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Volodymyr Shaternik, Olexandr Suvorov, Andrii Shapovalov, Pascal Febvre. Charge Transport in Superconducting Heterostructures MoRe-Si(W)-MoRe with a Hybrid Semiconducting Barrier with Metallic Nanoclusters. 16th International Superconductive Electronics Conference (ISEC 2017), Jun 2017, Sorrento, Italy. <hal-02074877>

**HAL Id: hal-02074877**

**<https://hal.science/hal-02074877v1>**

Submitted on 20 Jan 2025

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# Charge Transport in Superconducting Heterostructures MoRe-Si(W)-MoRe with a Hybrid Semiconducting Barrier with Metallic Nanoclusters

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**Abstract**—Thin-film MoRe-Si(W)-MoRe heterostructures consisting of superconducting electrodes made of a molybdenum-rhenium alloy and of a hybrid semiconductor tunneling barrier of nanoscale silicon layer with nanoclusters of tungsten have been fabricated and studied. Current-voltage characteristics of the junctions have been measured for a wide voltage range of -900 to 900 mV and at temperatures ranging from 4.2 to 8 K, under the influence of magnetic fields and microwave irradiation. These characteristics showed the feasibility of the Coulomb blockade regime, resonant tunneling and resonant-percolation transport mechanism (supercurrent regime) depending on the tungsten content in the hybrid barrier and the applied bias voltage. The evidence of a quasi-one-dimensional transport in the heterostructures was revealed in the measurements of the critical current-versus-magnetic field dependences. Similarity of the charge transport features for hybrid barriers with metallic nanoclusters and those for microbridges of high- $T_c$  superconductors films proves that the studied hybrid structures could serve as a model system to clarify the nature of high- $T_c$  phenomena.

**Keywords**— tunneling, Josephson junctions, hybrid barrier, current-voltage characteristics, one-dimensional charge transport, quantum dot

## I. INTRODUCTION

Until recently, the idea [1] to use the conventional Josephson junctions as the basic elements for a superconducting quantum computer faced, as it seemed, difficult technical obstacle – the problem of small decoherence time of qubits. The idea [2] to use a one-dimensional charge transport in the quantum qubits (topologically protected from influence on these qubits of environment or electromagnetic irradiation) has initiated a large number of studies (see review [3]) of the

experimental realization of this idea in a hybrid structure such as superconductor-gated semiconductor nanowire-superconductor (a developed Josephson junction). As a result of this activity the qubit with the highest decoherence time, close to one minute, has been created in [4].

In [5]-[7] we have experimentally investigated thin-films hybrid superconductor-semiconductor (doped by metal)-superconductor (MoRe-Si(W)-MoRe) heterostructures. At low tungsten content in Si(W) barriers, these heterostructures demonstrate current-voltage characteristics (CVCs) with unusual characteristic shape [5], a single or several current peaks caused by electron tunneling through the allowed states in the barrier have been observed in such CVCs at bias voltages from 40 mV up to 300 mV. These singularities appear as a result of interaction between a charge localized within the barrier level and the electron cloud in one of the electrodes. Their amplitude becomes large if one uses superconducting electrodes as a result of the existence of well known BCS-singularity in the density of states of superconductors. After increasing the tungsten content in the Si(W) barriers up to 9-10 atomic percent (at%) one can see that the Josephson supercurrent flows in the investigated heterostructures, and we observed resonant current steps appearance in their CVC's measured under an external microwave irradiation [6]. The analysis of TEM data [7] suggests that a quasi-periodical two-dimensional grid of tungsten clusters is formed during the joint magnetron deposition of silicon and tungsten, due to self-organization effect in the silicon film. The clusters are 10-50 nm in diameter and located at a distance of 0.5-1  $\mu\text{m}$  from each other, and sustain charge transport. The presence of quasi-one-dimensional tunnel transport in the layered structures leads to

an unusual temperature dependence of their conductivity and magnetic field dependence  $I_c(H)$  with parallel magnetic fields. These dependencies are mainly similar to the corresponding ones for layered high-temperature superconductors, in which superconductivity arises in the copper-oxygen planes, and the electronic tunnel transport occurs in a direction perpendicular to the layers, i.e. it is also quasi-one-dimensional [8]. This article is devoted to the investigation of the features of charge transport in such heterostructures.

## II. EXPERIMENTAL RESULTS

In this work, thin film MoRe–Si(W)–MoRe heterostructures were fabricated and investigated. To fabricate MoRe films the magnetron sputtering of the MoRe target was carried out, followed by the deposition of films on the dielectric substrates. The Si(W) films are created by doing the magnetron sputtering of a composite target made of a silicon wafer on which a number of tungsten wires are put. It is followed by the deposition of the films on the lower MoRe film. The schematic view of six simultaneously fabricated junctions is given in Fig. 1.

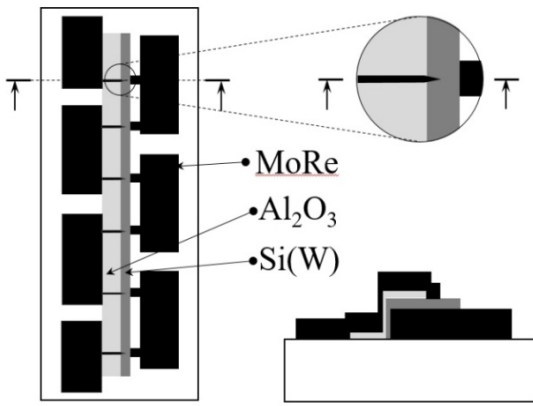


Fig. 1. Schematic view of six fabricated MoRe–Si(W)–MoRe heterostructures.

When the tungsten content in Si(W) barriers reaches  $n_w \sim 8-10$  at%, the CVCs of the MoRe–Si(W)–MoRe heterostructures demonstrate: 1) vertical current steps at  $V = 0$ , that is the Josephson supercurrent; 2) a large excess current  $I_{exc.}$  (see Fig. 2), which is defined as the upward and downward shift along the current axis of the linear region of the CVCs with respect to the CVCs in the normal state when the heterostructure has a resistance  $R_N$ . These MoRe–Si(W)–MoRe heterostructures are Josephson junctions with increased values of the characteristic voltage  $I_c R_N$ . With  $n_w \sim 4-5$  at% they demonstrate CVCs of a special type, as shown in Fig. 3. These  $I-V$  curves are characterized by the absence of current through the heterostructure until a certain threshold voltage is reached. Then a resonant current peak appears in the heterostructure CVC above the threshold voltage at  $V_{peak}$ . Fig. 4 shows given  $I_c$  dependencies on the magnetic field  $I_c(H)$  of the MoRe–Si(W)–MoRe heterostructures fabricated

with a relatively high content of tungsten  $n_w \sim 9-11$  at% in the Si(W) barriers.

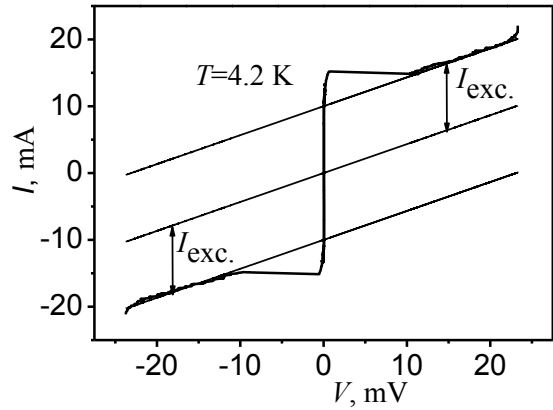


Fig. 2. Typical CVCs of the MoRe–Si(W)–MoRe heterostructures with a tungsten content in Si(W) barriers of  $n_w \sim 8-10$  at%,  $R_N = dV/dI_{20mV} = 2.32$  Ohms;  $I_c = 11$  mA;  $I_c R_N = 25.5$  mV.

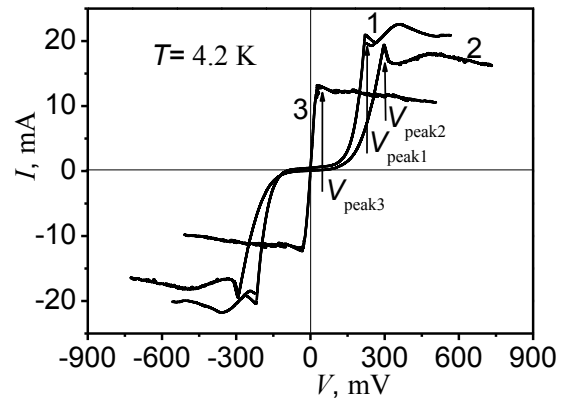


Fig. 3. Typical CVCs of the MoRe–Si(W)–MoRe heterostructures. Curve 1:  $n_w \sim 4$  at%,  $V_{peak1} = 180$  meV; curve 2:  $n_w \sim 4$  at%,  $V_{peak2} = 240$  meV; curve 3:  $n_w \sim 6-7$  at%,  $V_{peak3} = 12$  meV.

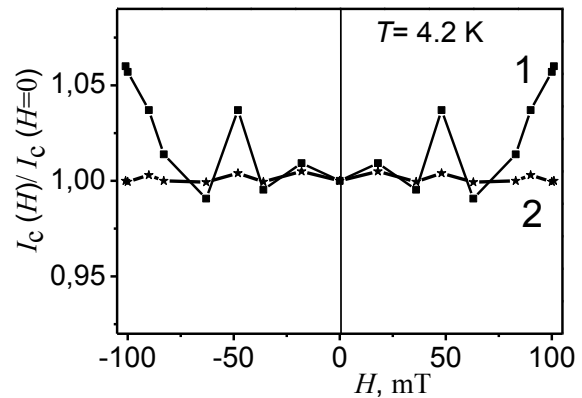


Fig. 4.  $I_c$  dependencies on the magnetic field  $I_c(H)$  of the MoRe–Si(W)–MoRe heterostructures. Curve 1:  $n_w \approx 9$  at%; curve 2:  $n_w \approx 11$  at%.

## III. DISCUSSION AND CONCLUSION

The presence of large excess currents  $I_{exc.}$  in the heterostructures CVC's (see Fig. 2) indicates that intense

Andreev reflections of electrons (holes) appear at the interfaces of the heterostructures. As the BTK model shows [9], it means the barrier transparency  $D$  at the interfaces is close to unity ( $0.5 < D < 1$ ), otherwise the Andreev reflections (and correspondingly,  $I_{\text{exc}}$ ) would not be observed. Significant influence of Andreev reflections on the CVC shape is confirmed as well by the disappearance of the observed peak (see Fig. 3) when the MoRe films become normal at  $T > T_c$ . In the model for superconducting asymmetric double-barrier junctions (based on niobium nitride) [10], [11], authors show that even if Andreev reflections are realized only in one interface of the junctions the current resonant peak occurs nevertheless in the junction CVC at bias voltage  $eV \approx (\Delta_1 + \Delta_2)$ . As it is mentioned in [10], [11] this peak is caused by the Andreev bound state appearance in this asymmetric double-barrier junction. Also, in our case, the silicon Si interlayer between W and MoRe, that contains charge layers, can change the bias voltage of this resonance peak in the CVCs.

We think that the necessary condition for inducing tunneling through a quantum dot (W cluster) for the current flow is the match of the Fermi level in one of the MoRe superconductors with a certain energy level in the quantum dot [5], [12]. In a metal cluster W (at the quantum dot), there are discrete energy levels  $E_1, E_2, \dots, E_n$ . Suppose that the voltage applied to the heterostructure is changed from  $V_a$  to  $V_b$  where  $E_{k-1} < eV_a < E_k$  and  $E_k < eV_b < E_{k+1}$ ,  $1 < k < n$  is an integer. Accordingly, the increment of current through the heterostructure for a voltage shift from  $V_a$  to  $V_b$  equals  $\Delta I \equiv (4e^2/\hbar)\Gamma_R$ , i.e. determined by the magnitude of the smearing  $\Gamma_R$  of this energy level  $E_n$  [13], as a result of the involvement of one more discrete allowed energy level  $E_n$ .

The differential resistance  $R_N \approx dV/dI$  of the heterostructure is:

$$R_N = \frac{dV}{dI} \propto \frac{V_2 - V_1}{\Delta I} \propto \frac{\hbar(E_2 - E_1)}{4e^2\Gamma_R} \quad (1)$$

It is known [14] that, for a weak signal, the supercurrent  $I_c$  is connected to the Josephson inductance  $L_{J0}$  that depends on the tunneling process within the junction:

$$I_c = \frac{\hbar}{2eL_{J0}} \quad (2)$$

Hence

$$I_c R_N \propto \frac{\hbar^2(E_2 - E_1)}{8e^3\Gamma_R L_{J0}} \quad (3)$$

One can see that the  $I_c R_N$  value becomes dependent on the size, shape, and orientation in the space of the clusters through which charges are transported. The proposed expression (3) is only an estimate. The problem itself requires a more detailed and thorough study.

The obtained  $I_c(H)$  dependence (see Fig. 4) in the form of a plateau with a small modulation is similar to the one for a Josephson junction with a slightly transparent barrier with several point contacts [14]. This also indicates a quasi-one-dimensional nature of charge transport in the investigated heterostructures.

To summarize, we have fabricated and investigated novel hybrid devices based on superconductor-semiconductor barrier (with a metal quantum dot)-superconductor heterostructures with characteristics similar to those of quasi-one-dimensional devices. We propose that the  $I_c R_N$  value of the fabricated heterostructures becomes dependent on the size, shape, and orientation in the space of the clusters through which charges are transported. The obtained  $I_c(H)$  dependence in the form of a plateau with a small modulation indicates a quasi-one-dimensional nature of charge transport in the investigated heterostructures.

#### ACKNOWLEDGMENT

The authors would like to thank M. Belogolovskii for valuable discussion and useful comments. The work is partly supported by the French-Ukrainian Partenariat Hubert Curien (PHC) DNIPRO No. 37984RL.

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