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Resonant Tunneling Properties of Gaussian Double Barrier Potential and Effect of the Electric Field Bias

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Abstract. Resonant tunneling properties of finite Gaussian double quantum barrier structure are studied in the absence and presence of electric field bias. Non-equilibrium Green's function method based on the finite difference method is used. A detailed analysis of the resonant energy level is given and the importance of system parameters is discussed. The dependence of the transmission properties on the barriers and electric field bias are revealed. A comparison between different barrier shape data is presented.

***Keywords*:** Non-equilibrium Green's functions, Gaussian double barrier, Resonant tunneling, Electric field bias.

Gausyen Çift Bariyer Potansiyelinin Rezonans Tünelleme Özellikleri ve Elektrik Alan Biasının Etkisi

Özet. Gausyen kuantum çift bariyer yapısı, elektrik alan biası yokluğunda ve varlığında incelenmiştir. Sonlu farklar metodu temelli denge-dışı Green fonksiyonları yöntemi kullanılmıştır. Rezonans enerji seviyesinin ayrıntılı analizi ve sistem parametrelerinin önemi tartışılmıştır. İletim özelliklerinin bariyerlere ve elektrik alan biasına bağımlılığı incelenmiştir. Farklı bariyer şekillerinin verileri ile bir karşılaştırma sunulmuştur.

***Anahtar Kelimeler*:** Denge-dışı Green fonksiyonları, Gausyen çift bariyer, Rezonans tünelleme, Elektrik alan biası.

1. INTRODUCTION

The resonant tunneling phenomena through a one dimensional double-barrier system have enticed interest among theoretical and experimental studies [1, 2]. Electron energy spectrum of quantum wells or barriers are originated from the quantization, material compositions and geometry of structure which are adjustable parameters [3]. These structures are already used in designing in detectors, high switching devices applications and memory devices applications.

Studies of different shape of the double barriers and wells have attracted the attention of scientists since the early days of quantum mechanics. The experimental study of semiconductor barrier structures is expanding rapidly, and electric field effects are shown to be of great importance [1-3]. In recent years, various theoretical approaches such as Airy function transfer matrix method [4, 5], Wigner function method [6] and Non-equilibrium Green's function method [7, 8] have been employed to calculate the resonance energy and transmission properties of electrons in a double barrier potential. Despite several works having been devoted to the search of different shape of the double-barrier structure, to the best of our knowledge, no effort has been paid to the resonant tunneling characteristics of Gaussian double barrier (GDB).

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In the present paper, resonant tunneling properties of Gaussian double quantum barrier potential are theoretically calculated in the presence of electric field bias. The reason behind the consideration of Gaussian potential profile is that it is very close to the real devices potential profile and fabrication methodologies that are available.

The outline of the rest of this paper is as follows. In Section 2, we present the model and method. Results are given in Section 3 and we finally summarize our conclusions in Section 4.

2. MODEL AND METHOD

As a model potential, we consider one dimensional Gaussian double barriers of height V_L and V_R, respectively. Double Gaussian quantum barriers can be defined as

$$U(x) = V_L e^{-\frac{(x+L_W)^2}{2\sigma^2}} + V_R e^{-\frac{(x-L_W)^2}{2\sigma^2}} \quad (1)$$

σ is the standard deviation, Lw is peak position and separation between two barrier heights is $2L_w$ as depicted in Figure 1. The time-independent Schrödinger equation for a one dimensional potential $U(x)$ is

$$-\frac{\hbar^2}{2m^*}\frac{d^2\psi}{dx^2} + U(x)\psi = E\psi \quad (2)$$

where m^* is the effective mass of the electron, E is its energy. We assume that the electron's effective mass is constant over the entire region.

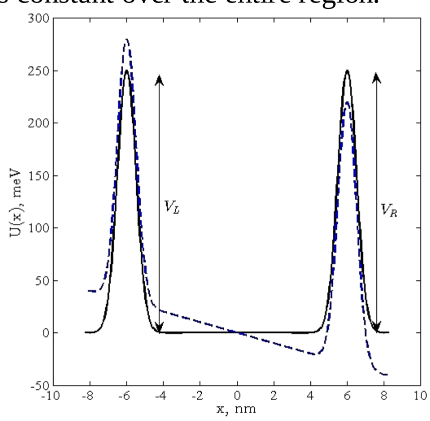

Figure 1. Potential profiles of Gaussian double barriers. The values of the parameters are given as $V_L = V_R = 250$ meV, $L_w = 6.0$ nm $\sigma = 0.05$ nm. The solid line represents the potential profile of symmetrical GDB structure without electric field bias and dashed lines stand for case when the electric field ($F = 50.0$ kV/cm) is applied.

To establish the non-equilibrium Green's function formalism based on finite difference discretization, since the formulation is given and discussed in Refs. [7, 8] in detail, we will give only definition. Retarded Green's function is defined as,

$$[G^r] = [(E + i\eta)I - H - \Sigma_L - \Sigma_R]^{-1} \quad (3)$$

where η is an infinitesimally small positive number. Σ_L and Σ_R are self-energy terms of left and right contact (see refs [7,8]). Transmission coefficient $T(E)$ can be computed as follows:

$$T(E) = Tr[\Gamma_L G^r \Gamma_R G^{r+}] \quad (4)$$

Where $\Gamma_L = i[\Sigma_L - \Sigma_L^+]$ and $\Gamma_R = i[\Sigma_R - \Sigma_R^+]$ are referred to broadening functions.

3. RESULTS

Electronic application of resonant tunneling devices can be studied from the knowledge of resonant tunneling energies and transmission coefficient $(T(E))$. Accurate estimations of these parameters play an important role in devices design. In this section, numerical calculation of resonance energy (E_{res}) and $T(E)$ has been performed by using the non-equilibrium Green's function method based on finite difference discretization.

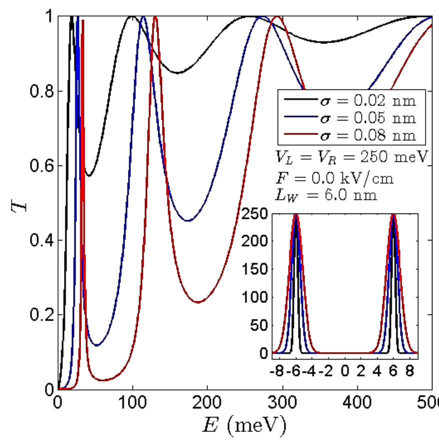

Figure 2. The transmission coefficient changes due to the chancing standard deviation of GDB.

The T versus E plots in Figure 2 show the variation of the transmission probability with the energy of an electron incident on a GDB. The results reveal that increasing of σ causes sharper unity resonant tunneling peaks and shifting to the higher energy region. Besides, the width of peak depends on the softness of the barrier structure. We can also see resonance energy levels shifting to the higher energy region with increasing standard deviation of GDB in Table 1.

Table 1. Resonance energy states of DGB with different σ for $V_L = V_R = 250$ meV, $L_w = 6.0$ nm $F = 0.0$ kV/cm.

σ (nm)	E_{res1} (meV)	E_{res2} (meV)
0.01	14.41	93.69
0.02	18.02	99.1
0.03	21.02	103.9
0.04	24.02	108.7
0.05	26.43	113.5
0.06	28.83	118.9
0.07	30.63	124.3
0.08	33.03	130.6
0.09	34.83	136.3
0.1	37.24	142.3

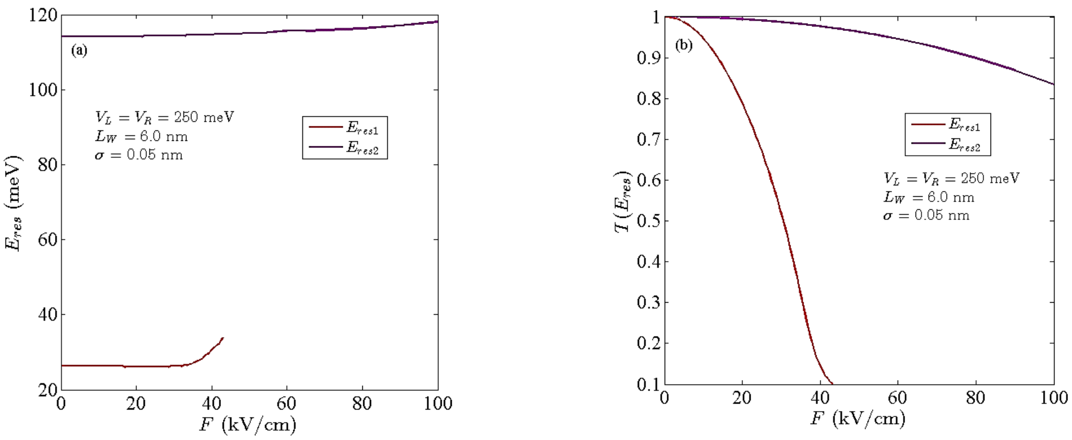

Figure 3. The variation of the (a) resonance energy and (b) amplitude of the resonant peak as a function of applied electric field bias.

Figure 3 illustrates how the resonance energy and transmission coefficient at resonance energy changes due to the chancing electric field bias. We fixed the system parameters to $V_L = V_R = 250$ meV, $L_w = 6.0$ and $\sigma = 0.05$ nm. To understand the electric field bias effect, in Fig. 3 (a) location of the resonant peak (E_{res}) and (b) the transmission probability at resonance energy $(T(E_{res}))$ are plotted, respectively. It is seen that the transmission probability at resonance energy decreases with the increasing electric field bias. Electric field bias causes an asymmetry. Asymmetry of the GDB potential is explored and is found to reduce transmission of the resonant energies. This mechanism can be used to control population trapping in the central well.

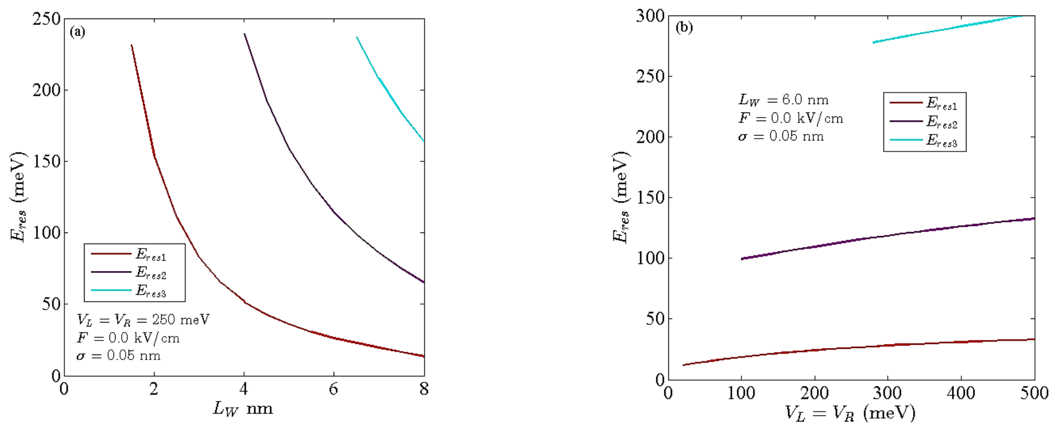

Figure 4. Dependence of the resonance energies (a) peak position (b) with respect to varying barrier heights.

The effect of the barrier separation on the transmission probability for GDB is seen from Figure 4 (a). With higher barrier separation, resonant tunneling phenomenon occurs at lower energy. We see that the resonance energies decrease exponentially with the increasing barrier separation. These findings show that the shift in the resonant energy is sensitive to the L_w . Meanwhile, crucial feature of the figure is the emergence of a third resonant energy occurred at higher energy that is a marker on the existence of third quasi-bound state. The effect of the barrier width on the resonant peak is shown in Figure 4 (b) for constant $L_w = 6.0$ nm and $\sigma = 0.05$ nm. From this figure, as expected we observe that, due to the enhanced confinement of the electron, increment in the barrier height leads to a shift in the position of the resonance energies toward a higher energy region.

The dependence of transmission coefficient on the barrier height and width makes manifest the sensitivity on the smoothness of the potential profile. When all energy range is considered, Gaussian double-barrier structures have lower resonant tunneling energy compared to rectangular double-barrier structures [9, 10]. Moreover, distinctive features of the resonant energy emerge for varying widths and heights of the potential barriers.

4. CONCLUSION

In this paper, we investigate the electric field bias and structure parameter effect in Gaussian double-barrier structure. The calculated results affirmed that the structure parameters of the systems and bias field strongly affect the resonant tunneling characteristics and thus can be controlled by these parameters. Different functional forms of the barriers may be studied to learn their characteristic features. A further challenging problem is to consider multiple barriers and external applied electric and magnetic field effects, which are necessary to model realistic devices.

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