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Electronic properties of double GaAlAs/GaAs and GaInAs/GaAs quantum wells as dependent on well width

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Abstract. Herein, the electronic properties of double Ga_{1-x} Al_x As/GaAs quantum wells (A model) and Ga_{1-x} In_x As/GaAs quantum wells (B model) have been examined related to the well width. The wave functions, the subband energies and the probability densities of these systems under effective mass approach were determined by the solution of Schrödinger equation. According to the results obtained, the major diversities of A and B models are the effective mass and the energy gap. For A model, GaAlAs is the barrier and GaAs is the well. Whereas for B model, GaAs is the barrier and GaInAs is the well. Also, the potential depth and the energy levels of A model are continuously smaller than of B model. The well width has a great impact on the electronic features of the double quantum well (DQW). These features have a convenient attention for the purpose of adjustable semiconductor devices.

Keywords: Double GaAlAs/GaAs quantum well, Double GaInAs/GaAs quantum well, Well width, Electronic properties.

Çift GaAlAs/GaAs ve GaInAs/GaAs kuantum kuyularının kuyu genişliğine bağlı olarak elektronik özellikleri

Özet. Bu çalışmada, çift Ga_{1-x} Al_x As/GaAs kuantum kuyularının (A yapısı) ve Ga_{1-x} In_x As/GaAs /GaAs kuantum kuyularının (B yapısı) elektronik özellikleri kuyu genişliğine bağlı olarak incelenmiştir. Etkin kütle yaklaşımı kullanılarak, Schrödinger denkleminin çözümüyle enerji seviyeleri, dalga fonksiyonları ve bu sistemin olasılık yoğunlukları hesaplanmıştır. Elde edilen sonuçlara göre, A ve B yapısının temel farklılıkları yasak enerji aralığı ve etkili kütledir. A yapısı için engel GaAlAs ve kuyu GaAs'dır. B yapısı için ise engel GaAs ve kuyu GaInAs'dır. Ayrıca, A yapısının potansiyel yüksekliği ve enerji seviyeleri her zaman B yapısından düşüktür. Kuyu genişliği, çift kuantum kuyusunun (DQW) elektronik özellikleri üzerinde büyük bir etkiye sahiptir. Bu özellikler, ayarlanabilir yarı iletken cihazların tasarımı için pratik bir ilgiye sahiptir.

Anahtar Kelimeler: Çift GaAlAs/GaAs kuantum kuyusu, Çift GaInAs/GaAs kuantum kuyusu, Kuyu genişliği, elektronik özellikler.

1. INTRODUCTION

The electronic features of the low-dimensional structures are highly dependent on the presence of the asymmetry of the potential profile of a semiconductor quantum well (QW). Such asymmetry in potential profile may provide an electric field or can rank the potential shape as a

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composition, and thus it is well known that the electronic features of QW structures vary substantially. We are concerned in observing the structure of a double quantum wells (DQW) shaped by two different semiconductors (e.g, GaAs/GaAlAs and InGaAs/GaAs). These systems contain two potential wells coupled by a barrier. They are very suitable structure for observing quantum electronic transport. Because GaAlAs / GaAs QW systems are applied in modern photo-electronics and high-speed electronic devices, the electrical and optical properties of the related systems have been widely investigated under both the pressure and external fields [1-7]. The segregation of indium atoms in the GaInAs layer has been extensively researched in current times, as the understanding of high-performance devices desires sudden hetero-interfaces [8-10]. It is also known that the indium atoms are powerfully related to the growth temperature and the GaInAs/GaAs structure is allocated from the growth surface during MBE growth.

The double-quantum well (DQW) structures are very interesting for the device industry because by the interlayer distance between wells and the barrier alters, a development in the transport features is realized. The presence of a quantum limiting effect for the energy levels of a thin single quantum well is mostly considered. In DQWs, it is necessary to define the potential limiting effects that characterize the energy levels of isolated wells and the eigenstates of the systems affected weakly through a potential barrier. DQW semiconductors are important hetero-structures for technological applications because they are anticipated to be the basis for application to new electron devices [11-12]. The focus benefit of multiple semiconductor structures over single QWs is the advanced exciton electro-optic response. The opto-electronic features of the excitons in DQWs promise a range of potential applications in high-speed spatial light modulators and switches. This study focused on the theoretical research of the electronic features of $Ga_{1-x}Al_x As/GaAs$ and $Ga_{1-x}In_x As/GaAs$ DQW depending on the well width (WW). A model and B model will be named for $Ga_{1-x}Al_x As/GaAs$ DQW and $Ga_{1-x}In_x As/GaAs$ DQW, respectively. There are on the left hand side Semi V-shaped QW (SVQW) and on the right hand side Inverse Semi V-shaped QW (ISVQW). As far as we know, this is the first literature study on the electronic features of such DQW. The motivation for using many DQW with different shapes is to create multi wavelength optical devices.

2. MATERIAL and METHOD

In the effective-mass approach, the wave functions and the state energies for electrons in DQW, which are enlarged along the z-axis, may be achieved by dissolving the one-dimensional Schrödinger equation with a suitable Hamiltonian.

$$\left(-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2}+V(z)\right)\Psi(z)=E\,\Psi(z) \tag{1}$$

where $V(z)$ is the confined potential, and E and $\Psi(z)$ are the eigen-energy and eigen-function of the Eq. (1) solution. The limited potential of DQW, b being the barrier width, L_R and L_L being the right and the left quantum WWs, respectively, are given by

$$V(z)=V_0\begin{cases}-\frac{1}{L_L}\left(z+\frac{b+L_L}{2}\right) & -\left(L_L+\frac{b}{2}\right)\le z\le-\left(\frac{L_L+b}{2}\right)\\ \frac{1}{L_L}\left(z+L_L+\frac{b}{2}\right)-\frac{1}{2} & -\left(\frac{L_L+b}{2}\right)\le z\le-\left(\frac{b}{2}\right)\\ \frac{1}{L_R}\left(z-\frac{(b+L_R)}{2}\right)+\frac{1}{2} & \left(\frac{b}{2}\right)\le z\le\left(\frac{L_R+b}{2}\right)\\ -\frac{1}{L_R}\left(z-\left(\frac{b}{2}+L_R\right)\right) & \left(\frac{L_R+b}{2}\right)\le z\le\left(\frac{b}{2}+L_R\right)\\ 1 & \text{elsewhere}\end{cases} \tag{2}$$

The effective mass of electron and the discontinuity in the conduction band edge of $Ga_{1-x}Al_xAs/GaAs$ [13-14] and $Ga_{1-x}In_xAs/GaAs$ [13, 15] are analyzed using the following equations.

$$m^*_{GaAlAs} = (0.067 + 0.083\,x)m_0 \quad (3a)$$

$$m^*_{GaInAs} = (0.067 - 0.04\,x)m_0 \quad (3b)$$

$$V_0{}^{GaAlAs} = \%60\left(E_g^{GaAlAs} - E_g^{GaAs}\right) \quad (4a)$$

$$V_0{}^{GaInAs} = \%60\left(E_g^{GaAs} - E_g^{GaInAs}\right) \quad (4b)$$

Where $E_g^{GaAlAs} = \left(E_g^{GaAs} + 1247\,x\right)$ meV, $E_g^{GaInAs} = \left(E_g^{GaAs} - 1619\,x + 555\,x^2\right)$ meV, $E_g^{GaAs} = 1424$ meV.

The confined potential of QW is significant for the enclosure of electrons. Thus, the finding possibility of the electrons in different QWs is provided by,

$$P_i^W = \int \left|\Psi_i^W(z)\right|^2 dz \qquad (i = 1,2; \quad W = L,R) \quad (5)$$

where R and L indicate the right QW (RQW) and the left QW (LQW), serially.

3. RESULTS AND DISCUSSION

We have theoretically examined the electronic features of A and B models depending on the x-concentration for DQW. In this study, $x = 0.15$, $b = 2.5$ nm, and $T = 300$K.

For different well width values (where $L = L_L = L_R$), Fig. 1 (A model) and Fig. 2 (B model) demonstrate the confinement potential, the bound energy levels and squared wave functions referred to these energies. As understood in Eq. (3) and Eq. (4), the important differences of A and B model are the energy gap and the effective mass. For A model, GaAs is the well and GaAlAs is the barrier, and the potential depth is about $V_0{}^{GaAlAs} = 112$ meV. For B model, GaInAs is the well and GaAs is the barrier, and the potential depth is about $V_0{}^{GaInAs} = 138$ meV. As estimated, the energy levels of A model with smaller potential depth are continually lower than the energy levels of B model. As seen from these figures, while A model have three bounded states for $L = 8$ nm, there are two bound conditions in B model. It is seen that the electron in the ground state is mostly located in LQW and the electron in the

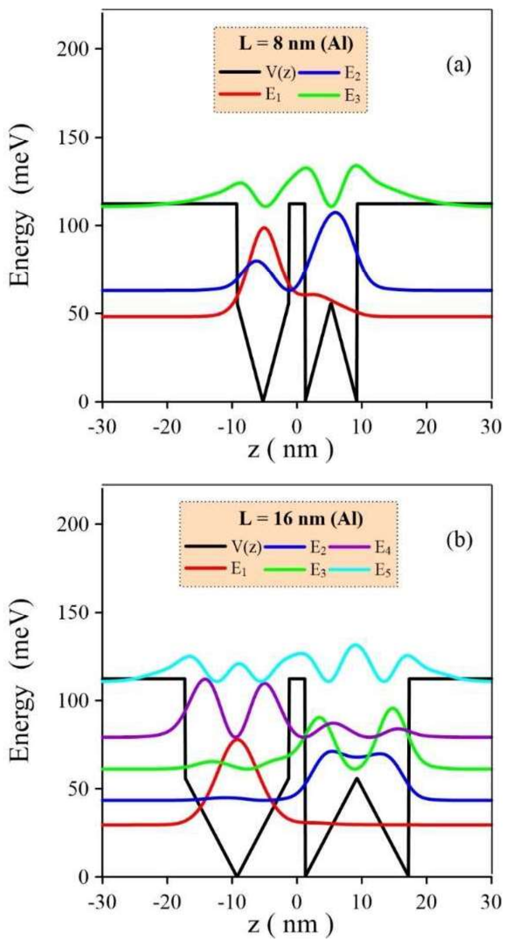

Figure 1. For DQW (A model), the confined potential and the bound energy levels with their squared wave functions for a) L= 8 nm, b) L = 16 nm.

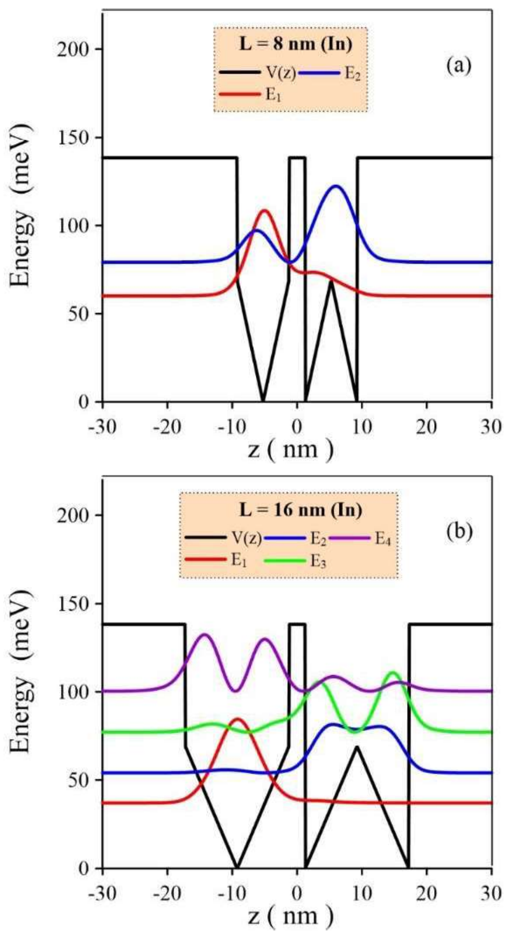

Figure 2. For DQW (B model), the confined potential and the bound energy levels with their squared wave functions for a) L= 8 nm, b) L = 16 nm.

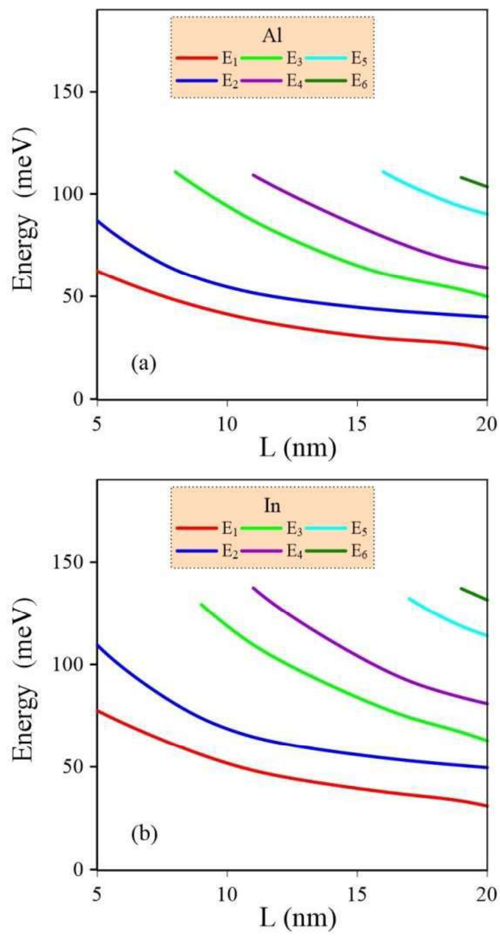

Figure 3. For DQW the variation of bound energy levels versus the L values for a) A model, b) B model.

second energy level is localized in RQW. For $L = 16\,nm$, there are five bounded states in A model and four bounded states in B model. The most affected by the change of the potential profile is the low energy particles, so the electron in the ground state energy is wholly found in LQW. But the electron in the second energy level behaves as if it is confined by a symmetrical double well in RQW. Other energy levels are based on the shape of QWs.

For A and B model, the variation of bound energy levels in DQW as a function of WW between $L = (5 - 20)\,nm$ are shown in Fig. 3a and Fig. 3b, serially. The energy levels of DQW with different QW shapes are different from each other. As expected, all energy levels change by increasing WW values. The energy levels of A model are constantly lower than the energy levels of B model. As the wells expand, the values of the energy levels decrease and more bounded state energy levels exist in the wells. The third bounded state energy appears in A model at $L = 8\,nm$, while in B model it occurs for $L = 9\,nm$. In both models, the fourth and sixth energy levels are localized in DQW at $L = 11\,nm$ and $L = 19\,nm$, serially. The fifth energy level for A and B model was located within the wells at $L = 16\,nm$ and $L = 17\,nm$, respectively. The differences are due to the smaller mass of the electron in B model. Therefore, if it is desired to obtain more bound state energy levels depending on L value, then A model should be preferred.

For A and B model, the finding probability of the electron in LQW and RQW for first three bounded energy states are given in Fig. 4a and Fig. 4b as a function of WW, respectively. In both models, for the initial value of $L = 5\,nm$, the ground state and the second state energy levels are located in LQW and RQW, serially, and they settle more as WW increases. The third energy level is found in both LQW and RQW where the well width is small ($L < 11\,nm$), but with the increase in WW (fourth energy level appears also at $L \geq 11\,nm$), it is located in RQW. The probability densities in A model is slightly higher than B model.

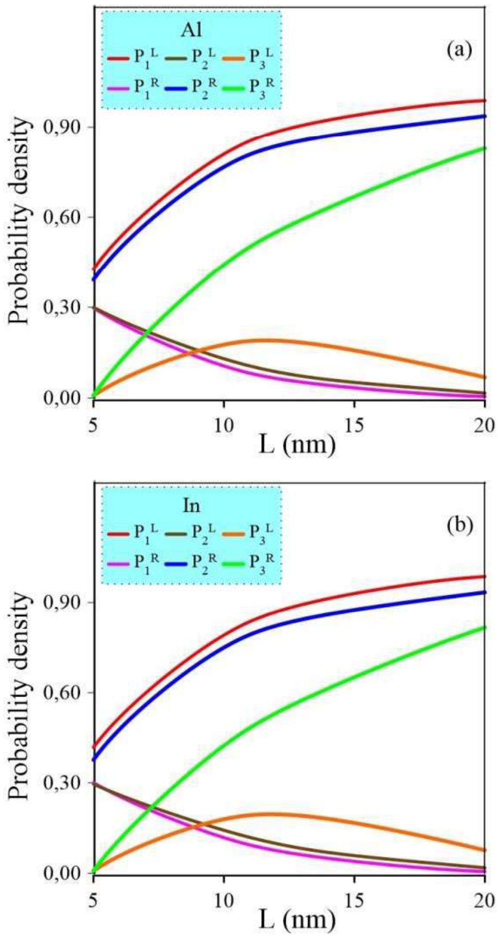

Figure 4. The probability density of the electrons in LQW and RQW for first three bound energy state as a function of the L values for a) A model, b) B model.

4. CONCLUSIONS

In present work, the electronic features of double $Ga_{1-x}Al_xAs/GaAs$ and $Ga_{1-x}In_xAs/GaAs$ /GaAs QWs are observed related to the well width. The greatest essential difference between these models is the size of energy levels. We analyzed the bound energy levels and the finding probabilities of the electrons in DQW. In particular, we have calculated the eigen-energies and the eigen-functions of these models. It is found that depending on the well width of the electronic features of DQW varies for A and B model. These features could be crucial in the improvement of continual wave operation of DQW semiconductor devices. So, we think that these results will provide an improvement in multiple electro-optical semiconductor devices applications, for proper selection of the structural parameters.

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