JOSEPHSON JUNCTIONS WITH SEMICONDUCTOR BARRIERS DOPED BY METAL

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Thin-film MoRe-Si(W)-MoRe junctions were fabricated by magnetron sputtering of targets in an argon atmosphere, followed by deposition of thin films through metal masks on poly-crystalline aluminum oxide (polycor) substrates or on sapphire substrates. In order to study the distribution of transparencies in the formed Si(W) barrier, the model of multiple Andreev reflections was used, within the framework of which the quasiparticle I–V characteristics of the junctions were calculated and compared with the experimental ones.

Key words: Josephson junctions, semiconductor barrier, I–V characteristics, model of multiple Andreev reflections, distribution of transparencies.

1. Introduction.

Superconducting Josephson junctions (superconductor-barrier-superconductor) have already found wide application in microelectronics, computer systems for recording and processing information, ultra-fast analog-to-digital converters, ultra-sensitive sensors of magnetic fields and microwave radiation, in medicine, biology, geology, etc.

At the moment, Josephson junctions look like the most promising element base for creating a quantum Josephson computer and a cryogenic superconducting ultra-fast computer based on RSFQ (rapid single-flux logic), the development of which is being intensively carried out in developed countries of the world.

Technologically, Josephson junctions are manufactured either in the form of thin-film superconductor-insulator(or metal)-superconductor structures or in the form of point contacts of superconductors. The disadvantage of thin-film S-I-S junctions is their relatively large capacity, which reduces the speed of these junctions and their operating frequencies.

The point contacts junctions have an attractive negligible capacitance, but are mechanically unstable in operation.

The objective of the study was to develop and manufacture Josephson junctions that would be free from the above-mentioned drawbacks.

2. Experiment.

Currently, nanostructured Josephson heterostructures are considered to be one of the most promising, in which charge transport occurs through energy states localized in their amorphous semiconductor barriers.

Thin-film MoRe-Si(W)-MoRe junctions (Fig.1) were fabricated by magnetron sputtering of targets in an argon atmosphere, followed by deposition of thin films through metal masks on polycrystalline aluminum oxide (polycor) substrates or on sapphire substrates.

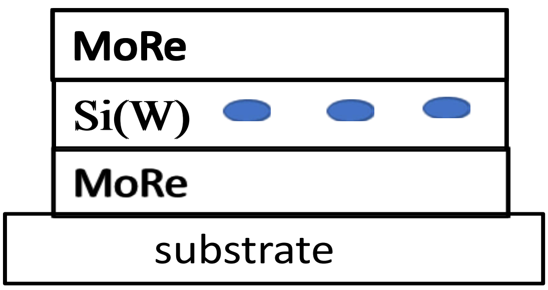


Fig.1. Schematic of the thin-film MoRe-Si(W)-MoRe junction.

The films deposition was carried out at room temperature, so the films were formed amorphous.

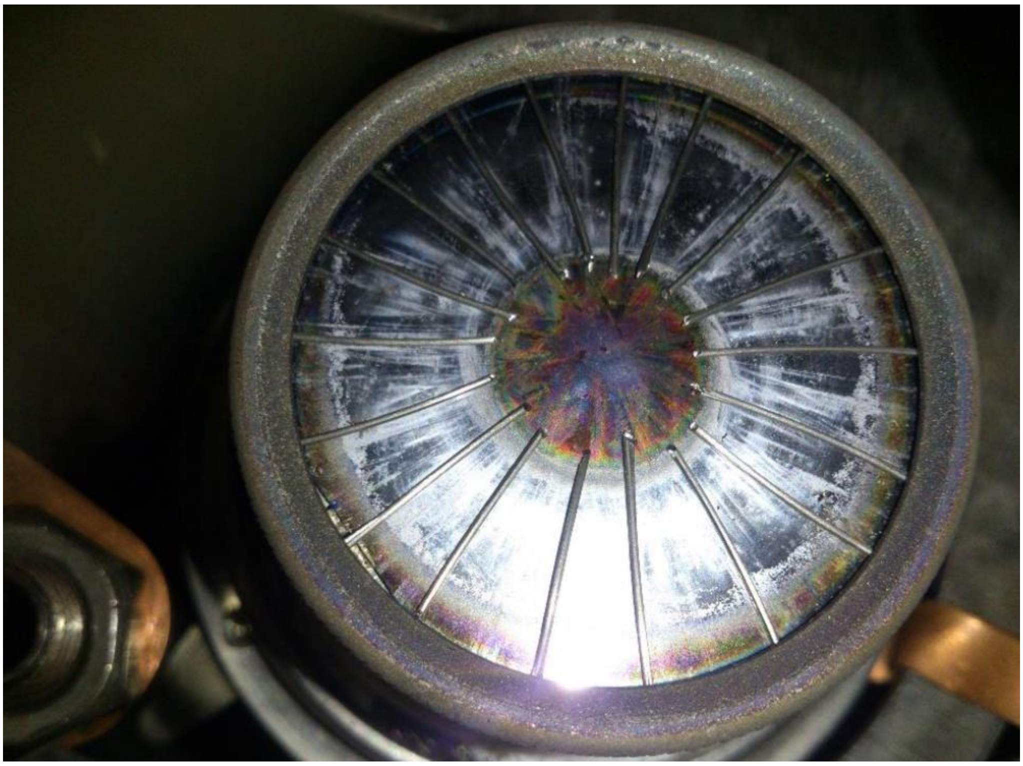


Fig.2 . Magnetron for sputtering Si(W),
complex target consists of a silicon plate with tungsten wires located on it.

The Si(W) barrier films were formed by sputtering a complex target consisting of a single-crystal silicon Si plate, on the surface of which tungsten W wires of 0.3 mm thickness and about 10 mm length were laid in the amount of 20–30 pieces (see Fig.2).

The manufactured thin amorphous MoRe films had a critical superconducting transition temperature $T_C \approx 9.1$ K. The Si(W) barrier films had a thickness of several nanometers.

The thickness of the films h was estimated using an optical microinterferometer MII-4, designed to measure the thickness of films on substrates by measuring the shift of the interference pattern bands, which is proportional to the thickness of the measured film .

In such measurements, we first make relative measurements, i.e. we compare the thicknesses of two films - the known and the studied one. In some films, we measured the thickness by a more accurate method, for example, by a scanning electron microscope (SEM), these films were used as reference.

It is impossible to study such a thickness of Si(W) films by transmission electron microscopy, since these films were burned through by the electron beam even at reduced voltages.

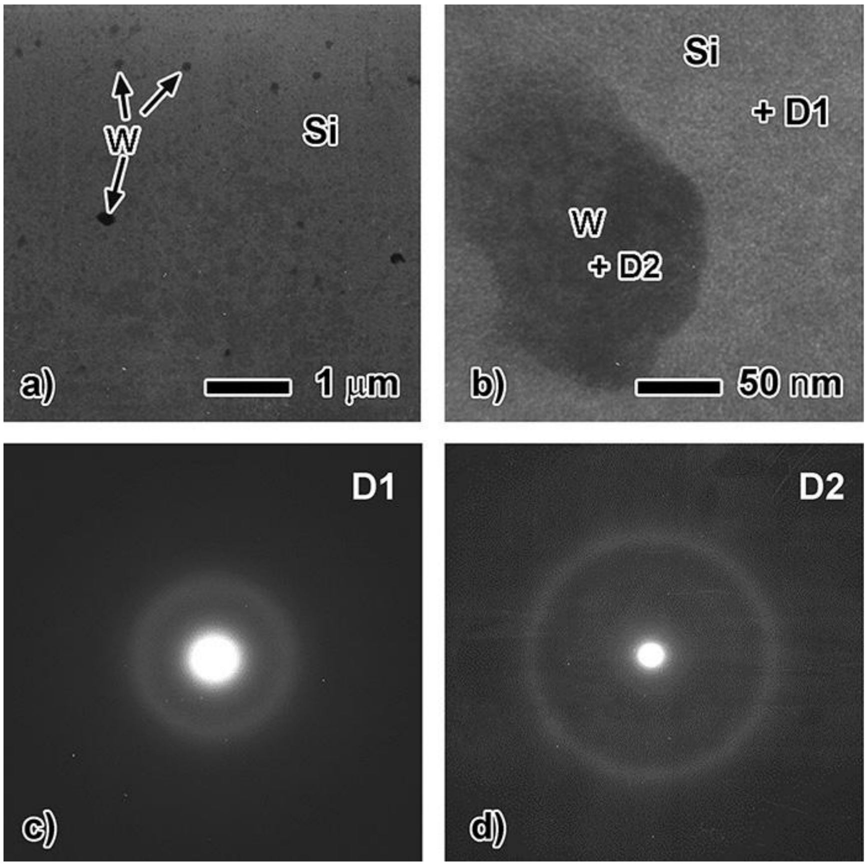


Fig. 3. TEM image of Si(W) film with 200 nm thickness, obtained with various resolutions - a) and b). Diffraction patterns c) and d) from the selected areas D1 and D2 indicated in Fig. 3b. The surface of film is parallel to the page.

But the study of transmission electron microscopy of thicker Si(W) films produced under the same technological conditions showed that clusters of amorphous tungsten W are formed in amorphous silicon films Si (see Fig.3).

It has been established that when depositing thin MoRe films with a thickness of 100-200 nm on polished polycor substrates at room temperature, amorphous films of molybdenum-rhenium alloy are formed, while the initial composition of the MoRe target (53 at. % Mo, 47 at. % Re) remains the same in the deposited MoRe films.

Studies using an atomic force microscope of the surface relief of the created MoRe films show that they are smooth, that is, that they have practically no relief, the height of the relief peaks is on average less than at least 0.5-1.0 nm. The critical temperature of the superconducting transition in MoRe films reaches T_C=9.1 K. The value of the superconducting critical current I_C of MoRe tracks with a width of 100 μm and a film thickness of 200 nm exceeds 0.4 A, i.e. the superconducting current density of the films exceeds $j_C \sim 10^6$ A/cm^2.

As a result of the study of the surface of the Si(W) films using a scanning electron microscope (both in the electron reflection mode and in the secondary electron mode), it was found that when depositing thin Si(W) films on the above-mentioned MoRe film with a deposition rate $v_{dep.} \sim 1$ nm/sec, smooth amorphous silicon films are formed, in which the height of the relief peaks is less than the resolution of the microscope, i.e. less than 10 nm. Studies of the composition of the formed Si(W) films, conducted simultaneously using micro-X-ray spectral analysis, showed that the films are homogeneous in composition and consist mainly of silicon Si, the films also contain oxygen atoms O with a concentration of ~ 10 at.% and only in some places of the films there are tungsten impurities W with a content of several atomic percents, unfortunately, the resolution of the microscope does not allow these studies to be carried out in more details.

In order to study in details the structure of the created Si(W) films, their surface was studied using an atomic force microscope in non-contact mode (AFM) (see Fig.4).

When operating in a contactless mode, the piezoelectric vibrator excites the probe oscillations at a certain frequency (most often, resonant). The force acting from the surface leads to a shift in the amplitude-frequency and phase-frequency characteristics of the probe, and the amplitude and phase of the oscillations change their values. The feedback system, as a rule, maintains the probe oscillation amplitude constant, and the change in frequency and phase at each point is recorded. However, it is possible to establish feedback by maintaining a constant value of the frequency or phase of the oscillations.

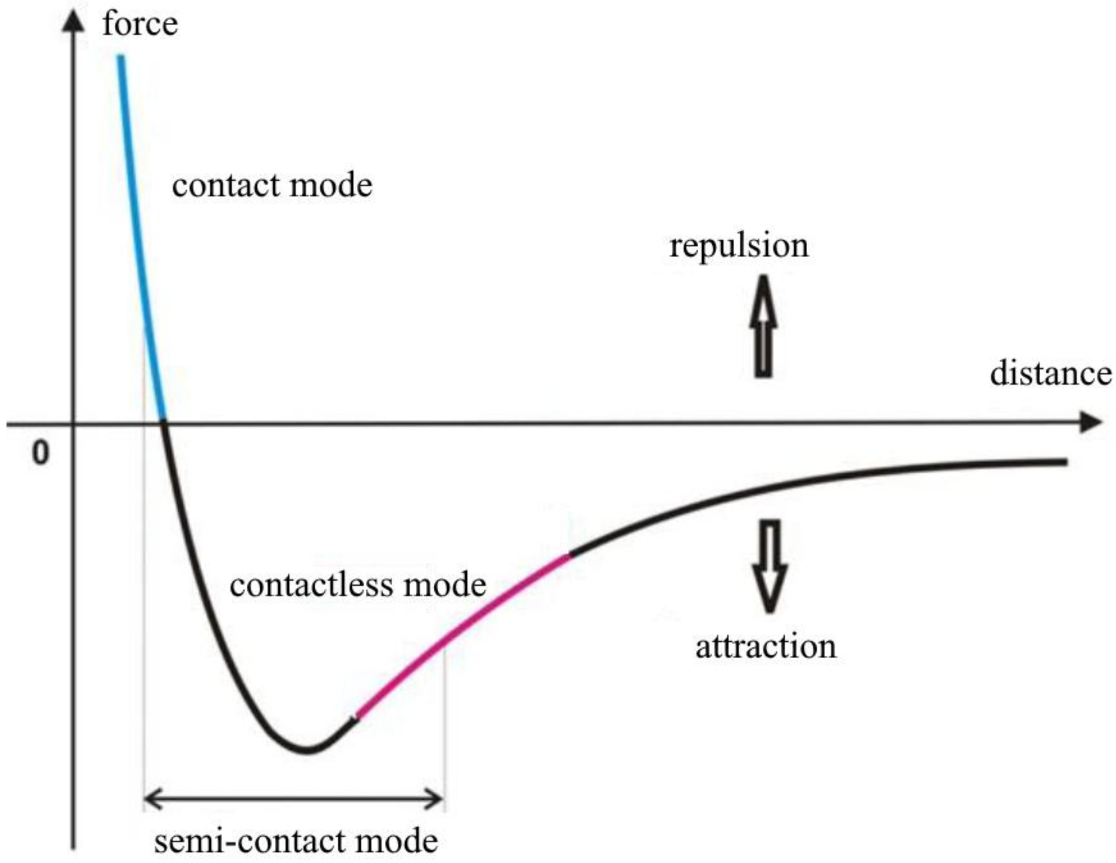
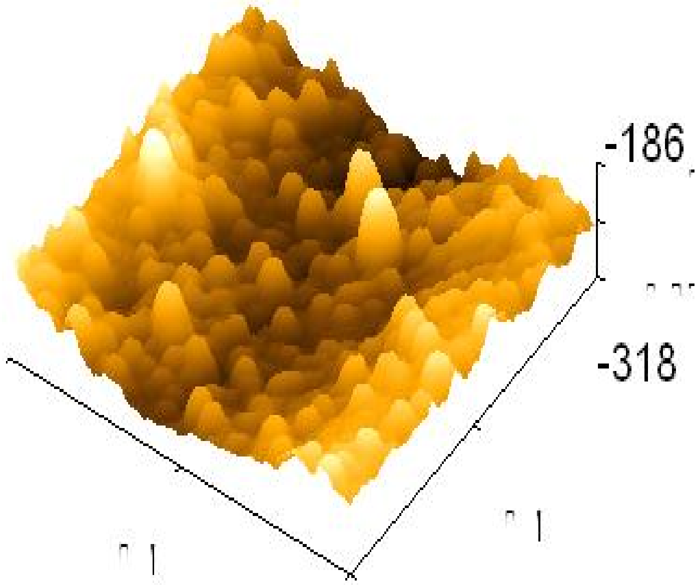
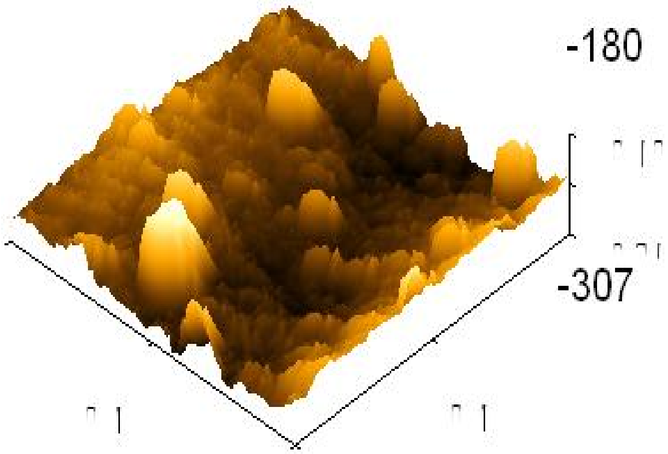


Fig. 4. Dependence of force and distance on the AFM operating mode

In order to study the structure of the Si(W) films in details, their surface was studied using an atomic force microscope in non-contact mode . As is known, the signal of an atomic force microscope in non-contact mode (the needle vibrates, while the change in the frequency of these needle vibrations is measured when its coordinate changes relative to the sample under study) is proportional to the magnitude of the Van der Waals force gradient along the vertical direction [1,2] (provided that the film under study is located horizontally). The AFM images of the Si(W) film under study obtained as a result of the study indicate that the Si film contains a network of clusters (W) with sizes of the order of a few nanometres, located at distances of the order of a hundred nanometres, which determines that the resulting image has the appearance of a network of peaks (see Fig.5).



a) Si(8W) on polycor



b) Si(8W) on MoRe

Fig.5. The AFM images of the Si(W) film under study.

A typical I–V characteristic of one of the MoRe-Si(W)-MoRe junctions is shown in Fig. 6.

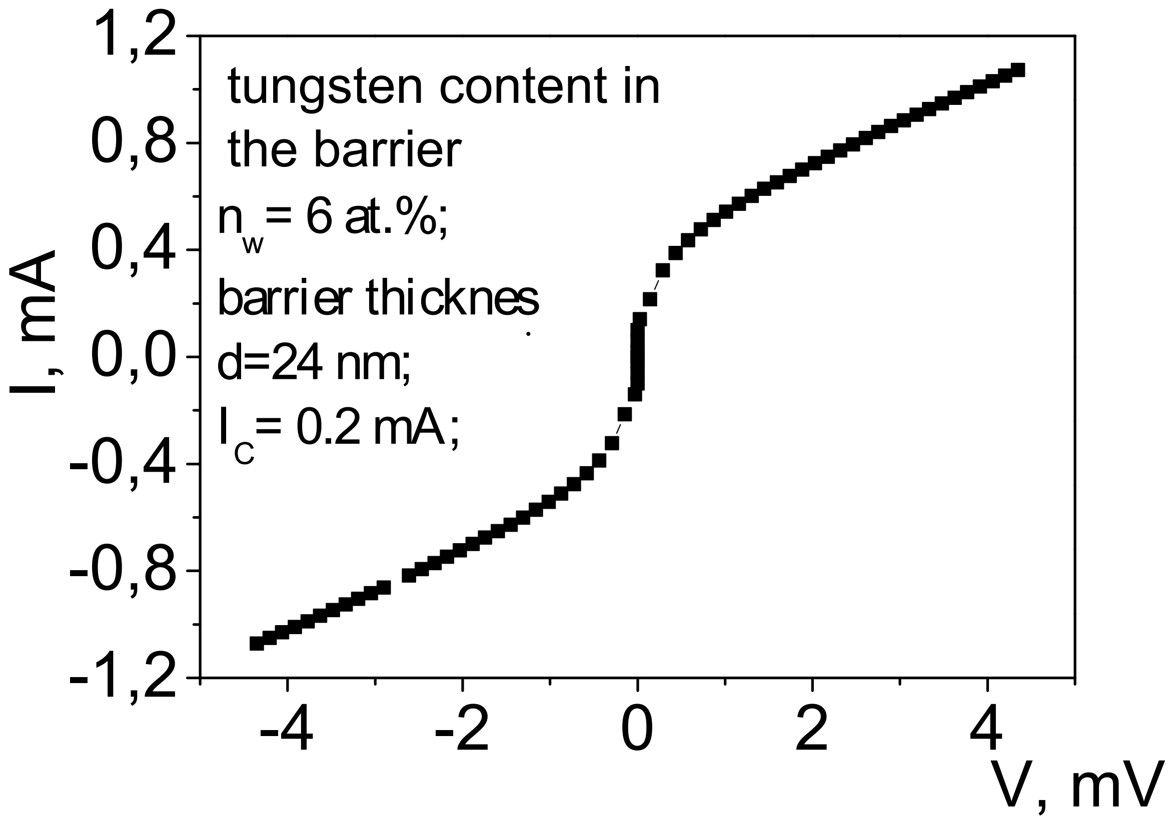


Fig.6. I–V characteristic of one of the MoRe-Si(W)-MoRe junctions.

Planar S-Sm-S Josephson junctions with an intermediate semiconductor layer (Sm) between two superconducting plates (S) during the long time are of great interest both from fundamental and practical viewpoints [3-5]. From the practical viewpoint this type Josephson junctions are of interest because they posses a rather low capacitance simultaneously with a high I_cR_n product values, what is important for different applications of Josephson junctions. This interest is supported now by numerous research works on effect of quantum dots within an insulating or semiconductor layer in S-I-S (S-Sm-S) type Josephson junctions and their role in electron quantum transport [4–7]. Some interesting ideas concerning the mechanism of Cooper pairs transport through quantum dots via resonant tunneling and super-current pass through the resonant-percolation trajectories and also some related peculiarities of the Josephson effect in these type junctions have been already discussed by theorists rather long ago [8–11].

Detailed experimental studies of thin film large (~100 μm*100μm) planar superconductor– semiconductor doped by metal–superconductor junctions (MoRe–Si(W)–MoRe) recently performed by V.Shaternik et.al. [12], have revealed some unusual features of the Josephson effect in these junctions. One of the most prominent peculiarities concerns the Josephson critical current dependence on applied magnetic field, oriented parallel to the films surface, $I_c(H)$. Instead of the classical Fraunhofer type $I_c(H)$ dependence, it was observed that the Josephson critical current weakly depends on applied magnetic field, and this dependence looks like a some background I_{c0} perturbed by weak oscillations on H value (see Fig.7)..

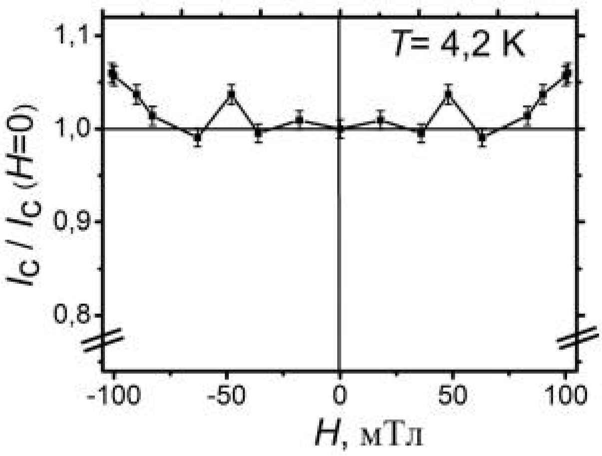
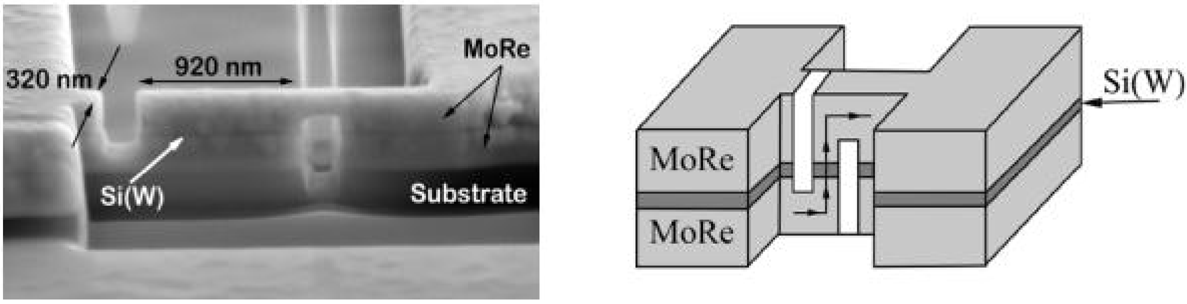


Fig.7. Typical $I_c(H)$ dependence for large MoRe–Si(W)–MoRe Josephson junctions [12].

For these Josephson junctions $Ic(H)$ is nearly independent on applied magnetic field H up to rather high H values, and only weak (about few percents) $Ic(H)$ oscillations were observed, which look like small periodic perturbations upon the background steady current I_{c0}, with a large period on H. This type of $Ic(H)$ dependence is very unusual for planar Josephson junctions settled in a parallel magnetic field.

An important result was obtained with a strong miniaturization of the studied Josephson junctions MoRe–Si(W)–MoRe. In the work [13], by using a focused ion beam (FIB), planar junctions MoRe–Si(W)–MoRe were reduced to submicron sizes, i.e. to sizes smaller than ~1 μm*1μm (see Fig. 8).



a **b**

Fig.8. SEM micrograph of the heterostructure formed by a combination of optical lithography, metal deposition and FIB milling steps (a) and the schematic of the Josephson-junction side view where the internal arrow demonstrates the supercurrent flow direction (b).

The miniaturized MoRe–Si(W)–MoRe junction exhibit classical Fraunhofer type *Ic(H)* dependence (see Fig.9).

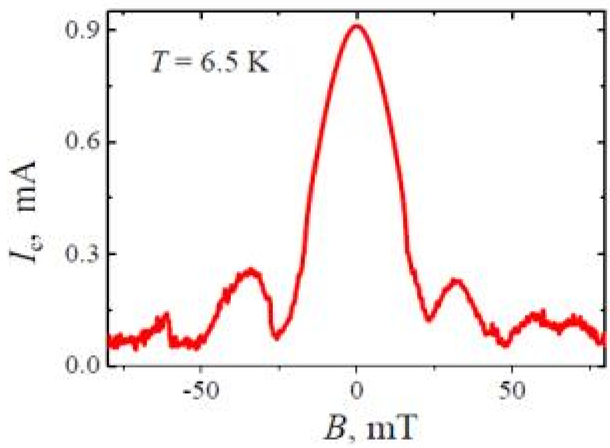


Fig.9. Magnetic field effect on the critical current of a submicron- sized MoRe–Si(W)–MoRe Josephson junction at T=6.5 K.

In the work, the influence of external microwave radiation with a frequency of 11 GHz on the current-voltage characteristics of the above-mentioned created heterostructures was investigated [14 -16], that is, a comparative experimental study of the current-voltage characteristics of large MoRe-Si(W)-MoRe heterostructures was carried out without and under the influence of external microwave radiation, typical current-voltage characteristics are shown in Fig. 10.

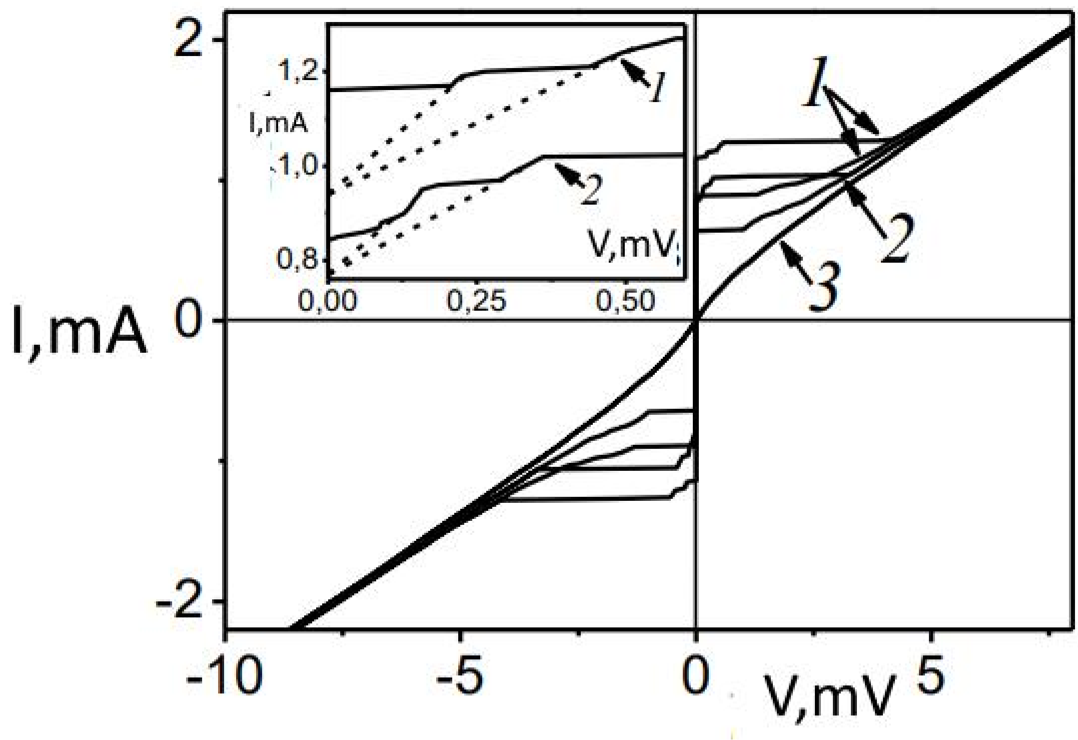


Fig. 10. Typical current-voltage characteristic of the MoRe-Si(W)-MoRe heterostructure with a tungsten content of 10 at% in the Si(W) barrier under the influence of external microwave irradiation. Given for three different microwave irradiation power levels: 1 – P1, 2 – P2, 3 – P3 (P1 < P2 < P3).

It should be noted that characteristic inclined steps (see Fig. 10) appear on the current-voltage characteristics of heterostructures exposed to external microwave radiation, the shape and position of which depend on the power of the applied microwave radiation. The presence and behavior of such steps [17] allow the authors to assume that in the studied heterostructures, when a certain critical value of the superconducting current Ic is exceeded, the mode of transport of

Cooper pairs (superconducting current) through coupled Andreev states is replaced by the appearance of phase slip centers of the superconducting order parameter in tungsten clusters [17, 18]. It can be assumed that as a result, the heterostructure is transformed into a superconductor–barrier–superconductor junction with dynamically created Josephson junctions (in accordance with the work of A.N. Omelyanchuk et al. [19]).

3. DISCUSSION.

In [20] there is considered theoretically the model of S-Sm(M)-S Josephson junction similar to that, schematically presented in Fig.11.

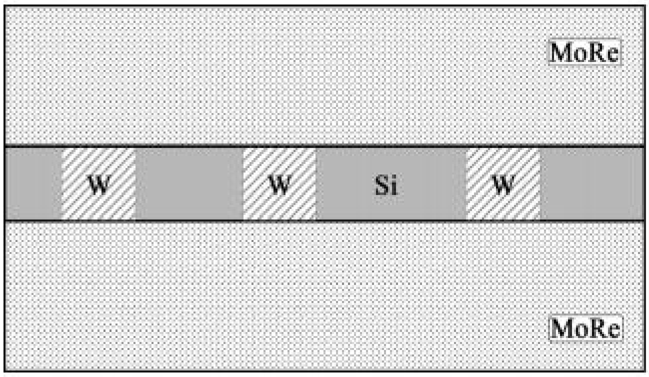


Fig.11. Schematic presentation of S-Sm(M)-S (MoRe–Si(W)–MoRe) Josephson junctions experimentally studied in [12].

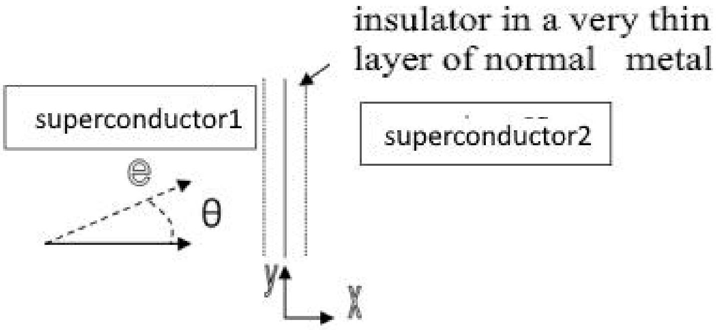
The Josephson current passes through a rather thick (~ 15 nm in experiments [12] performed on MoRe–Si(W)–MoRe junctions) semiconductor layer and Cooper pairs transfer proceeds due to electron tunneling over resonant trajectories [8–11] connecting W–nanoclusters within the Si-layer or through metallic nano-bridges formed by links of these nanoclusters.

This model seems to be useful for explanation of the unusual dependence of the Josephson critical current *Ic(H)* on applied parallel magnetic field in S-Sm(M)-

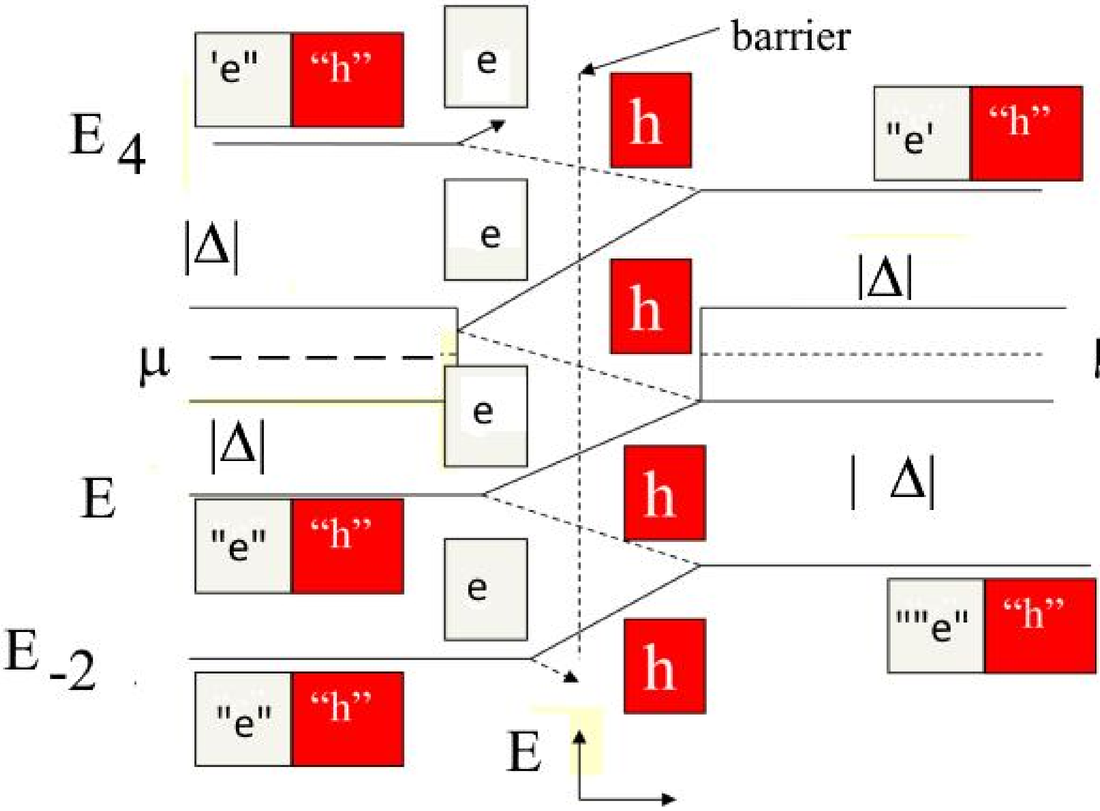
S type planar Josephson junction (MoRe–Si (W)–MoRe) (see Fig.7). Lack of the typical Fraunhofer type *Ic(H)* dependence for this type Josephson junctions is related to the discrete Josephson current flow through the set of parallel metallic nanobridges (or resonant percolation trajectories) formed by M-nanoclusters within the semiconductor intermediate layer [20].

In order to study the distribution of transparencies in the formed Si(W) barrier, the model of multiple Andreev reflections was used, within the framework of which the quasiparticle I–V characteristics of the junctions were calculated and compared with the experimental ones.

Let us consider the quasiparticle current-voltage characteristic of the superconductor-barrier-superconductor junction. The superconductor-barrier-superconductor junction is approximated by the superconductor– thin normal metal – δ-barrier – thin normal metal – superconductor junction S-N-I-N-S (see Fig.12).



a)



b)

Fig. 12.. a) schematic representation of the junction; b) energy scheme of multiple Andreev reflections (MAR) of a quasiparticle in a two-dimensional Josephson junction. Here e is an electron, h is a hole, ”e””h” is a Bogolyubov quasiparticle with a variable charge, E_i are energy levels, Δ is the energy gap, μ is the chemical potential level, the chemical potential level of the right superconductor is eV higher than μ of the left superconductor.

Here it is evident that the shape of the quasiparticle I-V characteristics of the S-N-I-N-S junction now strongly depends on the value of the δ-barrier transparency **t**. In this case, it becomes possible to calculate the I-V characteristics of junctions of all types – from S-N-S to S-I-S with an arbitrary transparency **t** of the barrier (see Fig. 13). Based on such approaches, quasi-particle current-voltage characteristics of junctions with inhomogeneous barriers with a universal or any other distribution of transparency are calculated [31] also.

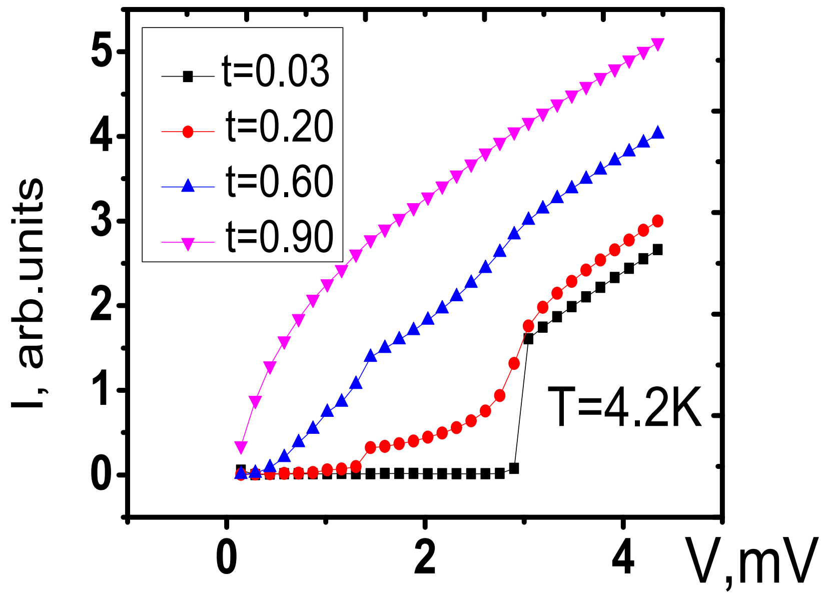


Fig. 13. Quasiparticle current-voltage characteristics of junctions with homogeneous barriers with transparency **t** were calculated in the multiple Andreev reflection model [32].

Generally speaking, quantum transport through a mesoscopic physical system is associated with complex dynamic processes, such as the interaction of current carriers with various kinds of imperfections of the crystal lattice, with each other, etc., and therefore depends on the dimensionality of the sample being studied, its shape, the electron density of states, the specific implementation of the random potential and many other parameters specific to the object. However, it is believed that there is a universal transparency distribution function ρ(D), which does not depend on any microscopic properties of the sample, but is determined by a limited number of its macroscopic characteristics.

The proposed ideas [34] regarding the presence of transparency distribution functions in Josephson junction barriers substantiate the existence of a technique for reconstructing the transparency distribution in experimentally studied Josephson junction barriers by calculating the quasiparticle current-voltage characteristics of the junctions and comparing them with those obtained experimentally. For example, when the transparency **t** value changes from unity to about 0.01, a clearly distinguishable feature appears on the quasiparticle current-voltage characteristic in the form of a current step at a bias voltage equal to the sum of the energy gaps of the superconductors forming the Josephson junction (see Fig. 13). The figure 14 shows the quasiparticle current-voltage characteristics calculated under the assumption that some sections (marked S_1) of the barrier under study have a transparency of 1, and some sections (marked S_2) of it have a transparency of 0.01, the barrier is divided by area into 100 sections, respectively. It is evident how a feature appears on the calculated quasiparticle current-voltage characteristic, caused by the sum of the gaps $\Delta_1+\Delta_2$ of superconductors of the junction.

It is evident that, judging by Fig. 14, the Josephson junction under study has a barrier containing a large number of sections with transparency close to unity and a large number of sections with zero transparency (do not change the I-V characteristic).

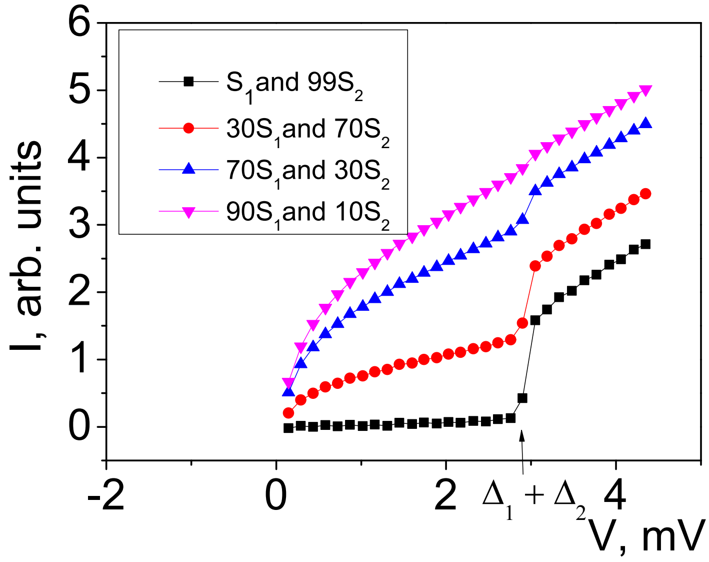


Fig.14. Quasiparticle I–V characteristics for barriers with non-uniform transparency.

4. Conclusion.

Josephson junctions of a new type MoRe-Si(W)-MoRe with barriers in the form of thin films of the semiconductor Si(W) doped with metal W have been developed and manufactured. Experimental studies of the formed Si(W) films using a transmission electron microscope, a scanning electron microscope and an atomic force microscope in the contact-less mode have shown that the Si(W) films consist of amorphous silicon in which clusters of amorphous tungsten are generated. Experimental studies of the $I_c(H)$ dependencies of large MoRe-Si(W)-MoRe junctions have shown that the dependencies have the character of a pedestal with weak oscillations of I_c. It is shown that with strong miniaturization of the junctions under study, their $I_c(H)$ dependence has the form of the classical Fraunhofer-type $I_c(H)$ dependence. At the same time, it has been experimentally shown that due to the absence of gettering properties in the MoRe alloy, thin MoRe films can withstand much stronger miniaturization than niobium Nb films. It is suggested that phase slip centers are formed in the junctions under study under the action of external microwave radiation. The experimental I–V characteristics of the MoRe-Si(W)-MoRe junctions are compared with those calculated within the framework of the multiple Andreev reflection model. It is shown that the junctions behave as having a set of barrier sections with high transparency close to unity. It is emphasized that due to the use of barriers of a new type (semiconductor doped with metal) the specific capacitance and, consequently, the capacitance of thin-film tunnel Josephson junctions decreases at least by an order of magnitude, which is extremely important from the point of view of practical applications of these junctions of a new type. It is also emphasized that despite the fact that the created junctions can have a current-voltage characteristic characteristic of S-N-S junctions, nevertheless the known undesirable effect of proximity between these S and N layers does not occur in such junctions, which is also extremely important from the point of view of practical applications of these Josephson junctions of a new type.

5. References

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