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# Resonant Current Steps in Josephson Structures with a Layer from a Material with Strong Spin–Orbit Interaction

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**Abstract**—The microwave and magnetic parameters of Josephson Nb/Au/$Sr_2IrO_4$/$YBa_2Cu_3O_x$ mesastructures with a layer of $Sr_2IrO_4$, a material representing a Mott antiferromagnetic insulator with a high spin–orbit interaction energy $E_{SO}$ ~ 0.4 eV, were studied. Shapiro steps, oscillating with radiation power, appeared under monochromatic electromagnetic radiation confirm the Josephson properties of these structures. In the presence of a weak magnetic field $H < 15$ Oe, the voltage–current characteristics (VCCs) had resonant current steps at voltages $V_n$, which were inversely proportional to the size $L$ of structures in plane. Polarity reversal in the electrical current $I$ led to asymmetry in the arrangement of resonant current steps. At a specified magnetic field $H$, the voltage $V_n$ remained constant, and the amplitudes of resonant current steps nonmonotonically changed.

**Keywords:** mesa-heterostructure, spin–orbit interaction, strontium iridate, Fiske steps

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## 1. INTRODUCTION

In recent years, there has been an increased interest in superconducting structures with strong spin–orbit interaction (SOI), in particular, due to the possibility of the implementation of spin–triplet pairing [1, 2] and Josephson structures with time-reversal invariance breaking [3, 4] in them. The experimental observation of the Josephson effect in the Nb/Au/$Sr_2IrO_4$/$YBa_2Cu_3O_x$ mesastructures with a barrier layer of $Sr_2IrO_4$, a material representing a canted Mott antiferromagnetic insulator with a high SOI energy $E_{SO}$ ~ 0.4 eV and a weak ferromagnetism of ~0.04 $\mu_B$ per Ir atom was communicated in the paper [5]. A specific feature of these structures is the simultaneous coexistence of current superconductivity in mesastructures, a zero-bias conductivity peak (ZBCP), and an increase in conductivity at voltages $V > 5$–10 mV.

It is known that the influence of even a weak magnetic field leads to the appearance of resonant Fiske steps in the voltage—current characteristic of a SIS tunnel junction (S is superconducting electrodes, and I is a non-magnetic insulator) [7, 8] at voltages $V_n = n\Phi_0 c'/2L$, where $n$ is the number of a step, $\Phi_0$ is a magnetic flux quantum, $c' = c(t/\varepsilon\Lambda)^{1/2}$ is the Swihart velocity [9], $c$ is the light velocity in vacuum, $L$ is the junction width, $t$ is the thickness of an insulator layer in the transmitting line with a dielectric permittivity $\varepsilon$, and $\Lambda$ is the depth of magnetic field penetration into the layer and superconductors. In the case of a superconducting tunnel junction with an insulator characterized by magnetic properties, the penetration depth becomes as

$$\Lambda = \mu t + \lambda_{L1}\coth(d_1/2\lambda_{L1}) + \lambda_{L2}\coth(d_2/2\lambda_{L2}),$$

where $\mu$ is the magnetic permeability, and $d_i$ and $\lambda_{Li}$ ($i = 1, 2$) are the thicknesses of superconducting films and their London magnetic field penetration depths, respectively.

The effect of barrier layer magnetism on the dynamics of the propagation of electromagnetic waves in superconducting contacts was theoretically considered for SIFS- and SFIFS-structures [10] and $SI_FS$ [11], where F is a ferromagnet, and $I_F$ is a ferromagnetic insulator. However, no deviations predicted in the papers [10, 11] from the theory [7] were observed on SIFS structures in the experimental works [12, 13]. At the same time, the existence of strong spin–orbit interaction in the $I_{SO}$ layer may change the dynamics of the propagation of electromagnetic waves in a $SI_{SO}S$ structure. This paper communicates the experimental study of resonant current steps in $S_1I_{SO}S_2$ structures

$Nb/Au/Sr_2IrO_4/YBa_2Cu_3O_x$ with a barrier layer of $Sr_2IrO_4$, a material with a high SOI energy.

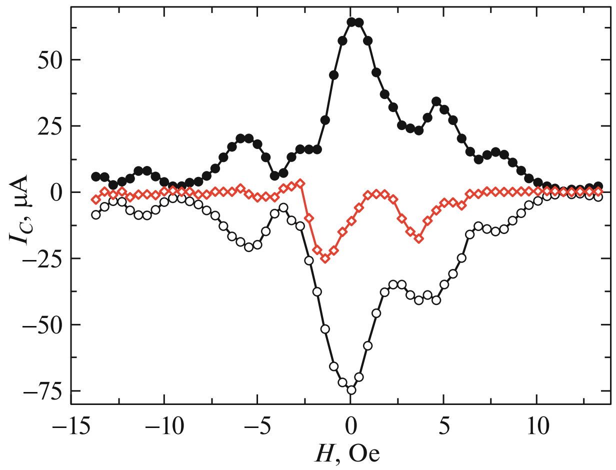

**Fig. 1.** Dependences $I_C(H)$ for the superconducting mesastructure with $L$ = 40 μm for positive (dark circles) and negative (light circles) polarities of the biasing current $I$ and magnetic dependence (rhombs) for the difference between critical currents with positive and negative biases.

## 2. RESULTS AND DISCUSSION

The technology used for the manufacturing of superconducting mesastructures (SMS) and the results of measuring their electrophysical parameters were communicated in the papers [6, 14, 15]. SMSs were manufactured of epitaxial $Sr_2IrO_4/YBa_2Cu_3O_x$ heterostructures with an $YBa_2Cu_3O_x$ film thickness of ~100 nm via the additional sputtering of Nb and Au films with a $SiO_2$ insulator. The topology of micrometer-sized mesastructures was formed by photolithography and ion-plasma and electron-beam etching. This paper discusses the results of the experimental study of $Nb/Au/Sr_2IrO_4/YBa_2Cu_3O_x$ superconducting mesastructures, whose $Sr_2IrO_4$ layer had a thickness $t$ = 5 nm, and the dimensions $L$ in plane were varied from 20 to 50 μm.

The magnetic field dependence of the critical current $I_C(H)$ for both polarities of the specified current $I$ through a superconducting mesastructure is plotted in Fig. 1. Let us note that the magnetic field was adjusted with a solenoid, the current through which was varied from $I_H = 0$ and further to a positive value of $I_H$ (field $H_+$) and backward to its negative value ($H_-$). In Fig. 1, the curves were measured at a field varied from $H_+$ = 13.2 Oe to $H_-$ = −13.7 Oe. The solenoid and the superconducting mesastructure were located inside a screen of multilayered amorphous permalloy, which decreased the Earth's field by nearly an order of magnitude. Small values of the critical current $I_C$ and the resonant steps $I_n$ smeared by fluctuations were determined by the method [6]. VCC families were recorded in the regime of current-biasing source in the order from $0 \to I_+ \to I_- \to 0$. Here, $I_+$ and $I_-$ are the ultimate values of measured currents with subscripts denoting their polarities. Similar notations, $I_{C+}$ and $I_{C-}$, were used for the critical currents of different polarity. It can be seen from Fig. 1 that the oscillating dependences $I_{C+}(H)$ and $I_{C-}(H)$ have zero minima within a range of $H$ from −15 to −7 Oe and at $H > 10$ Oe, thus evidencing the absence of pinholes. The first minimum calculated from the theoretical Fraunhofer dependence $I_C(H)$ gives a value close to experiment $H_1 = \Phi_0/\mu_0\Lambda L \approx 4$ Oe at $\lambda_{L1}$ = 150 nm for $YBa_2Cu_3O_x$ and $\lambda_{L2}$ = 90 nm for Nb, though the experimental dependence $I_C(H)$ at $H > 0$ appreciably differs from the Fraunhofer curve in shape. The distinction between $I_{C+}(H)$ and $I_{C-}(H)$ in both the magnetic field direction, $H > 0$ and $H < 0$, and the polarity of the measured current $I$ through a superconducting mesastructure is observed. The $I_{C+}(H)–I_{C-}(H)$ dependence observed within a narrow range of fields $H$ is also shown in Fig. 1. Let us note that the case of the "wide" junction $L > 4\lambda_J$, where $\lambda_J = (\Phi_0/\mu_0\Lambda j_C)^{1/2}$ is the Josephson magnetic field penetration depth ($j_C = I_C/L^2$ is the critical current density), does not explain the asymmetry and distinction of the critical currents $I_{C+}$ and $I_{C-}$, as $\lambda_J$ = 170 μm and, on the contrary, we have the opposite inequality $\lambda_J > 4L$.

The measurements of voltage–current characteristics and differential resistance dependences $R_D(V)$ were also performed under electromagnetic radiation at a frequency $f_e$ = 50 GHz and different radiation powers $P$ (see Fig. 2). It can be seen that an equidistant character of voltages $V_N = N\Phi_0 f_e$ at Shapiro steps takes place at a high precision for both polarities of the voltage $V$ as shown in the figure for $N$ = 1, 2, 3. At the same time, the amplitudes of Shapiro steps, as can be judged from the depth of $R_D$ minima normalized to $R_N$ are different for values of $V$ with opposite polarity. Such asymmetry may be due to the distinction between the spin-polarized components of current through a superconducting mesastructure and requires particular study. It is worth to pay attention to Shapiro steps and $I_C$ amplitudes, which oscillate with change of electromagnetic radiation power and also argue for the absence of pinholes. Figure 2 also illustrates the dependence $R_D(V)$ measured without microwave radiation (curve *a*). It can be seen that even weak radiation with a 30-dB decay of the power $P$ almost smoothens the resonant current features, and the Shapiro steps with a number to $N$ = 2 can be clearly detected.

The location of resonant current steps with respect to the voltage were determined from the minima of the differential resistance $R_D = dV/dI$ of a superconducting mesastructure under the magnetic field $H$. The dependence of the differential resistance $R_D$ on the voltage at a magnetic field $H$ = −1.3 Oe is shown in

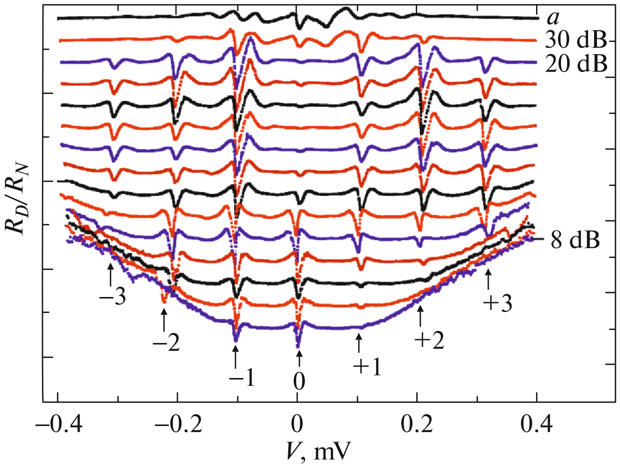

**Fig. 2.** Differential resistance $R_D$ normalized to $R_N$ versus voltage $V$ under electromagnetic radiation at $f$ = 50.09 GHz for the superconducting mesastructure with $L$ = 40 μm with a shift along the ordinate axis and an attenuator introduced decay in the radiation power $P$ from 30 dB and further from 20 to 8 dB with a step of 1 dB. Arrows point Shapiro step numbers N, 0 corresponds to the critical current. Curve *a* was measured without microwave radiation.

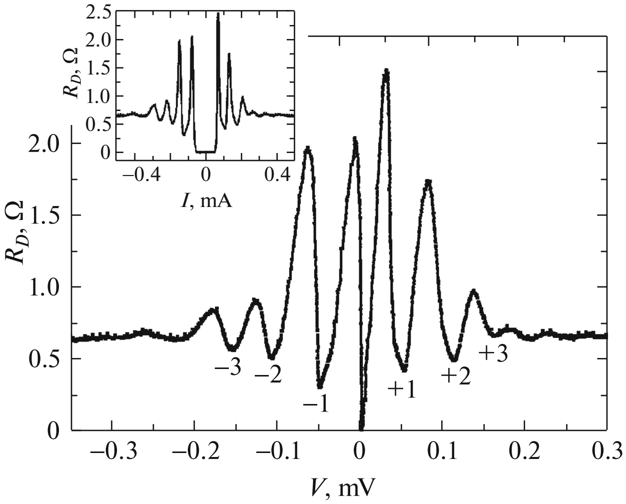

**Fig. 3.** Differential resistance $R_D$ versus voltage $V$ and current $I$ (inset) for the superconducting mesastructure with $L$ = 40 μm at a magnetic field intensity $H$ = –1.3 Oe for the case of 30% suppression of the critical current $I_C$ on the VCC branch measured at a negative bias ($V < 0$) at $T$ = 4.2 K. Numbers mark the numbers $n$ of $R_D$ minima.

Fig. 3. The numerical symbols in Fig. 3 are the numbers of $R_D$ minima. At this magnetic field value, the $R_D$ minima can be clearly seen up to $n = 3$. The corresponding SMS $R_D(I)$ dependence indicating the existence of critical current is shown in the inset to Fig. 3.

The voltages $V_n$ corresponding to the minima of $R_D$ for $n$ = 1–5 for the same superconducting mesastructure are shown in Fig. 4. It can be see that there is no equidistance for the positions of resonant steps with respect to the voltage. Moreover, there is asymmetry for the voltage $V$ of a superconducting mesastructure; thus, the voltages of singularities ($R_D$ minima) for $n = +1$ and $n = -1$ with different voltage polarities differ from each other by more than 10 μV. Let us point out that the error in the measurement of singularities is influenced by noises and does not exceed ±0.25 μV.

The values $V_nL/n$ with the numbers $n$ = 1 and 2 of resonant steps, whose Swihart velocities must be equal to each other due to constant $t/\varepsilon\Lambda$, are given for four SMS on the same substrate in the inset to Fig. 4. Such a dependence of $V_n$ on the width $L$ corresponds to the appearance of Fiske steps [7]. It can be seen that the deviation of the parameter $V_nL/n$ characterizing the velocity $c'$ from the average value for the superconducting mesastructures with $L$ = 30, 40, and 50 μm has proven to be nearly 5% and slightly higher for the superconducting mesastructure with $L$ = 20 μm. A small shift in the voltages of Fiske steps with high numbers $n$ was also observed in [13] and may be explained by the effect of the ambient medium with dielectric properties other than for the tunnel barrier material [16]. However, in our case, the deviation begins as soon as from $n = 1$. Taking into account high $\varepsilon \sim 45$ measured for single-crystal $Sr_2IrO_4$ [17], the influence of the dielectric $SiO_2$ environment may have an effect in our case only at $n \gg 1$.

The amplitudes of Fiske steps measured at a magnetic field $H < 0$ for $n = +1$ and $n = -1$ are given in

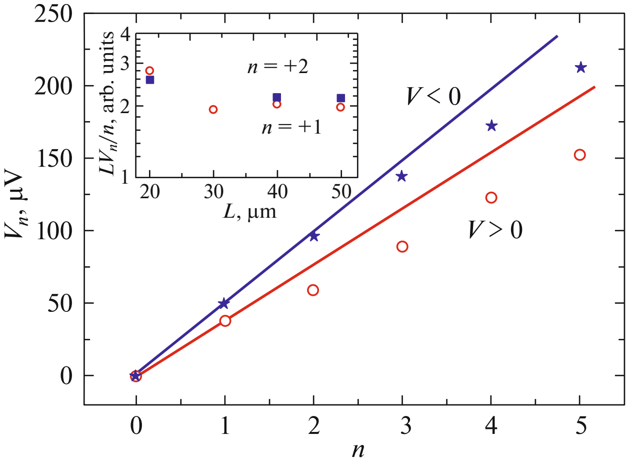

**Fig. 4.** Voltages of resonant steps $V_n$ on the superconducting mesastructure with $L$ = 40 μm at positive and negative bias voltages: linear dependences $V_n(n)$ (straight lines) corresponding to the equidistance of voltages $V_n$ with respect to $V_1$ for $n = +1$ ($V > 0$) and $n = -1$ ($V < 0$). Swihart velocity ($LV_n/n$) versus $L$ for four SMS on the same chip for $n = +1$ and $n = +2$ (inset).

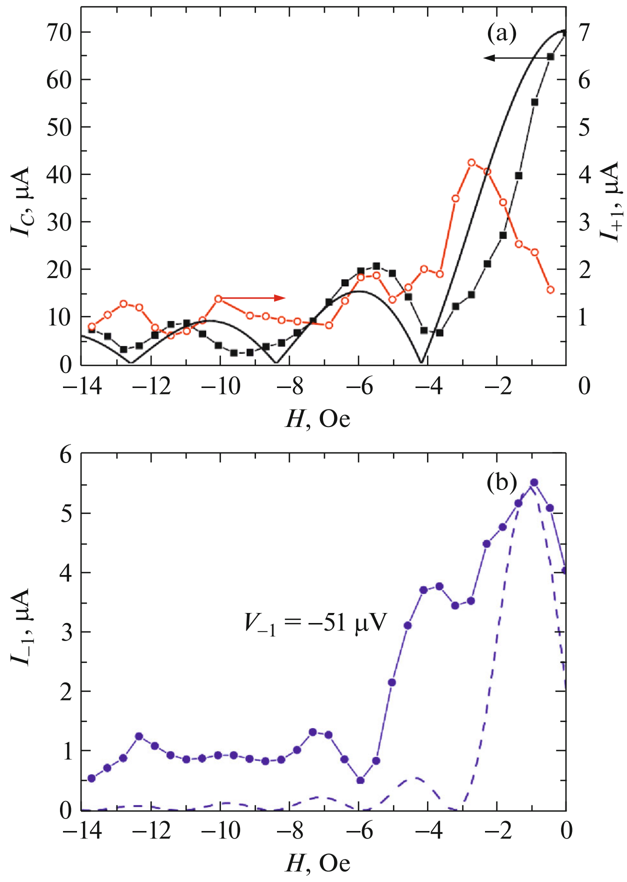

**Fig. 5.** (a) Average critical current $I_C = (I_{C+} + I_{C-})/2$ (squares) and amplitude of Fiske steps $I_{+1}(H)$ versus magnetic field for $n = +1$ at $V = +39$ μV with theoretical Fraunhofer curve $I_C(H)$ (solid line); (b) amplitude of Fiske steps $I_{-1}(H)$ versus magnetic field for $n = -1$ at $V = -51$ μV with theoretical curve $I_{-1}(H)$ (dashed line). Maximum theoretical $I_C$ and $I_{-1}$ are put together with their experimental values.

Fig. 5, where the shape of $I_C(H)$ is closer to the theoretical Fraunhofer dependence shown in Fig. 5a. The fitting parameters used for the Fraunhofer dependence were the first two minima of $I_C(H)$ and the average amplitude $(I_{C+} + I_{C-})/2$. The existence of steps can be seen even at $H = 0$, most likely, due to superconducting current asymmetry $I_{C+} \neq I_{C-}$ (see Fig. 1). The theoretical magnetic field–amplitude dependence [8] for the Fiske step $I_{-1}$ with $n = -1$ at a voltage of $V_{-1}$ is shown in Fig. 5b. The used parameters of fitting with respect to the field $H$ for the theoretical function $I_{-1}(H)$ were the magnetic fields of the first two maxima $I_{-1}(H)$ with a shift in $H$ at 1 Oe (or $\Phi_0/6$), which also leads to the shift of zero for $I_1(H)$ at $H = 0$ in comparison with the theory [8]. Let us also pay attention to an oscillating character of the magnetic field dependences of $I_{+1}$ and $I_{-1}$ and relatively high amplitudes of secondary maxima in comparison with their theoretical values. All the detected resonant current Fiske steps with rather well identifiable numbers $n$ are shown in Fig. 6. It can also be seen that the positions of Fiske steps with respect to the voltage $V_n$ are resistant to the change in the magnetic field. The deviation from equidistance and the difference between $V_n$ switching the sign of $n$ may be due to the effect of fluctuations in the local magnetization of the antiferromagnetic layer with strong spin–orbit interaction on the spectrum of Josephson plasma waves. The anomalous Josephson effect with a phase shift at $\varphi_0$ requires the implementation of conditions, e.g., with the splitting of spin bands and the existence of spin–orbit interaction [18, 19]. In our experiment, the applied magnetic field has a level, which is much lower than Zeeman splitting, but the SMS characteristics may be appreciably influenced by magnon-plasmon wave interaction, which was theoretically considered for the ferromagnetic case [10, 11]. However, the question of interaction between plasma and spin waves in an antiferromagnet with strong spin–orbit interaction still remains open.

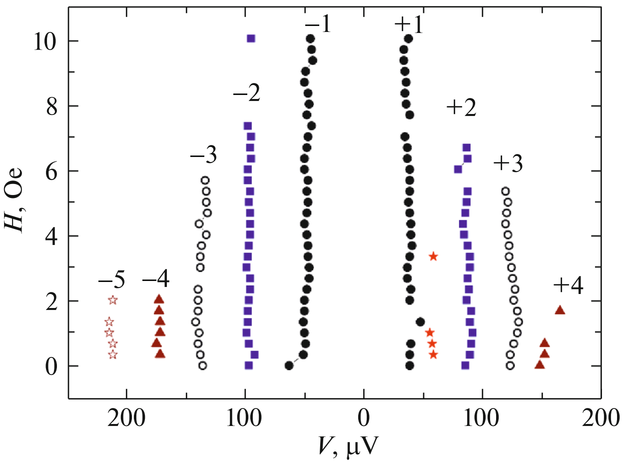

**Fig. 6.** Fiske steps in the $H$–$V$ plane with their numbers $n$.

## 3. CONCLUSIONS

In superconducting Nb/Au/$Sr_2IrO_4$/$YBa_2Cu_3O_x$ mesastructures with a $Sr_2IrO_4$ layer, which had a thickness of 5 nm and was epitaxially grown on a $YBa_2Cu_3O_x$ film, resonant current steps and the Josephson effect were observed. Unequal amplitudes of the critical current $I_{C+} \neq I_{C-}$ took place after switching the polarity of electrical current through a structure. Electromagnetic radiation of millimeter wavelength range induces the appearance of Shapiro steps oscillating with radiation power, thus arguing for both the absence of pinholes and the existence of zero minima in the dependence $I_C(H)$. The deviation of Fiske steps oscillation with a field $H$ from equidistance and asymmetry in the dependence $I_C(H)$ are most likely produced by the effect of strong spin–orbit interaction in the $Sr_2IrO_4$ barrier layer material, which is known as an antiferromagnetic insulator with high dielectric permittivity.

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## CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interests.

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