ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 3, September 2013

Electron Transmission Influenced by Gate-Voltage in a Resonance Mesoscopic System

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***Abstract* — Electron transmission (transmittance) in a symmetric coupled-quantum-well system with a triple-barrier (TB) is calculated using Landauer-Buttiker formalism. The coupled-quantum-well (CQW) is modeled by tight-binding method. The transmittance for both positive and negative applied bias voltage is presented. It is observed that the non-local tunneling is enhanced by decreasing the applied a plunger-gate voltage (V_{pg}) in the positive bias voltage while the local tunneling is almost unaffected. In contrast, in the negative bias voltage, the local tunneling is suppressed by decreasing the applied plunger-gate voltage. These observed features may strongly support the so-called electron pumping nano devices.**

Index Terms — **Electronic transport in mesoscopic systems, quantum well devices, single-electron tunneling, tight-binding method.**

I. INTRODUCTION

Resonance tunneling of an electron through a multi-barrier device is one of the basic physical phenomena that lie at the heart of quantum mechanics. In the last two decades, attention has been given to the multi device semiconductors including classical study [1] and quantum properties. The TB systems have recently become an interesting mesoscopic system. This can be clearly attributed to their wide range of applications in the photonic devices [2]. Electron transport in TB systems is extensively studied to investigate thermal properties [3-5], current-voltage characteristics [6,7], and geometrical effect of the TB systems on electron transmission [8,9]. Further study of TB system have been done including interaction of hole and photon with electron. In the presence of electron-hole interaction [10], the current is decreased via a so-called hole accumulation effect. The transmittance for both symmetric and asymmetric TB system has been calculated [11]. It is shown that the enhancement of inter-well transmittance is relatively depends on the geometric of the TB system.

Up to now, several formalisms have been used to calculate the electron transmittance through multi-barrier nanostructure including effective-mass equation [12], propagation matrix method [13], Boltzmann transport equation [14] and Green function method [15,16]. These methods have been intensively used for investigating the resonance electron transmission peaks in the TB systems, but without taking the effect of applied plunger-gate voltage on the transmittance peaks into account. The V_{pg} may control the electron motion through the quantum channels. Consequently, the resonance peaks can be also controlled. The modeling of electron transmission through a TB system under applied plunger-gate voltage in both forward and reverse bias voltage is still lacking. In this work, we have used Landauer-Buttiker method to calculate the transmittance of electrons through a TB system that connected to two electron reservoirs from both left and right ends. The effect of plunger-gate voltage on the electron transmission through a symmetric TB system is presented for both positive and negative applied bias voltage.

Generally, in the presence of V_{pg}, the energy spectrum of the central system is shifted with respect to the chemical potential (Fermi-level) of the electron reservoirs (lead). As a result, so-called double-resonance peaks are observed. These peaks are attributed to both non-local tunneling (electron tunneling from the electron reservoir to the TB system) and local or inter-well tunneling (electron tunneling from one of the quantum well to the other quantum well) processes.

The present study covers the following sections. In Sec. II a short description of the Hamiltonian system together with the calculation of the transmittance coefficients have been presented. The main results have been presented and discussed in Sec. III. Finally, Sec. IV is devoted for conclusion.

II. THEORY

In this section we briefly show the main lines of our model and its theoretical method. The system is a composite of a finite central system (S) which is connected to two leads from both left (L) and right (R) ends. The left and the right leads play a 'source' and 'Drain' roles, respectively, as presented in Fig. 1 (top panel). The chemical potential of the left (μ_L) and right (μ_R) leads are assumed to be constant. The central system is a triple-barrier structure, with equivalent heights and widths to those barriers that form a CQW system. The CQW is symmetric in size, which means that its constituent's quantum-wells have the same width. The symmetric CQW or symmetric TB system gives symmetric energy levels to the central system as shown in Fig. 1 (bottom panel). Applying an external plunger-gate voltage to one of the two quantum wells causes to break down that symmetry energy levels; this in turn effects the electron transmission in the system. In our calculations we have assumed that the plunger-gate voltage V_{pg} is applied to the left quantum well. In numerical calculations, the Landauer-Buttiker is applied in the lattice model to calculate the transmittance. The tight-binding

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method is used here, so the TB system is modeled by a discrete lattice. The generic Hamiltonian of the composite

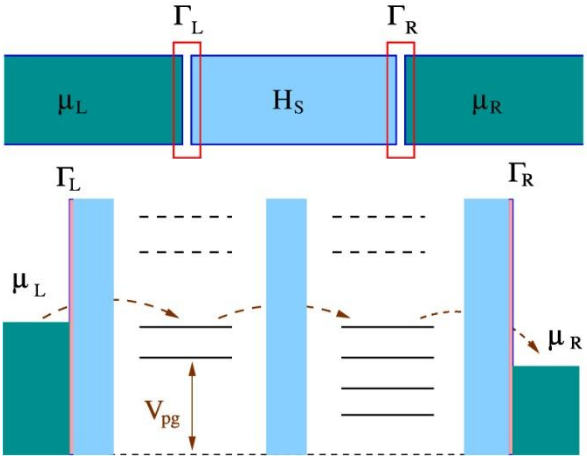

Figure 1. Schematic representation: of the central system and the two leads (top panel), and the energy levels of the TB system with broadening coupling $\Gamma_{L,R}$ in the transfer region (bottom panel) in the case of postive bias. The chemical potential of the left and the right leads are denoted as μ_L and μ_R respectively.

System, which consists of the central system and the leads, is

$$H = H_S + H^{L,R} + H_T^{L,R} ....(1)$$

$H^{L,R}$ are the Hamiltonian of the left (L) and right (R) leads, respectively. H_T with superscript (L,R) defines the energy-dependent coupling between the TB system and both left (L) and right (R) leads; while H_S is the TB system Hamiltonian which can be defined as follow:

$$H_S = \sum_{n=1}^{M} (\varepsilon_n + V_{TB} + eV_{pg}) \,|\, n\rangle\langle n \,| ....(2)$$

where M is the number of sites in the TB system, ϵ_n is the single electron energy, V_{TB} is a potential that defines the triple-barriers [11], e is the electron charge. The transfer Hamiltonian H_T is represented by:

$$H_T^{L,R} = t \sum_{n=1l} (|\, n\rangle\langle 1n \,| + H.c.) ....(3)$$

Herein, t is the coupling strength between the TB-lead systems. The label *1l* stands for the first closed site of TB-system to the (l = L,R) lead, and the notation *ln* denotes the site of the (L,R) lead which is the closed one to the TB-system.

The electron transmission can be defined as the probability that any single electron impinging on the central system from the leads will tunnel and contribute to the transport. If the Hamiltonian of the TB system H_S is known, we can easily get the transmission coefficient from Landauer-Buttiker formalism [15] which can be written as:

$$T(E) = Tr(\Gamma_L G^S \Gamma_R G^{S\dagger}) ....(4)$$

where G^S is the Green function of the TB-system which can be defined as:

$$G^S_{n,1n} = \langle n \,|\, (H_S - \Sigma_L - \Sigma_R)^{-1} \,|\, 1n\rangle.$$

$\Gamma_{L,R}$ contains information about the coupling broadening , and depends on the self-energy $\sum_{L,R}$ of the leads.

III. Results And discussion

In this section, we present the main numerical calculations which are obtained from previous theoretical section. We assume that the electric nanostructure is fabricated by GaAs-based semiconducting materials with electron effective mass $m^* = 0.067m_e$. A one-dimensional finite TB-system has been considered. It is connected to 1D leads which is held at constant temperature, such that the thermal energy becomes $k_BT = 0.025$ eV.

In our considered lattice model, the composite system is described as follow: each barrier has 2 sites and each of the quantum-wells has 10 sites with a lattice constant of a = 0.3 nm. The number of sites can be increased, but at substantially higher computational costs. The TB system is assumed to be symmetric, which means that both quantum-wells have the same size. The length of each quantum well (L_{QW}) is equal to 2.7 nm. The barriers have equivalent width, $W_b = 0.3$ nm, and height, $h_b = 1$ eV.

In the following section, we show how the electron transport processes can be influenced by the plunger-gate voltage, and then the transmittance for both positive and negative bias voltage has been calculated

A. *Positive Bias Voltage*

Here, by positive bias voltage we mean forward bias voltage. The chemical potential of the left lead μ_L is assumed to be higher than the chemical potential of the right lead μ_R. As has been clearly reported in previous studies [17], we have observed double-peaks in the TB-system devices. These peaks are attributed to resonance between energy levels of the system with the chemical potential of the leads. The first peak is due to resonance between energy levels of left (right) quantum-well with the chemical of the left (right) lead. In this process an electron tunnels from the left (right) leads to left (right) quantum-well. This process is called non-local tunneling. On the other hand, the second peak denotes the resonance between the energy levels of the quantum-wells. This is known as local-tunneling (or inter-well tunneling).

In this work, we applied a plunger-gate voltage to the left quantum-well as shown in Fig. 1 (bottom panel). Depending on both value and sign of the applied voltage, both local and non-local electron tunneling processes are affected. Fig. 2 shows the electron transmittance in the presence of a positive bias voltage with a fixed bias voltage $\Delta\mu = \mu_L - \mu_R = 0.12$ eV. The results are presented for three different plunger-gate voltages $V_{pg} = 0.02$V (blue dotted line), 0.0V (red line) and -0.02V (green dotted line). The energy levels are tunable as a

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ISO 9001:2008 Certified
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function of plunger-gate voltage, V_{pg}, following E_S (V_{pg}) = $E_S(0)$ + e V_{pg}. The left peak reaches its maximum value when $E_S(V_{pg}) = \mu_L$. At this point the transmittance becomes 100% as we will see in the following.

At V_{pg} = 0.02 V (blue dotted line), corresponds to the upward shift in the left quantum-well energy levels, two peaks are observed at E_L = 0.088 eV and E_R = 0.143 eV with transmittance ratio ~50% and ~90% respectively. At this value of V_{pg} perfect transmittance does not exist.

In the absence of the plunger gate voltage (V_{pg} = 0.0 V) (red line) the transmittance of the left peak is enhanced to ~82% at E_L = 0.08 eV, while the transmittance of the right peak is enhanced to ~100% at E_R = 0.13 eV. This reflects the fact that the local-tunneling (inter-well tunneling) is dominated in the absence of the plunger-gate voltage. We should remember that the inter-well tunneling exhibits a full quantum-mechanical behavior.

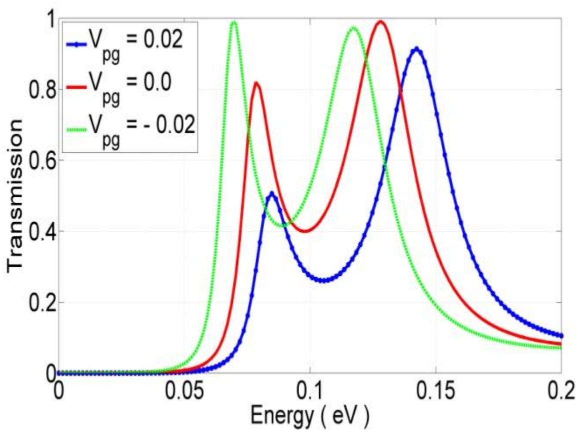

Figure 2. Transmittance versus electron energy of the positive bias volathe Vbias = 0.16 eV for three different value of V_{pg}, V_{pg} = 0.02 V (blue dotted line), V_{pg} = 0.0 V (red line) and Vpg = -0.02 V (green dotted). The TB-lead coupling t = 0.175 eV. Length of each quantum well is 2.7nm, the barrier width Wb = 0.3 nm.

By tuning V_{pg} to -0.02 V (green dotted line), corresponds to the downward shift in the left quantum-well energy levels, two resonance peaks, left peak (transmission ratio ~100%) and right peak (transmission ratio ~95%), have again been observed. The left peak is denoted the resonance between the chemical potential of the left lead μ_L and an energy level of the left quantum-well, in which the TB-lead system have to satisfy $E_L(V_{pg}) = E_L(0)$ + e V_{pg}. The energy level $E_S(0)$ = 0.08 eV is shifted down to $E_L(0)$ + e V_{pg} = 0.08 – 0.02 = 0.06 eV, which gets resonance with the chemical potential of the left lead μ_L = 0.06 eV. This causes an electron tunnel to the left quantum-well from the left lead. At this point the transmittance becomes 1 (~100%). This transmittance enhancement in the right peak is arising from a better alignment of the energy levels between quantum wells. At this plunger-gate voltage, both the non-local tunneling and the local tunneling are dominated in the TB system.

B. Negative Bias Voltage

In the presence of negative applied bias voltage (reverse bias voltage) the electrons are flowing in the opposite direction, which means that the electrons are going from the right lead to the TB system then to the left lead. Here, transmittance peaks observed between the resonance energy levels between quantum-wells and resonance energy between the left quantum -well and the left lead are investigated.

Fig. 3 shows the transmittance peak for three different negative bias voltages, V_{pg} = 0.02 V (blue dotted line), V_{pg} = 0.0 V (red line), and V_{pg} = -0.02 (green dotted line).At V_{pg} = - 0.02 V (green dotted line) the transmittance ratio for both left and right peaks are ~48% and ~90% respectively.

In the absence of the applied plunger-gate voltage (V_{pg} = 0.0V) (red line) the non-local tunneling process become dominant in the TB system. In this case the transmittance ratios are ~82% and ~100% for the left and right peak respectively.

At V_{pg} = 0.02 V, two resonance peaks are appeared with transmittance ratio ~100% and ~98% for the left and the right quantum-well, respectively. Here, perfect alignment between the energy levels of the left lead and the left quantum well exists. In addition, there is also perfect alignment between energy levels of the left and right quantum wells. At this range of the plunger-gate voltage both the non-local and local tunneling are observed.

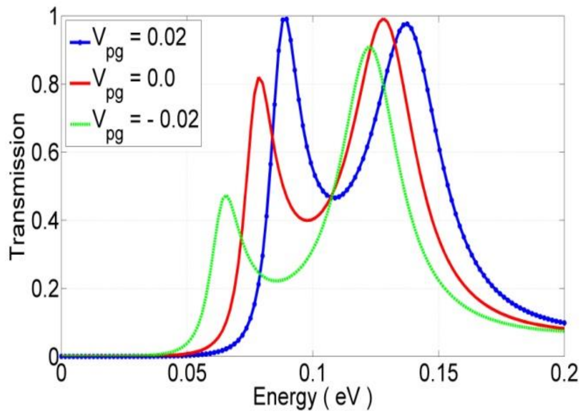

Figure 3. Transmittance versus electron energy of the negative bias volathe Vbias = 0.16 eV for three different value of V_{pg}, V_{pg} = 0.02 V (blue dotted line), V_{pg} = 0.0 V (red line) and V_{pg} = -0.02 V (green dotted). The TB-lead coupling t = 0.175 eV, and = μ_L - μ_L = eV. Length of each quantum well is 2.7nm, the barrier width Wb = 0.3 nm.

Fig. 4 demonstrates the transmittance versus the plunger-gate voltage. Here, the transmittance ratio is ~100% at V_{pg} = 0.02 V. This peak corresponds to the left peak of the Fig. 3 (blue line). In this case the TB system exhibits non-local and local tunneling features.

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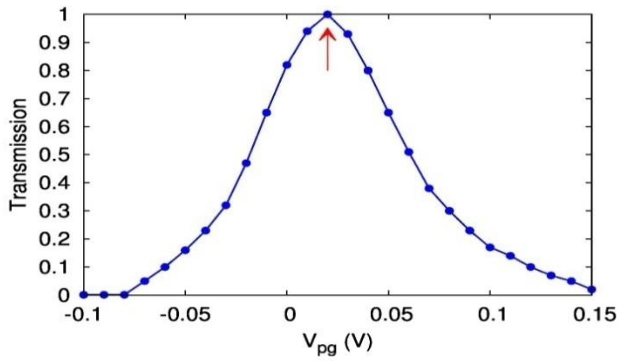

Figure 4. Transmittance versus plunger-gate voltage for the case of Vpg = 0.02 of the Fig. 3 (blue dotted line). Electron energy E = 0.08 eV, t = 0.175 eV. The other parameters are the same as Fig. 3.

IV. CONCLUSION

We have investigated the electron transmittance through a multi-barrier mesoscopic electronic system by using Landauer-Buttiker formalism, in this method a Green function was used to introduce the electron transmittance. In the numerical calculations, the tight binding method has been used to model the TB-system.

In our results, a double resonance peak structure in the transmittance was observed which is attributed to resonance between the energy levels of the quantum wells and resonance between the energy levels of the TB-system and the chemical potential of the leads.

We demonstrated that the electron transmittance is affected by an applied bias voltage. In the positive bias voltage, the non-local tunneling effect is dominated by decreasing the plunger-gate voltage, while the local-tunneling remains unchanged. But in the negative bias voltage, the situation is completely different; the local-tunneling effect is enhanced by increasing the plunger gate voltage. Further investigation can be done in our system in the future such as magnetization effect on the transmittance in the TB-system.

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