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Josephson Parameters of Bicrystal Junctions of a New Type Based on Metal Oxide Semiconductors

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Abstract—We have studied symmetric bicrystal Josephson junctions of a new type based on metal oxide superconductors in which the base planes are misoriented relative to the [100] direction by an angle within 22°–28°. These junctions exhibit record high values of the critical parameters at T = 77 K: the critical current density reaches $I_C = (2–5) \times 10^5$ A/cm^2 and the characteristic voltage is $V_C = I_C R_N$ = 0.6–0.9 mV. The properties of the new junctions have been determined for the first time under the influence of monochromatic microwave radiation in the millimeter wavelength range and have been studied as functions of the magnetic field and temperature. The observed dependences of the critical current and the Shapiro step height on the electromagnetic field amplitude agree well with the theoretical predictions according to the resistive shunted junction model of the Josephson junction. The new junctions can be used in real superconducting devices operating at liquid nitrogen temperatures. © *2005 Pleiades Publishing, Inc.*

According to the existing theoretical models of the Josephson junction [1–4], the critical frequency f_C is related to the characteristic voltage $V_C = I_C R_N$ (I_C is the critical current and R_N is the normal resistance) by the Josephson formula $f_C = 2eV_C/h$ and is determined by the order parameter Δ of superconductors forming the junction. In the case of junctions based on metal oxide superconductors with high critical temperatures (T_C = 90 K) and the superconducting order parameter amplitude $\Delta_0/e \approx 20$ mV, the V_C value must already be on the order of several millivolts at liquid nitrogen temperature. In practice, the maximum characteristic voltages up to $V_C \approx 300$ μV were obtained using the bicrystal Josephson junctions on $SrTiO_3$ substrates [5].[1]

Recently, it was reported [7, 8] that a special modification of the topology of bicrystal substrates used for the deposition of metal oxide superconductor films allows the V_C to be increased to about 1 mV. However, no evidence was presented in [7, 8] to confirm that the observed dc parameters (I_C, R_N) are consistent with the dynamic (microwave) characteristics of the junctions. Such data are necessary, since a small coherence length ($\xi_0 \approx 2$ nm) in the base plane of metal oxide superconductors results in that a superconducting current passing through shorted paths with the lengths above ξ_0 does not produce the ac Josephson effect [9, 10]. As a result, the high V_C values obtained from the results of I_C and R_N measurements may not correspond to the dynamic characteristics of the junctions, such as the Josephson generation amplitude, phase dependence of the critical current, and microwave impedance.[2]

This Letter reports on the results of investigations into the dc and dynamic (microwave) parameters of junctions grown on substrates made of neodymium gallate ($NdGaO_3$), a material characterized by low dielectric losses in the millimeter wavelength range.

The samples were prepared on bicrystal substrates with a topology different from the standard variant, according to which the base planes are misoriented by rotation relative to the [001] direction in the metal oxide superconductor crystal structure (rotational or planar bicrystal junctions, PBJs). Our bicrystal substrates were manufactured so that the base planes would make an angle with the [100] direction (tilted bicrystal junctions, TBJs). The orientations of the axes of metal oxide superconductor crystal structures of the PBJ and TBJ types are shown in Fig. 1. As is known, misorientation of the crystallographic axes of the junction components by the angles α and β relative to the interface normal (in PBJ) or the substrate normal (in TBJ) determines the electric parameters of such junctions [7–10]. A distinctive feature of the TBJ in comparison to the PBJ is relatively weak faceting of the

[1] The values of $V_C \approx 300$ μV were also observed on shunted tunnel niobium junctions at liquid helium temperatures (T = 4.2 K) [6].

[2] The V_C values obtained from dc measurements were higher than the values observed in the dynamic regime for the Josephson junctions on the substrate step and the edge junctions [9, 10].

metal oxide superconductor film near the bicrystal boundary [7, 8].

The junctions were manufactured on $NdGaO_3$ (NGO) bicrystal substrates. The base plane was (110)NGO, on which (001)-oriented $YBa_2Cu_3O_x$ (YBCO) films can be grown. The conditions of epitaxial growth in the [100]YBCO//[001]NGO system are retained for small tilts of the (110)NGO plane relative to the substrate normal [13].[3] The misorientations of the junction components were $\alpha = \beta = 11°$ and 14° (symmetric TBJs). The epitaxial YBCO films with a thickness of 150 nm were deposited by means of the dc cathode sputtering of a stoichiometric YBCO target in oxygen at a high pressure (3 mbar). The films were deposited onto substrates heated to 780–800°C and then cooled to room temperature for 1.5 h in the oxygen atmosphere. The obtained heteroepitaxial YBCO films had critical temperatures within T_C = 87–89 K.[4] The Josephson bridges across the bicrystal boundary had a width of 4 μm and a length of 10 μm and were formed by high-frequency plasma etching in argon, followed by chemical etching in a 0.5% bromine solution in ethanol [12, 13].

The current–voltage (I–V) curves were measured at various temperatures in a range from 4.2 to 77 K. The measurements were performed in the absence of magnetic field, in a field of up to H = 100 Oe, and on the samples exposed to a monochromatic electromagnetic radiation with a frequency f_e from 30 to 100 GHz. In order to decrease the influence of uncontrolled external fields, the investigation was performed in a screened room, with filtration of the signals in all leads connected to a sample.

The samples of bicrystal Josephson junctions had critical current densities $j_C = (2–5) \times 10^5$ A/cm^2 and characteristic voltages $V_C = I_C R_N$ = 0.6–0.9 mV at T = 77 K. The results of the determination of electric parameters of the Josephson junctions are summarized in the table. As can be seen from these data, the PBJ samples exhibit significantly lower critical characteristics (I_C and V_C at T = 77 K) as compared to the TBJ samples with the same cross section areas. The barrier transparency evaluated for TBJs from the value of $R_N S = (3–7) \times 10^{-9}$ Ω cm^2 [14] (which is close to that for PBJ [13]) and averaged over the momentum directions and junction areas was $D \approx 10^{-1}$.

Figure 2 shows the typical I–V curve of a TBJ sample. The curve corresponds to the hyperbolic law characteristic of a resistive shunted junction model of the Josephson junction, with two channels of the charge transfer: via the current of quasiparticles (V/R_N) and the superconducting current $I_S(\varphi) = I_C \sin\varphi$ [1, 15]. A large (up to 50% of I_C) excess current (deviation from the Ohm law) observed at voltages above 3 mV was indicative of the presence of an additional channel for the forward (nontunneling) charge transfer. The temperature dependence of the critical current (see the left inset in Fig. 2) is close to linear, in contrast to the theoretical dependence for the tunneling junctions based on the s-wave superconductors (SIS junctions) [1], which exhibits saturation at $T < 0.5T_C$. In the process of current transfer in the SIS junctions, an important role is played by Andreev states with the energies ε on the

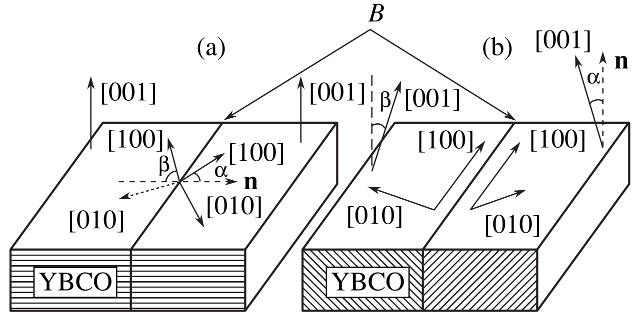

Fig. 1. Schematic diagram showing the bicrystal Josephson junctions of two types: (a) rotational or planar bicrystal junction (PBJ); (b) tilted bicrystal junction (TBJ); B is the bicrystal boundary; dashed lines show the interface normal (PBJ) and the substrate normal (TBJ) directions; cross-hatching indicates the orientation of the metal oxide superconductor layers.

Electric parameters of PBJ and TBJ samples at liquid nitrogen temperature (T = 77 K)

Junction type	$\alpha + \beta$ ($\alpha = \beta$)	Sample no.	I_C, μA	R_N, Ω	V_C, μV
PBJ	24°	J2	70	1.1	77
		J4	140	0.64	90
		J5	200	0.17	34
PBJ	28°	J2	10	3.0	30
		J2	21	3.7	78
		J4	24	3.5	84
		J5	24	3.2	77
TBJ	22°	J1	1250	0.54	675
		J2	1210	0.54	653
		J3	2100	0.43	903
		J4	1300	0.56	728
TBJ	28°	J1	30	6.7	201
		J2	72	3.0	216
		J3	75	4.5	337
		J4	63	4.1	258

[3] Because of a small difference in the crystal lattice parameters along the a and b axes, the epitaxial YBCO films exhibit alternation of the [100] and [010] directions. For certainty, we indicate below only the [100]YBCO direction.

[4] The parameters of YBCO films were substantially similar when the epitaxial layers were grown by laser ablation.

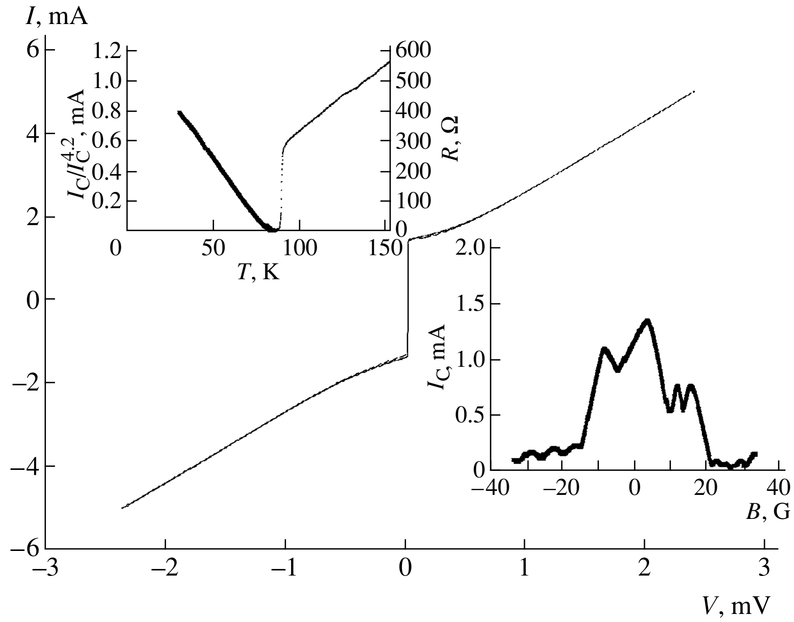

Fig. 2. Typical *I–V* curves of the tilted bicrystal junction (T = 77 K). The insets show the temperature dependence (left) and the magnetic field (T= 77 K) dependence (right) of the critical current.

order of Δ (high-energy Andreev states). In the junctions with direct conductivity, where the superconducting current transfer is determined by low-energy Andreev states ($\varepsilon \ll \Delta$), the $I_C(T)$ function is close to linear in a broad temperature range [1]. In PBJs formed by superconductors with a predominating order parameter of the d-wave type (DID junctions) [2–4], both types of Andreev states are involved in the current transfer, their contributions being dependent on the incidence angle of quasi-particle [2–4, 16]. In contrast, the low-energy states are not formed for the orientation of crystallographic axes typical of the TBJs, where one axis in the base plane of the metal oxide superconductor is parallel to the interface normal [2–4, 16].

The difference between the mechanisms of current transfer in PBJs and TBJs is also substantially manifested in the angular dependence of the critical parameters of the bicrystal Josephson junctions. For PBJs, the characteristic voltage V_C exhibits rather weak variation in a large interval of angles up to ±33°, although the normal resistance may exhibit a tenfold increase (see table [8]). It should be noted that, for a misorientation of ±45°, the j_C value significantly decreases and V_C exhibits a tenfold drop to reach 0.5 mV at helium temperatures [17]. For TBJs, the experiments revealed a much stronger angular dependence of V_C, which decreased by a factor of 3 when the misorientation angle was increased by only 6° (see table). This behavior well agrees with the theory [11], which takes into account both the large ratio of the superconducting gap width to the Fermi energy (Δ/E_F) characteristic of metal oxide superconductors and the large anisotropy of the Fermi surface. In the presence of these factors, the quasi-momenta of the incident electron and reflected hole diverge by a certain angle in the course of the Andreev reflection at the intersection of tilted planes. This leads to a violation of the coherence of multiple Andreev reflections and, eventually, to a decrease in the superconducting current. There must be a certain critical misorientation angle at which the critical current rapidly drops to zero, although this sharp variation can be smeared by inhomogeneity of the interface. For the junctions with small misorientation angles ($\alpha + \beta <$ 13°), the shape of the observed *I–V* curves differs from hyperbolic and is typical of a viscous flow of the vortex flux [1, 8].

The right inset in Fig. 2 shows the behavior of the critical current as a function of the magnetic field. As can be seen, the $I_C(B)$ function exhibits a maximum at $B = 0$. However, the $I_C(B)$ curve significantly differs from the Fraunhofer profile and is asymmetric, which is typical of the distributed Josephson junctions [1, 15]. Indeed, the Josephson magnetic field penetration depth for $j_C = 3 \times 10^5$ A/cm^2 (λ_J = 0.5 μm) is significantly smaller than the junction width (4 μm). Thus, our junctions can be considered as distributed already at liquid nitrogen temperature.

In order to determine the difference between the dynamic parameters and the dc characteristics, we have studied the *I–V* curves for a monochromatic microwave radiation $A\sin(2\pi f_e t)$ in the millimeter wavelength range (f_e = 56 GHz). The behavior of the critical current and the Shapiro steps on the electromagnetic wave amplitude well agreed with the theoretical dependences determined for a resistive shunted junction model of the Josephson junction (Fig. 3). The difference between the

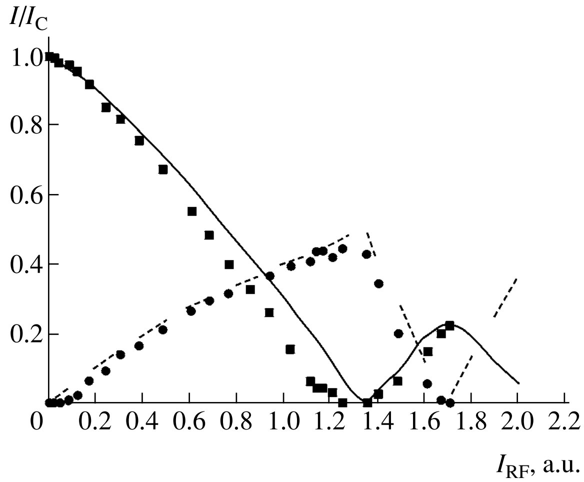

Fig. 3. Experimental plots of the critical current (squares) and the first Shapiro step (circles) versus microwave signal amplitude (at f_e = 56 GHz). Curves show the corresponding theoretical dependences calculated for f_e/f_C = 0.22, f_C = $2eI_CR_N/h$, and the I_C and R_N values determined by dc measurements.

experimental value of the maximum normalized first step ($(I_1/I_C)_{max}$ = 0.46) and the theoretical value ($(I_1/I_C)_{max}$ = 0.43) at a normalized frequency of f_e/f_C = 0.23 was about 7%. The fact that the experimental value is higher than the theoretical one indicates that the effective critical current may decrease by 7% as a result of the inhomogeneous current distribution. It should be noted that the absence of subharmonic Shapiro steps (at $V = hf_e/2en$) and the zero minimum values of $I_C(P_e)$ and $I_1(P_e)$ are indicative of the purely sinusoidal character (the absence of higher $\sin(n\varphi)$ harmonics) of the dependence of the superconducting current on the phase difference [18].

At lower (helium) temperatures, the excess current exhibits growth, although the junctions have very high values of the characteristic voltage V_C (up to 16 mV). However, the use of such junctions in practical systems is hindered by the significant deviation of their behavior from that according to the resistive shunted junction model. Thus, despite the presence of the excess current, the *I–V* curves show a good correspondence between the dynamic (Josephson) and dc parameters of the TBJ samples at liquid nitrogen temperature (77 K). The high characteristic voltage (V_C > 0.6 mV) observed in more than 70% of the samples studied suggests that these junctions are very promising elements for both high- and low-frequency superconducting electronics.

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