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Comparative study of resonant and sequential features in electron field emission from composite surfaces

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ABSTRACT

A simple model of a layered hetero-structure was developed and used to simultaneously compute and compare resonant and sequential electron field emission currents. It was found that, while various slope changes appear in both current-field characteristics, for the sequential tunneling type of emission, such features are merely interference effects. They occur in parts of the structure, prior to the electrons' lingering in the quasi-bound states from which field emission proceeds. These purely quantum effects further combine with the flow effects resulting from the steady current requirement and give corresponding field variations of the electron population of the quasi-bound states, which further react on the resonant part of the current. A spectral approach of the two types of field emission is also considered by computing the total energy distribution of electrons in each case. The differences between these possible spectra are pointed out and discussed.

1. Introduction

Sequential tunneling has been proposed for a long time as a possible transport process in hetero-structures [1], along with the resonant tunneling one. To some extent, these two processes have been regarded as equivalent [2] and sometimes probably confounded (merely since resonant tunneling was long viewed as a very appealing and promising transport process across hetero-structures) [3]. Certain authors viewed sequential tunneling as a consequence of some sort of internal damping in the hetero-structure that destroys the coherence of the electronic wave functions required for resonant tunneling [4]. Such processes do obviously occur [5,6], but one should also consider situations when both sequential *and* resonant tunneling contribute simultaneously to the total current. Further research, performed mainly in the context of electron field emission (FE) phenomena from composite emitters [7–11], outlined marked differences between these two processes. Correct interpretation of FE current–voltage (I–V) characteristics requires a more careful revisiting of the theoretical backgrounds of both tunneling mechanisms. Indeed, features resulted from both resonant and sequential tunneling may appear on the same I–V diagram and one should be able to distinguish between them and eventually to estimate the relative contributions of both these effects. Equally important is to appreciate the differences in FE energy spectra resulting from electrons emitted through resonant tunneling and through sequential tunneling, as well as to control their behavior. This could help drawing useful conclusions regarding the fabrication and operation of FE-based electron sources working preferentially with one or the other of the two tunneling mechanisms.

To outline some of these issues (though it is clearly acknowledged that the problem is hugely complicated in its full detail), a relatively simple model of layered hetero-structure has been analyzed in the present research. When thinking of sequential tunneling, one basically assumes that the outgoing particle emerges from some quasi-bound states where it was prepared following at least one previous tunneling process. Consequently, our model hetero-structure was fitted with a potential energy barrier consisting of a thin layer of insulating wide band gap (WBG) substance deposited right on the cathode. The quasi-bound states form in another layer of conductive material further deposited on the WBG. When an external field, perpendicular to these layers, is applied in the vacuum a second barrier is formed at this interface, thus allowing the extraction of FE electrons. Our discussion places a special emphasis on the configuration parameters of the structure. Thus, it is found that the I–V characteristics obtained through resonant tunneling are mainly influenced by the configuration of the potential well (the topmost conductive layer). On the contrary, the various features appearing on the sequential I–V diagrams seem to be determined by the parameters of the WBG barrier. A detailed analysis is performed in order to elucidate this aspect.

Unlike previous approaches [12–15], the electrons undergoing FE through sequential tunneling are selected from those unable to resonantly penetrate the structure by the couplings between the resonant and the quasi-bound states. These interactions have thus been considered as a possible replenishment mechanism of the quasi-bound states involved in the sequential FE. Adding to the complexity of the present analysis, it was assumed that the local equilibrium of the electron

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population in the quasi-bound states is established as a result of the balance between the steady-state emission and replenishment flows [7,16].

The implications of the type of tunneling (resonant or sequential) on the total energy distribution of the FE electrons are also evaluated and a clear difference in the spectral responses of the two mechanisms is pointed out.

2. Model description

Tunneling electron transport in resonant and/or sequential regimes may occur in a very broad range of circumstances. The considered FE layered hetero-structure is obviously one of the simplest choices intended to avoid covering any essential physical aspects by various possible technical complications. As indicated, it consists of a thin (in the range of few nanometers) planar conductive layer separated from a cathode by an equally thin WBG parallel layer, where any space charge is neglected. The thicknesses of these layers will be further denoted by *a* and *b*, respectively. The anode is placed remotely in the vacuum. Thus, the structure comprises a potential energy well in the conductive layer between two barriers, the WBG and the vacuum ones. The energy diagram for this structure is shown in Fig. 1 for three values of the vacuum field strength. The cathode is considered as a heavily doped semiconductor and the origin of the energy scale is taken at its conduction band minimum. The position is measured along the *z*-axis, which is assumed perpendicular to the planar hetero-structure and pointing towards the vacuum side. It is clear that a continuum of running states with positive energies exists across the system. This would allow for possible resonant electron transfer from the cathode into the vacuum (on the obvious provision that the coherence of the electronic waves is preserved across the structure). In a quasi-classical picture, an electron originating in the cathode area may behave in two possible ways: 1) It may remain in its initial running state where it has the chance to get all the way to the vacuum; 2) It may be transferred in a quasi-bound state of the potential well through interactions with various lattice imperfections. If the electron takes the first way, then it is said of behaving coherently and its eventual emission into the vacuum is resonant. In the second alternative, an electron population is expected to establish in the quasi-bound states of the potential well wherefrom they further decay into the vacuum through a so-called sequential tunneling FE process.

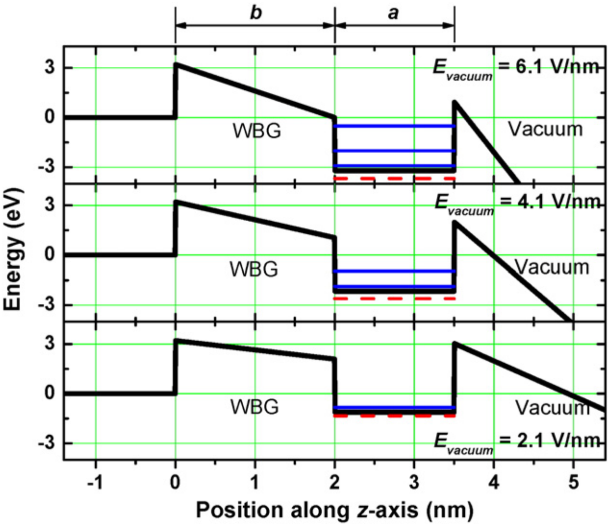

Fig. 1. Energy diagrams of the model hetero-structure for three values of the field applied in the vacuum region (only conduction bands are visible). The origin of the energy scale is taken at the cathode's conduction band minimum. Positions are measured along the *z*-axis, which is perpendicular to the layers and points towards the vacuum side. The local Fermi level in the topmost conductive layer is plotted in dashed (red) line and the energies of the quasi-bound states are drawn with thinner (blue) solid lines.

To address the resonant FE, the typical matching relations of the one-electron wave function's envelop must be stressed at every interface [17]:

$$\psi_i(z_{ij}) = \psi_j(z_{ij}) \tag{1}$$

and

$$\frac{1}{m_i}\frac{\partial\psi_i}{\partial z}(z_{ij}) = \frac{1}{m_j}\frac{\partial\psi_j}{\partial z}(z_{ij}), \tag{2}$$

where *i* and *j* are indexes for the two adjacent regions, *z* is the spatial coordinate perpendicular to the interfaces, z_{ij} is the position of the interface and $m_{i,j}$ are the corresponding electron effective masses. The ensuing computation of the resonant transmission probability is relatively lengthy, but straightforward [17] and will be skipped in the present discussion. Although the considered hetero-structure is simple enough to allow for a quasi-analytical treatment of the problem in terms of plane waves and Airy functions [13], a compact expression of the resonant transmission probability is not possible. Only the near-resonant tunneling regimes can be approximately described by relatively simple formulas [17]. As we are interested in the whole energy range of the emitted electrons, no such compact approximations may be used and the computations of the transmission probability have been performed numerically. We note here that this quantity, $T_{res}(W)$, depends only on the "*z*-part" of the electron energy, *W*, which is obtained by extracting its "in-plane" kinetic energy from the total energy *E*: $W = E - \frac{\hbar^2}{2m}(k_x^2 + k_y^2)$, where *m* and $k_{x,y}$ are the local values of the electron effective mass and "in-plane" components of the wave vector, respectively. Using the quasi-classical definition of the supply function *N*(*W*) (that is the rate at which conduction electrons hit the unit area of the cathode–WBG interface), one may write the resonant FE current density as:

$$J_{res} = e\int_0^\infty N(W)T_{res}(W)\mathrm{d}W, \tag{3}$$

where *e* is the value of the elementary charge. The explicit form of *N*(*W*) can also be found in classical reference texts [18]:

$$N(W) = \frac{m_1 k_B T}{2\pi^2\hbar^3}\ln\left(1 + e^{\frac{\mu_0 - W}{k_B T}}\right), \tag{4}$$

where m_1 is the effective mass of the electron in the cathode, μ_0 is the chemical potential (also called Fermi level thereafter) in the cathode and k_B is the Boltzmann's constant.

In dealing with the sequential tunneling FE, one must address both the decay of the quasi-bound states through the vacuum barrier and the replenishment of these states with electrons from the continuum, following their interactions with the lattice imperfections. In this category, one must include the lattice vibrations, the interfaces, various impurities, etc. Generally, such interactions are described by quite complicated and specific Hamiltonians [5,6] and the detailed forms of the rates of these processes depend strongly on the concrete emitting structure. As our arguments target the general behavior of such emitters, we deferred entering in such complicated details and considered several steps of approximation. First, instead of detailing the processes that drive the electrons into the quasi-bound states, we used the approximation of a common constant matrix element of all such replenishment interactions. Also, as the widths of the WBG layer, as well as that of the topmost conduction one, are to be