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RADIO PHENOMENA IN SOLIDS AND PLASMA

Nonlinear Dynamics of a Hybrid Josephson Heterostructure with Cuprate Antiferromagnetic Interlayer

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Abstract—The nonstationary Josephson effect in a hybrid heterostructure based on the $YBa_2Cu_3O_{7-\delta}$ cuprate superconductor and cuprate antiferromagnetic barrier interlayer $Ca_{0.5}Sr_{0.5}CuO_2$ and with the upper superconducting electrode Au/Nb is experimentally investigated. At the frequency of external exposure f = 70 GHz, close to the plasma frequency of the Josephson junction, a giant increase in the noise signal was detected, which was explained by the appearance of stochastic oscillations on the heterostructure. Stochastic oscillations, but with less intensity, occur at the frequency f = 45 GHz. At the same time, on the current–voltage characteristics, there are intervals with negative dynamic resistance.

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INTRODUCTION

Recently, the study of Josephson structures with magnetic layers has attracted increased interest [1, 2]. Previously, an anomalous proximity effect in superconductors with a high critical temperature was observed in $La_{2-x}Sr_xCuO_4/La_2CuO_{4-\delta}/La_{2-x}Sr_xCuO_4$ structures [3], as well as in hybrid $Nb/Au/Ca_xSr_{1-x}CuO_2/YBa_2Cu_3O_{7-\delta}$ heterojunctions [4–6]. In particular, it was shown [6] that antiferromagnetic ordering of the magnetization can lead to an anomalous proximity effect, which is determined by the singlet component of the condensate wave function. Because of this, the critical currents in such structures can coincide in order of magnitude even in the case when the thickness of the antiferromagnetic interlayer significantly exceeds the decay length of the condensate wave function in ferromagnetic layers. It is also known [7] that nonstationary processes in Josephson junctions in conditions other than equilibrium are often impossible to describe by the usual model of a resistively shunted junction (RSJ model). To describe the behavior of the Josephson junction in the nonstationary case, in addition to the frequency f and amplitude I_{UHF} of external microwave radiation, of important value is the ratio of the characteristic frequency $f_0 = (2e/h)I_cR_N$, cutoff frequency $f_{RC} = 1/2\pi R_N C$, and plasma $f_p = (2eI_c/hC)^{1/2}$, as well as the McCumber parameter $\beta_C = f_0/f_{RC}$, where I_c is the critical current, R_N is the resistance in normal state, C is the junction capacitance, and e and h are the electron charge and Planck's constant, respectively.

In superconducting $Nb/Au/Ca_{0.5}Sr_{0.5}CuO_2/YBa_2Cu_3O_{7-\delta}$ heterostructures fabricated on substrates with the slope of the (110) $NdGaO_3$ plane by 11 degrees around the direction [–111] $NdGaO_3$, a superconducting current was discovered, which is of Josephson nature, and the current-phase dependence of the superconducting current was different from the sinusoidal one owing to the 20% contribution of the second harmonic (~sin2φ) [4, 5]. However, nonstationary processes in heterostructures fabricated on $NdGaO_3$ substrates without the above slope remained insufficiently studied.

1. EXPERIMENTAL

A thin film of barrier layer $Ca_{0.5}Sr_{0.5}CuO_2$ was deposited by laser ablation at a temperature of 750°C on top of superconductor $YBa_2Cu_3O_{7-\delta}$ whose deposition temperature was 770°C. The top electrode of the heterostructure was a Au/Nb superconductor. The topology of the structure was formed by photolithography, plasma-chemical, and ion-beam etching. As a result, square mesa-structures with sizes L = 10–50 μm in the plane of the substrate were obtained.

Measurements of the fabricated heterostructures were performed at T = 4.2 K at the frequencies of the microwave signal f = 45 and 70 GHz in conditions of shielding from microwave interference, and measurements of the current–voltage characteristics were performed using analog equipment with battery power source. Electromagnetic irradiation signal power P

was changed by polarizing attenuators within attenuation to 70 dB. Integral power of intrinsic noise P_h and the spectrum of the signal arising on the heterostructure were recorded by a cooled HEMT amplifier with a operating band from 1 to 2 GHz. The amplifier had its own noise temperature $T_{n1} = 8 \pm 2$ K and gain $G_1 =$ 20 dB at $T = 4.2$ K. The balance circuit of the input amplifier stage ensured stable operation of the amplifier in a wide load resistance range of 10–100 Ω and lowered the temperature of the background radiation applied to the sample through a coaxial cable. The noise characteristics of the measuring system were influenced by the second stage of the room amplifier with $T_{n2} = 130$ K and $G_2 = 40$ dB and by a length of coax cable with attenuation $\alpha \leq 0.2$ dB connecting the HEMT amplifier to the sample. The output signal was monitored by a spectrum analyzer and simultaneously detected by a quadratic semiconductor detector.

2. RESULTS AND DISCUSSION

On the current–voltage characteristics of the experimental samples, an excess current was not observed, and the McCumber parameter was within $\beta_C = 1–3$, estimated from the hysteresis by the direct and reverse change of the bias current. Magnitude I_cR_N had the value of 205–214 μV for structures with sizes $L = 20–40$ μm. Further on we will discuss sample with size $L = 20$ μm, the thickness of the barrier layer $d = 40$ nm, $I_c = 48$ μA, $R_N = 4.3$ Ω, and $\beta_C = 2$. Figure 1a shows the current–voltage characteristics recorded under the influence of a microwave signal at frequency $f = 45$ GHz. Shapiro steps are seen at voltages $V_n = nhf/2e$, where n is the number of the Shapiro current step. Note, for $n = 0$ the designation I_0 will be used. According to the RSJ model in the junction without capacitance with size $L < 2\lambda_J$, where λ_J is the Josephson magnetic field penetration depth [8], steps with fractional n are missing [7]. However, fractional steps were also found in the experiment. So, steps with $n = 1/2$ are visible on all CVC in Fig. 1a. At the same time, step distortions were recorded, showing negative dynamic resistance (voltage decrease with increasing DC bias current I), as seen on the CVC with 16 dB attenuation in Fig. 1a. At a higher measurement frequency $f = 70$ GHz (see Fig. 1b), unstable regions appear on the I–V characteristic between the Shapiro steps. Such distortions of the current–voltage characteristics are known in the literature as devil's staircase [9–11] and are the result of the stochastic behavior of a nonlinear system. At the same time, the presence of Shapiro steps indicates that the spectrum of the self-oscillations of the heterostructure contains frequency components synchronized by an external monochromatic signal. Figure 2 shows the dependence of the amplitudes of the critical current I_0 and Shapiro steps

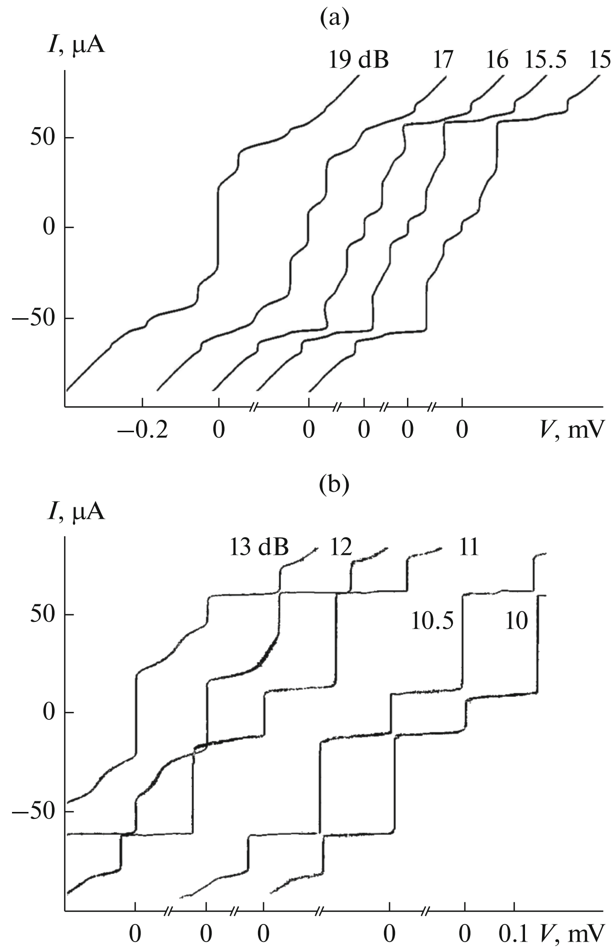

Fig. 1. Family of CVC taken at $T = 4.2$ K under the influence of a microwave signal with a frequency $f = 45$ GHz (a) and $f = 70$ GHz (b) for different values of attenuation introduced by an attenuator. The dependences for clarity are shifted along the voltage axis; the values $V = 0$ correspond to the position of the critical current. Voltage scale V in Fig. 1a is given for the current–voltage characteristic with attenuation of 19 dB; in Fig. 1b, at attenuation of 10 dB.

I_1, I_2, and I_3 on the normalized value of the microwave current exposure $i_{UHF} = I_{UHF}/I_c$ at frequency $f =$ 45 GHz. The theoretical dependences shown in Fig. 2 are given using the RSJ model [8], which describes well the behavior of the Josephson junction in the high-frequency limit $f > f_0$. However, the experimental data in the figure demonstrate features that cannot be modeled within the RSJ model with regard to the ratio of frequencies f, f_0, and f_p and β_C (see, for example, [12]). So, Fig. 2a shows a feature on the interval $i_{UHF} =$ 2–3 and a sharp increase at $i_{UHF} = 2.5$; the feature on the interval $i_{UHF} = 0.5–0.75$ at the second Shapiro step I_2 (see Fig. 2c) is also interesting. An example of the emergence of a subharmonic step with $n = 1/2$ is pre-

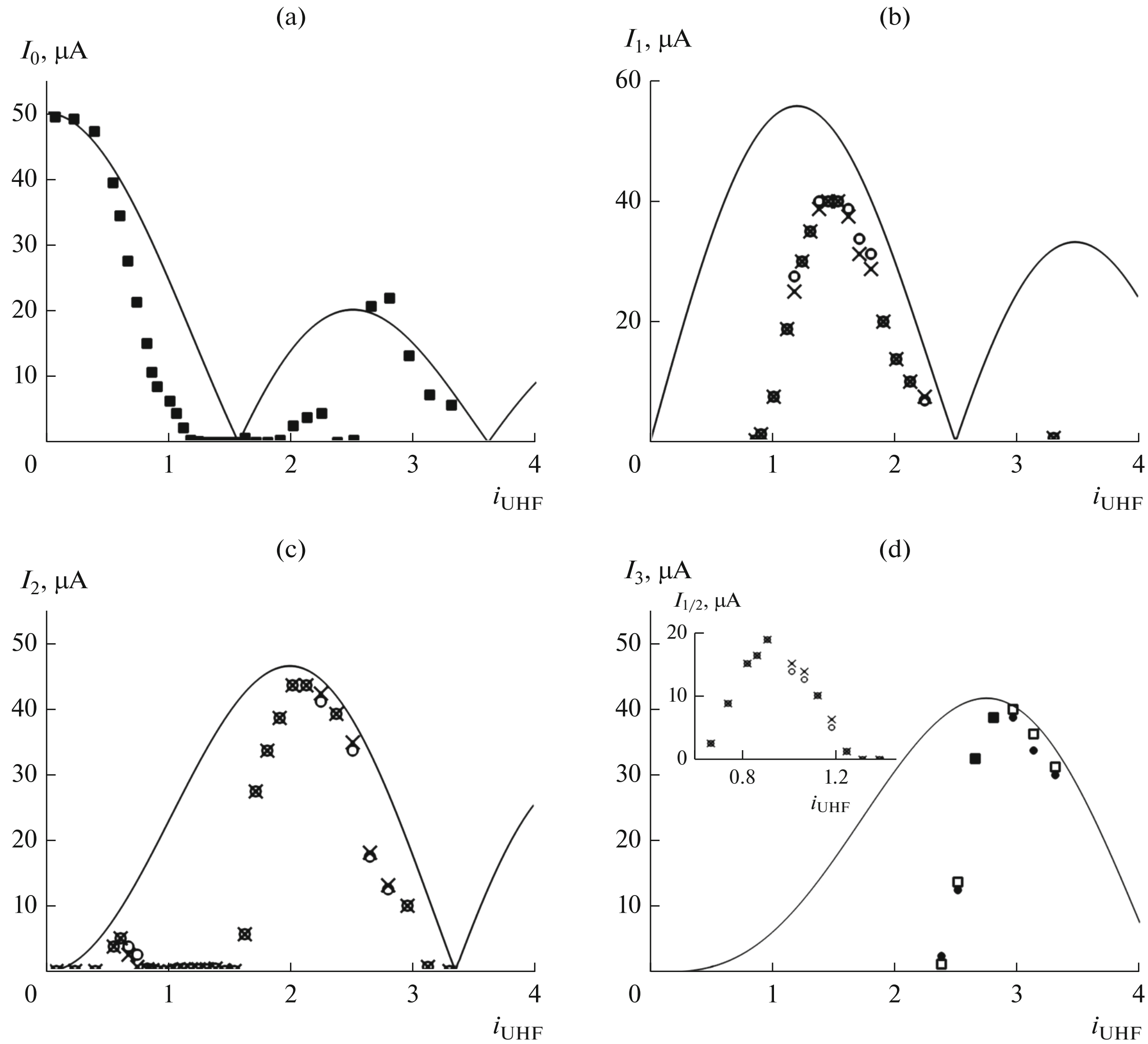

Fig. 2. Dependences of critical current amplitudes I_0 (a) and Shapiro steps I_1 (b), I_2 (c), and I_3 (d) on the normalized value of the microwave current at frequency $f = 45$ GHz. Crosses and circles are experimental data obtained at bipolar voltages; solid curves are theoretical dependences with an argument that serves as a fitting parameter. Inset to Fig. 2d shows the amplitudes of the subharmonic step $I_{1/2}$.

sented in the inset to Fig. 2d. From Fig. 2, it is also seen that, at certain intervals of i_{UHF}, Shapiro steps were absent, and then with increasing i_{UHF}, they started to appear again. The change in the amplitudes of the Shapiro steps at frequency $f = 70$ GHz occurred monotonically without discontinuities of the oscillation form (see Fig. 3) despite the instabilities in the CVC between the steps. Note that, at this frequency, the maxima of the amplitudes of the Shapiro steps increased, which follows from the RSJ model for $f/f_0 = 0.7$. With such a ratio of frequencies, chaotic oscillations are already possible, since the ratio f/f_p is already close to one [7, 13]. The emergence of chaos in structures with a magnetically active barrier was considered in [14]. Most likely, the stochastic behavior of the Josephson junction phase is influenced by both the proximity of the frequency of the external influence to the plasma frequency and the presence of magnetic correlations in the magnetically active $Ca_xSr_{1-x}CuO_2$ barrier.

Figure 4 shows the family of dependences P_{n} on bias current I arising on the heterostructure when exposed to microwave radiation at $f = 45$ GHz at various power values. Note that the onset of the noise signal corresponds to values i_{UHF} at which the fractional Shapiro step appear and the singularity on $I_2(i_{\mathrm{UHF}})$. With increasing microwave power P, current range I expands to cover wider intervals of i_{UHF}, but at the same time the maximum amplitude of P_{n} varies slightly (see dependences at attenuations of 23–19 dB

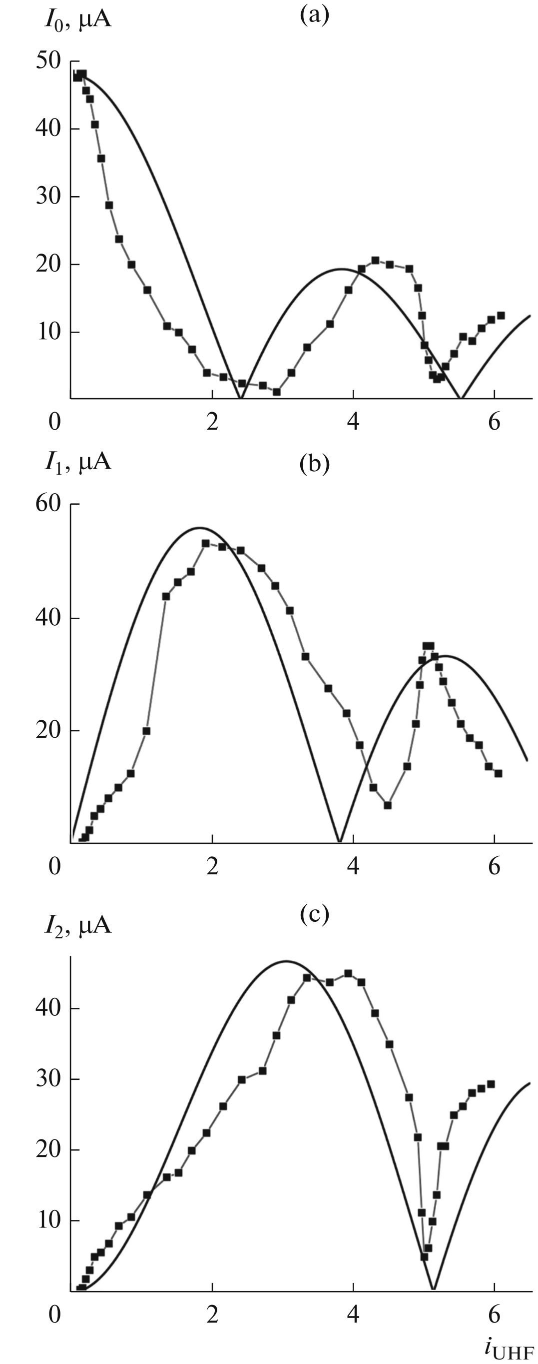

Fig. 3. Dependences of critical current amplitudes I_0 (a) and Shapiro steps I_1 (b) and I_2 (c) on the normalized value of the microwave current at frequency $f = 70$ GHz. Squares are experimental values, connected for clarity by a line; solid curves are theoretical dependences with the argument serving as a fitting parameter.

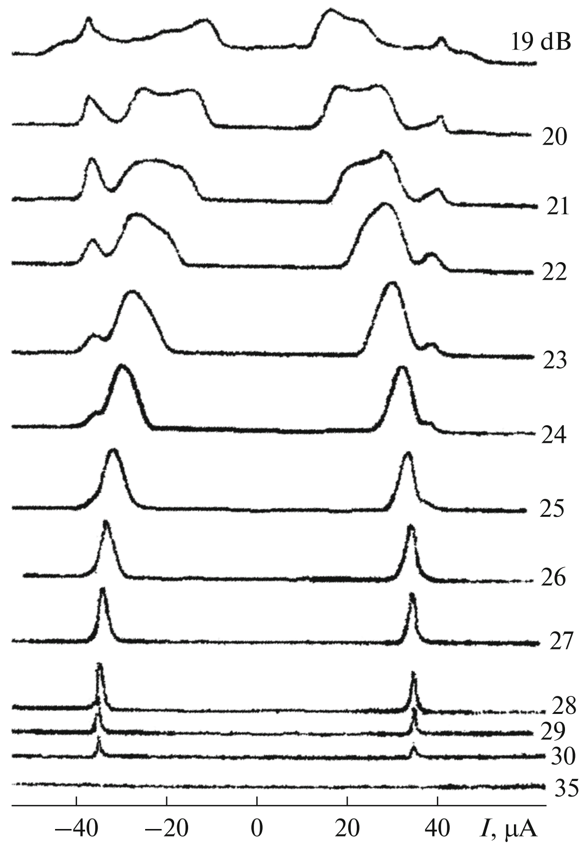

Fig. 4. Family of dependences of noise signal intensity on bias current I obtained by exposure to microwave radiation at $f = 45$ GHz for different attenuation values introduced by the attenuator. The noise signal was recorded by a HEMT amplifier in the frequency range from 1 to 2 GHz.

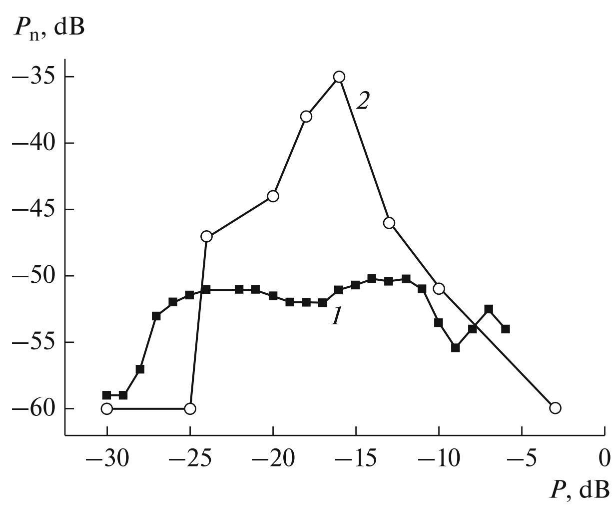

Fig. 5. Dependences of noise signal intensity P_n on relative change in microwave power P at frequencies $f = 45$ (curve *1*) and 70 GHz (curve *2*).

in Fig. 4). A more intense noise signal occurs at frequency $f = 70$ GHz, as can be seen from the data in Fig. 5, where the dependences of P_n on P are shown for both frequencies of the experiment.

CONCLUSIONS

In superconducting a $Nb/Au/Ca_{0.5}Sr_{0.5}CuO_2/YBa_2Cu_3O_{7-\delta}$ heterostructure with an antiferromagnetic barrier interlayer, the nonstationary Josephson effect is observed, which coexists with stochastic oscillations at frequencies of external influence close to the plasma. At a microwave frequency of about 0.6 of the plasma, distortions of the current–voltage characteristics are observed in the form of a negative dynamic resistance and an increase in noise on the structure. Unusual dynamics of such structures with a low effect of the junction intrinsic capacitance, characterized by the McCumber parameter $\beta_C = 2$, can be explained by the nontrivial phase dynamics caused by the magnetic properties of the barrier layer, enhanced by the plasma resonance of the Josephson junction.

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