MoRe-based tunnel junctions and their characteristics

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Abstract. Perspective Josephson Mo-Re alloy-oxide–Pb, Mo-Re alloy-normal metal–oxide–Pb and Mo-Re alloy-normal metal–oxide–normal metal–Mo-Re alloy junctions have been fabricated and investigated. Thin (~50-100 nm) MoRe superconducting films are deposited on Al2O3 substrates by using a dc magnetron sputtering of MoRe target. Normal metal (Sn, Al) thin films are deposited on the MoRe films surfaces by thermal evaporation of metals in vacuum and oxidized to fabricate junctions oxide barriers. Quasiparticle I–V curves of the fabricated junctions were measured in wide range of voltages. To investigate a transparency spread for the fabricated junctions barriers the computer simulation of the measured quasiparticle I–V curves have been done in framework of the model of multiple Andreev reflections in double-barrier junction interfaces. It’s demonstrated the investigated junctions can be described as highly asymmetric double–barrier Josephson junctions with great difference between the two barrier transparencies. The result of the comparison of experimental quasiparticle I–V curves and calculated ones is proposed and discussed. Also I–V curves of the fabricated junctions have been measured under microwave irradiation with 60 GHz frequency, clear Shapiro steps in the measured I–V curves were observed and discussed.

1. Introduction
The key problem in Josephson junction fabrication is the problem of decreasing of junction capacitance and obtaining for them the high values of Josephson critical current density simultaneously. It’s possible to realize this by using a Josephson junction miniaturization and by increasing isolator I transparency in them. Present niobium (Nb) technology limits a possibility to miniaturize the junctions down to a wanted size because niobium is a strong getter. MoRe films behaves like as the noble metals and are not the getter, so they are perspective from the point of view of miniaturization of Josephson junctions on their base.

Artificial tunnel barriers formed by room-temperature thermal oxidation of metallic overlayers on superconducting base electrode surfaces are usually believed to be amorphous [1,2]. There is, however, a paucity of specific literature data on the barrier crystallinity and its effects. Liehr and Ewert had reported low-temperature glow-discharge oxidation of thick aluminium films evaporated in an ultrahigh-vacuum (UHV) of 10^{-10} Torr produced crystalline Al-oxide barriers [3]. But for aluminium evaporated in a high vacuum (HV) of approximately 10^{-7} Torr an identical oxidation process resulted in amorphous aluminium oxide barriers [3]. Liehr and Ewert [3] suggested the type of oxide formed
depends upon the size of crystallites in the fabricated aluminium film. Sufficiently small crystallites, obtained when depositing in a high vacuum where the adatom surface mobility is lower and the nucleation rate higher than that in the ultrahigh-vacuum, result to an amorphous oxide [2]. It’s known tunnel junctions with oxidized metallic layer barriers discussed in the literature have been usually fabricated in high vacuum and on fine-crystalline base electrodes so that the amorphicity of such barriers was very probable even when not verified [2]. In most cases these junctions exhibited quasiparticle current-voltage (I-V) characteristics with well-defined gap-voltage current step and very low subgap conductances [2].

Usually we have not a possibility to measure experimentally such parameters of the very thin oxidized metallic overlayers I as their crystalline structure and grain size in spite of the fact that this is very important from the point of view of the fabricated barrier properties. And actually situation is even more complicated because we should not only to know the overlayer structure but also we need to obtain finally a set of transmission coefficients (named “transparencies”) for them to estimate the fabricated junctions properties [4]. As discussed in [4-6] this important information can be obtained experimentally in other way by measuring the quasiparticle dc I-V curves of the fabricated junctions and by computer simulation of them in frame of the multiple Andreev reflections (MAR) theory model. Now investigation of multiple Andreev reflections of quasiparticles in S-I-S tunnel junctions is very actual because for the barriers with high transparency they play important role.

2. Sample preparation and characterization

The investigation in the field of fabrication and measuring of tunnel junctions on the base of superconducting Mo-Re films prepared by coevaporation from Mo and Re electron-beam sources were first reported in [1-2]. In our work the superconducting Mo-Re films are prepared by deposition of thin Mo-Re films onto various dielectric substrates at room temperature by using a dc magnetron sputtering of MoRe targets. The targets and deposited films were composed of 45% Re. The deposition rate was typically ~2 nm/sec. We have observed that a small water and oxygen impurities in plasma causes a crucial negative influence in the process of MoRe films fabrication, in the process of aluminum or tin spreading on the MoRe surface, in uniformity of the deposited Al or Sn layers and in the uniformity of the fabricated AlxOy or SnxOy layers in the fabricated treelayer S-I-S structures, so we’ve designed and used a special cryogenic trap for these impurities.

Tunnel barriers were formed by either sputtering or evaporating a 2 – 30 nm-thick Al overlayer at a substrate temperatures close to the room temperature (<100°C). The MoRe/Al bilayer was then oxidized in the vacuum chamber in dry oxygen for a period of 10 min at various oxygen pressure values. Either a Mo-Re counterelectrode was deposited, or the samples were taken to another evaporator to have Pb-counterelectrode evaporated through an metal mask.

![Figure 1. Top view of the etched films.](image1)

![Figure 2. Crosssection of the etched films.](image2)
In fig. 1 there is shown a result of etching of a MoRe thin film (deposited on silicon wafer with oxidized surface) by standard Nb-process of etching (CF$_4$ plasma at 15 Pa pressure and at accelerated voltage -400 V). In fig. 2 one can see a crossection of one of the etched film which has been obtained by using an atomic force microscope. It seems the film has very smooth surface and edges. MoRe alloy is very close to the noble metal, (Re is the real noble metal), so it oxidation rate is very small, for example we oxidized film surface in room air during 24 hours and as a result any tunnel barrier didn’t appear in the film surface. MoRe alloy has not any getter properties (it’s well known Nb is a strong getter and has large oxidation rate).

Our STM tunnel spectroscopy investigations in various points of MoRe films including near film edges give us a possibility to conclude that these films have the same well known tunnel spectra of BSC superconductors in every points and have undestroyed edges, so these films could be miniaturized as well.

3. Results and discussion

We have obtained trilayer S-I-S structures with various quasiparticle I-V curves in which well-defined gap-voltage current step is observed. Some of the curves belong to the junctions with low leakage (see fig.3) and others belong to the junctions with higher leakage. To analyze and systematize these junction curves we have used well known theory model of the multiple Andreev reflections (MAR) [7-11] in them. We describe S$_1$-I-S$_2$ junction now as an S/N-I-N/S junction with infinitely thin normal metal (N) layers. To calculate multiple Andreev reflections (MAR) here Bogolyubov two-component

$$\Psi_{\Sigma} = \sum_n \left[ \delta_{n,0} \left( \begin{array}{c} u_n(E_n) \\ v_n(E_n) \end{array} \right) e^{i\phi_n} + h. \right] \left( \begin{array}{c} \tilde{u}_n(E_n) \\ \tilde{v}_n(E_n) \end{array} \right) e^{-i\phi_n} + + d_{1,n} \left( \begin{array}{c} \tilde{u}_n(E_n) \\ \tilde{v}_n(E_n) \end{array} \right) e^{i\phi_n} e^{-i(E_n + \phi_n/2)} \right)$$

(1)

here $q^{th} \approx k_F$. In the normal metal region the wave function to the left and right of the barrier and wave function of the right superconductor are given in the analogous manner. Respectively, $q_0$ – is a phase shift in the junction in the initial time moment. We have three interfaces where the wave functions and their derivatives are to be matched (about details see [11]). The calculated in the framework of the proposed model quasiparticle I-V curves are given in Fig.4.

In Likharev paper [4] there is experimentally demonstrated that in tunnel Josephson junctions with large specific transparency of the ultrathin barriers the theoretically predicted distribution functions of transparencies D in junction barrier play the great role and should be taken in account. Such distribution function $\rho(D)$ (see insert of fig.5) for the disordered interface is [5]

![Figure 3. Typical experimental I-V curve.](image1)

![Figure 4. Calculated I-V curves in MAR model.](image2)
\[
\rho(D) = \frac{G}{\pi G_0} \frac{1}{D^{3/2} \sqrt{1 - D}}
\]

(2)

here \( G \) – the averaged conductivity, \( G_0 = 2e^2/h \), \( \rho \) – the probability.

In fig.5 top I-V curve (marked with \( 0.00036499 < D < 1 - \varepsilon \)) shows the theoretical dependence which were obtained by averaging the results of the MAR theory for the current \( I(D) \) carried by a single mode of transparency \( D \) over the distribution of transparencies given by (2)

\[
I_{\text{aver}} = \int_0^1 dD \rho(D) I(D)
\]

(3)

Firstly this I-V curve was published in [4] for the junction with universal distribution of transparencies (2) proposed by Schep and Bauer (S-B) [5] for a dirty interface as a junction barrier. As authors of [5] emphasized the universality of \( \rho(D) \) has its limits. Either close to the localization regime or close to the ballistic regime equation (4) used in [5] is no longer valid. Even in the metallic regime the universality can be broken by extended defects, such as tunnel barriers, grain boundaries, or interfaces [12,5]. So, in this work we have calculated quasiparticle I-V curves of the S-I-S junctions in the frame of this approach but with a changing of the integral (3) limits. From the very beginning we choose the cutoff at small \( D \) as proposed in [5] and up limit as very close to 1, we have obtained I-V curve for the universal distribution. One can see in the fig.5 the calculated I-V curves for the case of unchanged bottom integral (3) limit and slightly changed top integral limit, in fig.6 corresponding \( dI/dV(V) \) curves are given. This case corresponds that probability of transparencies close to 1 decreases in junction due to some changing of the junction fabrication conditions. In the fig.7 there are the calculated I-V curves for the case of unchanged bottom integral (3) limit and strongly changed top integral limit, in fig.8 corresponding \( dI/dV(V) \) curves are given. We have compared our experimental quasiparticle I-V curves of the fabricated S-I-S junctions with calculated ones and we obtained that every experimental curve can be coincided with calculated in this approach curve good enough taking in account I-V curve shape and subgap peculiarity presence (mainly at \( eV = 2\Delta/2 \)). So, in fig. 5 and fig.7 the experimental and calculated curves are not mismatched. Simultaneously and other more complicated situation appears, for example, some junctions can have approximately the same curve shape but different sufficiently their averaged conductivities, this case, probably, can be interpreted so that a part of junction area has conductivity close to 0 and doesn’t take part in the charge transport through the junction barrier. In any case such kind analysis gave us a possibility to obtain a useful correlation between the changing of technological parameters of junction fabrication process and the changing of the experimentally measured quasiparticle I-V curves.
One can see in the fig. 9 the calculated I-V curves for the case of strongly changed bottom integral (3) limit and unchanged top integral limit, in fig. 10 corresponding dI/dV(V) curves are given. This case corresponds that probability of low transparent areas appearance decreases in junction due to some changing of the junction fabrication conditions.

For the some fabricated junctions the prominent features in the quasiparticle current-voltage curves have been observed: a so-called ‘knee’ in the energy-gap region (see fig. 11). They are discussed changing of the junction fabrication conditions.

Our situation is more close to the ballistic case and reflection amplitudes of two barriers (I_1 and I_2) in series with normal metal N middle interlayer be-

\[
\begin{align*}
\frac{t_e}{e} &= \frac{r_0^e e^{i2kFd\cos \theta}}{1-r_0^e e^{i2kFd\cos \theta}}; \\
\frac{t_t}{e} &= \frac{r_0^t e^{-i2kFd\cos \theta}}{1-r_0^t e^{-i2kFd\cos \theta}}; \\
\frac{T}{e} &= \frac{r_0^t e^{i2kFd\cos \theta}}{1-r_0^t e^{i2kFd\cos \theta}}; \\
\frac{r_2}{e} &= \frac{t_2^2 e^{i2kFd\cos \theta}}{1-r_2^2 e^{i2kFd\cos \theta}}; \\
k_d &= kd(1 + \frac{E}{2E_F}); \quad k_d = kd(1 - \frac{E}{2E_F});
\end{align*}
\]

(4)
In whole the calculation procedure of the quasiparticle I-V curves for double-barrier junctions is the same as earlier but with taking in account the (4) formulae, details are given in [15, 11]. The first barrier $I_1$ here has a small transparency so it simulates the real dielectric barrier in junction. Other situation appears with the second barrier $I_2$, it transparency is close to 1, it presence is necessary for ‘knee’ structure existence but there is not any technological reason for it appearance (interface oxidation or others). This slight barrier $I_2$ here exists due to effect of ‘superweak’ superconductivity in N/S sandwiches which is working as a quasiparticle trap (details see in [15] and [16]).

4. Conclusions
Mo-Re based junctions have been fabricated and their quasiparticle current-voltage characteristics were investigated experimentally. Computer simulation of the obtained quasiparticle I-V curves has been done in the frame of multiple Andreev reflections model for the Schep-Bauer distribution case. It’s demonstrated the comparison of the experimental and calculated in this model curves is useful from the point of view of development and optimization of the junction fabrication technology.

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[1] Talvacchio J, Janocko M and Greggi J 1986 Journal of Low Temperatures Phys. 64 395
[2] Braginski A, Talvacchio J, Janocko M and Gavaler J 1986 J. Appl. Phys. 60 2058
[3] Liehr M and Ewert S 1983 Z. Phys. B 52 95
[4] Naveh Y, Patel V, Averin D, Likharev K and Lukens J 2000 Phys. Rev. Lett. 85 5404
[5] Schep K and Bauer G 1997 Phys. Rev. B 56 15860
[6] Dorokhov O 1982 JETP Lett. 36 318
[7] Averin D and Bardas A 1995 Phys. Rev. Lett. 75 1831
[8] Bardas A and Averin D 1997 Phys. Rev. B 56 R8518
[9] Bratus E, Shumeiko V and Wendin G 1995 Phys. Rev. Lett. 74 2110
[10] Hurd M, Datta S and Bagwell P 1997 Phys. Rev. B 56 11232
[11] Shaternik V, Ivanjuta A and Shaternik A 2006 Low Temperature Physics 32 633
[12] Nazarov Yu 1994 Phys. Rev. Lett. 73 134
[13] Golubov A and Kupriyanov M 1988 Journal of Low Temperatures Phys. 70 83
[14] Golubov A and Kupriyanov M 1989 Sov. Phys. JETP 69 805
[15] Shaternik V, Larkin S and Khachaturova T 2006 Physica C 435 96
[16] Long Z, Stewart M and Valles J 2006 Phys. Rev. B 73 140507