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YBCO Bicrystal Junctions on Sapphire: d-Wave Impact and Possible Applications

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The current transport and Josephson effect have been investigated in YBCO junctions, fabricated on the sapphire bicrystal substrates. The YBCO film with thickness $t \cong 150$ *nm was deposited by dc sputtering on the epitaxial* CeO_2 *buffer layer made by rf magnetron sputtering. The junctions were characterized at dc and at mm waves. 5 μm wide junctions have moderately high normal state resistance* $R_N = 5 \div 30\ \Omega$ *with critical currents* $I_c = 50 \div 200\ \mu A$ *which give* I_cR_N *product of order of* $0.5 \div 2$ *mV. The tolerance of characteristic interface resistance* (R_NS) *was around 30% for the junctions on a chip. Experimental data, discussed in terms of d-wave symmetry, demonstrate possibility of design of small scale integrated Josephson microwave circuits.*

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1. INTRODUCTION

The high values of normal-state resistance R_N and critical frequency $f_c=(2e/h)I_cR_N$, as well the absence of hysteresis on the I-V curve of high-Tc superconducting (HTSC) Josephson junctions even at liquid-helium temperature T=4.2K make them appreciably superior to low-temperature superconducting junctions. The high critical temperature gives promising opportunities for applications at frequencies higher than those, corresponded to energy gap of ordinary (say, Nb) superconductor. However, the aspects involved in the reproducible fabrication of high quality HTSC Josephson junctions on one hand, and the mechanism, describing current transport, on the other hand are the problems which have not been solved yet. The most reproducible junctions having a critical current spread of ±12% per chip are fabricated on $SrTiO_3$ bicrystal substrates[1], but because of their high dielectric constant $\varepsilon>1000$ they are unsuitable for high-frequency applications. Sapphire having a relatively low $\varepsilon \approx 9$-11 and low losses ($\tan\delta \approx 10^{-8}$ at 72 GHz), is the traditional material used in microwave electronics. Here we present the results of fabrication and characterization of HTSC Josephson junctions on sapphire bicrystal substrates. The high frequency dynamics of those junctions is discussed.

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2. RESULTS AND DISCUSSION

The Josephson junctions were fabricated on the $(1\underline{1}02)$ plane of sapphire bicrystal substrates for which the directions $<11\underline{2}0>$ Al_2O_3 for both parts were misoriented at the angles ±12° to the plane of the interface. The $YBa_2Cu_3O_x$ (YBCO) film was deposited by dc sputtering at high oxygen pressure after the CeO_2 epitaxial buffer layer rf magnetron sputtering at T=700C. The following epitaxial relation: $(001)YBCO//(001)CeO_2//\{1\underline{1}02\}Al_2O_3$, $<110>YBCO//<001>CeO_2//<11\underline{2}0>Al_2O_3$ was fulfilled for deposited films (Fig.1). Thin film YBCO bridges each 5 μm wide and 10 μm long, crossing the bicrystal boundary, were fabricated by rf plasma and Br_2-ethanol etching[2]. The angle γ between the normal to the interface and current direction was varied from 0° to 54°. The bicrystal junctions (BJ) with current density 10^4-10^5 A/cm^2 gave the parameters at T=4.2K: R_N=5-30 Ω, I_c=50-200 μA with I_cR_N=0.5-2 mV.

The typical I-V curve of the BJ is shown on Fig.2. It obviously demonstrates behavior very close to RSJ model which has two channels for current: quasiparticle V/R_N and superconducting $I_s(\varphi)=I_c\sin\varphi$. Very small (or even negative) excess current on I-V curve at V>10 mV points on the absence of channels with direct (nontunnel) conductivity . However, $I_C(T)$ function shown in the inset to Fig.2, has

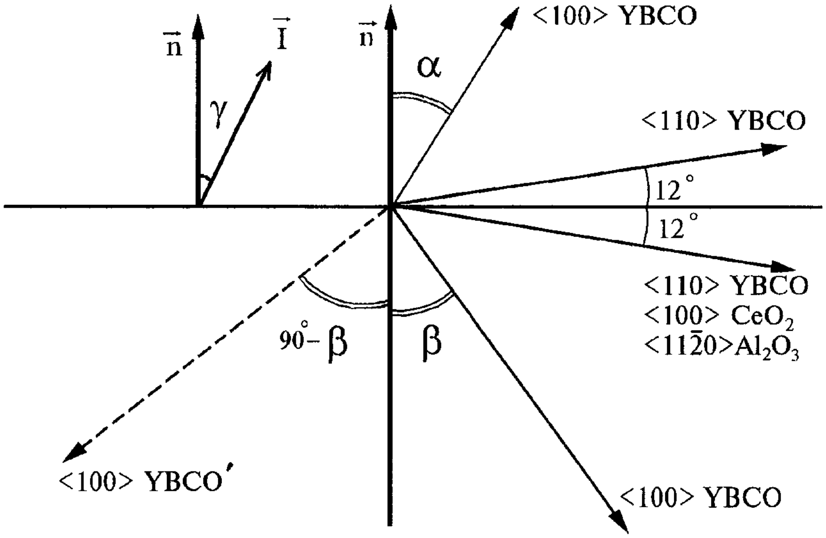

Fig.1. Crystallographic axis orientations of CeO_2 and YBCO films in sapphire bicrystal junction with α=33°, β=-33°($D_{33}ID_{-33}$). The domain of the film with the direction <100>YBCO′ misoriented on the angle β'=90°-β is the twin to YBCO.

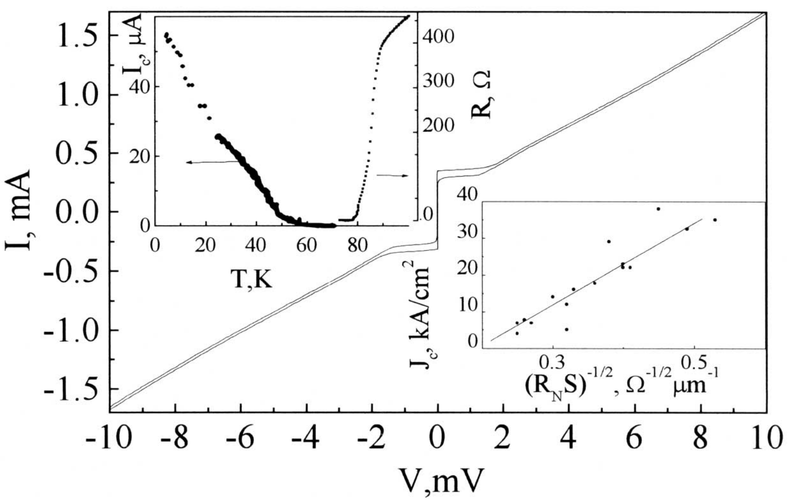

Fig.2. The I-V curve at T=4.2K for a typical bicrystal junction. Temperature dependence of the resistance R(T) and critical current $I_c(T)$ are shown in the left inset. Dependence of the critical current density vs inverse square root of characteristics interface resistance at T=4.2K is shown on right inset.

rather linear temperature dependence which distinguishes from the known theoretical one for tunnel SIS junctions[3]. In accordance to the d-wave theory of superconducting junctions (DID)[4-6], various non-linear $I_C(T)$ dependencis caused by the existance of bound states at the BJ interface should be observed. Our measurements, as well as some other published data[7] instead show a monothonous (smooth) rise of I_C with decreasing T.

Current-phase relation $I_S(\varphi)$ strongly depends on the type of contacts between superconductors. For $T_c-T<<T_c$ the deviations of $I_S(\varphi)$ from $I_S(\varphi)=I_C\sin\varphi$ are small for any of superconducting junction, but at $T<<T_c$ $I_S(\varphi)=I_C\sin\varphi$ remains for SIS junction [3] regardless the transparencies of the barrier $\bar{D}<<1$. On the other hand for DID junctions $I_S(\varphi)=I_C\sin\varphi$ takes place only for certain range of T, α and $\bar{D}$ [4,6,8].

To estimate the deviation from $I_S(\varphi)=I_C\sin\varphi$ we have measured I-V curves under applied monochomatic mm wave radiation $A\sin(2\pi f_e t)$, $f_e=40\div100$ GHz [2]. Fig. 3 shows the variation of $I_c(A)$ and subharmonic Shapiro step $I_{1/2}(A)$ for two BJs with $\gamma=0$ (symmetrical bias) and $\gamma=54°$(nonsymmetrical one). The calculated functions using RSJ model for $f_e>2eI_cR_N/h$ in the case of $I_s(\varphi)=I_c\sin\varphi$ and $I_s(\varphi)=(1-\delta)I_c\sin\varphi+\delta I_c\sin2\varphi$ for $\delta=0.2$ are presented on Fig.3. For $\delta<1$ the difference between these two theoretical dependencies of $I_c(P_e)$ is small and both cases fit well to experiment. At the same time, a small deviations $I_S(\varphi)$ from sin-type dependence yield subharmonic (fractional n/m) Shapiro steps. The maximum amplitude of

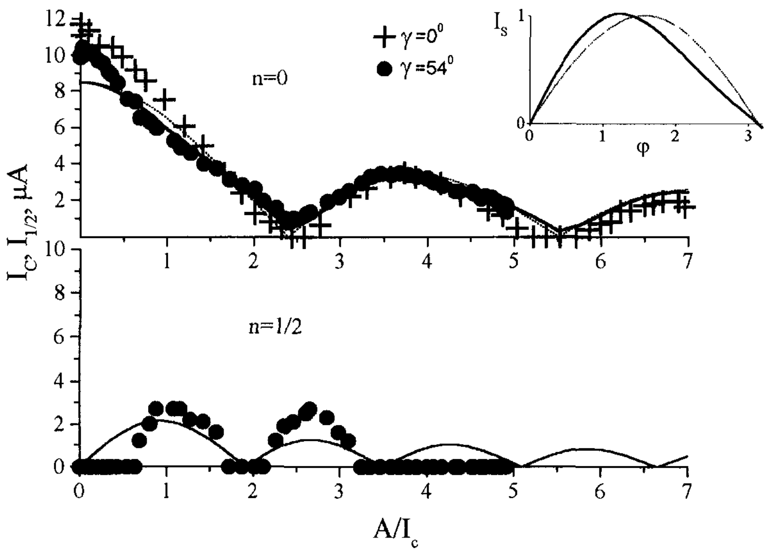

Fig.3. Normalized RF current dependence of the critical current and half Shapiro steps for two BJ γ=0 (crosses), and γ=54°(filled circles). Dashed and solid lines show the calculated curves for δ=0 and δ=0.2 correspondingly. The current-phase relation for these two cases are shown in inset.

subharmonic steps $I_{m/n}$ are proportional to harmonics sin(nφ) in $I_S(\varphi)$. The precise measurements of $I_n(A)$, as well $I_{m/n}(A)$ at T=4.2 K ($T/T_c \approx 0.05$) allows us to state the absence of sin(2φ) components in $I_S(\varphi)$ function for BJ with symmetrical biasing (γ=0÷36°) with accuracy at least of 5%. For γ>40° δ increases monotonously.

The $I_S(\varphi)$ can be determined from the energy of bound Andreev levels E_B in the junction since $I_s(\varphi) \propto dE_B/d\varphi$[4,6]. The results of $I_s(\varphi)$ calculation for symmetrical and mirror symmetrical junction with misorientation 45° are shown on fig.4. Taking into account the twins in superconducting films, the experinental samples may be considered as a parallel connection of pairs of similar two BJs (in our experiment $D_{33}ID_{-33}$ and $D_{33}ID_{57}$). E_B are very closed to $E_B = \pm\Delta\sqrt{\bar{D}}\sin(\varphi/2)$ for misorientation angles in the range 10°÷45°. Even calculated $I_S(\varphi)$ for $D_{45}ID_{45}$ as well as for $D_{45}ID_{-45}$ are nonsinusoudal, the resulting current through the parallel connection of these junctions is $I_s(\varphi) \approx I_c \sin\varphi$ (see fig.4) as we observed in experiment. Note I_c is proportional to $\sqrt{\bar{D}} \propto (R_N S)^{-1/2}$ as observed in experiment (see inset of fig.2).

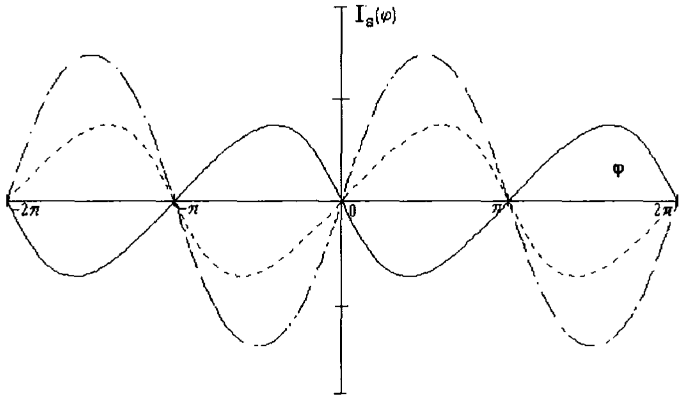

Fig.4. Current-phase relation calculated for symmetrical ($D_{45}ID_{45}$)-dotted line and mirror symmetrical ($D_{45}ID_{-45}$)-solid line bicrystal junctions for $\bar{D}=10^{-4}$, T=4.2K. Dashed line corresponds to the parallel connection of these two junctions.

In summary, we developed the technique for fabrication high-Tc bicrystal junction on sapphire. The 30% variation of characteristics resistance of the junctions on a chip, together with high resistance R_N and characteristic frequency f_c, allow one to design microwave circuit with 10-20 junctions on a chip. The deviations of experimental measured current-phase relation from the calculated ones within the d-wave model for symmetric bycrystal tunnel junctions are possibly caused by structural interface inhomogenieties including film twinning.

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