Superconducting Current - Phase Dependence in Josephson YBCO Bicrystal Junctions on Sapphire

Igor V. Borisenko, Gennady A. Ovsyannikov, Karen Y. Constantinian, Evgeni A. Stepantsov

***Abstract*—The deviation of superconducting current-phase relation (CPR) in Josephson junction (JJ) from sinusoidal one is very important for the application of JJ in electronics. The dependencies of the amplitudes of the harmonic and subharmonic Shapiro steps were used to study CPR of YBCO JJ on a bicrystal sapphire substrate. It is shown that for a symmetric set of the transport current across the symmetric bicrystal junction, the CPR is closed to sinusoidal one that differs from the theoretical predictions based on d-type of superconducting wave function in the electrodes. The divergence from symmetry in the transport current across JJ causes the CPR to deviate from sinusoidal type and the deviation increases with increasing degree of asymmetry. This change in the CPR is discussed within the model, which takes into account the formation of coupled Andreev states in JJ of superconductors with a d-type of superconducting wave function.**

***Index Terms*—bicrystal Josephson junction, current-phase relation, Shapiro steps.**

I. INTRODUCTION

THE DEPENDENCE of the superconducting current I_S on the phase difference φ between the order parameters of the two superconductors forming the Josephson junction (current-phase relation - CPR) determines the dynamic parameters of the Josephson junctions (JJ) such as the Josephson inductance, the microwave impedance, the spectral composition of the Josephson generation and so on. Calculation of Josephson circuits are usually made assuming [1] a sinusoidal CPR $I_S(\varphi)=I_c \sin \varphi$ (I_c is the critical current of JJ), which is observed in tunnel junctions between ordinary s-superconductors (SIS) over a wide range of temperature[2]. However, in JJ with direct (nontunnel) conductivity, like point contacts (ScS), a nearly sawtooth dependence of $I_S(\varphi)$ is observed at low temperature, which may expressed in terms of Fourier components: $I_S(\varphi)=\sum\delta_n \sin (n\varphi)$, $n\geq1$. The reason for the complex dependence of $I_S(\varphi)$ is, possibly, the contribution of multiple Andreev reflections to superconducting current. In the most JJs Andreev's levels are described by the formula[2,3]:

$$E_b=\pm\Delta\sqrt{(1-\overline{D}\sin^2(\varphi/2))}, \qquad (1)$$

where Δ is the superconducting gap. The levels are placed close to Δ in tunnel junction with small transparency of the barrier ($\overline{D}$<<1) and the peculiarity induced by its, weak observed in experiments. Mostly properties of tunnel junctions well described by the tunnel Hamiltonian model [2,3]. The situation is considerably changed in JJ with direct conductivity (where the bound states with energies $\varepsilon<\Delta$ occur) and JJ of high-T_c superconductors (HTSC), most of which are assumed to be d-superconductor[4-6]. Here we report measurement of CPR of HTSC Josephson junction on bicrystal sapphire substrates.

II. EXPERIMENTAL

A. Fabrication technique

The Josephson junctions were fabricated on the r-cut sapphire bicrystal substrates (crystallographic plane (1$\underline{1}$02) Al_2O_3) consisting of two crystals for which the directions

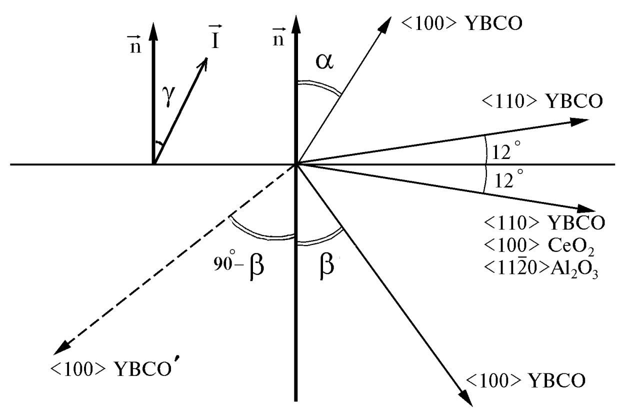

Fig.1. Crystallographic axes orientations of CeO_2 and YBCO films in sapphire bicrystal junction with α=33°, β=-33°($D_{33}ID_{-33}$). The domain of the film with the direction <100>YBCO' misoriented on the angle β'=90°-β is the twin to YBCO.

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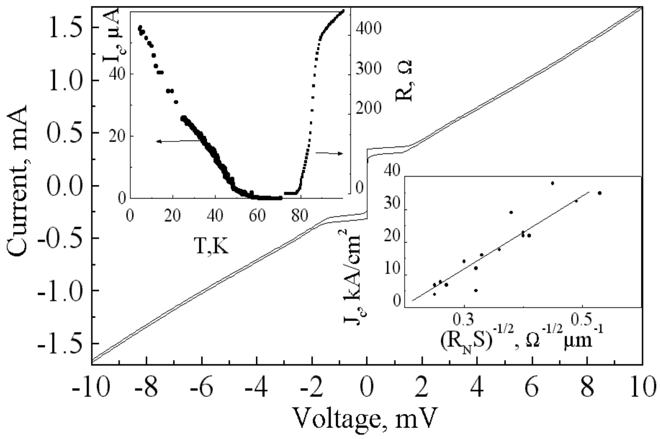

Fig.2. The I-V curve at T=4.2K for a typical bicrystal junction. Temperature dependence of the resistance R(T) and critical current $I_c(T)$ are shown in the left inset. Dependence of the critical current density J_c vs. inverse square root of characteristics interface resistance $(R_NS)^{-1/2}$at T=4.2K is shown on right inset.

<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 growth at T=750-770°C by dc sputtering (in diode configuration) at high oxygen pressure (4 mbar) after the CeO_2 epitaxial buffer layer rf magnetron sputtering at T=600-750°C and pressure 0.01 mbar in an Ar/O_2 mixture. 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 formed by rf plasma and 0.5% ethanol solution of Br_2 etching [7]. We have made the samples in which the YBCO bridges crossed the boundary at the angle γ between the normal to the boundary interface and current direction varied from 0° to 54° (see Fig.1).

B. Dc measurement results

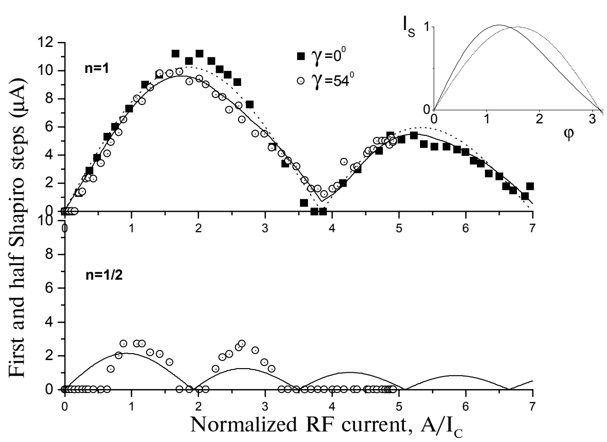

Fig.3. Normalized RF current dependence of the first and half Shapiro steps for two junctions γ=0 (squares), and γ=54° (open circles). Dashed and solid lines show the calculated curves for δ=0 and δ=0.2 correspondingly. The current-phase relations $I_S(\varphi)$ for these two cases are shown in inset.

The junctions with current density 10^4-10^5 A/cм^2 $V_0=I_cR_N=0.5\div2$ mV at T= 4.2K were obtained. The typical I-V curve of the junction is shown on Fig.2. It obviously demonstrates a behaviour very close to Resistive Shunted Junction (RSJ) model which has two channels for current: quasiparticle V/R_N and superconducting $I_S(\varphi)=I_c\sin\varphi$[2]. Very small (or even negative) excess current on I-V curve at V>10 mV indicates on the absence of channels with direct (nontunnel) conductivity [2]. $I_C(T)$ function shown in the inset to Fig.2, has linear temperature dependence, which distinguishes from the known theoretical one for SIS junctions [2]. At T_c-T<<T_c, where the influence of thermal fluctuation is strong, I_c (T) is close to $(T_c-T)^{1/2}$ dependence.

The following formula has been used for determination of the average barrier transparency $\overline{D}=2\ \rho^{YBCO}l^{YBCO}/(3R_NS)$, where $\rho^{YBCO}l^{YBCO}\approx3\cdot10^{-10}\ \Omega$ cm^2 for YBCO [8,9]. For typical $R_NS=5\cdot10^{-8}\ \Omega$ cm^2, we obtained $\overline{D}=4\ 10^{-2}$. Bottom inset on Fig.2 shows the current density dependence $j_c=I_c/S$ from R_NS. Obtained experimentally dependence of j_c is proportional to $(R_NS)^{-1/2}\ \propto\sqrt{\overline{D}}$, it is unusual for SIS junctions, for which $j_c\propto\ \overline{D}$ [2].

C. CPR measurement technique

CPR is usually determined from the measurements of the amplitude-frequency characteristics of a microwave resonator coupled with an interferometer, in which the JJ is shunted by the superconducting inductance L. For a reliable determination of CPR L should be small $L<\Phi_0/2\pi I_c$ (where Φ_0 is the magnetic flux quantum). For realistic interferometer dimensions of the order of a few tens of microns I_c should not exceed 10 μA, which severely restricts the choice of samples[10].

For determination of CPR we use a different method based on measuring the critical current and Shapiro steps as a function of the amplitude of the external monochromatic electromagnetic radiation $A\sin(2\pi f_et)$. Changes in Shapiro steps were first used to estimate CPR in superconducting tin bridges[11] and were then applied to HTSC structure [12]. Within RSJ model for $\omega=hf_e/2eI_cR_N\geq1$ the maximum values of subharmonic Shapiro steps uniquely determine the amplitudes of the harmonic components δ_n . For $\delta_1=1-\delta_2$, $\delta_n=0$, n>2 we have for amplitudes of the steps[9]:

$$I_1(a)=\max I_c\{[(1-\delta_2)J_1(a/\omega)\sin\theta+\delta_2J_2(2a/\omega)\sin2\theta]\},$$
$$I_{1/2}(a)=\max I_c[\delta_2J_1(2a/\omega)\sin2\theta], \quad (2)$$

where the maximum is determined over the phase shift θ between the self-induced oscillation and the external signal, J_n are n-th order Bessel functions and $a=A_{RF}/I_c$ is normalized amplitude of the external radiation.

To estimate deviation from $I_S(\varphi)=I_C\sin\varphi$ we have measured I-V curves under applied monochromatic mm wave radiation $f_e=40\div100$ GHz. The Shapiro steps on I-V curves, observed

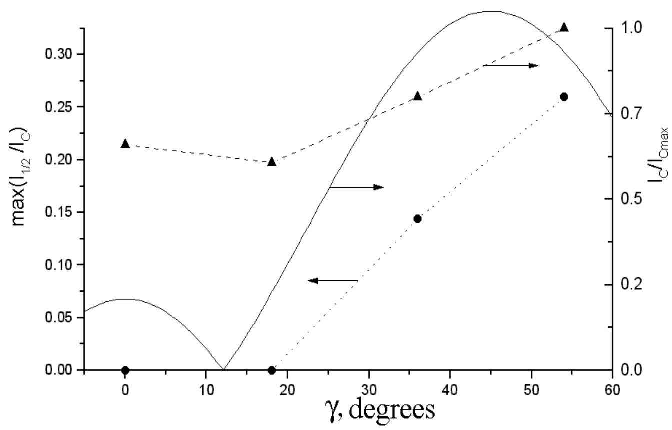

Fig.4. Dependencies of the maximum of the Shapiro subharmonic step and the critical current density on the angle of the deviation of the current direction from the normal. The solid curve gives the critical current of JJ as a function of the angle of asymmetry of the bicrystal interface [13]

at voltages corresponding to harmonics of the microwave frequency, demonstrate presence of Josephson coupling in the junctions. Fig. 3 shows the variation of $I_1(A)$ and subharmonic Shapiro step $I_{1/2}(A)$ for two junctions with symmetrical and nonsymmetrical biasing (γ=0, 54° on Fig.1). 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 $I_S(\varphi)=(1-\delta)I_c\sin\varphi+\delta I_c\sin 2\varphi$ at $\delta=0.2$ are presented on Fig.3. For $\delta<1$ the difference between two theoretical dependencies of $I_1(P_e)$ is small and both cases fit well to experiment. At the same time, a small deviations $I_S(\varphi)$ from sin-type CPR yields subharmonic (fractional n/m Shapiro steps). The maximum amplitude of 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 CPR for the JJs with symmetrical biasing (γ=0÷36°) with accuracy at least of 5% ($\delta_2<0.05$). For γ>40° δ_2 increases monotonously (Fig.4).

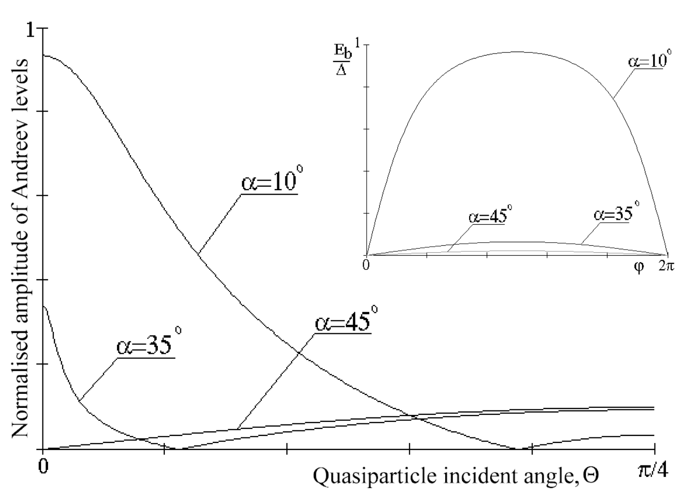

Fig.5. Maximum of Andreev's levels in $D_\alpha ID_{-\alpha}$ junctions over φ for several α. The inset shows phase dependence of Andreev's levels in $D_\alpha ID_{-\alpha}$ junction for several α, θ=π/10.

III. DISCUSSION

A. Andreev's states in d-wave Josephson junctions

A superconducting order parameter with d-wave symmetry changes sign in a-b plane, when rotated on 90^0 around c-axis. Since quasiparticle changes its momentum when scattered at the bicrystal boundary, and there is a sign difference of order parameter before and after scattering, a bound state appears. An electron travelling towards the surface of d-superconductor, which is not parallel to a crystal axis, is reflected back into d-superconductor and is subsequently Andreev reflected into hole by the positive pair potential. In the next step the hole follows the same path backwards, reflected at the surface, finally Andreev –reflected into another electron by negative pair potential. The surface of d-superconductor plays a role of point contact with $\bar{D}=1$ and the sign change in the pair potential corresponds to the phase difference π[4-6]. It is the essential physical difference between tunnel Josephson junctions of s- and d-superconductors, the position of Andreev's level when the phase difference across the junction is zero. For tunnel junction of d-superconductors (DID) the Andreev's energy level is very close to Fermi level as for s-superconductor the energy is close to the gap.

For the DID junction with gaps $\Delta_{R(L)}=\Delta_0\cos(2\theta+2\alpha(\beta))$ E_b depends on 4 angles: quasiparticle incident angle - θ, phase - φ and misorientation angles - α(β). Maximum over φ Andreev levels in mirror symmetric (β=-α) junctions ($D_\alpha ID_{-\alpha}$) vs θ at several α are presented at Fig.5. For α=10°÷45° a small amount of quasiparticle in the range θ=0÷10° the condition $\max|E_b|>0.1\Delta_0$ satisfied. Therefore, the averaged income of these quasiparticles would be small. From inset of Fig.5 one can see that in the range α=10°÷45° $E_b(\varphi)$ dependence is very close E_b for misorientation angle α=45°. We can use as an approximation the following equation for description Andreev's level in $D_\alpha ID_{-\alpha}$ junction in wide range of α=10÷45°[4-6]

$$E_b=\pm\Delta(\theta)\cos[(\varphi-\pi)/2)]\sqrt{\bar{D}(\theta)}, \qquad (3)$$

B. *Determination of superconducting current using Andreev's levels*

The $I_S(\varphi)$ can be determined from the energy of bound Andreev levels E_B in the junction [6].

$$I_S \propto \sum_n \int \cos(\theta_n)\frac{dE_{bn}(\theta,\varphi)}{d\varphi} f(E_{bn}(\theta))d\theta, \qquad (4)$$

where the summation is taken over all Andreev's level E_b, $f(E_b)$ is Fermi's disrtibution funtion.

Result of our calculation $I_S(\varphi)$ for $D_{45}ID_{-45}$ gives δ_2=0.2, compare with experimental δ_2<0.05. The reason for the discrepancy could be several physics phenomena, which have not been accounts in the theory [5,6]. The first one is facetting of interface boundary that means the current through the junction could be considered consists of several components. For simple (trapezium) approximation of interface boundary they are as following: the current part from symmetrical junction ($D_\alpha ID_{-\alpha}$) and from two asymmetrical junctions (D_0ID_α and $D_\alpha ID_0$). According to estimation [6] the j_c of the last components is proportional to $\bar{D}^2$, while for $D_\alpha ID_{-\alpha}$ $j_c \propto \sqrt{\bar{D}}$. So the contribution of asymmetrical junctions could be neglected.

For twinned film in the system with orthorhombically distortion it is established the presence of a s-wave component and the dominance of d-wave part [12, 14]. d-wave component is identical on both sides of twin, whereas s-wave component changes sign. As results the gap for example at direction [100]YBCO changes amplitude over twin boundary[14]. Since the sizes of twin is typically 10 nm the variation of gap corresponds inhomogeneous JJ. Averaging over about 100 twin boundaries could be reason for sin-dependence of CPR.

In symmetrical junction of d-wave superconductor at low T in wide range of α $E_B \infty\sqrt{\bar{D}}$ and $j_c \infty\sqrt{\bar{D}}$ as follow from eq. (4). The dependence of $j_c \infty\sqrt{\bar{D}}$ was observed for all investigated junctions (see Fig.2).

The comparison of absolute value and temperature dependence of I_c is difficult within the simple model [6] because of the roughness of the interface and consequently the contribution of midgap states is reduced. In accordance to the d-wave theory of JJ [4-6], various non-linear $I_C(T)$ dependencies caused by the existence of bound states at the interface should be observed. Our measurements, instead show a monotonous (smooth) rise of I_C with decreasing T [8]. A distinctive feature of d-wave pairing is the sensitivity of the d-wave superconductor to inhomogeneties and interfaces. Quasiparticle scattering at interfaces distorts the order parameter and significant depreses the gap. It happens in the case, when the normal of the interface differs from crystallographic axes even for specular reflecting boundaries [4]. This phenomenon influences on the critical current of the junction as normal metal layer. Consequently at $T \approx T_c$, gap suppression would cause to quadratic dependence of $I_c(T)$, which we observed in experiment (Fig.2).

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