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Resonant Tunneling in Multibarrier Semiconductor Heterostructure in Relativistic Framework

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ABSTRACT

A mathematical model based on relativistic approach is proposed for the determination of transmission coefficient within the energy range of $\varepsilon < V_0$, $\varepsilon = V_0$ and $\varepsilon > V_0$ for a multibarrier GaAs/$Al_yGa_{1-y}As$ heterostructure. The effect of number of barriers and number of cells in the well and barrier regions on the resonant energies are studied in detail. An additional resonant peak in resonant energy spectrum indicated the presence of a new surface state.

***Key words :** Multibarrier resonant tunneling, transmission coefficient, surface state.*

1. Introduction

The resonant tunneling of an electron wave through multiple potential barriers is one of the basic phenomena in quantum mechanics. It is known that, when the number of barriers is greater than one, for certain incident energies the electrons tunnel out without any significant attenuation in their intensity. In a multi barrier structure (MBS), the transmission coefficient is the relative probability of an incident electron crossing the multiple barriers. Resonant tunneling in the MBS corresponds to unit transmission coefficient across the structure. One of the most striking features of the multi-barrier systems is the occurrence of quasi-level resonant tunneling energy states. Incident electrons on the MBS with energies equal to any one of these quasilevel resonant energy states, suffers resonant tunneling. Resonant tunneling is a consequence of the phase coherence of the electron waves in the quantum wells of the MBS. These quasi level resonant energy states group themselves into tunneling energy bands separated by forbidden gaps. Each allowed energy band comprises (N-1) number of resonant energy states; N being the number of barriers in the MBS.

Research activities on multibarrier resonant tunneling have gained momentum on both theoretical and experimental front since the pioneering work of Tsu [1] and Zhang et al [2]. This motivation may be attributed to the potential and extensive applications of the resonant tunneling phenomenon in high speed electronic devices that encompasses lasers, modulators, photodetectors and signal processing devices [1]. The interest in this field has been catapulted to a new height with the advent of epitaxial growth techniques, and particularly, the technique of molecular-beam epitaxy (MBE) and metalorganic chemical vapour deposition (MOCVD), through which fabrication of perfect superlattices and multi-quantum-well structures became a reality. Besides, the study of tunneling through multibarrier structure (MBS) provides a deeper understanding of the transport phenomena through semiconductor superlattices and similar structures, such as quantum-dot arrays. Hence, a theoretical model for accurate determination of resonant energies in such multibarrier structures [3-5] might help the experimentalists to fabricate ultrahigh-speed electronic and optoelectronic devices. Recently, the electronic conductance in double quantum well systems have been reviewed in [6] and the study of tunneling of a particle or a photonic wave packet through an arbitrary number of finite rectangular opaque barriers has also been reported [5]. Analysis on tunneling across an arbitrary shape of potential barrier and the calculation of tunneling coefficients based on the analytic transfer-matrix technique is provided in a general framework by Zhang et al [7]. A deeper insight of the transport phenomena through semiconductor superlattices, resulting from the study of tunneling through multibarrier system, is given in [8].

Crystalline semiconductor superlattices are usually constructed by growing two compounds, such as GaAs/$Al_y Ga_{1-y}$ As, where the lattice constants are almost identical. It has been reported by Esaki [9] that the model on super lattices is analogous to the Kronig-Penny model with the following conditions; (i) the barrier height is the energy mismatch in the conduction band edges of two materials with different compositions, (ii) The masses in the well and barrier regions are different and they correspond to the effective masses at the conduction band edges respectively.

The electrons in condensed matter consisting of heavy atoms acquire velocities in the order of 10^6m/sec or more. For such velocities, one needs to incorporate relativistic effects. In fact, relativistic effects become important for metals with atomic numbers greater than about 55 and for semiconductors and semimetals with atomic numbers greater than 32. So the tunneling through MBS involving semiconducting materials of heavy atoms requires to be studied relativistically. All the works reviewed so far pertains to calculations in the nonrelativistic framework. The very few works reported on the study of resonant tunneling in MBS using relativistic treatment [10] is limited to the study of resonant energies in the range $\varepsilon \langle V_0$, V_0 being the height of the Potential barrier.

A study of resonant tunneling with incident energies $\varepsilon \geq V_0$ is expected to bring the features of the resonant tunneling energy bands more clearly. Further the resonant tunneling energies depend on the parameters such as the height of the potential barrier controlled through the mole fraction of barrier material vis-a-vis the well material, the thickness of the barrier and well layers and the number of barriers in the structure. We have not come across any such attempt to study theoretically relations of resonant energies on these factors.

The present paper aims to study (i) the tunneling in the multi-barrier systems in a comprehensive manner using relativistic treatments for incident energies for both $\varepsilon \langle V_0$ and $\varepsilon \geq V_0$ (ii) finding an analytical relation between the wave vectors and the resonant energy states in the tunneling energy bands, (iii) examine the dependence of resonant tunneling energies in the MBS on various factors like the height of the potential barrier, the thickness of the barrier, and well layers and the number of barriers in the structure.

We consider a MBS constructed by growing two different semi conducting materials in alternate layers, for example, GaAs and $Al_yGa_{1-y}As$, as shown in Fig. 1(a). The materials in the alternate layers have similar band structure but different energy gaps leading to a potential distribution in the growth direction. The MBS potential is assumed to take the form of alternate rectangular barriers and wells at the conduction and valence band edges along the growth direction and is considered to be superimposed on the intrinsic periodic potential of the host crystal. The effect of periodic crystal potential of the host material is incorporated through the inclusion of band effective mass of the material. Schematic energy diagram for these stacking layers are shown in Fig. 1(b). The low gap material, GaAs, forms the well while the large gap material $Al_yGa_{1-y}As$ forms the barrier of the superlattice. The barrier height at the conduction band edge is assumed [11] to be 88% of the difference between the band gaps of two materials. The MBS with well and barrier regions, originated from the band offset at the conduction band edge is shown in Fig.1(c).

The relativistic treatment of the problem is carried out in the single electron approximation with the use of space dependent effective mass. The transmission coefficient across the MBS is obtained through the transfer matrix. The relativistic treatment requires the two-component spinor solutions to the one-dimensional Dirac equation for a constant potential in the effective mass approximation. The transmission coefficient of electrons through the MBS is determined as a function of the incident electron energy. The resonant energies were obtained in both these treatments by numerical computation and also the relation of the resonant tunneling energies in the tunneling band is obtained analytically.

2. Relativistic treatment of tunneling through symmetric multibarrier semiconductor heterostructure

The tunneling of electrons through multibarrier semiconducting heterostructures can be better understood by a model, as shown in Fig. 1(a). In this model, the multibarrier structure is obtained by a finite number of binary superlattices. A binary superlattice is obtained by alternately stacking layers of semiconducting materials, namely, GaAs and $Al_y Ga_{1-y}$ As. These two materials have similar band structures but different energy gaps. The schematic energy diagram for the stacking layers is shown in Fig. 1(b). The small gap material GaAs forms the well while the large gap material $Al_yGa_{1-y}As$ forms the barrier of the superlattice. The barrier height is assumed [11] to be 88% of the difference between the band gaps of two materials. The superlattice with well and barrier regions, originated from the band offset is shown in Fig.1(c). The model consists of N barriers of thickness 'b', and N-1 wells of thickness 'a'. Thus, the superlattice has a period 'c', where c= (a+b). The height of the potential barrier is considered as V_0.

To derive an expression for the tunneling coefficient for the multibarrier system in the relativistic framework, we need to consider the one-dimensional Dirac equation for an electron in the potential shown in Fig. 1(c).

$$[-i\hbar c\,\sigma_x \frac{d}{dx} + \sigma_z m^* c^2 + V(x)]\phi(x) = E\,\phi(x) \tag{1}$$

where σ_x and σ_z are the usual 2X2 Pauli spin matrices, and $\phi(x)$ is the two component wave function. The wave function in the nth well region ($V_0 = 0$) can be obtained as:

$$\phi_n^{(w)}(x) = A_{2n-1}\begin{bmatrix}1\\ \xi\end{bmatrix}e^{ik_1x} + B_{2n-1}\begin{bmatrix}1\\ -\xi\end{bmatrix}e^{-ik_1x} \tag{2}$$

where $k_1 = \frac{\sqrt{\varepsilon(\varepsilon + 2m_w^* c^2)}}{\hbar c}$, $\xi = \sqrt{\frac{\varepsilon}{\varepsilon + 2m_w^* c^2}}$ and $\varepsilon = E - m_w^* c^2$

The wave function in the nth barrier region can be obtained as

$$\phi_n^{(b)}(x) = \begin{cases} A_{2n}\begin{bmatrix}1\\ i\eta\end{bmatrix}e^{-k_2x} + B_{2n}\begin{bmatrix}1\\ -i\eta\end{bmatrix}e^{k_2x} & for\ \ \varepsilon \langle V_0 \\ A_{2n}\begin{bmatrix}1\\ 0\end{bmatrix} + B_{2n}\begin{bmatrix}x\\ -i\hbar/(2m_b^* c)\end{bmatrix} & for\ \ \varepsilon = V_0 \\ A_{2n}\begin{bmatrix}1\\ \delta\end{bmatrix}e^{ik_3x} + B_{2n}\begin{bmatrix}1\\ -\delta\end{bmatrix}e^{-ik_3x} & for\ \ \varepsilon \rangle V_0 \end{cases} \tag{3}$$

where,

$$k_2 = \frac{\sqrt{\left(2m_b^* c^2 + \varepsilon - V_0\right)\left(V_0 - \varepsilon\right)}}{\hbar c} \quad , \quad k_3 = \frac{\sqrt{\left(2m_b^* c^2 + \varepsilon - V_0\right)\left(\varepsilon - V_0\right)}}{\hbar c},$$

$$\eta = \sqrt{\frac{V_0 - \varepsilon}{2m_b^* c^2 + \varepsilon - V_0}} \qquad and \qquad \delta = \sqrt{\frac{\varepsilon - V_0}{2m_b^* c^2 + \varepsilon - V_0}}$$

In the relativistic treatment the continuity condition across the interfaces of the nth barrier with nth and (n+1)th well region based on conservation of the probability density and the current density appear as :

$$\phi_n^{(w)}(nc - b/2) = \phi_n^{(b)}(nc - b/2)$$
$$\phi_n^{(b)}(nc + b/2) = \phi_{n+1}^{(w)}(nc + b/2)$$

The transfer matrix, M_1, for a single barrier relates the coefficient matrix $\begin{bmatrix} A_3 \\ B_3 \end{bmatrix}$ of the 3rd well region with that of the first well region $\begin{bmatrix} A_1 \\ B_1 \end{bmatrix}$ after tunneling through the first barrier. The matrix elements of M_1 appear as:

$$\left(M_1\right)_{11} = \left(M_1\right)_{22}^* = \begin{cases} \left(\cosh k_2 b + \dfrac{i\left(\xi^2 - \eta^2\right)}{2\xi\eta}\sinh k_2 b\right) e^{-ik_1 b} & for\ \varepsilon \langle V_0 \\ \left(1 - \dfrac{m_b^* c\xi b}{i\hbar}\right) \quad e^{-ik_1 b} & for\ \varepsilon = V_0 \\ \left(\cos k_3 b - \dfrac{i\left(\xi^2 + \delta^2\right)}{2\xi\delta}\sin k_3 b\right) e^{-ik_1 b} & for\ \varepsilon \rangle V_0 \end{cases} \tag{5}$$

$$\left(M_1\right)_{12} = \left(M_1\right)_{21}^* = \begin{cases} \dfrac{\xi^2 + \eta^2}{2i\xi\eta}\sinh k_2 b & for\ \varepsilon \langle V_0 \\ \dfrac{m_b^* cb\xi}{i\hbar} & for\ \varepsilon = V_0 \\ \dfrac{\xi^2 + \delta^2}{2i\xi\delta}\sin k_3 b & for\ \varepsilon \rangle V_0 \end{cases} \tag{6}$$

The 2x2 matrix M_n which relates the coefficient matrix $\begin{bmatrix} A_{2n-1} \\ B_{2n-1} \end{bmatrix}$ of the nth well region with that of the *(n+1)* th well region $\begin{bmatrix} A_{2n+1} \\ B_{2n+1} \end{bmatrix}$ and appears as:

$$M_n = \left(F^*\right)^{n-1} M_1 F^{n-1} \tag{7}$$

where,

$$F = \begin{bmatrix} e^{ik_1 d} & 0 \\ 0 & e^{-ik_1 d} \end{bmatrix} .$$

Thus the transfer matrix W_n which relates the coefficient matrix of the incoming and outgoing wave in the N barrier system appears as

$$\begin{bmatrix} A_{2N+1} \\ B_{2N+1} \end{bmatrix} = \left[W_N\right] \begin{bmatrix} A_1 \\ B_1 \end{bmatrix} \quad ,$$

where, $W_N = M_N M_{N-1} \ldots\ldots M_2 M_1$.

On substitution of from eq (7), the transfer matrix takes the form

$$W_N = \left(F^*\right)^N G^N \quad ,$$

where the matrix $G = F\, M_1$

The matrix W_N is hermitian and its determinant has unit value. Now the G matrix can be diagonalized to the matrix G_d as

$$S^{-1} G\, S = G_d \quad ,$$

Where, $G_d = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$

and, S is the diagonalizing matrix of the matrix G .

λ_1 and λ_2 are the eigenvalues of the matrix G and *satisfy* the following relations.

$$\lambda_{1,2} = \frac{G_{Tr} \pm \sqrt{G_{Tr}^2 - 4}}{2} \quad . \tag{8}$$

The sum of the eigenvalues of G is equal to the trace of the matrix defined as $G_{Tr,}$ which appears as

$$G_{Tr} = \begin{cases} 2\left[\cos k_1 a \,\cosh k_2 b + \dfrac{\eta^2 - \xi^2}{2\xi\eta}\sin k_1 a \sinh k_2 b\right] & \mathit{for}\ \varepsilon \langle V_0 \\ 2\left[\cos k_1 a - \dfrac{m_b^* c\xi b}{\hbar}\sin k_1 a\right] & \mathit{for}\ \varepsilon = V_0 \\ 2\left[\cos k_1 a \cos k_3 b - \dfrac{\xi^2 + \delta^2}{2\xi\delta}\sin k_1 a \,\sin k_3 b\right] & \mathit{for}\ \varepsilon \rangle V_0 \end{cases} \tag{9}$$

$\lambda_1 + \lambda_2 = G_{Tr}$ And $\lambda_1 \lambda_2 = 1$.

The above conditions can be summed up as:

$$\begin{aligned} \lambda_1 &= \frac{1}{\lambda_2} = e^{i\theta} \qquad \theta = \cos^{-1}\left(G_{tr}/2\right) && \mathit{for} \quad G_{Tr} \langle 2 \\ \lambda_1 &= \lambda_2 = 1 && \mathit{for} \quad G_{Tr} = 2 \\ \lambda_1 &= \frac{1}{\lambda_2} = e^{\theta} \qquad \theta = \cosh^{-1}\left(G_{tr}/2\right) && \mathit{for} \quad G_{Tr} \rangle 2 \end{aligned} \tag{10}$$

Using these relations the transfer matrix W_N can be written as

$$W_N = \left(F^*\right)^N S\, G_d^N\, S^{-1} \quad .$$

The transmission coefficient T_N across N barriers can be obtained as

$$T_N = \frac{\left|A_{2n+1}\right|^2}{\left|A_1\right|^2} \quad .$$

In the extreme right [(N=1)th] well, as there is no reflected component, one can set B_{2N+1} = 0. Using this fact the transmission coefficient, T_N , across the N-barrier system can be obtained as:

$$T_N = \frac{1}{\left|\left(W_N\right)_{11}\right|^2} = \frac{1}{1 + \left|\left(W_N\right)_{12}\right|^2} \tag{11}$$

where $(W_N)_{12}$ appears as

$$\left|(W_N)_{12}\right|^2 = \begin{cases} \left|(M_1)_{12}\right|^2 \left|\dfrac{\sin N\theta}{\sin\theta}\right|^2 & for\ \ G_{Tr} \rangle 2 \\ \left|(M_1)_{12}\right|^2 N^2 & for\ \ G_{Tr} = 2 \\ \left|(M_1)_{12}\right|^2 \left|\dfrac{\sinh N\theta}{\sinh\theta}\right|^2 & for\ \ G_{Tr} \rangle 2 \end{cases} \qquad (12)$$

The transmission coefficient T_N across the N barrier system for the three different situations corresponding to the incident energy $\varepsilon < V_0$, $\varepsilon = V_0$ and $\varepsilon > V_0$ can thus be obtained by substituting the relation for the matrix element $(M_1)_{12}$ for these cases from eq (6).

3. Numerical Analysis

The numerical analysis is basically concerned with (i) the transmission coefficient across multibarrier systems for incident energies $\varepsilon < V_0$, $\varepsilon = V_0$ and $\varepsilon > V_0$,(ii) determination of resonant tunneling energies for which the transmission coefficient is unity The procedure for computing the transmission coefficient in the relativistic treatment is based on numerical computation of Eq. (11) incombination with Eqs. (12), (6) and (10). Thereafter these datas were sorted to obtain the resonant tunneling energies in the multibarrier systems by using a search program to find the energies for which transmission coefficient is unity. For the numerical evaluation of T_c and ε_m, we have chosen the GaAs/$Al_yGa_{1-y}As$ (y< 0.45) superlattice with the values of various parameters as follows:

a = the well width = ncw x a_w, where ncw is the number of cells in the well material in each well slab and a_w is the lattice constant of the well material GaAs.

a_w = 5.6533 Å

b= the barrier width = ncb x a_b, where ncb is the number of unit cells of the barrier material in each barrier slab and a_b is the lattice constant of the barrier material $Al_{0.3}Ga_{.0.7}As$.

m_1^* and m_2^* = the effective masses of the well (GaAs) and the barrier $Al_{0.3}Ga_{.0.7}As$ region materials of the superlattice
= 0.065 m_0 and (0.067 + 0.83x 0.3) m_0 ; m_0 is the free electron mass.

E_{g1} and E_{g2} = energy band gap in the well and barrier materials
= 1.428 eV and (1.424 + 1.247x 0.3) eV.

V = height of the potential barrier = 0.88 ($E_{g2} - E_{g1}$)

The energy band gap of $Al_yGa_{1-y}As$ becomes indirect when the value of mole fraction (y) exceeds 0.45, and hence does not conform to the band diagram (shown in Fig. 1(b)). Therefore, for the present calculations we have considered y=0.3.

4. Results and Discussion

The transmission coefficient for GaAS/ $Al_{0.3}Ga_{.0.7}As$ multi barrier systems in a relativistic framework is calculated on the basis of Eq.(11) in combination with Eqs.(12)and (6). Fig (2) depicts the transmission coefficient versus incident energy. The graphs 2(a) and 2(b) show the variation of $T_c \sim \varepsilon$ for systems with ncw=5, ncb=5 having 3 barriers and 9 barriers respectively. The $T_c \sim \varepsilon$ curve for 9 barrier systems with ncw=5, ncb=8 is presented in graphs in 2(c) and that for ncw=8 and ncb=5 in graph 2(d). The graphs clearly show that the transmission coefficient varies rapidly and attains the value of unity for certain incident energies. These energies are referred as resonant energies both for $\varepsilon < V_0$ and $\varepsilon > V_0$.

The resonant energy corresponds to the condition T_c =1 and are obtained from the $\varepsilon \sim T_c$ graphs by a search program. Fig. 3 displays the resonant energies for systems with varied ncw, ncb and N. The resonant energies groups themselves into allowed tunneling bands separated by forbidden gaps. In the forbidden region the transmission coefficient remains zero. In each allowed tunneling band there are N-1 resonant states; N being the number of barriers in the system. In the first band the variation of T_c seems to be rapid and becomes zero in the neighborhood of the maxima. However, the variation of T_c is not that rapid for resonant energies in the higher bands. The T_c in the higher bands remains near the maximum value of unity and the peaks are less sharp.

However in each system, there is one extra energy state observed , where T_c become one. We feel this might be a surface state.

(a) We would like to highlight some of the important aspects of resonant energies obtained on the basis of Eqs. (12) during the resonance tunneling, the electron energy resonates at the bound states of quantum well. Hence, the numbers of allowed minibands in these multi barrier systems are found to be equal to the number of bound energy states in the single finite quantum well having the same parameters as that of the MBS. It may be worth noting here that the number of bound states, j, for $\varepsilon < V_0$ in a finite well depends on the width, *a*, and potential height, V_0, of the quantum well through the relation :

$$j = Int(\beta) + 1$$

where, $\beta = \sqrt{\left(\frac{a}{\pi}\right)^2 \left(k_1^2 + k_2^2\right)_{E=V}} = \sqrt{\frac{8a^2 m_1^* V}{h^2}}$ and

Int. (β) =Integer value of β.

Hence due to phase coherence the number of tunneling bands in multibarrier systems for $\varepsilon < V_0$ will be equal to 'j' which depends on the well width and the height of the potential barrier and is independent of the barrier width

(b) The Eq (11) in combination with Eq (12) is akin to the energy relation for a lattice of period (*a*+*b*) calculated using effective mass dependent Kronig-Penney model. The allowed energy bands are restricted to values of $G_{Tr} < 2$ which corresponds to the allowed values of $\cos\theta$ in Eq.(12).

As can be seen from Eq. (11) in combination with Eq. (12), the resonant state will correspond to $\sin N\theta = 0$ where θ is given in Eq. (10). Thus, there occurs *N-1* values of resonant energies in each band for $\theta = n\pi / N, \quad n = 1, 2, ..., N-1$. Thus for the *N*-barrier superlattice with $(N-1)$ wells, each allowed mini energy band will contain (*N*–1) number of resonance energy states corresponding to the $(N-1)$ values of θ.

Fig. 3(a) presents the resonant energy states for ncw=5 and ncb=5 but for the number of barriers N to be 5, 7, 9. We have considered incident energies up to 1.4eV. In all these three centre we have obtained three allowed tunneling bands with each allowed band containing N-1 resonant states. For low values of N, E_m lies in the center of the band, as N increases E_m spreads out from the central regions of the bands towards the edges. In Fig. 3(b) depicts the resonant energy state for 9 barrier system with constant barrier width with ncb=5 and varying well width with ncw=1, 5, 8 respectively. The number of allowed tunneling bands increases from 2 to 4 when we move from ncw=2 to ncw=8. Further, with increase in ncw, the width of the allowed bands and the forbidden gaps become narrower. The energies of the bound state of the quantum wells move to lower energy values as the width of the well increases. It is worth pointing that in an infinite quantum well the energies of the bound states are inversely proportional to the square of the well width and any increase in well width will cause the bound states to shift to the lower values. Here, the surface state have the same values for all the three cases of well width suggesting that the energy of the surface state is independent of the well width. Fig. 3(c) represents the resonant tunneling energies for the 9 baririer systems for constant well width with *ncw=5* and varying barrier width *ncb*=2, 5, 8. An increase in barrier width causes a decrease in the overlap interactions between the states of adjacent wells resulting in a decrease in the bandwidth which is evident in the graph Fig. 3(c) as we go from *ncb*=2 to *ncb*=8. In Fig. 3(d), resonant energies are presented for a system for 9 barrier system having constant lattice periodicity but varying well width and barrier width. As the barrier width decreases, the surface state moves to lower values of energy. In Fig. 3(d) the inset graph represent the tunneling bands for the *ncw*=5, *ncb*=5 and N=9 system in an extended zone scheme. In all these graphs the surface state is shown as arrow mark.

4. Conclusions

In this work, a model for computation of transmission coefficient for multibarrier semiconductor heterostructure in the relativistic framework is proposed. The resonant energy values are found to be dependent on the number of barriers, number of cells in the well region and number of cells in the barrier region. The results indicate the presence of a new surface state in the resonant energy spectrum. For the system we have considered, the resonant energies calculated through the relativistic treatment tallies exactly with the corresponding values calculated through nonrelativistic framework as for as lower bands are concerned [12]. In the higher tunneling bands the resonant tunneling energies in the relativistic treatment is found to have slightly higher values than those in the nonrelativistic treatment with the relativistic correction appearing only in the fifth place of the energy values. The computation of resonant tunneling energies by this research work may help the experimentalist to fabricate the high-speed semiconductor devices for potential applications.

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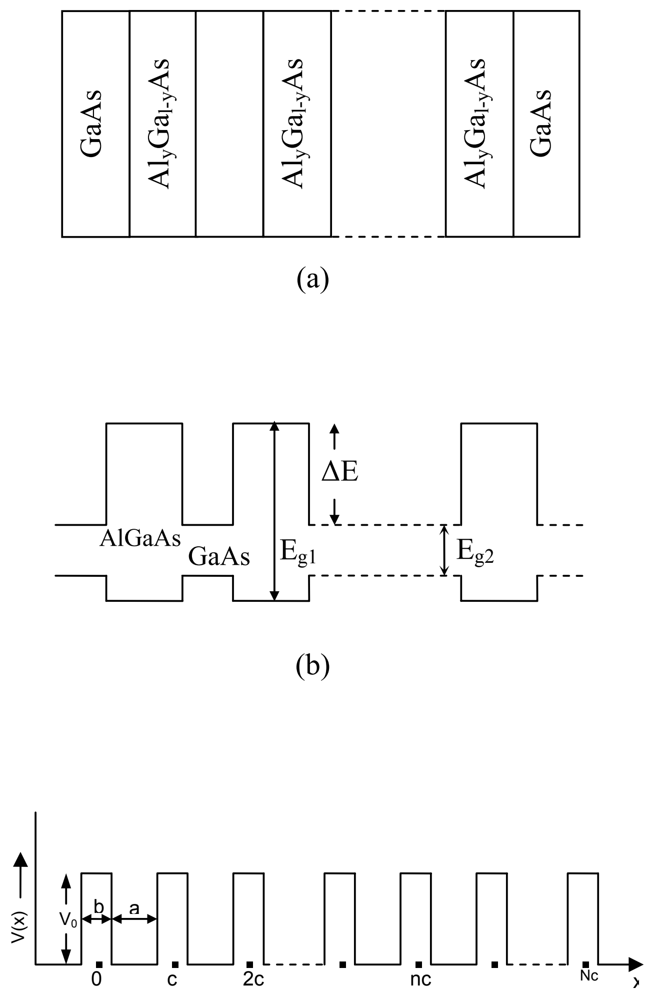


(c)

Figure 1

(a) Schematic diagram of a binary superlattice obtained by alternately stacking layers of semiconducting materials (GaAs and $Al_{0.3}Ga_{0.7}As$). (b) Energy Band diagram of stacking layers. (c) The multibarrier heterostructure with well and barrier regions originating from the band offset.

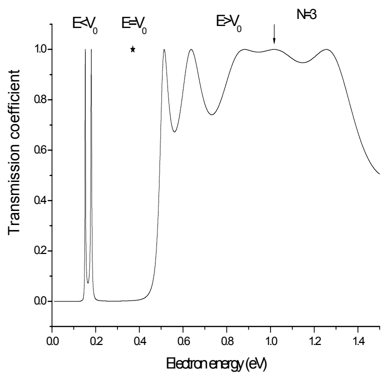
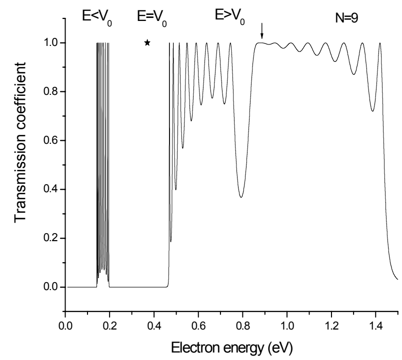


Figure 2(a)



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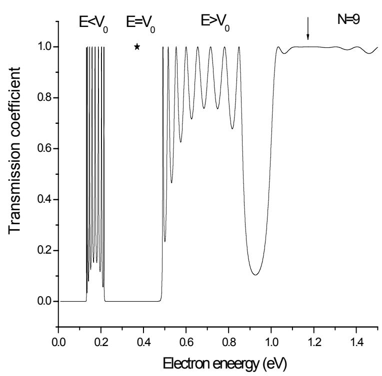

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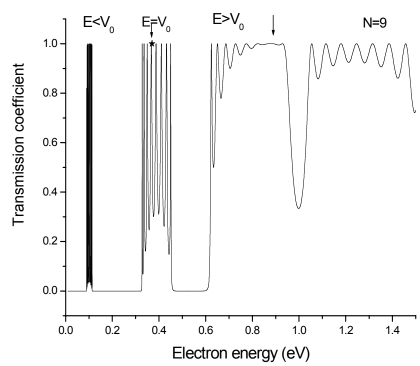

Figure 2(d)

Figure 2 : Transmission coefficient versus electron energy for GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice by varying number of barriers 'N', number of cells in the well region 'ncw', number of cells in the barrier region 'ncb'. The arrow indicates the position of the surface state**.** The star symbol indicates the position $E=V_0$ and shown in the figure to compare the T_c for $E < V_0$ and $E > V_0$. (a) N=3, ncw=5, ncb=5, (b) N=9, ncw=5, ncb=5, (c) N=9,ncw=5, ncb=4, (d) N=9, ncw=8, ncb=5.

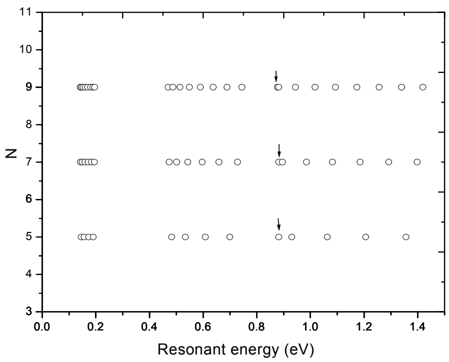

Figure 3(a)

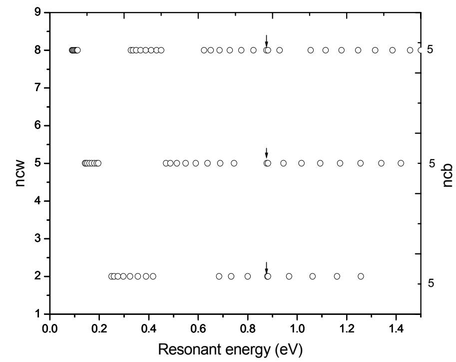

Figure 3(b)

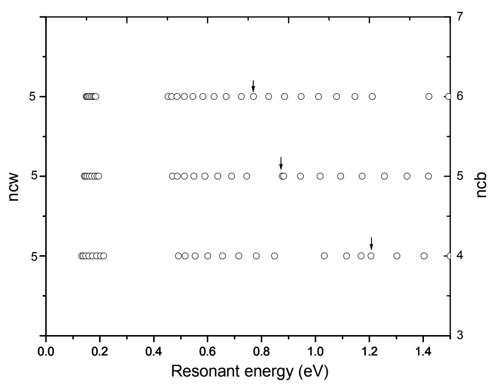

Figure 3(c)

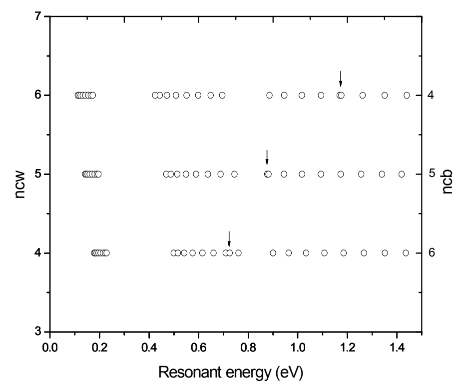

Figure 3(d)

Figure 3 : Resonant energy (E_m) values for $GaAs/Al_{0.3}Ga_{0.7}As$ superlattice. The arrow indicates the position of the surface state. (a) the number of barriers 'N' is varied from 5 to 9, and the number cells in the well region ncw=5, the number cells in the barrier ncb=5. (b) N=9, ncw=2,5,8 , and ncb is fixed at 5. (c) N=9, ncw is fixed at 5, and ncb=4,5,6. (d) N=9, both ncw and ncb are varied simultaneously keeping the total no of cells constant.