RF} \sin(2\pi \rm f_e t)$, $f_{\rm e} = 56$ GHz. Experimental dependences of the critical current and Shapiro steps vs. amplitude of the external electromagnetic radiation may be well fitted by the RSJ model (Fig. 6). The deviation of the normalized experimental

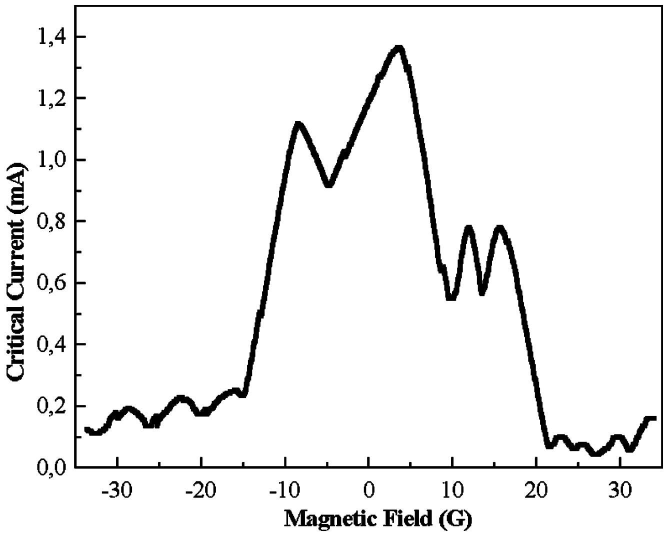

Fig. 5. Typical magnetic-field (at $\mathrm{T} = 78\ \mathrm{K}$) dependences of the critical current for BTJ.

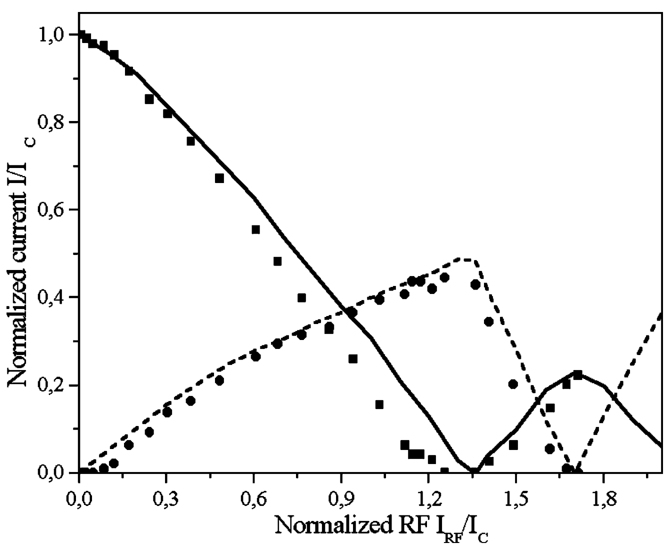

Fig. 6. Amplitude dependences of the normalized critical current $\mathrm{I_C(I_{RF})/I_C(0)}$ (squares) and first Shapiro step $\mathrm{I_1(I_{RF})/I_C(0)}$((solid rounds) for BTJ at external frequency $\mathrm{f_e} = 56\ \mathrm{GHz}$. Solid lines and dotted line—theoretical dependences at $\mathrm{f_e/f_0} = 0{,}23$.

maximum of the first Shapiro step $(I_1/I_C)_{\max} = 0.46$ from the calculated one $(I_1/I_C)_{\max} = 0.43$ is about 7% at normalized frequency $f_e/f_C = 0.23$. The difference $(I_1/I_C)_{\max}$ shows that the effective critical current value is about 7% lower because of the inhomogeneous current distribution. Note that absence of subharmonic Shapiro steps (at voltages $V = \mathrm{h}f_e/2\mathrm{e}n$), and zero minimum values of $I_C(I_{RF})$ and $I_1(I_{RF})$ dependences indicate pure sinusoidal superconducting current-phase relation [13]. Thus, in spite of the excess current observations we have obtained a good concordance of DC and dynamic BTJ and ABTJ junction parameters at liquid nitrogen temperature.

IV. Conclusion

Observation of high characteristic voltages $V_C > 0.6\ \mathrm{mV}$ at $T = 77$ K in more than 70% of the investigated symmetric and asymmetric basal plane tilted bicrystal Josephson junctions make them very attractive for application as elements of superconducting electronics. The high value of V_C was confirmed by measurements at mm wave.

The existence of practically isotropic (001) $\mathrm{YBa_2Cu_3O_{7-x}}$ film on one side of the asymmetric BTJ easily allows to fabricate additional circuits and wirings while maintaining high critical parameters. Furthermore, asymmetric basal plane tilted junctions can be also fabricated using a biepitaxial technology by the proper selection of a buffer layer material for tilting of the YBCO basal planes.

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