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Current transport mechanism in YBCO bicrystal junctions on sapphire.

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ABSTRACT: YBCO junctions were made on r-cut sapphire bicrystal substrates in which the directions <11$\underline{2}$0> for both parts of the substrate have the angles ±12° to the plane of the interface of electrodes. The junctions were tested at dc and mm waves. The junctions with 5 μm width have high normal resistance R_N=10÷20 Ω, I_cR_N=1÷2 mV and tolerance of characteristic interface resistance around 30% on a chip. DC, microwave and magnetic characteristics of the junctions have been investigated experimentally. The sinusoidal superconducting current-phase relation and a linear dependence of critical current density vs square root of the barrier transparency was revealed. Experimental results are discussed in framework of predictions for superconducting current transport via Andreev bound surface states in bicrystal junction.

1. INTRODUCTION

The high values of normal-state resistance R_N and critical frequency f_c=(2e/h)I_cR_N, as well the nonhysteretic I-V curves of high-Tc superconducting (HTSC) Josephson junctions make them appreciably superior to low-T_C superconducting junctions at liquid-helium temperature (T=4.2K). The high critical temperature and proper superconducting gap give 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 (Vale 1997), but because of their high dielectric constant ε>1000 they are unsuitable for high-frequency applications. Sapphire having a relatively low ε≈9-11 and low losses (tan δ≈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 in a view of determination of current transport mechanism. The high frequency dynamics of those junctions is discussed.

2. EXPERIMENTAL RESULTS

The Josephson junctions were fabricated on the r-cut 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 of electrodes. 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. 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 the 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 (Mashtakov 1999). 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 I_c/S=10^4÷10^5 A/cm^2 at T=4.2K gave the

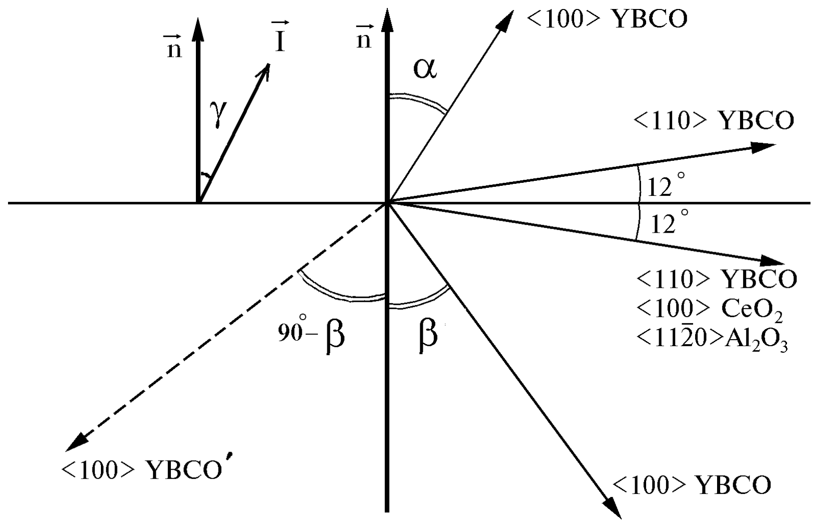

Fig.1. Crystallographic axes orientations of CeO_2 and YBCO films in sapphire bicrystal junction with α=33°, β=-33°. The domain of the film with the direction <100>YBCO′ misoriented on the angle β'=90°-β is the twin to YBCO.

parameters: R_N=5÷30 Ω, I_c=50÷200 μA with I_cR_N=1÷2 mV. $I_c(T)$ nearly linear increases with T reduction at $T<<T_c$ (Andreev 1994). On other hand at $T_c-T<<T_c$, where thermal fluctuations predominate, the approximated dependence I_c (T) is closer to the quadratic dependence $I_c \propto (1-T/T_c)^2$. Other dc parameters of the junctions discussed elsewhere (Mashtakov 1999). The most unusual thing for investigated junctions was I_c linear dependence vs square root of barrier transparency $\sqrt{\overline{D}}$

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

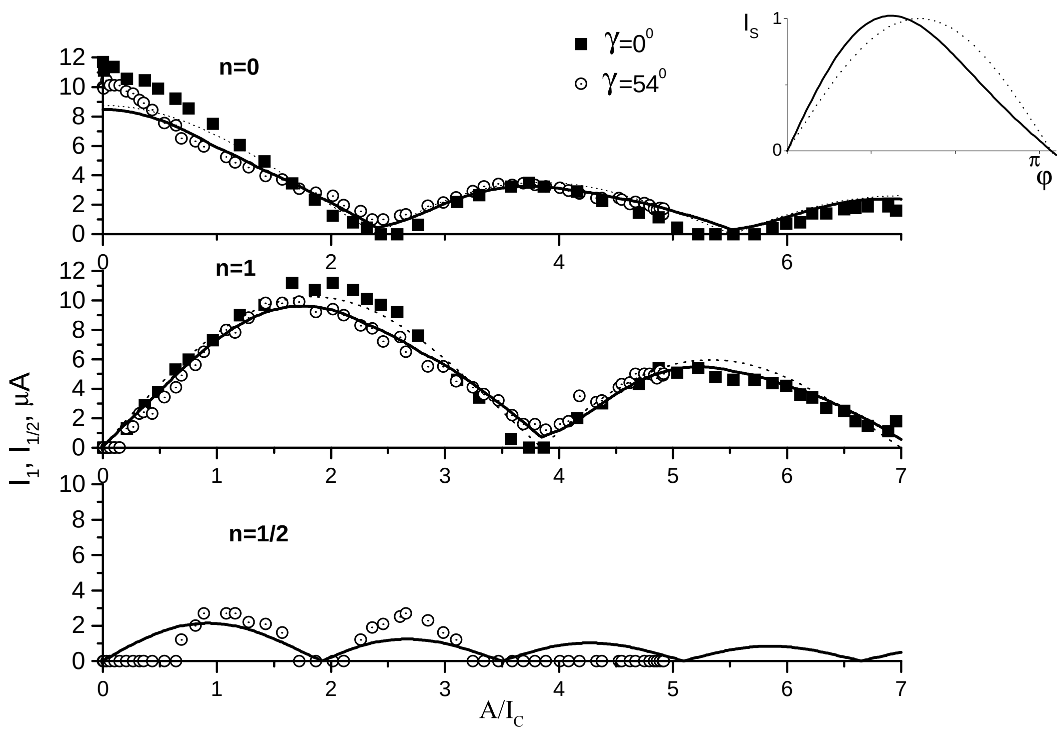

Fig.2. Normalized RF current dependence of the critical current (n=0), first Shapiro step (n=1) and half Shapiro steps (n=1/2) for two BJ γ=0 (filled squares), and γ=54°(opened circles). Dashed and solid lines show the calculated curves for δ=0 and δ=0.2 correspondingly for current-phase relation $I_s(\varphi)=(1-\delta)I_c\sin\varphi+\delta I_c\sin 2\varphi$. The current-phase relation for these two cases are shown in inset.

superconducting junction, but at $T \ll T_c$ $I_S(\varphi)=I_C\sin\varphi$ remains for SIS junction (Likharev 1979) regardless the transparencies of the barrier $\overline{D} \ll 1$. On the other hand for junctions of d-wave superconductors (DID) $I_S(\varphi)=I_C\sin\varphi$ takes place only for tunnel junctions in certain range of T, α and $\overline{D}$ (Tanaka 1997, Riedel 1998, Barash 1995).

To estimate the deviation from $I_S(\varphi)=I_C\sin\varphi$ we have measured I-V curves under applied monochromatic mm wave radiation $A\sin(2\pi f_e t)$, $f_e=40\div100$ GHz (Mashtakov 1999). Fig. 2 shows the variation of $I_c(A)$, first $I_1(A)$ and half $I_{1/2}(A)$ Shapiro steps 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 $I_s(\varphi)=(1-\delta)I_c\sin\varphi+\delta I_c\sin2\varphi$ $\delta=0.2$ are presented on Fig.2. The difference between these two theoretical dependencies of $I_{c,1}(A)$ is small and in both cases its well fit 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 subharmonic steps $I_{m/n}$ are proportional to harmonics $\sin(n\varphi)$ in $I_S(\varphi)$. The precise measurements of $I_n(A)$ (n=0,1,2), as well $I_{m/n}(A)$ at T=4.2 K ($T/T_c\approx0.05$) allows us to state the absence of $\sin(2\varphi)$ components in $I_S(\varphi)$ function for all investigated BJs with symmetrical biasing ($\gamma=0\div36°$) with accuracy at least of 5%. For strong asymmetric biasing ($\gamma>40°$) the contribution of the component $\sin2\varphi$ increases monotonously.

3. DISCUSSION

The $I_S(\varphi)$ can be determined from the energy of bound Andreev levels E_B in the junction since $I_s(\varphi)\propto dE_B/d\varphi$ (Tanaka 1997, Riedel 1998). For SIS junctions the dependence

$$E_b(\varphi) = \Delta_0\sqrt{1-\overline{D}\sin^2\left(\frac{\varphi}{2}\right)} \tag{1}$$

gives $I_S(\varphi)=I_C\sin\varphi$. For the tunnel junction of two d-wave superconductors with gaps $\Delta_{R(L)}=\Delta_0\cos(2\theta+2\alpha(\beta))$ E_b depends on 4 angles: quasiparticle incidence angle -θ, phase -φ, misorientation angles α(and β). Andreev levels for mirror symmetric d-wave junctions ($\alpha=-\beta$) at several α are presented at Fig.3a. One can see that in the range $\alpha=10°\div45°$ $E_b(\varphi)$ dependence is very close to E_B (2) corresponds to $\alpha=\pi/4$ exactly:

$$E_B=\pm\Delta\sqrt{\overline{D}}\sin(\varphi/2) \tag{2}$$

Note, proportionality $I_c \propto \sqrt{\overline{D}}$ observed in experiment (Ovsyannikov 1999) directly follows from equation (2).

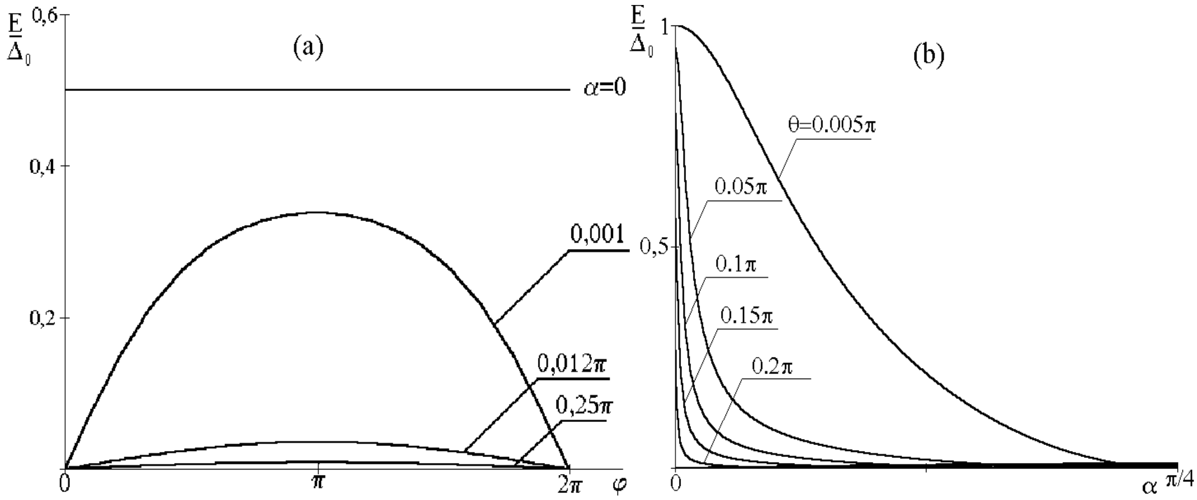

Fig3. (a)- Andreev levels in $D_\alpha ID_{-\alpha}$ junction for several α, $\overline{D}=10^{-4}$, $\theta=\pi/6$, T=4,2K. $E_B(\varphi)$ confined with equations (1) and (2) for $\alpha=0$ and $\pi/4$ correspondingly. (b)-Amplitude of Andreev levels in $D_\alpha ID_{-\alpha}$ for several θ, $\overline{D}=10^{-4}$, T=4,2K.

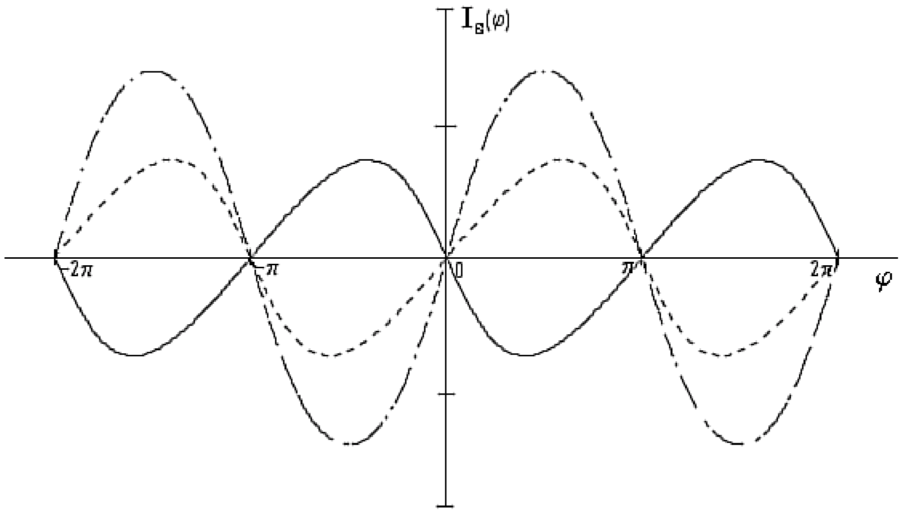

Fig.4. Current-phase relation calculated for symmetrical (45°, 45°)-dotted line and mirror symmetrical (45°,-45°)-solid line bicrystal junctions. Dashed line corresponds to the parallel connection of these two junctions. T==4,2K, $\overline{D}$ =10^{-4}.

The behavior of the amplitude of Andreev levels with increasing misorientation angle α at several quasiparticle incidence angles (θ) is shown on fig.3b. For α=10°÷45° the condition max$|E_B|>0.1\Delta_0$ satisfied for small amount of incident quasiparticles in the range θ=0÷10°. Therefore the averaged income of the quasiparticles would be small.

The results of $I_s(\varphi)$ calculation for symmetrical and mirror symmetrical junction with misorientation angle 45° using the technique (Reidel 1998) 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 two similar BJs (in our experiment $D_{33}ID_{-33}$ and $D_{33}ID_{57}$). Even the calculated $I_S(\varphi)$ for $D_{45}ID_{45}$ as well as for $D_{45}ID_{-45}$ are nonsinusoidal for experimental T==4,2K and $\overline{D}$ =10^{-4}, 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. For larger values of the γ (36°÷54°) the nonsinusoidal parts of the $I_s(\varphi)$ dependence doesn't cancel and subharmonic step appears at the I-V curve under microvawe irradiation due to nonsymmetrical contribution of two types of BJs.

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