LASER FIELD EFFECT ON THE SUBBAND STRUCTURE IN SEMICONDUCTOR QUANTUM WIRES WITH CONICAL POTENTIAL PROFILE

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Efectele câmpului laser nerezonant asupra nivelelor electronice de subbandă într-un fir cuantic semiconductor cu potenţial de confinare conic sunt investigate în aproximaţia masei efective. Energiile şi funcţiile de undă sunt obţinute folosind metoda elementului finit ţinând cont de forma exactă a potenţialului de confinare modificat de laser. Câmpul laser transversal distruge simetria cilindrică a potenţialui de confinare, ridică degenerarea stărilor electronice şi induce o deplasare neuniformă a nivelelor de subbandă. Rezultatele ar putea fi utile pentru controlul activ al proprietăţilor optoelectronice al acestor structuri de joasă dimensionalitate.

The effects of the non-resonant laser field on the subband electronic levels in a semiconductor quantum well wire with conical potential profile are investigated within the effective-mass approximation. The energies and wave functions are obtained by using a finite element method which accurately takes into account the laser-dressed confinement potential. The transverse laser field destroys the cylindrical symmetry of the quantum confinement potential, breaks down the electronic states degeneracy and induces a non-uniform shift of the subband levels. The results could be used for an active control of the optoelectronic properties of such low-dimensional structures.

Keywords: quantum well wire; conical confinement potential; laser field; finite element method.

1. Introduction

It was proved that the electronic and optical properties of low-dimensional semiconductor structures under dynamic fields are different from those of a bulk semiconductor [1-5]. Since 1D systems may be applied in ultrafast electronics design, one may find interesting to study their response to intense external fields. Some theoretical studies have addressed this issue by focusing on shallow donor states [6-8] and intersubband transitions [9] in laser dressed QWWs for radiation polarized perpendicular to the wire axis. By making use of a nonperturbative method, a significant laser-induced shift of the electronic levels was found, more

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pronounced for thinner QWWs [8,10]. Most of the previous works considered cylindrical QWWs with hard-wall confinement potential (0 in the well, V_0 or ∞ in the barrier). To the best of our knowledge this is the first study of the laser-dressing effect on a QWW with conical potential profile. It provides a theoretical background for further studies of the intersubband absorption under non resonant laser fields. Our results can be used for designing novel electronic devices in which the conduction subband tuning plays an significant role.

The paper is structured as follows. Section 2 describes the theoretical framework. Section 3 presents the influence of the transverse laser field on the energy levels for electrons confined in a GaAs/AlGaAs cylindrical QWW with conical potential profile. The possibility of tuning the subband levels by varying the laser intensity and frequency was discussed. Finally, the main ideas are reviewed in conclusions Section 4.

2. Theory

We consider an $Al_{\kappa(\rho)}Ga_{1-\kappa(\rho)}As/Al_{0.3}Ga_{0.7}As$ QWW with an R radius and a conical shape of the confinement potential which is assured by a proper gradient of the Al concentration $\kappa(\rho)$. The QWW is irradiated with a radially polarized laser beam of angular frequency ω, non-resonant with the energy levels of the electrons in the wire. The confinement potential has the cylindrical symmetry

$$V(\rho) = \begin{cases} V_0 \dfrac{\rho}{R}, & \rho \in [0, R) \\ V_0, & \rho \in [R, \infty) \end{cases}, \tag{1}$$

where V_0 is the conduction-band offset and $\rho = \sqrt{x^2 + y^2}$ is the electron's radial position in the wire.

The quantum confinement effect in the plane (x, y) becomes important if radius R is comparable to the electron's Bohr radius in the bulk semiconductor. We will show that the laser significantly modifies the energy levels associated with the lateral confinement.

If the laser is off, the electron's energy levels are solutions of the atemporal Schrödinger equation in cylindrical coordinates

$$-\frac{\hbar^2}{2m*}\left[\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right) + \frac{1}{\rho^2}\frac{\partial^2}{\partial\varphi^2}\right]\Phi(\rho,\varphi) + V(\rho)\Phi(\rho,\varphi) = E\Phi(\rho,\varphi), \tag{2}$$

where $m*$ is the electron effective mass.

Under a laser field described by the vector potential $\mathbf{A}(t) = \hat{\mathbf{x}}A_0 \sin(\omega t)$ the quantum states can be obtained from the time-dependent Schrödinger equation in rectangular coordinates

$$\left[\frac{(\mathbf{p}_{\perp}+\hat{\mathbf{x}}eA_x(t))^2}{2m^*}+V\left(\sqrt{x^2+y^2}\right)\right]\Phi(x,y,t)=i\hbar\frac{\partial\Phi(x,y,t)}{\partial t}, \qquad (3)$$

where $\mathbf{p}_{\perp}$ is the in-plane electron momentum.

By applying the time-dependent translation $x \rightarrow x + \frac{eA_0}{m^*\omega}\cos(\omega t)$, one has

$$\left[\frac{\mathbf{p}_{\perp}^2}{2m^*}+\widetilde{V}(x,y,t)\right]\widetilde{\Phi}(x,y,t)=i\hbar\frac{\partial\widetilde{\Phi}(x,y,t)}{\partial t}, \qquad (4)$$

where

$$\widetilde{V}(x,y,t)=V\left(\sqrt{(x+\alpha_0\cos(\omega t))^2+y^2}\right) \qquad (5)$$

is the laser-dressed confinement potential with $\alpha_0 = \frac{eA_0}{m^*\omega}$ denoting the laser parameter. In the high-frequency limit the laser-dressed bound states for the transversal motion are solutions of the time-independent Schrödinger equation

$$\left[-\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)+\widetilde{V}_a(x,y)\right]\widetilde{\Phi}(x,y)=\widetilde{E}\widetilde{\Phi}(x,y), \qquad (6)$$

where $\widetilde{V}_a(x,y)$ is the zero-order Fourier component of the dressed potential energy given by Eq.(5)

$$\widetilde{V}_a(x.y)=\frac{\omega}{2\pi}\int_0^{2\pi/\omega}\widetilde{V}(x,y,t)dt . \qquad (7)$$

By solving Eq.(6) with a finite element method [11,12], one may obtain the transverse eigenfunctions $\widetilde{\Phi}_k(x,y)$ and the corresponding laser dressed transverse energies $\widetilde{E}_k$ as functions of the laser parameter.

3. Results and discussion

The numerical calculations were performed for an $R = 75\,\text{Å}$ AlGaAs QWW with conical confinement profile. The size of considered GaAs nanostructure is smaller than the electronic Bohr radius in bulk GaAs ($\cong 100\,\text{Å}$). An isotropic effective mass $m^* = (0.0665+(0.08+1/300)\kappa)m_0$ of the electron throughout the nanostructure was assumed (m_0 denoting the free electron mass).

The conduction-band offset $V_0 = 228$ meV was introduced by taking into account the Miller's rule ($V_0 = 60\%\Delta E_{gap} \approx 0.7\kappa + 0.2\kappa^2$ in eV units, with $\kappa = 0.3$).

Figure 1(a) shows the conical confinement potential of the cylindrical QWW, in the absence of the laser radiation. Figures 1(b,c) illustrate the potential modifications induced by the laser field with a parameter α_0 smaller and respectively larger than the wire's radius. The complex behavior of the confinement potential as the laser parameter increases, will lead to a non-uniform shift of the subband energy levels. The laser strongly elevates the bottom of the quantum confinement profile and consequently a very larger blueshift is expected for the ground energy. Interestingly, for $\alpha_0 > R$ (Fig. 1(c)), the dressed confinement potential of the "conical" QWW looks like a double-well; this behavior has been also reported for SQWs [3,5].
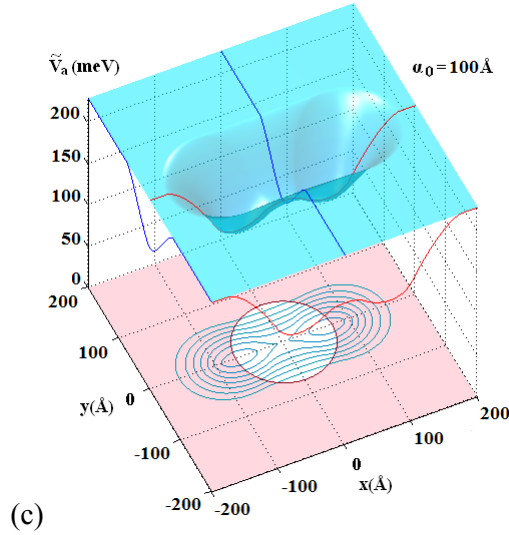

(a)

(b)

(c)
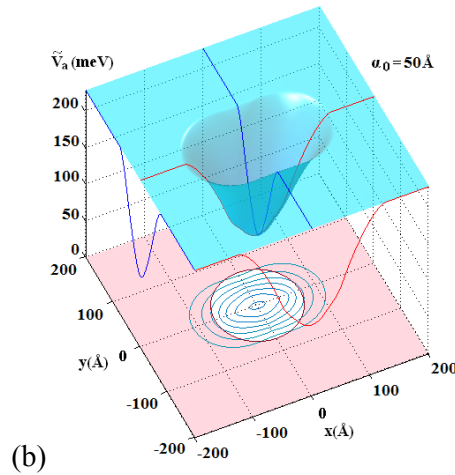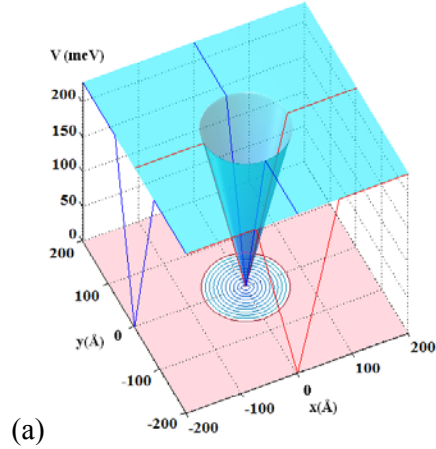
Fig. 1. Conical confinement potential of a cylindrical QWW with $R = 75$ Å for a) no laser; b) a laser parameter smaller than the radius; c) a laser parameter larger than the radius.

The transverse laser field polarized along the x axis modifies the confinement potential in x and y directions in different ways (Fig. 1). The cylindrical confinement symmetry is destroyed and this effect is more pronounced as the laser parameter increases. In the absence of the laser field, there are two bound states of the electron in the QWW (the second being double degenerated): $E_1 = 131.8 \, meV$, $E_2 = E_3 = 213.7 \, meV$. The laser field breaks down the degeneracy of the excited subband level.

Figure 3 presents the laser-induced changes of the probability density function for the first conduction subband. At $\alpha_0 = 0$ (Fig. 1(a)), the electron is located on-axis with maximum probability density and has practically zero probability to be found in the barrier zone ($\rho > R$). As the laser parameter increases (Fig. 1(b)), the on-axis maximum diminishes but in the same time the density function expands in the barrier. At very large values of the laser parameter (Fig. 1(c)), there are two equal maxima of the probability density along the polarization direction of the laser. It may be observed that finding the electron outside the wire becomes quite probable, his quantum state still resting bound.
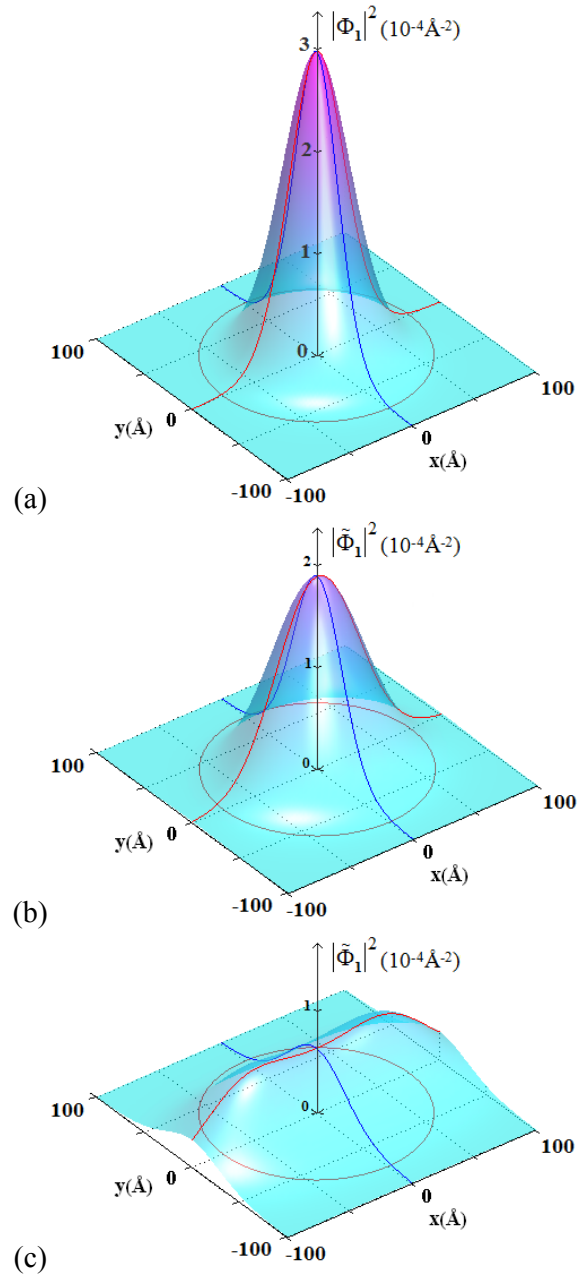
Fig. 2. Density of probability function $|\Phi_1|^2$ describing the electron transverse localization associated with the ground subband state, for three values of the laser parameter: a) $\alpha_0 = 0$; b) $\alpha_0 = 50$ Å; c) $\alpha_0 = 100$ Å.

We found that the first subband energy is increased with almost $65\,\text{meV}$ when the laser parameter is raised from 0 up to $100\,\text{Å}$ (Fig. 3). The transverse cross sections of the probability density associated with the ground state show that the electron wave function is distorted by the laser field (Fig. 3(b),(c)), losing its angular symmetry and penetrating into the barrier region.

(a)   (b)   (c)
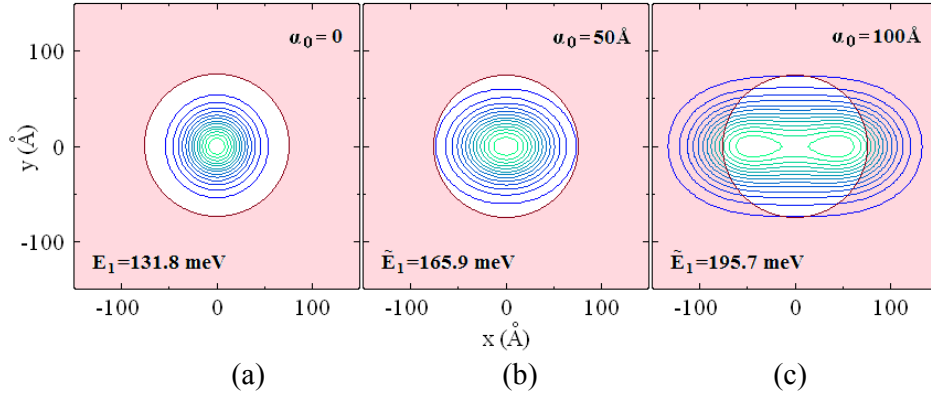
Fig. 3. Contour plots of the electron probability density and eigenvalues of the energy associated with the lowest conduction subband in the absence of the laser field (a) and for two values of the laser parameter (b,c).

The first excited subband energy is slowly redshifted as the laser parameter increases (Fig. 4). This behavior may be explained by the laser-induced enlargement of the confinement potential of the QWW on the x direction in the upper-part of the well (Fig. 1). The contour plots of the electron probability density show that there are two identical maxima along the x axis (Fig. 4(b),(c)). These maxima migrates under intense laser field from the inner wire (Fig. 4(a,b)) to the interface $\rho = R$ (Fig. 4(c)). Therefore, at large values of the laser parameter, the probability of finding the electron inside the wire becomes smaller.
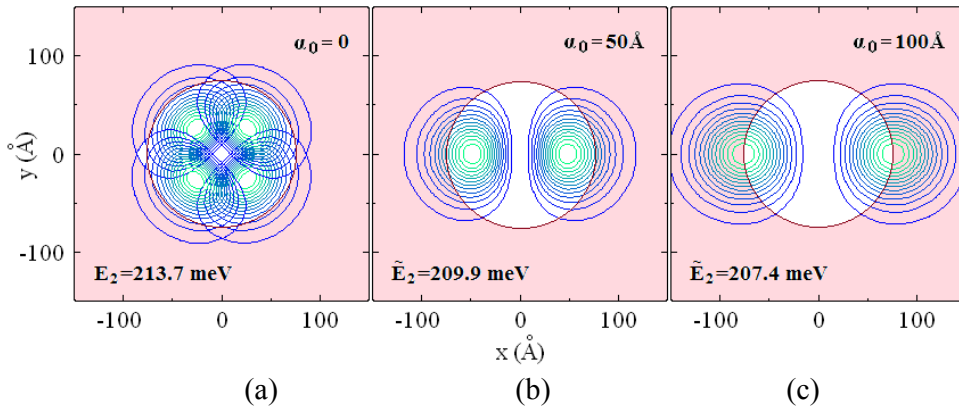

(a)   (b)   (c)

Fig. 4. The same as Fig. 3, for the first excited subband.

Under laser field, the second excited subband has two maxima along the y direction (Fig. 5(b)). Its energy level is increased as the laser parameter raise up, since the confinement is augmented by the laser field on the y direction (Fig. 1(b,c)). For $\alpha_0 > 50$ Å , this subband become unbound.
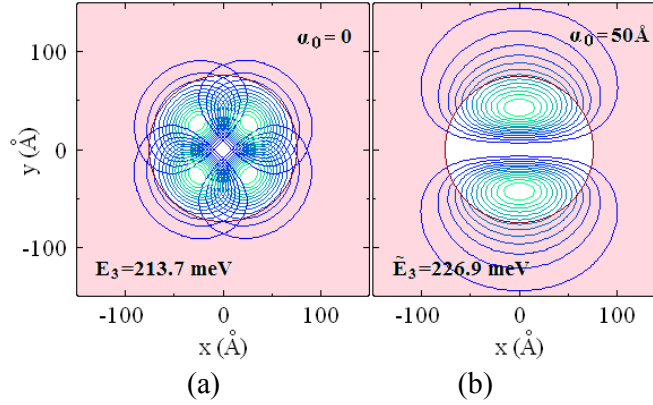

(a)   (b)

Fig. 5. The same as Fig. 3, for the second excited subband. For $\alpha_0 > 50$ Å this state becomes unbound.

As one may observe, the excited subband levels have the same energy for $\alpha_0 = 0$ (Figs. 4(a) and 5(a)). In fact, when the laser is off, there is a single excited state which is double-degenerate. The laser field breaks down the degeneracy by destroying the cylindrical symmetry of the confinement potential (Fig. 1). Consequently, when the laser is on, the degenerate state splits up into two orthogonal states with different energies, as seen above. The laser-induced degeneracy breakdown is better illustrated in Fig. 6, where the conduction subband structure of the QWW is presented as a function of the laser parameter.
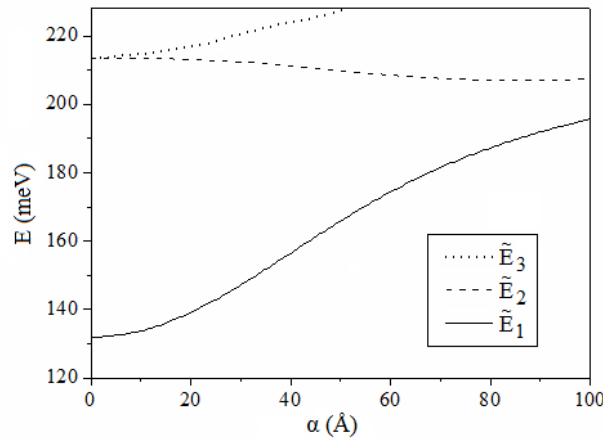

Fig. 6. Subband energy levels versus laser parameter.

As a consequence of the subbands shifts induced by the laser field, the intersubband transitions and the related optical properties will be affected. The interband transitions will be modified as well, since the laser field will also induce a blueshift of the ground level of the hole in the valence band (even if this one is expected to be smaller than for the electron). For GaAs/AlGaAs low-dimensional structures the hole states are less sensitive to the transversal laser action, for two reasons: i) the mass of the heavy-hole inside the QWW is five times larger than the effective mass of the electron, so that the laser parameter α_0 is five times smaller for the valence band; ii) the offset for the heavy-hole is smaller than the conduction band offset, so that the laser radiation effect is weakened. The dressing effects generally depend on the size of the wire being more pronounced at stronger carrier confinement, i. e. for lowest-lying levels and small R values. Therefore, the desired energy range for the intersubband and interband transitions may be obtained by properly changing the size and/or composition of the heterostructure.

4. Conclusions

In this paper we have presented a theoretical study of the non-resonant ILF effects on the electronic subband levels in an AlGaAs cylindrical QWW with conical confinement potential. Within the effective mass approximation, the calculations were performed by using a FEM and taking into account the precise THz laser dressing effect on the potential energy. The transverse laser field has been shown to considerably modify the electron energy levels. We showed that by changing the transverse laser parameter, one can obtain the tunability of the interband and intraband optical transitions in semiconductor QWWs. It is probable that these general conclusions will remain qualitatively valid in QWWs of different transverse geometries and potential shapes. The effects described can be used for designing new laser-accordable optoelectronic devices.

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R E F E R E N C E S

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