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Influence of external microwave radiation on transport characteristics of superconducting MoRe–Si(W)–MoRe junctions

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Specific response of superconducting devices to electromagnetic radiation is a core phenomenon for various applications, ranging from the voltage standard to single photon detectors. One of such effects is the stimulation of the superconductivity itself by microwaves. In the work, we have investigated the impact of external microwave irradiation on the stair-step current-voltage characteristics of MoRe–Si(W)–MoRe Josephson junctions arisen due to phase-slip events in the studied samples. At frequencies above a threshold value, we have observed the stimulation effect that can be explained by a non-equilibrium redistribution of filled energy levels in W clusters. In conclusion, we discuss the main tasks for future research.

Keywords: Josephson hybrid junctions, one-dimensional transport, phase-slip events, microwave radiation.

1. Introduction

Microwave-stimulated superconductivity was discovered more than fifty years ago first in superconducting (S) bridges [1] and later in films [2, 3], tunnel junctions [4] and cylinders [5]. Recently, this effect was shown to improve a quality factor of superconducting Al resonators [6]. The counterintuitive stimulation phenomenon was explained in the paper by Eliashberg [7] as an impact of the irradiation-induced redistribution of quasiparticles energies up from the gap edge. In our work, we have studied an effect of external microwaves on the stair-step current-voltage *I* vs *V* characteristics of MoRe–Si(W)–MoRe Josephson junctions whose origin was related to phase-slip events in the studied samples.

The quantum phase-slip phenomenon is arising in current-biased quasi-one-dimensional (1D) and quasi-two-dimensional (2D) superconducting samples due to quantum fluctuations of the order parameter. This effect can be understood as a dynamic equivalent of the charge tunneling through a conventional Josephson junction with weak links, static in space and time [8]. The paper [9] provides a detailed overview of experimental and theoretical papers devoted to the study of the impact of an external microwave field on superconducting channels (thin films, whiskers, etc.) where an initial homogeneous S state becomes unstable. The transition to a spatially inhomogeneous state is following by the emergence of inclined current steps in *I*–*V* curves for such samples.

It would be interesting to study how the effect of the microwave irradiation reveals itself in the current-voltage characteristics of Josephson junctions where S electrodes are linked with 1D nanoscale wires where superconductivity can be induced by the superconducting proximity effect. In general, Josephson junctions are unique physical objects that allow probing quantum phase coherence and studying dissipation-driven quantum phase transitions [10]. The presence of phase-slip centers in 1D wires connecting two superconducting electrodes would generate stepped structure in the dissipative part of the *I*(*V*) characteristic for a Josephson junction and our aim was to observe experimentally an influence of microwave irradiation on the structure.

Earlier [11, 12], we fabricated and investigated properties of appropriate MoRe–Si(W)–MoRe heterostructures with hybrid barriers formed by a Si semiconductor layer with W metal nanoclusters. In this paper, we present our novel results for such devices with 1D metallic W conductors, which are subjected to an external microwave irradiation, with an emphasis on the effect of the electromagnetic stimulation of a superconducting critical current I_c that results in the appearance of specific steps in its dependence on the microwave power levels.

2. Experimental technique and results

The fabrication of MoRe–Si(W)–MoRe heterostructures with hybrid barriers was implemented using the vacuum equipment based on two vacuum universal posts VUP-5M produced by SELMI, the former Sumy Electron Microscopes Plant, Sumy. For the deposition of MoRe films by the magnetron method, we used a molybdenum-rhenium target made from a 0.5 mm thick foil with a 48 % Re–52 % Mo composition. The deposition of a silicon layer with tungsten nanoclusters was realized by making a complex target consisting of a single-crystal silicon wafer and tungsten wires located on it; the details can be found in our papers [11, 12].

The films were deposited through shadow masks. The junction topology is shown in Fig. 1. The bottom MoRe layer was formed as a 0.3 mm wide track (1). After that, a thick layer of an isolating Al oxide (2) was deposited on the MoRe layer along the edge of the track, its aim was to prevent the current flow through the film ends (1). Next, a tungsten-doped silicon layer (3) was deposited. The last one was the top MoRe layer (4), a 0.2 mm wide track by 0.1 mm over the silicon layer. The formation of W nanoclusters with a size of about 15×50×50 nm were formed inside a silicon layer that had a thickness of about 15 nm. Their large size distribution was confirmed by studying a model Si(W) layer of a greater thickness with an electron transmission microscope [11] and a Si(W) layer with an atomic force microscope [12]. A more advanced technology for creating submicron-sized MoRe–doped Si–MoRe Josephson junctions with a low specific capacitance is described in our papers [13, 14].

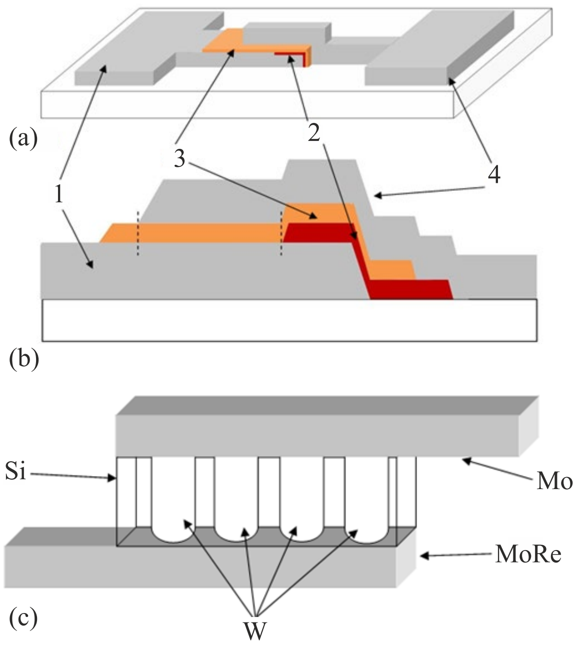

Fig. 1. Topology of the in-plane MoRe–Si(W)–MoRe film heterostructures consisting of MoRe films (1 and 4), an insulating Al_2O_3 layer (2), and a hybrid Si(W) barrier (3). The panel (b) shows the device cross-section, the panel (c) demonstrates the junction schematically.

In this work, we present our measurements of the junction current-voltage characteristics at the liquid-helium boiling point $T = 4.2$ K in two regimes, without and under the influence of an external microwave electromagnetic irradiation. A sample holder with a Josephson junction on a dielectric substrate was placed in a cryostat in a direct contact with liquid helium. The Josephson junction was coupled to microwave cables using lead antennas, resulting in two symmetrical capacitive couplings. Therefore, the studied Josephson junction was connected to a microwave radiation source in the voltage source mode. The microwave radiation power was varied by changing the value of the microwave generator voltage V_G. Then the power of the microwave signal entering the heterostructure was estimated proportional to V_G^2 and normalized to the maximum value $V_{G,\max}^2$. The obtained values $P_i = V_{G,i}^2 / V_{G,\max}^2$ for the generator frequency 11 GHz can be found in the caption to Fig. 2(a) and 2(b).

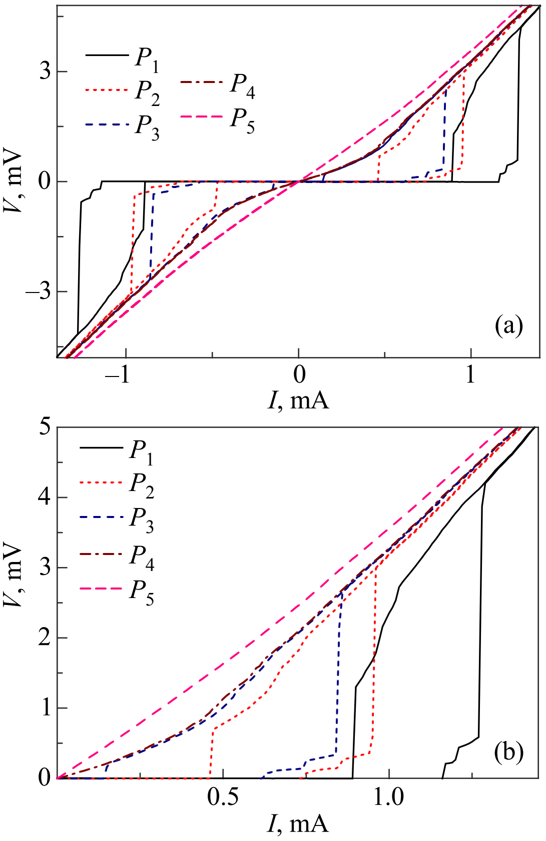

Fig. 2. General (a) and detailed (b) views of $I - V$ characteristics of the MoRe–Si(W)–MoRe heterostructure with an W content of ~ 9 at. % and a barrier thickness of 15 nm. The samples were exposed to the microwave irradiation of the 11 GHz frequency at the relative power levels $P_i = V_{G,i}^2 / V_{G,\max}^2$: $P_1 = 0.01$, $P_2 = 0.36$, $P_3 = 0.46$, $P_4 = 0.49$, and $P_5 = 1.0$. I–V curves with indices 1, 2, and 3 were hysteretic.

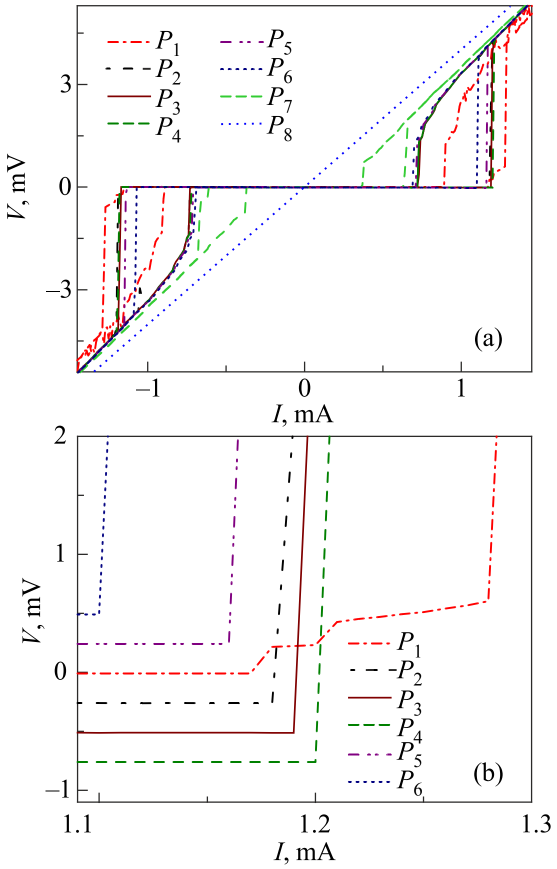

Fig. 3. General (a) and detailed (b) views of *I–V* characteristics of the MoRe–Si(W)–MoRe heterostructure with an W content of ~ 9 at. % and a barrier thickness of 15 nm. The samples were exposed to the microwave irradiation of the 18 GHz frequency at the relative power levels $P_i = V_{G,i}^2 / V_{G,\max}^2$: $P_1 = 1.6 \cdot 10^{-6}$, $P_2 = 4.0 \cdot 10^{-4}$, $P_3 = 5.6 \cdot 10^{-4}$, $P_4 = 5.0 \cdot 10^{-3}$, $P_5 = 2.6 \cdot 10^{-2}$, $P_6 = 7.4 \cdot 10^{-2}$, $P_7 = 0.19$, and $P_8 = 1.0$. *I–V* curves with indices 1–7 were hysteretic. The curves in the part (b) were shifted along the vertical axis.

The dc current-voltage characteristics of the MoRe–Si(W)–MoRe Josephson junctions were recorded in the current source mode. The measured *I–V* curves in the presence of the external 11 GHz microwave irradiation at various power levels P_i are shown in Fig. 2.

Figure 3 exhibits *I–V* curves for the Josephson MoRe–Si(W)–MoRe junctions in the presence of an external microwave irradiation with a frequency of 18 GHz, the irradiation power levels are indicated in the caption to Fig. 3.

Figure 4 shows general (a) and detailed (b) traces of the normalized critical current exhibiting phase-slip centers in the studied junctions versus the normalized voltage of the microwave generator: squares and circles correspond to the irradiation frequencies of 18 and 11 GHz, respectively.

It can be seen that the behavior of the studied junctions differs significantly, namely, at the frequency of 18 GHz the experimental I_c/I_{c0} vs $V_{G,i}^2 / V_{G,\max}^2$ dependence exhibits maximum that is not observed in the related curve measured at 11 GHz.

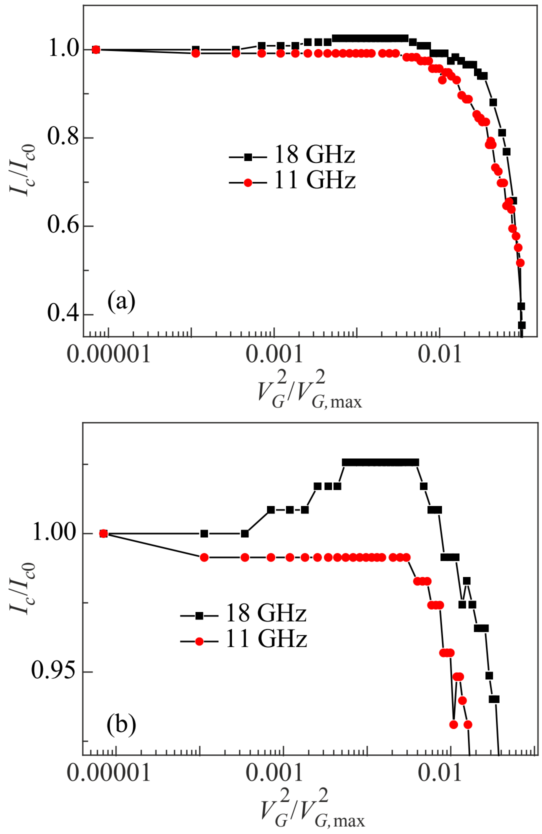

Fig. 4. General (a) and detailed (b) traces of the normalized value of the critical current exhibiting phase-slip centers in the studied junctions versus the normalized voltage of the microwave generator; squares and circles correspond to the irradiation frequencies of 18 and 11 GHz, respectively.

3. Discussion

Typical W cluster sizes ~ 15×50×50 nm are less than the coherence length $\xi \geq 100$ nm in the MoRe alloy and beyond the London penetration depth [15]. It means a uniform distribution of the charge current density and the order parameter over the cluster cross-section. Hence, the clusters are quasi-one-dimensional structures (channels), the formation of magnetic flux vortices in them and, hence, their effect on the cluster resistivity are impossible. The paper [16] provides a detailed review of experimental and theoretical papers devoted to the study of the behavior of superconducting channels (thin films, whiskers, etc.) under an external microwave electromagnetic field. It was noted that tilted current steps arise in the *I–V* curves of superconducting channels, with an increase in the microwave radiation power, due to the appearance of phase-slip centers in the channels. With an increase in the power of the high-frequency field, the channel resistances R_i (i = 1, 2, 3 ...), determined from the slope of the corresponding initial sections of the *I–V* characteristic, changes discretely. We do observe such behavior in our case (see Figs. 2 and 3).

As is known, the superconductivity stimulation by an electromagnetic field is possible when its frequency is lower than $2\Delta/\hbar$, where Δ is the energy gap of a superconductor and higher than τ^{-1}, where τ is the relaxation time of inelastic collisions. Then the distribution function $n(\varepsilon)$ of electrons is shifted towards higher energies, which leads to a stationary non-equilibrium state and an increase in the energy gap as well as other superconducting characteristics. The change in $n(\varepsilon)$ will be proportional to the field intensity E^2 (for not too large fields) and the relaxation time of excitations. Using an expression for the lower frequency boundary of the stimulating effect [16], we find that for $\ln(8\Delta/\hbar\omega) > 1$

$$\omega_L^2 = \frac{2\pi\gamma\Delta}{\hbar \ln\left(\frac{8\Delta}{\hbar\omega}\right)} = \frac{2\pi\Delta}{\hbar\tau_\varepsilon \ln\left(\frac{8\Delta}{\hbar\omega}\right)}. \qquad (1)$$

To estimate this value, we choose the inelastic relaxation time $\tau_\varepsilon \approx \tau$, the characteristics time found in the experiments relating phase-slip centers in superconductors [16]. For the helium temperature $T \approx 4.2$ K we have $\tau_\varepsilon \approx 10^{-9}$ s. After some calculations, we get $\omega_L \simeq 39$ GHz that agrees in order of magnitude with our data. Therefore, within the framework of this model, the change in the considered MoRe–Si(W)–MoRe heterostructures is adequately explained at low microwave powers. Indeed, at the irradiation frequency of 11 GHz, the observed dependence $I_m(P)$ is nearly constant while, with increasing frequency to 18 GHz, it is replaced by the $I_m(P)$ dependence with a maximum (Fig. 4), i.e., the stimulating effect arises under the external microwave irradiation.

4. Conclusions

In this work, we have found the emergence of tilted current steps in current-voltage characteristics of MoRe–Si(W)–MoRe junctions with increasing the power level of the applied external microwave radiation. We have interpreted them as the manifestation of phase-slip centers in the junctions under study. The estimates performed using related Eliashberg theoretical model indicate a non-equilibrium occupation of energy levels in W clusters resulting in the superconductivity stimulation effect. The experimental I_m/I_{m0} vs $V_{G,i}^2/V_{G,\max}^2$ dependence of the normalized critical current on the radiation power level was nearly constant at 11 GHz and exhibited a maximum at 18 GHz. Generally, our results well agree with the Eliashberg theory and demonstrate the stimulating effect in the Josephson junctions with 1D weak links in the Si(W) barrier.

Future research should clarify the following issues: (i) an effect of the noise factors on superconductivity stimulation [17], (ii) the role of inelastic scatterings in a complex barrier [18], (iii) possible influence of the minigap induced in W nanoscale grains [19], and (iv) an impact of the Fermi surface anisotropy in superconducting electrodes [20].

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Вплив зовнішнього мікрохвильового випромінювання на транспортні характеристики надпровідних переходів MoRe–Si(W)–MoRe

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Специфічний відгук надпровідних пристроїв на електромагнітне випромінювання є основою різних застосувань, починаючи від стандарту напруги та закінчуючи одиночними фотонними детекторами. Одним із таких ефектів є стимуляція самої надпровідності мікрохвилями. Досліджено вплив зовнішнього мікрохвильового опромінення на східчастому відрізку вольт-амперної характеристики джозефсонівських переходів MoRe–Si(W)–MoRe, які виникають внаслідок ефекту фазового проковзування в досліджуваних зразках. На частотах вище порогового значення спостережено ефект стимуляції, який можна пояснити нерівноважним перерозподілом заповнених енергетичних рівнів в кластерах W. Обговорено основні завдання майбутніх досліджень.

Ключові слова: гібридні переходи Джозефсона, одновимірний транспорт, фазове проковзування, мікрохвильове випромінювання.