Electron tunneling in small-area junctions

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Abstract

Electron tunneling in small-area junctions has been treated. It is found that at appropriate successful set of barrier parameters and electronic characteristics of electrodes quantization the latteral component of the wave vector manifests itself in the differential conductance as quite noticeable singularities. The second derivative of the tunnel current versus applied voltage should contain a dictinct periodic structure. It is pointed out that possibility of manifestation of size-quantum effect should be taken into account in spectroscopic studying

Key words: electron tunneling, electron standing waves

Quantized electron standing-wave states in thin films have been studying since seventies of the past century [1–5]. But all previous works have dealt with a conventional tunnel junction configuration where the wave vector component k_z (perpendicular to the barrier plane) is quantized. However, such a configuration is not only possible. In recent years the small-area tunnel junctions (for example, break-junctions, point contacts, etc.) are gaining acceptance where the lateral component $k_{||}$ (paralel to the barrier plane) can be quantized. In our opinion, the quantization of the lateral wave vector can occur in the barrier itself. Indeed, in the barrier the electron wave function is decaying only in the z-direction (perpendicular to the barrier plane) as only the k_z -component is imagine, while lateral component $k_{||}$ is real and in this plane the tunneling electron is discribed by a non-decaying wave. So under appropriate conditions, if the junction area is small enough, the electronic spectrum of tunneling electrons can be akin to a set of two-dimension bands arranged perpendicular to the barrier plane.

For the sake of definiteness we shall deal with a contact in which the end of the thin quantized film is adjacent to a bulk metal electrode (see the inset in Fig.1). Similar tunneling contacts were used in [6] for studing anisotropic properties of metal oxide superconductors. For simplicity, we assume that both electrodes are fabricated of the same metal with a quadratic energy-momentum relation so their Fermi energies $E_{F_1} = E_{F_2}$. The tunnel current calculation has been performed following assumptions put in [3,4]. To describe the barrier, we use a trapezoidal model, according to which the application of V causes the shape of the potential barrier to change according to the law $\phi(z, V) =$

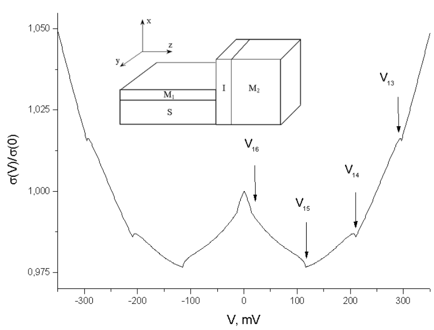

Fig. 1. Conductance vs voltage calculated for parameters: $\varphi_1 = \varphi_2 = 4\ eV$, $d = 10$ Å, $E_{F_1} = E_{F_2} = 1\ eV$, $L = 100$ Å The inset shows the configuration of the tunnel contact under consideration: M_1-thin film quantized electrode, M_2-conventional electrode, $I-$.insulator, $S-$substrate.

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$\phi_1 + (\phi_2 - eV - \phi_1)\, z/d$, where ϕ_1 and ϕ_2 are the barrier heights, d is the barrier thickness. We assume the tunneling to be elastic and specular, i.e., the total energy of a tunneling electron and its parallel component of quasimomentum are conserved. At $T = 0$, the occupied states for the nth subband of the quantized electrode lie in the circle whose radius is $k_1 = \sqrt{2m\,(E_{F_1} - E_n)}/\hbar$ (all energies are measured from the bottom of the conduction band of the initial electrode). At the bias voltage the states of electrons taking part in the tunneling lie within the semi-ring defined by the radii k_1 and $k_2 = \sqrt{2m\,(E_{F_1} - eV - E_n)}/\hbar$ and $k_z > 0$. In contrast to [3,4], these electrons have different tunneling probabilities $P\,(E_z, V)$ and group velocities therefore the calculation of the tunneling current needs integrating over all these states. For $eV < E_{F_1} - E_n$ we have obtained

$$J_n\,(V) = K\left[\int_0^{E_{F_1}-E_n} P\,(E_z,V)\,k_1\,(E_z)\,dE_z - \int_0^{E_{F_1}-eV-E_n} P\,(E_z,V)\,k_2\,(E_z)\,dE_z\right], \qquad (1)$$

for $eV > E_{F_1} - E_n$,

$$J_n\,(V) = K \int_0^{E_{F_1}-E_n} P\,(E_z,V)\,k_1\,(E_z)\,dE_z \qquad (2)$$

$$k_1\,(E_z) = \sqrt{2m\,(E_{F_1} - E_n - E_z)}/\hbar,$$

$$k_2\,(E_z) = \sqrt{2m\,(E_{F_1} - eV - E_n - E_z)}/\hbar,$$

where $K = \sqrt{\frac{m}{2}}\frac{e}{(\pi\hbar)^2}$.

Analytical expressions for the contribution of the nth subband to the tunneling conductivity have been obtained by differentiating formula (1) and (2) with respect to voltage. The total conductivity is the sum over all two-dimensional subbands

$$\sigma\,(V) = \sigma_0\,(V) + 2\sum_{n=1}^{N} \sigma_n\,(V)\,. \qquad (3)$$

Results obtained in the WKB-approximation for the quantized electrode with thickness $L = 100$ Å are presented in Fig.1. It shows that for electrodes with the Fermi energies of the order of 1 eV the electron standing wave states manifest themselves in the tunneling conductivity at voltages $V_n = (E_{F_1} - E_n)\,/e$ as quite detectable singularities. According to [7], a zero bias anomaly in $\sigma\,(V)$ (Fig.1) should be attributed to the small value of the Fermi energy. In Fig.2 the dependence of the second derivative d^2I/dV^2 versus bias voltage V obtained by numerical differentiating is presented. It contains sharp dips located at nearly regular intervals over all range of the bias voltages. In a contact with a not uniformed quantized electrode the dips due to the parts of different thickness are superimposed. This leads to a non-reproducible structure in the $d^2I/dV^2 - V$ curve. This fact could explain the complex structure observed in experimental curves far beyond the electron-phonon interaction spectrum [8].

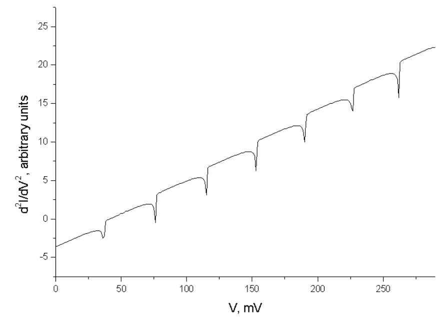

Fig. 2. d^2I/dV^2 versus bias voltage V numericaly calculated for $L = 250$ Å The remaining calculating parameters coincide with corresponding values in Fig.1

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