MoRe–based and MgB$_2$-based tunnel junctions and their characteristics

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Abstract. Perspective Josephson Mo-Re alloy-oxide–Pb, MgB$_2$-oxide–Mo-Re alloy 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 Al$_2$O$_3$ substrates by using a dc magnetron sputtering of MoRe target. Thin (~50-100 nm) MgB$_2$ superconducting films are deposited on Al$_2$O$_3$ substrates by using e-beam evaporation of boron and thermal coevaporation of magnesium. 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. Results of computer simulation of quasiparticles I-V curves of junctions are presented and discussed. The $I_C(T)$ characteristics, measured for Josephson heterostructures with different thickness of metal layer $s$ and exposure dose $E$, essentially deviate from an Ambegaokar- Baratoff (A&B) $I_C(T)$ behavior and Kulik-Omelianchuck (K&O) curves, because of proximity effect caused by the comparatively high value of $s$ (up to 100 nm).

1. Introduction
The main difficulty in thin films Josephson junction fabrication is the problem of decreasing of junction capacitance and obtaining for then 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 and MgB$_2$ 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.

Thin films artificial tunnel barriers are usually believed to be amorphous [1,2] because they are formed by room-temperature thermal oxidation of metallic overlayers deposited on superconducting base electrode surfaces. There is, however, an insufficiency of specific literature data on the barrier
crystallinity and its effects. Liehr and Ewert had reported that 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 that the type of oxide formed depends upon the size of crystallites in the fabricated aluminium film. Very 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]. 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].

Investigators are not measuring experimentally, usually, 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. Of course, now there are another possibilities to investigate experimentally atoms positions in the barriers, for example, by using STM or AFM. But actually situation is even more complicated because surely we need to know the overlayer structure before and after the oxidization but also we need to obtain finally a set of transmission coefficients (named “transparencies”) for the barrier to estimate the fabricated junction properties [4]. As demonstrated in [4-6] this important information can be obtained experimentally in other way, it means by the measurements of 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. It means there is very actual the investigation of quasiparticles multiple Andreev reflections in tunnel junctions based on the new perspective materials, because for the barriers with high transparency they play important role and could be controlled by fabrication conditions.

2. Sample preparation and characterization

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 \(\sim 2 \text{ nm/sec}\). 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 Al\(_2\)O\(_3\) or Sn\(_x\)O\(_y\) layers in the fabricated treelayer S-I-S structures, so we’ve designed and used a special cryogenic trap for these impurities. The superconducting MgB\(_2\) [7,8] thin films (thickness \(100 – 300 \text{ nm}\)) have been deposited on Al\(_2\)O\(_3\) (0001) wafers. The residual gaseous pressure was \(5\times10^{-5} \text{ Pa}\) during the deposition. The deposition temperature is \(T_{\text{dep}} \approx 280 - 290 \text{ C}\). Magnesium (Mg) and boron (B) have been evaporated by a molybdenum boat and electron-beam gun, respectively. The rate of evaporation were controlled by flux stabilizers, and then component deposition rate correspondingly were controlled to be \(1.5 \text{ nm per second}\) for Mg (to compensate a reevaporation), and \(0.07 \text{ nm per second}\) for B. Then the each film was patterned by molybdenum shadow masks or by photolithography and Ar ion-beam etching. Critical temperature \(T_c\) and critical current density \(J_c\) of the MgB\(_2\) thin films have been measured by dc four-probe method.

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 and MgB\(_2\)/Al bilayers were then oxidized in the vacuum chamber in dry oxygen for a period of 10 min at various oxygen pressure values, it means at various oxidation exposure \(E\) values. Oxidation exposure \(E\) equals oxygen pressure \(P\) multiplied by oxidation time interval \(t\). Then a Mo-Re counterelectrode was deposited through an metal mask.
3. Results and discussion
Fig.1 shows the typical dependence of resistance on temperature for deposited MgB$_2$ thin films. The critical temperature of the films is $T_c=33$K and lower, the critical current densities of them evaluated as $J_c \approx 10^6$ A/cm$^2$ at 4.2 K, 0T as well.

![Figure 1. Typical dependence of resistance on temperature $\rho(T)$.](image1)

![Figure 2. Experimental quasiparticle I-V curve for MgB$_2$-Al$_2$O$_3$-MoRe junction with Schep-Bauer universal distribution of transparencies.](image2)

We have obtained trilayer $S_1$-I-$S_2$ structures on the base of MgB$_2$ and MoRe thin films with various quasiparticle I-V curves in which well-defined gaps current step (at $eV = \Delta_1 + \Delta_2$) is observed. Some of the curves belong to the junctions with low leakage and others belong to the junctions with higher leakage (see fig.2,3). To analyze and systematize these junction curves we have used well known theory model of the multiple Andreev reflections (MAR) \[9-13\] 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 (about details see \[13\]).

In Likharev paper [4] there is experimentally demonstrated that in tunnel Josephson junctions with large specific transparencies 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 the universal distribution function $\rho(D)$ (see insertion of fig.2) for the disordered interface is \[5\]

$$\rho(D) = \frac{G}{\pi G_0} \frac{1}{D^{3/2} \sqrt{1 - D}} \quad (1)$$

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

In fig.2 one can see the experimental quasiparticle I-V curve (marked by symbols) and the theoretical one (marked by solid line) matched with it, which was obtained by averaging the results of the MAR theory for the current $I(D)$ carried by a single mode of transparency $D$ over the universal distribution of transparencies given by (1)

$$I_{\text{aver.}} = \int_0^1 dD \rho(D) I(D) \quad (2)$$

Firstly such 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 [14,5]. 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 (2) limits. From the very beginning we choose the cutoff at small $D = 0.00036499 \approx 4 \cdot 10^{-4}$ as proposed in [5] and up limit as very close to 1, we have obtained I-V curve for the universal transparency distribution (see fig. 2).

It’s well known there are perspective to fabricate miniature SIS Josephson junctions with as high I-V curve nonlinearity as possible from the point of view of such applications for them as SIS-detectors, mixers and receivers, as rapid single-flux quantum (RSFQ) logic circuits [15], superconducting qubits and others. So, it’s interesting to have a possibility to control an internal shunting of the SIS junctions by changing the transparency distribution in their barriers from the point of view of operation of the devices using shunted SIS junctions [15]. Taking this in account we have done a comparative analysis of the MgB$_2$-Al$_2$O$_3$-MoRe and MoRe-Al$_2$O$_3$-MoRe quasiparticle I-V curves [16] and conditions of these junctions fabrication. MoRe thin films usually have very smooth surface as has been demonstrated by us in [16],[17]. The deposited on them Al films demonstrates the effect of Al film relief smoothing as a result of increasing of rate of the Al film deposition [17]. The deposition rate change (and relief change as a result) gives a possibility to change the transparency distribution in the fabricated SIS junctions and describe that in frame of the MAR model as demonstrated in [16],[17]. Now such kind behaviour we observe for MgB$_2$-Al$_2$O$_3$-MoRe junctions also, see fig. 3 (in insertion of fig.3 one can see corresponding quasiparticle I-V curves published in [16] for MoRe-Al$_2$O$_3$-MoRe junctions). In fig. 3 one can see the experimental quasiparticle I-V curves (symbols) of the junctions in which aluminum layers were deposited at various deposition rates $r_{depAl}$. Also in fig.3 the calculated quasiparticle I-V curves (solid lines) for the case of strongly changed bottom integral (2) limit and unchanged top integral limit are given matched with the corresponding experimental ones (details see in [17], [16]). This case corresponds that probability of low transparent areas appearance decreases in junctions due to some changing of the junction fabrication conditions. So, in fig.3 the experimental and calculated curves are not mismatched.

The two gap superconductivity in magnesium diboride now generally accepted and supported by
numerous experiments [18], suggests that the Fermi surface of MgB$_2$ is highly anisotropic and consists of principally distinct sheets characterized by strong and weak electron-phonon coupling, respectively. Due to the exponential decay of the electron wavefunction in an insulating layer, tunnelling currents are dominated by electrons transiting the layer with momenta within narrow cone around the junction normal. That is why in polycrystalline samples, chances to observe a larger gap are very small and the tunnelling current is dominated by $\pi$-band [18],[19]. So, in our experiments we observe $\Delta_\pi \approx 2$ meV also.

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.4).They are discussed within a simple Landauer-Büttiker scattering approach to the phase-coherent quasiparticle transport in a quasiballistic S-I$_1$-N-I$_2$-S heterostructure with an extremely great difference between the barrier transparencies. It’s well known that in the papers [19], [20] the ‘knee’ was reproduced within the dirty proximity effect model by Golubov and Kupriyanov. Our situation is more close to the ballistic case so we discuss it in frame of the MAR model. To obtain the ‘knee’ we should propose that in the investigated junction there are two $\delta$-shape barriers separated by normal metal layer and as result we calculate quasiparticle I-V curves for the S$_1$/N-I$_1$-N$_{middle}$-I$_2$-N/S$_2$ structures (details see in [22] and [16]). 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 [22] and [23]).

Measurements of the critical current in junctions were obtained as a function of temperature from the critical temperature of MoRe (it was close 9 K ) down to 4.2 K. The junction critical current was evaluated using a 1 $\mu$V criterion. The $I_C(T)$ characteristics, measured for Josephson heterostructures with different thickness of metal layer s and exposure dose E, essentially deviate from an Ambegaokar- Baratoff (A&B) $I_C(T)$ behavior and Kulik-Omelianchuck (K&O) curves, because of proximity effect caused by the comparatively high value of $s$ (up to 100 nm).

4. Conclusions
MgB$_2$ and Mo-Re based junctions have been fabricated and their quasiparticle current-voltage characteristics were comparatively 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 with broken universality. 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. It’s demonstrated that the nonlinearity of the fabricated SIS junctions can be done close to the predicted by the MAR theory model with the universal Schep-Bauer distribution of transparency. It seems the larger gap nonlinearity is negligible small for the fabricated and investigated MgB$_2$-based junctions. It’s demonstrated the smaller gap nonlinearity for the fabricated and investigated MgB$_2$-based junctions can be controlled by fabrication conditions. Well known feature in the quasiparticle current-voltage curves have been observed: a so-called ‘knee’ in the energy-gap region. ‘Knee’ structure appearance is an evidence of transformation of the investigated SIS junctions into the highly asymmetrical double-barrier junctions (S$_1$/N-I$_1$-N$_{middle}$-I$_2$-N/S$_2$ ), in its slight barrier I$_2$ exists due to effect of ‘superweak’ superconductivity in N/S sandwich which is working as a quasiparticle trap.

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