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Charge tunneling across strongly inhomogeneous potential barriers in metallic heterostructures: A simplified theoretical analysis and possible experimental tests

Mikhail Belogolovskii*

Donetsk Institute for Physics and Engineering, National Academy of Sciences of Ukraine, 83114 Donetsk, Ukraine

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ABSTRACT

Universal aspects of the charge transport through strongly disordered potential barriers in metallic heterojunctions are analyzed. A simple theoretical formalism for two kinds of transmission probability distribution functions valid for smooth tunneling barriers and those with abrupt boundaries is presented. We argue that their universality has simple mathematical origin and can arise in totally different physical contexts. Finally, we analyze possible applications of superconducting junctions to test the universality of transport characteristics in structurally disordered insulating films *without any fitting parameters* and point out that the proposed approach can be useful in understanding the dynamics of surface screening currents in superconductors with an inhomogeneous near-surface region.

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1. Introduction

Phenomenon of electron tunneling through a thin insulating layer underlies the work of numerous solid-state devices, such as tunnel diodes, Josephson trilayers, memory elements based on magnetic tunnel junctions, etc., and is one of the most fundamental research topics in condensed matter physics [1]. The functionality of a tunnel device is very sensitive to the quality and reliability of the nonconductive interlayer. Standard tunneling theories consider the potential barrier within two extreme approaches: (i) a semiclassical WKB approximation with a slowly varying potential and (ii) that with sharply falling down boundaries (see the insets in Fig. 1). A typical example of the first type of tunneling devices is a triangular potential well, usually encountered at the semiconductor heterojunction interfaces. Metal–insulator–metal (MIM) heterostructures belong to the second type of the junctions. In both cases the main potential parameters are frequently assumed to be constant along the barrier plane.

Miniaturization of electronic devices, the principal driving force behind the modern microelectronics industry, has led to the fact that precise control of the material properties of thin insulating interlayers in MIM junctions as well as those of a Schottky potential-energy barrier at a metal–semiconductor interface becomes more and more difficult. As a result, a significant amount of different defects appears within the potential barrier. Due to the exponential dependence of the electron transmission probability on the barrier height and width, their presence considerably complicates the implementation of the claim for maximum junction reproducibility. In particular, such a problem arises in amorphous oxides where the lack of long-range order allows for local rearrangements of atoms. This effect becomes strongly pronounced in ultra-thin oxide films due to the deficit oxygen [2]. Another example discussed in the paper is the presence of a self-organized percolative filamentary structure in conducting marginally stable (anomalously soft) materials which can be especially pronounced at their surfaces [3]. We expect that our theory presented below can be applied to different types of highly disordered interfaces as well as to surface sheaths in metallic inhomogeneous structures.

From the first sight, in such systems it is very difficult to achieve a balance between the two generally opposed features,

* Tel.: +380 669392450.
E-mail address: bel@fti.dn.ua

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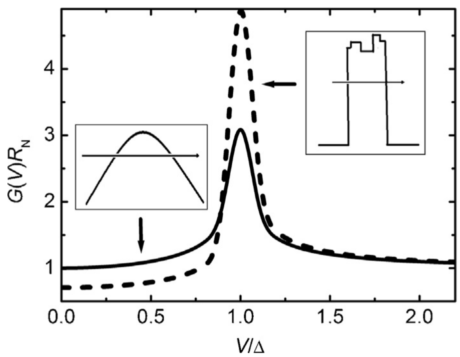

Fig. 1. Normalized conductance spectra of NIS junctions with a strongly disordered insulating interlayer, R_N = const is the junction resistance in a normal state. The solid and dashed lines were calculated with distribution functions (1) and (2), respectively. The insets show schematically shapes of the potential barriers that were assumed in deriving the relations (1) and (2).

reproducibility and disorder. At the same time, in the interfaces with a strong disorder the situation is simplified by the inherent complexity of the problem which manifests itself in a large number of degrees of freedom. Indeed, in this case, we can apply statistical tools for quantifying transport properties of the films and, on the base of the knowledge, we are able to seek new strategies for controlling and improving their material characteristics. In this work, we discuss two generic features of the defect-related charge transport across strongly inhomogeneous potential barriers, the mathematical simplicity of underlying physical models and the emergence of universality.

Characteristics of transmission through random media are determined by the statistics of eigenvalues of the scattering matrix **S** which encodes fully multiple scatterings within the medium and thus forms the basis of a powerful approach to quantum and classical wave propagation [4]. For a scattering sample with N propagating channels, the elements S_{ba} of the $N \times N$ scattering matrix are the flux transmission coefficients between N inputs and N outputs, a and b. In general, description of the wave propagation in strongly scattering media is a fundamental challenge in disordered systems theory. But some important points of this problem have been reliably established. In particular, thirty years ago it was found that in quasi-one-dimensional samples transmission of waves in some eigenchannels can be strongly enhanced and that the eigenvalues D_n of the Hermitian matrix $S^{\dagger}S$ have a bimodal distribution consisting of a large number of strongly reflected “closed” eigenchannels and a number of “open” eigenchannels with $D_n \simeq 1$ [5,6]. The same bimodal result was derived later by Nazarov [7] for the distribution of transmission eigenvalues in higher dimensional diffusive samples.

In the literature there are two analytical formulas for the probability distribution function of local barrier transmission coefficients (transparencies) D in disordered potential barriers. The first one

$$P_1(D) = \frac{\pi\hbar\bar{G}}{2e^2}\frac{1}{D(1-D)^{1/2}} \tag{1}$$

was derived by Dorokhov for diffusive conductors [5] but recently was successfully applied also to classical waves such as light, sound, and microwave radiation [8–10]. The second analytical expression

$$P_2(D) = \frac{\hbar\bar{G}}{e^2}\frac{1}{D^{3/2}(1-D)^{1/2}} \tag{2}$$

was got by Schep and Bauer [11] who considered extremely high and infinitely thin barriers between metallic electrodes. In the next section of the paper we shall show that the two formulas for a strongly inhomogeneous set of potential barriers can be easily derived using a standard scattering approach to elastic tunneling events [4] wherein Eqs. (1) and (2) correspond to a semiclassical WKB approximation with slow spatial dependence of the potential barrier in the transition region and that with abrupt barrier walls, respectively.

Note that in both limiting cases shown schematically in the insets in Fig. 1 system's transport characteristics are controlled by the only macroscopic parameter $\bar{G} = \int_0^1 P(D)G(D)dD$, the disorder-averaged macroscopic conductance, where $G(D) = (2e^2/h)D$. Hence, the distribution functions look very universal. In this context, the notion of universality means that quantitative features of the charge transport across a heterostructure with a locally disordered potential barrier (such as asymptotic behavior, etc.) can be deduced from a single global parameter, without requiring knowledge of the system details. In the third section we attract attention to the fact that comparatively simple dependence of the barrier transparency D on a single governing parameter obtained for smooth and sharp barriers is not limited to these cases but is of a more general character. We provide examples of such relationships which are identical mathematically (and, thus, have the same distribution functions) but come from entirely different physical origins.

Possible means to test the reliability of relations (1) and (2) are discussed in the fourth section. It is argued that the best way to verify them is to perform low-temperature transport measurements in trilayered MIM samples where one or two electrodes are in the superconducting state. It is so due to a very high sensitivity of the shape of measured characteristics to the barrier transmission coefficient D [12]. Moreover, normalization of experimental curves measured in the superconducting state on relevant normal-state characteristics [1] or determination of the ratio of two principally different quantities in a superconducting state (see below) permits to eliminate the last adjustable parameter in formulas (1) and (2), the average macroscopic conductance of the insulating interlayer. This makes it possible to perform test experiments *without any fitting parameters.* Some new experimental data are analyzed from this perspective. At the end of this section, we discuss SQUID-magnetometry measurements of superconducting surface characteristics of borides [13,14] to demonstrate the applicability of the universal function (1) to non-transport experiments as well. In the last section the results of this work are summarized.

2. Two universal distribution functions for local transparencies of microscopically disordered potential barriers

In order not to complicate the calculations and to restrict ourselves to principal aspects of the problem, let us consider for simplicity a planar MIM junction. Components $\mathbf{k}_{||}$ of charge wave vectors parallel to the barrier plane are real quantities which do not change when the charge crosses the metal/insulator interface [15]. At the interface, charge Bloch states with energies $E = \hbar^2k^2/(2m)$ (m is the electron mass) which are below the Fermi level E_F and at the same time within the dielectric forbidden gap do not vanish right at the metallic surface but rather penetrate into the insulator decaying as $\exp(-\kappa x)$ at the distance of a few atomic layers. The eigenstates of the Hamiltonian for the trilayered MIM structure can be obtained by matching at the M/I interface ordinary bulk Bloch states in the M electrodes and a wave function within the barrier which decays in the direction x perpendicular to interfaces with the decay length given by κ^{-1}. If so, the wave functions in the I interlayer can be actually considered as Bloch functions of the bulk insulator with an associated complex wave vector $\tilde{k} = k_{||} + i\kappa$ and we can regard on the transport problem across the MIM junction as one-dimensional one for a $M_1M_2M_3$ contact of three conductors with wave-vector components $k_{1x} = k_{3x}$ for the left and right electrodes and k_{2x} for the interlayer. In the following, in all three

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