Millimeter wave study of hybrid superconducting heterostructures with magnetic active interlayer

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Introduction. Josephson junctions with ferromagnetic barriers were fabricated and studied [1] for their ground state change from 0 to π: $I_S=I_C\sin(\varphi)$ to $I_S = I_C\sin(\varphi+\pi)$, where I_S is superconducting current, I_C - critical current, φ is the phase difference of pair potential between superconducting electrodes. Circuits, consisting from 0-junctions and π-junctions could be used for qubits –elements of quantum computer [2]. We report on hybrid Nb/Au/$(Ca_{1-x}Sr_x)CuO_2/YBa_2Cu_3O_7$ Josephson heterostructures made with antiferromagnetic (AF) barrier between superconducting electrodes, exhibiting current – phase relation (CPR), modeled as $I_S = (1-q)I_C\sin(\varphi)+ q\, I_C\sin(2\varphi)$. The epitaxial grown AF barrier layer $Ca_{1-x}Sr_xCuO_2$ was up to 50 nm thick. To investigate the origin of the zero voltage current for our hybrid heterostructures we applied microwave radiation and studied the ac Josephson effect. Measuring Shapiro step amplitudes and detector response functions we estimated the CPR for the junctions by methods described in [3, 4]. Studies of critical current versus magnetic field were performed for testing the uniformity of critical current density in the junctions. Recently L. Gorkov and V. Kresin predicted a reduced period of $I_C(H)$ magnetic field pattern for superconductor–antiferromagnetic–superconductor junction, comparing with a SIS tunnel junction having the same size [5]. Obtained $I_C(H)$ experimental results for our heterojunctions were in qualitatively agreement with this prediction.

Experimental methods $YBa_2Cu_3O_7$ (YBCO) films were deposited by eximer laser on $NdGaO_3$ substrates. At the same run the $Ca_{0.85}Sr_{0.15}CuO_2$ (CSCO) was deposited epitaxially. A 20 nm thick Au film was deposited over the CSCO, then 200 nm Nb top electrode. The technology includes a deposition of SiO insulator and ion beam etching. The heterostructures were squares, from 10 to 50 μm in size L, as described in [6]. Structure of the junctions and dc measurement method are shown in Fig. 1.

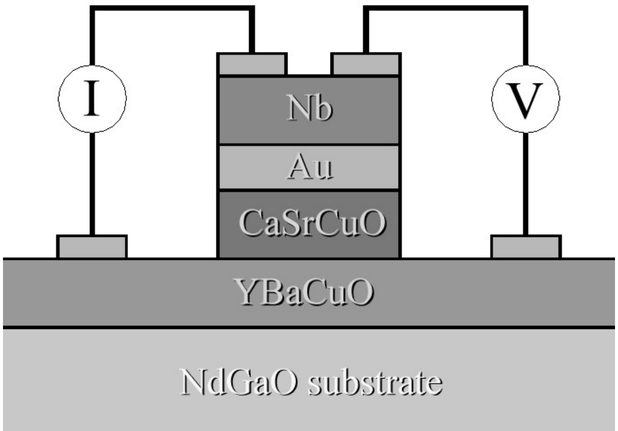

Fig. 1. Crossection of the hybrid heterostructure. Four point measurements of I-V curve are indicated.

Four point measurement of voltage – current characteristics, when microwave was applied, were performed. Detector responses were measured by modulated microwave signal. A response from junction at the modulation frequency was measured by PAR 124 Lock-in amplifier with input voltage resolution 2 $nV/(Hz)^{1/2}$. Magnetic field could be applied in the both directions: in parallel and perpendicular to the substrate plane.

Dependencies of critical current versus magnetic field The junctions show the $I_C(H)$ dependencies, which had a pronounced central peak. The central peak was much higher, than others, but its width ΔH was not double of other peaks widths, as known for Fraunhofer pattern. We have compared the $I_C(H)$ dependencies for Nb/Au/$(Ca_{1-x}Sr_x)CuO_2$/ $YBa_2Cu_3O_7$ and Nb/Au/$YBa_2Cu_3O_7$ junctions, as shown in Fig. 2.

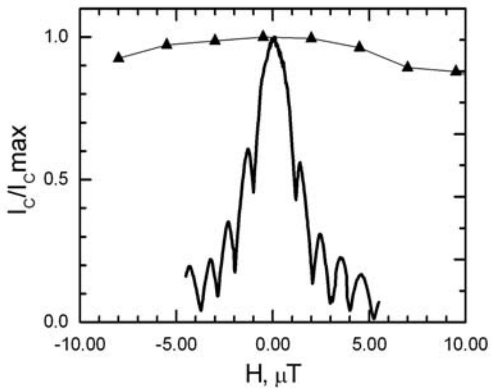

Fig. 2. The I_C(H) dependences for Nb/Au/$(Ca_{1-x}Sr_x)CuO_2$/$YBa_2Cu_3O_7$ – solid line, and for Nb/Au/$YBa_2Cu_3O_7$ junction – triangles. Both junctions are 50 μm in size. The structure with antiferromagnetic has CSCO thickness 50 nm, ΔH=1 μT. Fields were applied parallel to the substrate.

Field periods ΔH of the heterostructures with 50 nm CSCO layers are 30 times smaller, compare to Nb/Au/$YBa_2Cu_3O_7$ junctions. However, the periods were proportional to L^{-1} for the both structures.

Electrical properties of the junctions at millimeter waves If the current – phase relation of the junction has the both first and second harmonics, two kinds of Shapiro steps: integer one at voltages V_1=hf/2e and half integer at $V_{1/2}$ = hf/4e appear. The dependency of integer steps versus power P is described by:

$$i_1(P) = 2\max_{\Theta}(J_1(x)\bullet\sin(\Theta) + qJ_2(2x)\sin(2\Theta)) \quad (1)$$

Here $i_1 = I_1(P)/I_C$ is normalized height of the first step, J_1 and J_2 are the first and second order Bessel function, $x=I_{RF}/(\omega I_C)$ – normalized microwave amplitude. Normalized frequency $\omega=2eI_CR_N/hf$, R_N is normal state resistance of the junction, f – external frequency. Θ is the phase difference between external signal and the self Josephson generation. The minima of i_1(P) become non-zero, caused by the second harmonic. Critical current:

$$i_0(P) = \max_{\Theta}(J_0(x)\bullet\sin(\Theta) + qJ_0(2x)\sin(2\Theta)) \quad (2)$$

also have nonzero minima due to the second harmonic. The half integer step versus power:

$$i_{1/2}(P) = 2\max_{\Theta}(\sin(\Theta)\bullet qJ_1(2x)) \quad (3)$$

The formulas were derived from [4, 6] in high frequency and zero capacitance limits. Experimental data demonstrate good agreement with theory (1) – (3) as shown on figure 3.

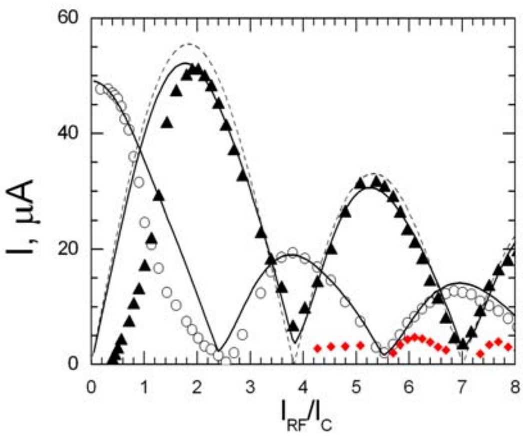

Fig. 3. Shapiro steps at f= 56 GHz, I_C – circles, I_1 – triangles, and of half integer steps – rhombuses. Solid lines – fit by (1) and (2). Dashed line is J_1 approximation. The junction has 50 nm CSCO and L=10 μm.

For data shown on Fig. 3, we obtain second harmonic term q ≈ 20% for CPR, using (1) – (3). Note, the approach [4, 6] is more accurate for higher frequencies and low microwave currents. Detector responses of the junctions in 90 ÷ 120 GHz range were measured. If the outputs from junction are η_1 for integer response at V_1, and $\eta_{1/2}$ for half integer response at $V_{1/2}$, the ratio of $\eta_{1/2}/\eta_1 \approx 4q^2$ in the high frequency limit.

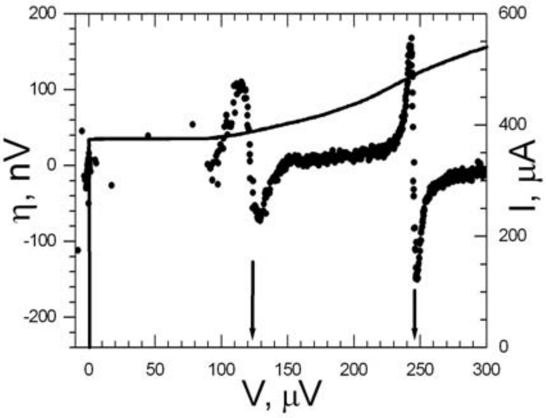

Fig. 4. Detector response (circles) on 120 GHz signal, ω=1, voltage – current characteristic – solid line. The junction had L = 10 μm, CSCO was 20 nm thick. Biasing voltages for integer and half integer responses are shown by arrows.

Applied microwave power to the junction was of 6 μW and the junction was in small signal regime, which shows linear dependency of response on microwave power. The ratio of $\eta_{1/2}/\eta_1$ for the data in Fig. 4 is of 0.6 and we estimate $q \approx 0.4$. Because of high I_CR_N product of 250 μV, more accurate estimation of the second harmonic portion requires to apply higher microwave frequencies, than 120 GHz to meet requirement ω>>1.

In conclusion we fabricated Nb/Au/$(Ca_{1-x}Sr_x)CuO_2/YBa_2Cu_3O_7$ superconducting heterostructures with I_CR_N product 100 ÷ 300 μV at T=4.2 K. Critical current density was 10 A/cm^2 through 50 nm thick $Ca_{1-x}Sr_xCuO_2$ layer, and increased for thinner layers. Critical currents of the heterostructures had much smaller periods in $I_C(H)$ dependencies compare to Josephson junctions without antiferromagnetic layer. Half – integer Shapiro steps and detector responses were observed for the most of heterostructures. Current phase relations of the heterostructures deviated from sinusoidal with 10 ÷ 40% portion of the second harmonic.

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