

Electron transport and microwave dynamics of hybrid Nb/Au/CaSrCuO/YBaCuO planar Josephson junctions

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Abstract. We report on measurements of dc electron transport and microwave dynamics of thin film hybrid Josephson junctions with an oxide antiferromagnetic interlayer. The base superconducting electrode YBaCuO and the antiferromagnetic (AF) interlayer CaSrCuO (with thickness $d = 20 - 70$ nm) were grown by laser ablation on NdGaO₃ substrates. I-V curves were well fitted to RSJ model and had no excess current, $I_C R_N$ products were of order 0.2 mV at $T=4.2$ K. We did not observe any noticeable reduction of $I_C R_N$ with increasing d . Such “tunnel-like” behaviour also resulted in appearance of singularities on I-V curve when magnetic field was applied. Oscillating with microwave power integer and half-integer Shapiro steps were registered along with sub-harmonic detector response. Moreover, for some of junctions a “devil” staircase structure was observed on I-V curves and giant noise-like signals were measured in 1-2 GHz band at the certain levels of microwave power. Observed features, noise performance and the impact of the second harmonic in current-phase relation on junction dynamics are discussed taking into account data for structures without AF interlayer.

1. Introduction

Unusual properties of superconducting hybrid junctions with an interlayer comprising magnetic materials are of great interest for fundamental physical and electronic applications. For instance, in ferromagnetic/superconducting/ferromagnetic (F/S/F) structures the superconductivity can be controlled by spin manipulation in F electrodes [1]. Another effect is the oscillatory behaviour of the superconducting order parameter induced in the ferromagnetic layer that may lead to π -phase shift in the ground state of S/F/S Josephson junction. Interesting effects occur also at superconducting and antiferromagnetic (AF) S/AF interfaces. Recently junctions Nb/Au/Ca_{1-x}Sr_xCuO₂/YBa₂Cu₃O_{7- δ} with S/AF interface have been fabricated [2], where YBa₂Cu₃O_{7- δ} (YBCO) is oxide d -wave superconductor, Au - normal metal, and Ca_{1-x}Sr_xCuO₂ (CSCO)– AF layer.

Josephson junctions driven far from equilibrium at microwave frequencies may demonstrate noticeable deviations of high frequency dynamics predicted by RSJ model [3]. That’s why the I-V

characteristics affected by microwaves and magnetic field; noise performance and detector response functions have been measured and discussed.

2. Samples and measurements

The CSCO/YBCO epitaxial double-layer was grown in situ by pulsed laser deposition on NdGaO₃ (NGO) substrates. In order to avoid micro-shorts the following precautions have been made: (i) CSCO films ($d=20 \div 50$ nm) were thicker than the RMS surface roughness of the YBCO layer; (ii) Nb/Au bilayer serves as superconducting counter-electrode. Junctions had shape of a square with linear sizes $L = 10, 20, \dots, 50$ μm . If Nb deposited directly on the top of YBCO film it results in formation of Nb/YBCO interface with very high resistance ($\sim 1 \Omega \times \text{cm}^2$) due to Nb surface oxidation. Temperature dependences of specific normal state resistance $R_N S$, where $S=L^2$ are shown on figure 1 for junctions with different thickness d ; resistance $\rho d/L^2$ of a bare Ca_{0.5}Sr_{0.5}CuO₂ is also plotted, demonstrating crucial change of interlayer properties, being sandwiched between superconductors.

Thickness dependence of specific resistance $R_N S$ for junctions with $x=0.5$ is shown in figure 2. It's seen that $R_N S$ values for junctions without AF layer are apparently larger than $R_N S$ for samples with $d=1.2$ nm.

For measurements at microwaves experimental variables were microwave frequency $f=36 - 120$ GHz and power P , controlled by attenuators in the range of $\alpha=0 \div 70$ dB. The background noise of the junctions was measured within 1-2 GHz using low noise cooled HEMT preamplifier and simultaneously controlled by spectrum analyser. All measurements were done at $T=4.2$ K in magnetically shielded cryostat in microwave-screened environment.

3. Results and discussion

Most of experimental samples had symmetric RSJ-type I-V curve without excess current and the product of critical current by normal resistance $I_C R_N \sim 200$ μV at $T=4.2$ K. All junctions had dimensions $L < \lambda_J$, where λ_J is Josephson penetration depth, and McCumber parameter $\beta_C=1 \div 3$. Thickness dependence of critical current density $j_C(d)$ for S-AF-S junction with $x=0.5$ in CSCO interlayer is shown in figure 3. Theoretical dependences $j_C(d)$ are also plotted for a model of S-AF-S junction with a magnetic interlayer consisting from 20 ferromagnetic layers with opposite magnetization. The best fit gives the theoretical dependence for the exchange field $h=H_{ex}/\pi kT=5$ plotted for the case when coherence depth in AF $\xi_{AF}=10$ nm.

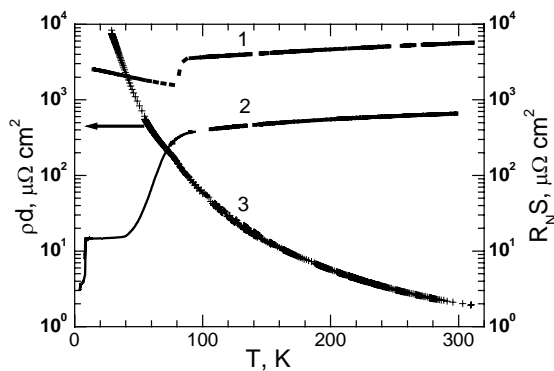


Figure 1. Temperature dependences of junction resistance: (1) $d=20$ nm, $S=10 \times 10 \mu\text{m}^2$, (2) $d=40$ nm, $S=50 \times 50 \mu\text{m}^2$ and (3) resistance $\rho d/S$ of a bare CSCO film with $x=0.5$, $d=40$ nm, $S=50 \times 50 \mu\text{m}^2$ deposited on NGO substrate.

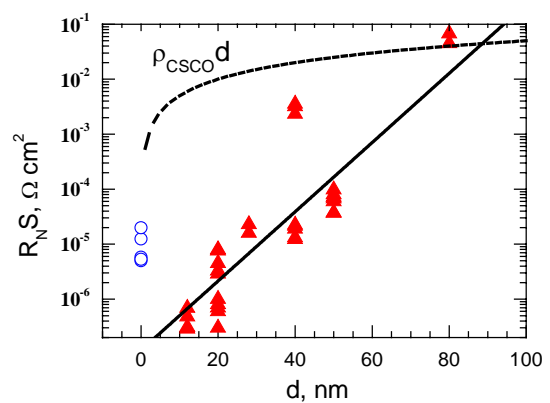


Figure 2. Thickness dependencies of specific resistance $R_N S$ for CSCO with $x=0.5$. Bold line corresponds to $\xi_{AF}=7 \pm 1$ nm. Open circles are data for junctions without AF interlayer. Dash line is calculated resistance for bare AF layer.

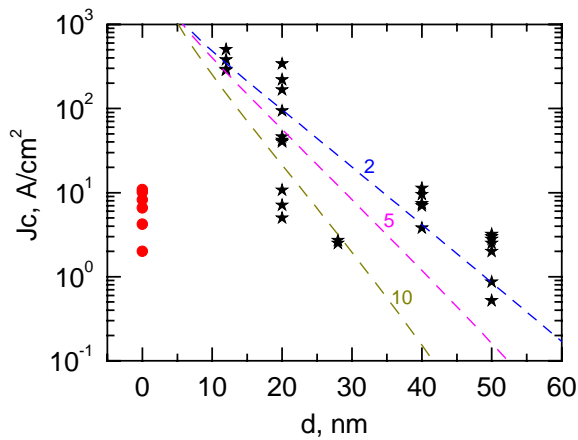


Figure 3. Thickness dependencies of critical current density for junctions with (and without at $d=0$) AF interlayer. Dashes are theoretical dependences for S-AF-S junctions with different intensity of exchange field h (numbers) of F layers in AF.

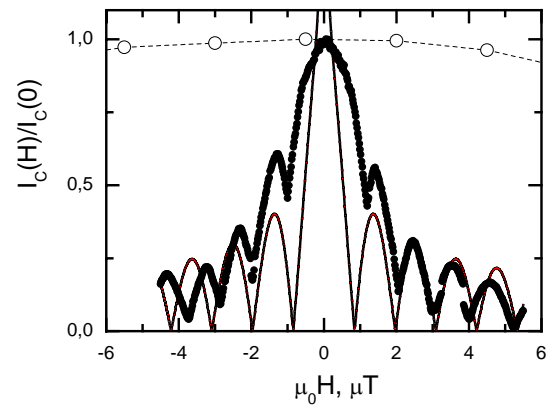


Figure 4. Magnetic-field dependence $I_C(H)$ for structures with $L = 50 \mu\text{m}$. With AF interlayer - black points, and thin line is calculated curve by theory [4]. A central part for a structure without AF layer - open circles.

Figure 4 demonstrate magnetic-field dependence $I_C(H)$ for junctions with and without AF interlayer, the both had the same dimensions, $L = 50 \text{ nm}$. The calculation of $I_C(H)$ by theory [4] for S-AF-S junctions is shown as well, demonstrating a huge increase in sensitivity to applied magnetic field for structures with AF interlayer [5].

Oscillating dependences of integer Shapiro step amplitudes with microwave power demonstrate good fit to RSJ model. At the same time, half-integer Shapiro steps were registered. Superposition of magnetic and microwave fields did not lead to distortion in symmetry of I-V curves and equal heights of Shapiro steps at positive and negative current bias were observed. In high frequency limit $\omega \gg 1$, $\omega = 2eI_C R_N / \hbar f$, a deviation from sinusoidal $I_S(\varphi) = I_{C1} \sin(\varphi) - I_{C2} \sin(2\varphi)$. superconducting current-phase relation (CPR) could be responsible for half-integer Shapiro steps. Half-integer Shapiro steps in single junction could be observed [6-8] depending of various combinations of parameters ω , β_C , L/λ_J and applied microwave power P . In order to estimate the weigh $q = I_{C2}/I_C$ of the 2nd harmonic in CPR when $L < \lambda_J$, $\omega, \beta_C \sim 1$ and $P \ll 1$ (microwave current $I_{RF} \ll I_C$) the frequency selective detector response was measured. This technique allows to estimate the modulus (but not the sign) of q when junction capacitance has minor influence on subharmonic response. Usually, the both, junctions with and without AF interlayer, had $q \sim 0.2$, repeatedly exhibiting a fraction of the second harmonic at frequencies $\omega \sim 1$. At the same time for a junction with AF interlayer fabricated on c -oriented YBCO film a “devil” staircase structure on I-V curve was observed under microwave irradiation at 45 GHz. Note, the ratio $L/\lambda_J = 0.23$ insures the lumped junction limit. Figure 6 shows such I-V curves evolution when applied power was changed. Distortion of the 2nd Shapiro step is seen at large power levels (figure 6b) within narrow attenuation range $\Delta\alpha \leq 3\text{dB}$. Fig.6a demonstrates unusually large half-integer $n=1/2$ Shapiro steps: up to 0.4 of critical current I_C . That could be caused by superposition of two processes, first one is due to existence of the second harmonic in current-phase relation, and the second one could be related to the period doubling under the large microwave signal when frequency of applied signal f_e is not far from plasma frequency of Josephson junction $f_P = (2eI_C/\hbar C)^{1/2}$, where e is electron charge, \hbar is Planck’s constant, C is junction capacitance. Figure 6c shows I-V curves with the jerks observed at biasing voltages between integer Shapiro steps when 70 GHz signal was applied and giant noise rise was registered by cooled amplifier within 1-2 GHz band. As power of applied signal

was large enough and a frequency mixing effect also takes place due to existence of self-Josephson radiation. In order to compare intensities of the frequency mixing products with the chaotic oscillations we estimated the output signal saturation in frequency mixing regime. Figure 6d shows the dependences of output signal levels vs. applied power of microwave signals at $f_e = 45$ GHz and 70 GHz when current bias was fixed, keeping the voltage near the half-integer Shapiro step $V_{1/2} = (2e/h)f_e$, where chaotic behaviour was observed. Frequency mixing saturation level is also shown. Experimental conditions for chaotic oscillations in “short” Josephson junctions were analysed [9] and were experimentally observed [10] in the case of superconducting tunnel junctions with $\beta_C > 25$. However, our junctions had relatively small β_C parameters and probe signals were in range $\omega \approx 0.5 \div 0.9$.

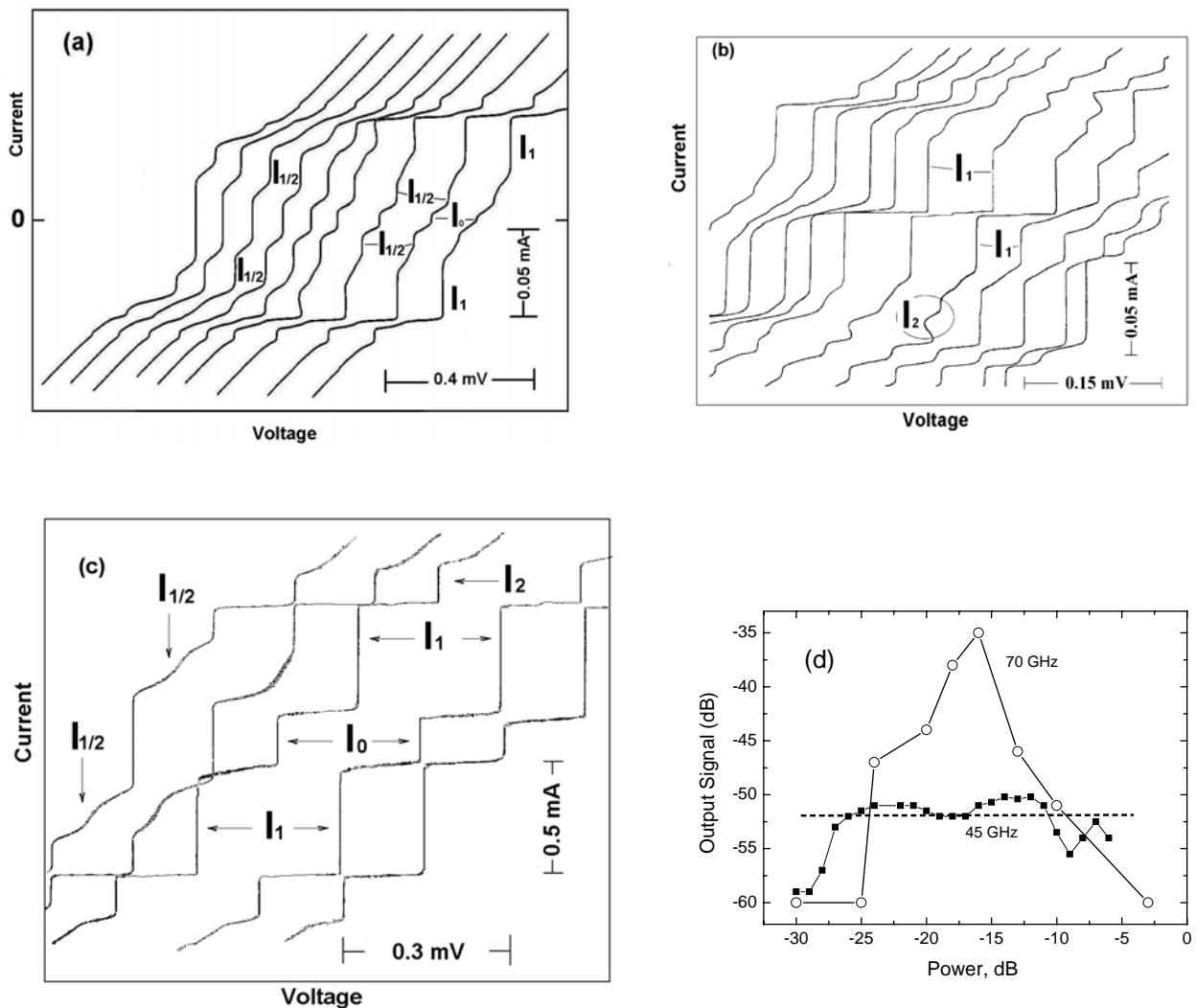


Figure 6. Families of I-V curves under different power levels of microwave irradiation $f=45$ GHz (a, b) and $f=70$ GHz (c). Critical current I_C , integer I_1 , I_2 and half-integer $I_{1/2}$ Shapiro steps are indicated. (b): $n=2$ Shapiro step distortion is pointed by circle. (c): Chaotic noise rise corresponds to the jerks on $I_{1/2}$ steps. All curves are shifted by voltage to the right with increase of applied power. AF interlayer was $d=20$ nm $\text{Ca}_{0.5}\text{Sr}_{0.5}\text{CuO}_2$, $L=20$ μm , $\lambda_J = 88$ μm , $I_C=55$ μA , $R_N=5.5$ Ω , and $\beta_C=2$. (d): Output signal measured in 1-2 GHz frequency band under microwave power P at 45 GHz (black symbols) and 70 GHz (open symbols). Dash line shows saturation level for frequency mixing.

Recently chaotic dynamics was predicted [11] for S/F/S Josephson structures with magnetic interlayer consisted of 3 separated F-layers with rotated magnetization. Although we did not obtain experimental evidence for the triplet Josephson effect in our structures, the latter finding points on very complicated high frequency dynamics in Josephson junctions with magnetic interlayer. These results show that along with the search for promising materials of magnetic interlayer aiming at applications at microwaves the dynamics of such junctions with magnetic interlayer should be studied in details in order to avoid chaotic behaviour and unstable operation.

4. Conclusions

Hybrid superconducting Josephson junctions with an antiferromagnetic $d=10 - 50$ nm thick interlayer were fabricated on NdGaO₃ substrates. Exponential decrease of critical current density with AF layer thickness was observed. Superposition of magnetic and microwave fields did not lead to distortion in symmetry of I-V curves: equal Shapiro step amplitudes were registered at positive and negative voltage biasing. The sensitivity to applied magnetic field for these junctions was found much higher than for conventional Josephson junctions. Then, half integer Shapiro steps observed along with the sub-harmonic frequency selective detector response. That points on deviation of current-phase relation from sinusoidal one. At the same time at the certain experimental conditions a “devil” staircase appears on I-V curve and the giant noise-like signal was registered for the junction fabricated using *c*-oriented YBCO electrode.

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