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The dependence of resonant tunneling transmission coefficient on well width and barriers number of $GaN/Al_{0.3}Ga_{0.7}N$ nanostructured system

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Abstract

A numerical computation for determination transmission coefficient and resonant tunneling energies of multibarriers heterostructure has been investigated. Also, we have considered $GaN/Al_{0.3}Ga_{0.7}N$ superlattice system to estimate the probability of resonance at specific energy values, which are less than the potential barrier height. The transmission coefficient is determined by using the transfer matrix method and accordingly the resonant energies are obtained from the $T(E)$ relation. The effects of both well width and number of barriers (N) are observed and discussed. The numbers of resonant tunneling peaks are generally increasing and they become sharper with the increasing of N. The resonant tunneling levels are shifted inside the well by increasing the well width and vice versa. These features and the transmission coefficient as a function of incident energetic particles play an important role in fabrication of high speed devices and a good factor for determination the peak-to-valley ratio of resonant tunneling devices respectively.

Key words
Resonant tunneling, Nanostructure, $GaN/Al_{0.3}Ga_{0.7}N$.

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إعتماد عامل النفوذ للتنفق الرنيني على عرض البئر وعدد الحواجز في نظام التركيبة النانوية من $GaN/Al_{0.3}Ga_{0.7}N$

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الخلاصة

تم البحث بإستخدام الحساب العددي في تعيين عامل النفوذية وطاقات التنفق الرنيني للتركيبة غير المتجانسة متعددت الحواجز. وكذلك أخذنا بنظر الأعتبار نظام الشبيكة الفائقة نوع $GaN/Al_{0.3}Ga_{0.7}N$ لتخمين أحتمالية التنفق عند قيم الطاقة المعينة، والتي هي أقل من أرتفاع حاجز الجهد. وقد تم تعيين عامل النفاذية من خلال إستخدام طريقة مصفوفة الإنتقال وبناءاً عليه الطاقات الرنينية المستخرجة من علاقة عامل النفوذية. إن تأثيرات كل من عرض البئر وعدد الحواجز قد لوحظت ونوقشت. إن عدد قمم التنفق الرنيني تزداد بصورة عامه و تصبح أكثر حدةً مع زيادة عدد الحواجز. وأن المستويات الطاقية في التنفق الرنيني تزاح إلى داخل عمق البئر والعكس صحيح. هذه الصور بالإضافة إلى معامل النفوذ بوصفه دالة للجسيمات الطاقية الساقطة على الحاجز تلعب بالنسبة للحالة الأولى قاعدة مهمة في تصنيع نبائط عالية السرعة والحالة الثانية بمثابة عامل جيد في تعيين نسبة القمة إلى الوادي في نبائط التنفق الرنيني على التوالي.

Introduction

Resonant tunneling through superlattice has gained importance because of its application in high speed electronic devices[1] that encompasses lasers, modulators, photo detectors and signal processing devices [2]. The first superlattice constructed from GaAs/GaPAs system, but it did not have the predicted negative differential conductance (NDC), but the first experimental verification of (NDC) in a GaAs/GaAlAs superlattice [3]. Since the pioneering work of Tsu and Esaki [4] on resonant tunneling phenomena through double barrier structures the topic has generated considerable theoretical and experimental interest [5]. Many of these studies are concerned with two-barrier system. In comparison, the study of tunneling through more than two barriers has attracted less attention [6].

In a multibarrier system (MBS), the transmission coefficient is the relative probability of incident electron crossing the multiple barriers. Resonant tunneling in the MBS corresponds to unit transmission coefficient across the structure [2, 5, 7]. One of the most striking features of the multi-barrier system is the occurrence of quasi-level resonant tunneling energy states. When electrons incident on the MBS with energies equal to any one of these quasi-level resonant energy states suffer resonant tunneling in another words when the electrons incident on the MBS with energies equal to resonant state energies tunnel out without any significant attenuation in their intensity. 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 barrier in the MBS [2, 5, 7,8].

Interest in gallium nitride has exploded in the past few years, leading to an expansion of its potential applications on an almost monthly basis. This broad spectrum of applications has led some to predict that GaN will eventually become the third most important semiconductor system behind GaAs and Si [9]. Nitride semiconductor is currently under intensive research, driven by the wide application potential in electronic and optical devices. Key to all of these devices is $Al_xGa_{1-x}N$, which is an indispensable component of both optical and electronic devices based on wide band gap nitrides [10]. Wurtzite GaN and AlN have direct room temperature band gap of 3.4 and 6.2 eV, respectively. In cubic form, GaN has direct band gap while AlN has indirect energy bandgap. GaN to be alloyed with AlN makes available a wide range of energy band gaps [9]. Some basic properties of GaN/AlGaN still remain poorly studied [11]. It is worth noting that GaN/AlGaN system is considered to be highly promising for tomorrow technology.

Hence, it is plausible to devise theoretical model for resonant tunneling of electrons in such multibarrier structures that might help the experimentalists to fabricate ultrahigh-speed electronic and optoelectronic devices[2]. We consider a MBS constructed by growing two different semiconducting materials in alternate layers, we used her, GaN and $Al_{0.3}Ga_{0.7}N$, which having similar band structure but different energy gaps leading to a potential distribution in the growth direction. The transmission coefficient across the MBS is obtained through the transfer matrix approach taking recourse to an exact solution of Schrödinger wave equation [5]. The resonant energies are obtained from transmission coefficient as a function of energy, T(E),[8]. In this paper, we report a study of tunneling of electrons through this MBS. Examine the dependence of resonant tunneling energies on well width and a number of barriers in the structure have been considered.

Theory

In this model, the multibarrier structure was constructed by growing two different semiconducting materials in alternate layers, namely GaN and $Al_{0.3}Ga_{0.7}N$. These two materials 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 barrier and wells at the conduction and valence band edges along the growth direction [2, 5]. The schematic energy diagram for the stacking layers is shown in Fig. 1(a). The small gap material GaN forms the well while the large gap material $Al_{0.3}Ga_{0.7}N$ forms the barrier of the superlattice [5].

The barrier height is assumed to be 75% of the difference between the band gaps of two materials. [12]. The MBS with well and barrier regions, originated from the band offset is shown in Fig. 1(b). In this structure, the barrier width (b),well width (a) and the superlattice period (c) are related with each other's (c=a+b) .

The transmission coefficient, (T_c), of the N barrier superlattice is formulated on the basis of transfer matrix method by using the one dimensional time independent Schrödinger equation, specifically, the Ben Daniel-Duke equation [13] for the electron in the potential V(x). The transmission coefficients (T_c) across N barrier can be obtained as (It detail will be discussed elsewhere [1, 2, 5, 6]):

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

$$|(W_N)_{12}|^2 = \begin{cases} |(M_1)_{12}|^2 \left|\frac{\sin N\theta}{\sin\theta}\right|^2 & for \quad G_{Tr} < 2 \\ |(M_1)_{12}|^2 N^2 & for \quad G_{Tr} = 2 \\ |(M_1)_{12}|^2 \left|\frac{\sinh N\theta}{\sinh\theta}\right|^2 & for \quad G_{Tr} > 2 \end{cases} \tag{2}$$

$$(M_1)_{12} = (M_1)_{21}^* = \begin{cases} \frac{k_1^2+k_2^2 f^2}{2ik_1k_2 f}\sinh^{-1} k_2 b & for \quad \varepsilon < V_o \\ \frac{k_1 b}{2if} & for \quad \varepsilon = V_o \\ \frac{k_1^2+k_2^2 f^2}{2ik_1k_2 f}\sinh^{-1} k_2 b & for \quad \varepsilon < V_o \end{cases} \tag{3}$$

$$G_{Tr} = \begin{cases} 2\left[\cos k_1 a \cosh k_2 b + \frac{k_2^2 f - k_1^2}{2k_1k_2 f}\sin k_1 a \sinh k_2 b\right] & for \quad \varepsilon < V_o \\ 2\left[\cos k_1 a - \frac{k_1 b}{2f}\sin k_1 a\right] & for \quad \varepsilon < V_o \\ 2\left[\cos k_1 a \cos k_3 b + \frac{k_3^2 f - k_1^2}{2k_1k_3 f}\sin k_1 a \sin k_3 b\right] & for \quad \varepsilon < V_o \end{cases} \tag{4}$$

$$\lambda_1 = \frac{1}{\lambda_2} = e^{i\theta}, \theta = cos^{-1}\left(\frac{G_{Tr}}{2}\right) \quad \text{for } G_{tr} < 2$$

$$\lambda_1 = \lambda_2 = 1, \quad \text{for} \quad G_{tr} = 2 \tag{5}$$

$$\lambda_1 = \frac{1}{\lambda_2} = e^{\theta}, \theta = cosh^{-1}\left(\frac{G_{Tr}}{2}\right) \quad \text{for} \quad G_{tr} > 2$$

where:

$$f = \frac{m_w^*}{m_b^*} \quad ; \quad k_1^2 = \frac{2m_w^*\varepsilon}{\hbar^2} \quad ;$$

$$k_2^2 = \frac{2m_b^*(V_o-\varepsilon)}{\hbar^2} \quad ; \quad k_3^2 = \frac{2m_w^*(\varepsilon-V_o)}{\hbar^2}$$

m_w^* and m_b^* are the effective masses of the well and the barrier region materials of the superlattice respectively. Where k_1 is the wave vector in the well, and k_2 and k_3, are the wave vector in the barrier region when $\varepsilon < V_o$, $\varepsilon > V_o$ respectively. While each of a and b are the well-width and barrier-width respectively and V_O is the height of the potential barrier.

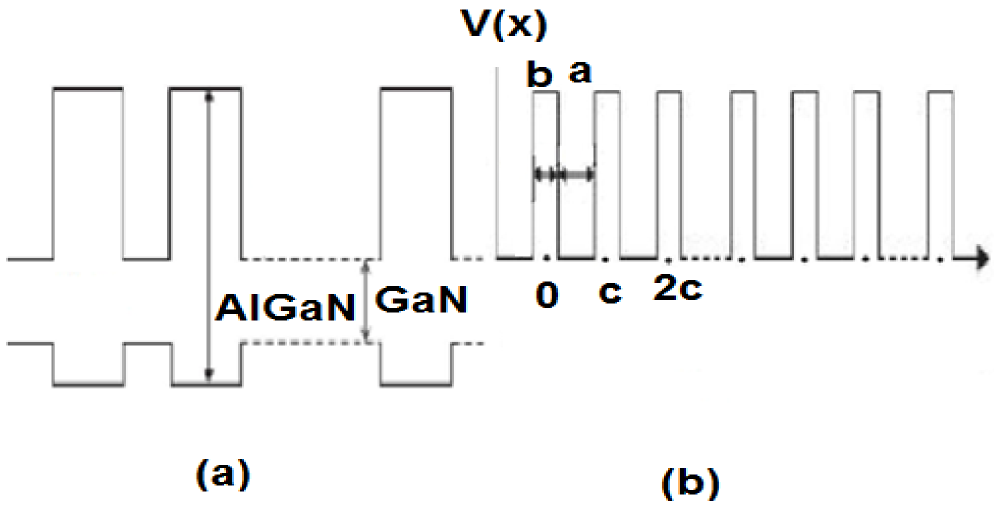

Fig. 1(a): Energy band diagram of stacking layers of GaN/AlGaN semiconducting materials (b) the multibarrier heterostructure with well and barrier regions originating from the band offset.

Numerical Analysis

The transmission probability of an electron is studied which incident from the left on the potential barrier for GaN/$Al_{0.3}Ga_{0.7}N$ superlattice. The numerical analysis is basically concerned with the transmission coefficient across multibarrier systems for incident energies $\varepsilon < V_O$, $\varepsilon = V_O$ and $\varepsilon > V_O$, with the values of various parameters as follows[12, 14, 15]:

- $a = \text{the well width} = (ncw * a_w)$,

where ncw is the number of cells in the well material and a_w is the lattice constant of the well ; a_w = 0.5185 nm. $b = \text{the barrier width} = (ncb * a_b)$,

where ncb is the number of unit cells of the barrier material and a_b is the lattice constant of the barrier material a_b = 0.5124 nm .

- m_w^* and m_b^* the effective masses of the well (GaN) and the barrier ($Al_{0.3}Ga_{0.7}N$) region materials of the superlattice ; $m_w^* = 0.2m_o$ and $m_b^* = 0.222m_o$; where m_o is the free electron mass.
- E_{g1} and E_{g2} are the energy band gap in the well and barrier materials respectively. E_{g1}=3.5 eV and E_{g2} =4.25 eV. The barrier height V_o is considered as 0.63 eV, which is the amount of energy mismatch in the conduction band edges ΔE_c of the two materials. In this paper, the amount of ΔE_c is taken to be 75% of the difference of the energy gaps of the two materials. Therefore, $V_0 = \Delta E_c = 0.75(E_{g2} - E_{g1})$.

Results and Discussion

The Transmission coefficient for GaN/$Al_{0.3}Ga_{0.7}N$ superlattice structure can be obtained from Eq. (1) in combination with Eqs. (2) and (3) for $\varepsilon < V_O$, $\varepsilon = V_O$ and $\varepsilon > V_O$. We have considered incident energies up to 1.5 eV. The tunneling probability exhibits peaks when the energy of the incoming electrons coincides with one of the quantized levels inside the well, these electrons suffers resonant tunneling.

As has been mentioned, when electrons incident on the MBS with energies equal to any one of quasi-level resonant tunneling energy states, tunnel out without any significant attenuation in their intensity.

These resonant states are for allowed tunneling bands separated by forbidden gaps for both $\varepsilon < V_O$ and $\varepsilon > V_O$ with each allowed band containing N-1 resonant states.

1. Effect of Number of Barriers

Fig.2 displays the transmission coefficient T(E) versus incident energy (E) for system ncw = 5, ncb = 5 having 2,3,5,7, and 9 barrier number respectively. For (N= 2, 3, 5, 7, 9) the resonance peak of transmission probability split into (1, 2, 4, 6, 8) peaks respectively. We have obtained four (4) allowed tunneling bands as shown in Fig. 2, each allowed band containing N-1 resonant states [2] i.e. the number of resonance energies in a state is corresponding to the number of the well N-1 in the system [16]. As N increases the resonant energies spread out from the central regions of the band towards the edges [2]. Moreover, the resonance splitting occurs each time a new barrier is added to the existing ones. The number of splitting is equal to the number of wells in the structure[17].

In another words, Fig. 2 shows that the resonance energy for N = 2 consist of a singlet. With increases N, the value of resonance energies (except N = 2) separates gradually from the energy value given by N=2 [16]. For N=2 the resonance peak of transmission coefficient (i.e. resonant energy) lies in the center of the band[2].The energy width of state which consists of multiples becomes broader as energy is increased [16].

If the number of barriers (N) increases, than the resonance get sharper and sharper , and we may conclude, when N go to infinity , they will fill the whole inner region of the mini band continuously as shown in Fig.3 [17]. Therefore, these energy levels change their position with number of barrier N increases. These features play an important role in fabrication of high speed devices.

The first peak in Fig. 2 is corresponding to the ground state level E_o while the second peak belongs to the first excited state E_1. Fig. 4 show the relationship between the ground state level E_o and first excited state E_1 as a function of the number of barriers. We observed that when increasing the number of barrier (N= 3, 5, 7, 9) each of E_o and E_1 of the quantum well move to the lower energy values. The variation of E_o and E_1 due to the splitting principle in energy levels gives rise to continuous bands known as (mini-band) which are separated by small forbidden gaps arises from increasing the number of barriers.

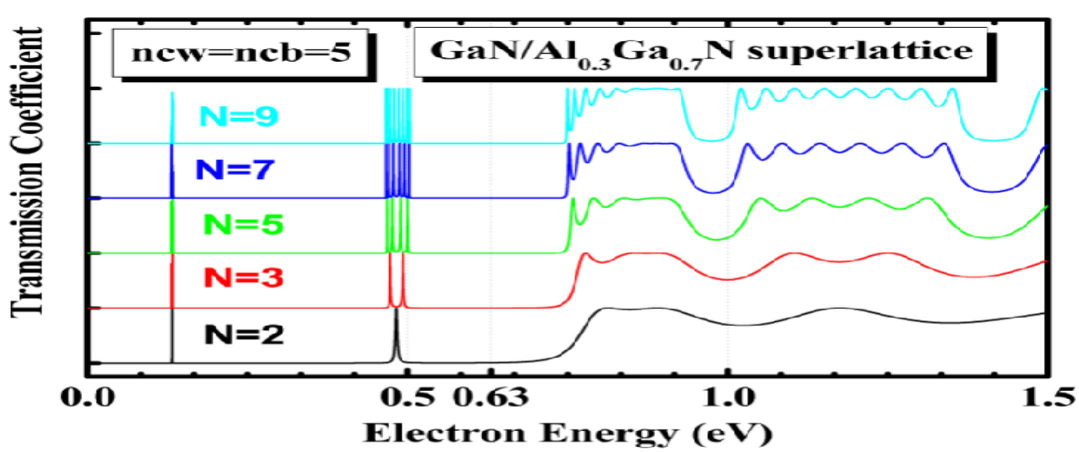

Fig. 2: Transmission coefficient T(E) versus incident energy (E) for GaN/$Al_{0.3}Ga_{0.7}N$ superlattice system by varying N, and constant ncw = ncb = 5 .

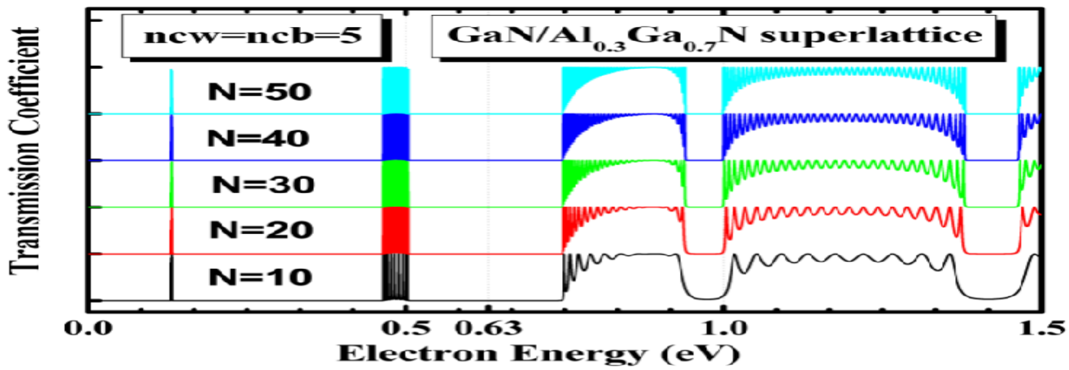

Fig.3:Transmission coefficient T(E) versus incident energy (E) for GaN/$Al_{0.3}Ga_{0.7}N$ superlattice system for big number of barrier N, and constant ncw = ncb = 5.

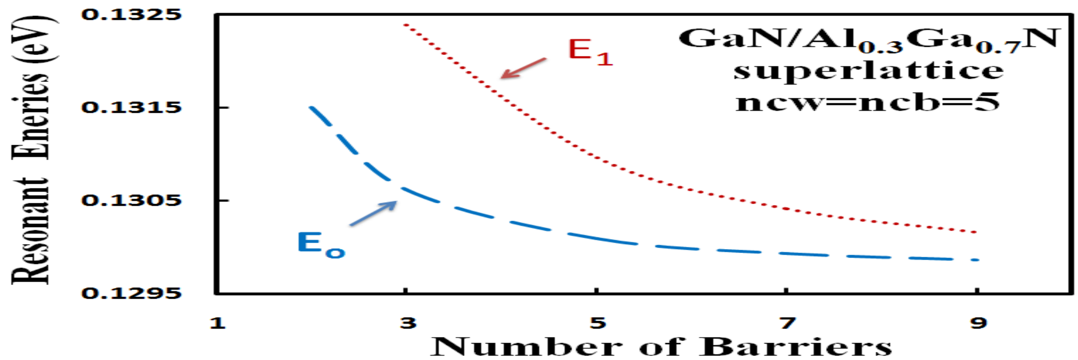

Fig. 4: Relationship between the ground state level E_o and first excited state E_1 as a function of the number of barriers.

2. Effect of well width

Fig.5 depicts the transmission coefficient T(E) versus incident energy (E) plot for GaN/$Al_{0.3}Ga_{0.7}N$ system having five barriers N = 5 with constant barriers width with ncb = 5 and varying well width with ncw = 3, 5, 7, 9 , respectively. When increasing the well width and another parameters are constant, they are a few interesting features of the results that we would like to summarize here. (1) Both the allowed minibands and the forbidden gaps become narrow, and the separation of these allowed electronic energies decrease. (2) The number of allowed tunneling bands increases from 3 to 6 when we varying well width from ncw = 3 to 9; i.e. the number of bands increase inside the wells as the width of the well increases. (3) Any decrease in well width will cause the resonant tunneling levels to shift to the higher values, inside the wells (blue shift).

From the law of the energy levels in an infinite quantum well, the energies of the bound states are inversely proportional to the square of the well width. This law explains why the resonant tunneling levels are shifted inside the wells (red shift) when increasing the wells width. This shifting is due to the quantum effect, so as the well narrows, the quantum confinement will strongly take place.

Fig.6 shows the resonant tunneling energies as a function of well width with ncw = 3, 5, 7, 9 ; barrier number (N = 3, 5, 7, 9) and the barrier width is constant (ncn = 5). We show in Fig. 6(a) the variation of ground state level E_o vs. ncw; while the variation of first excited state E_1 vs. ncw can be seen in Fig. 6(b). The resonant tunneling energies E_o and E_1 have lower energy values as the width of well increases. The ground state level E_o and first excited state E_1 move towards the lower energy values slightly with an increase in N. So, E_o and E_1 decrease, with increasing both of the well width and the number of barrier.

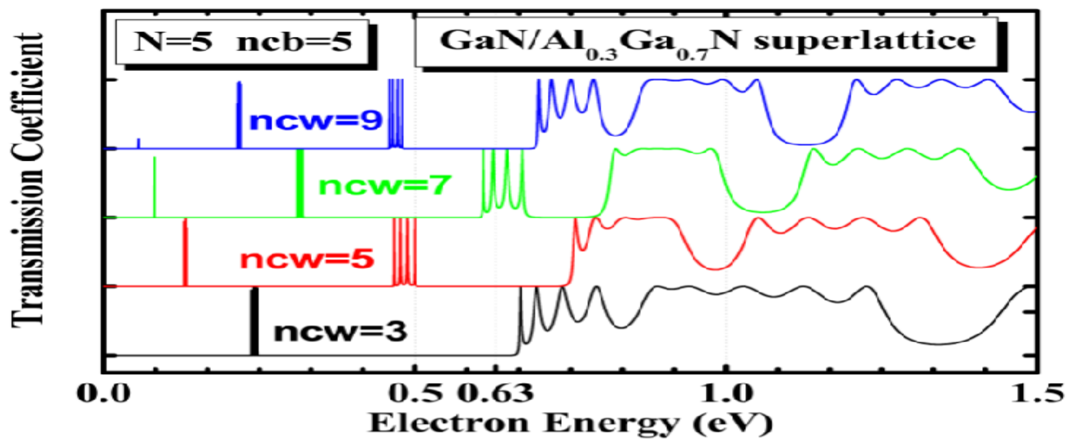

Fig. 5: Transmission coefficient T(E) versus incident energy (E) for GaN/$Al_{0.3}Ga_{0.7}$N superlattice system by varying well width with ncw = 3, 5, 7, 9 ; having five barriers N=5 with constant barriers width with ncb = 5.

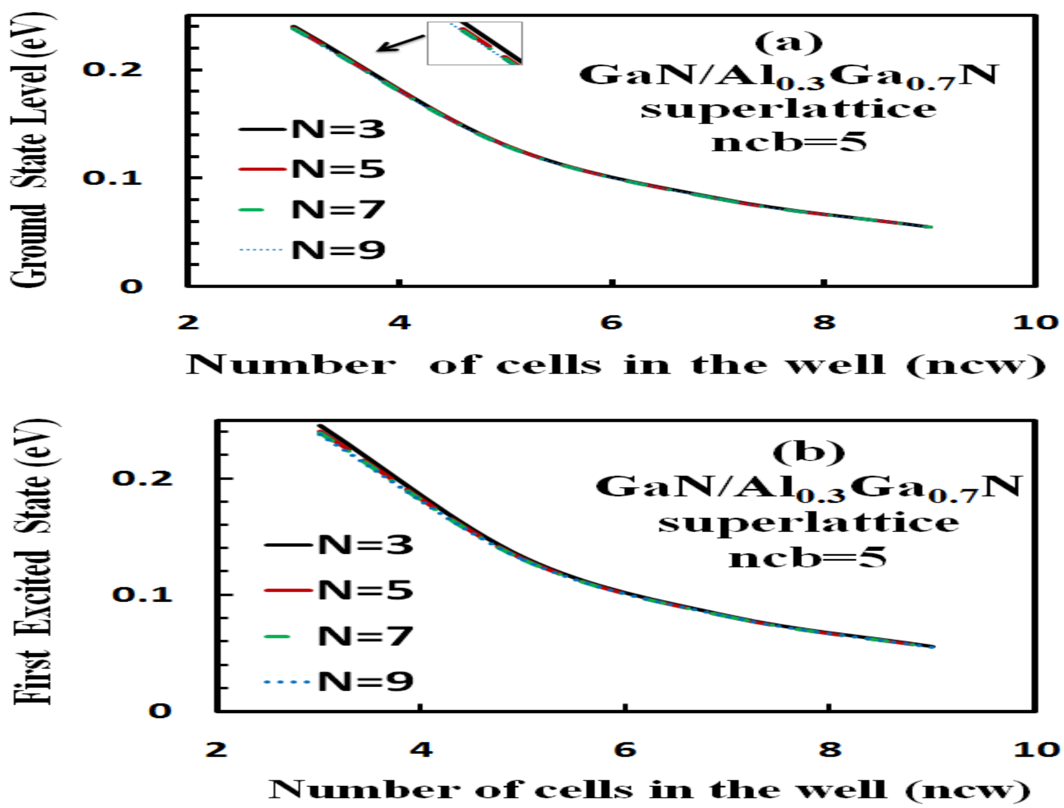

Fig. 6: The resonant tunneling energies as a function of well width at different number of barrier with constant barriers width with ncb = 5. (a) The variation of ground state level E_o vs. ncw .(b) The variation of first excited state E_1 vs. ncw.

Conclusions

From this work, we can conclude that the number of resonance peaks, in each miniband is equal to the number of quantum wells in the structure. The results indicate that if we increase the number of the barriers, then the values of resonance energies separates gradually from the energy value given by N=2. For double barriers, the resonance peak of transmission coefficient lies in the center of the band. Any decrease in well width will cause the resonant tunneling levels to shift to the higher values, inside the wells (blue shift). Therefore, the energy levels will change their position by varying both the well width and barrier number of $GaN/Al_{0.3}Ga_{0.7}N$ system. These changes in resonant levels can be controlled by the help of well width, and barriers number, which play an important role in fabrication of high-speed devices.

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