U.P.B. Sci. Bull., Series A, Vol. 71, Iss. 4, 2009 ISSN 1223-7027

THE OPTICAL STARK EFFECT IN PARABOLIC QUANTUM WELL WIRES UNDER HYDROSTATIC PRESSURE

Ecaterina C. NICULESCU[1], Alexandru LUPASCU[2], Liliana M. BURILEANU[3]

În lucrare se studiază proprietăţile unui fir cuantic sub acţiunea simultană a presiunii hidrostatice şi a unei radiaţii laser de frecvenţă înaltă. Calculul efectului Stark optic a fost făcut în aproximaţia masei efective. A fost studiată dependenţa nivelelor de energie de intensitatea radiaţiei laser pentru fire cuantice cu diferite dimensiuni.

In this paper we study the properties of the quantum-well wires under simultaneous action of hydrostatic pressure and high-frequency laser field. Calculation of the optical Stark effect is carried out in the effective mass approximation. Different geometries concerning the size of GaAs/AlGaAs quantum wires as well as the strength of the applied laser field were considered.

Keywords: quantum well wire, optical Stark effect, hydrostatic pressure

1. Introduction

With the recent advances in crystal growth and process techniques it is possible to confine electrons in extremely thin semiconductor wires, namely quantum well wires with nano dimensions. In these quasi-one-dimensional structures the electron motion along the axis of the wire is free but it is confined in the other two dimensions perpendicular to the axis. External fields have become an interesting probe for studying the physical properties of low-dimensional systems, both from the theoretical and technological point of view.

The effect of an applied electric field on the electronic levels in rectangular and cylindrical quantum well wires (QWWs) has been investigated by Montes *et al*. [1, 2]. Aktas *et al*. studied the energy spectrum for an electron in QWW with different shapes under the electric and magnetic fields [3, 4].

In recent years the studies have been extended to semiconductor nanostructures under intense electric fields generated by THz laser sources [5, 6].

[1] Prof., Physics Department, University POLITEHNICA of Bucharest, ROMANIA, e-mail niculescu@physics.pub.ro
[2]Prof., Physics Department, University POLITEHNICA of Bucharest, ROMANIA, e-mail lupascu@physics.pub.ro
[3]Lecturer, Physics Department, University POLITEHNICA of Bucharest, ROMANIA, e-mail burileanu@physics.pub.ro

In the frame of a non-perturbation theory and a variational approach Neto *et al*. [7] have derived the laser-dressed quantum well potential for an electron in a square quantum well. A simple scheme based on the considered effect of the laser interaction with the semiconductor through the renormalization of the effective mass has been proposed by Brandi and Jalbert [8]. Ozturk *et al.* have investigated the effect of the laser field on the intersubband optical transitions in square and graded quantum wells in the absence of electric field [5, 9] and under external electric field [10]. We recently investigated the effects of the laser field on the energy spectra in finite V-shaped, parabolic, square, and inverse V-shaped GaAs quantum wells under an electric field [11, 12]. The absorption coefficient related to the interband transitions was also discussed as a function of the laser parameter, geometric shape of the wells and the applied electric field.

The pressure and external field dependence of the optical and electric properties in the GaAs/$Ga_{1-x}Al_xAs$ systems have been extensively investigated. Oyoko *et al*. [13] have calculated the effect of hydrostatic pressure and temperature on shallow-impurity related optical absorption spectra in GaAs/GaAlAs single and double quantum wells. A. J. Peter *et al*. [14] have calculated the binding energies of donors in GaAs/GaAlAs single quantum well as a function of the pressure and temperature. Recently the combined effect of hydrostatic pressure and temperature on donor impurity binding energy in GaAs/$Ga_{0.7}Al_{0.3}As$ double quantum well in the presence of the electric and magnetic fields applied along the growth direction have been studied by using a variational technique within the effective-mass approximation [15].

In this paper we investigated the effects of the high-frequency laser field and hydrostatic pressure on the electronic levels in the GaAs/AlGaAs parabolic quantum well-wires (QWWs). Calculation was carried out in the effective mass approximation for various lateral widths of the wire.

2. Theory

The parabolic confinement quantum well-wire (PC-QWW) is obtained by using parabolic well potential in the *x*- and *y*- directions. The equation for the electron envelope function $\Psi(x,y)$ contains a non-separable potential $V(x,y)$ corresponding to a finite barrier height

$$-\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\Psi_0(x,y)+V(x,y)\Psi_0(x,y)=E_0\Psi_0(x,y) \tag{1}$$

where m* is the carrier effective mass, denoted respectively by m_w^* or m_b^* in the well and in the barrier. The parabolic confinement potential in the *x*- direction are written as

$$V_{\text{int}}(x) = V_0 \left(\frac{x}{L_x / 2} \right)^2, \quad |x| \le L_x / 2 \tag{2}$$

and a similar form for $V_{\text{int}}(y)$, and $V = V_0$ outside the well of dimension $L_x \times L_y$. Here V_0 is the conduction band offset at the interface.

The confining potential of the wire can be approximated by the form presented in Fig. 1. With this definition, $V(x,y) = V(x) + V(y)$, where $V(x)$ and $V(y)$ are independent finite well potentials. Errors occur only in the "corner regions" outside the wire where the two potential barrier heights V_0 sum to give $2V_0$. These regions are not expected to be sampled too much by the eigenfunctions, particularly those associated with lower energy states in wide wires.

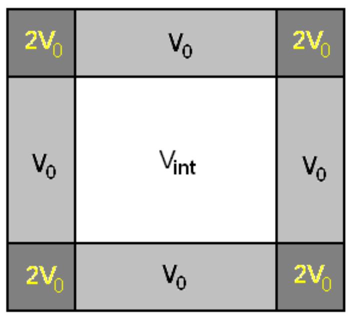

Fig.1. The approximate form for the potential of rectangular quantum wire with finite barriers

In this case, writing the wave function $\Psi_0(x,y)$ as $\psi(x)\psi(y)$, the equation (1) can be split into two one-dimensional equations and $E_{xy}^0 = E_x^0 + E_y^0$. The energy eigenvalues E_{xy}^0 could be improved by considering a perturbation on the two-dimensional system, which removes the $2V_0$ potential pillars. Using first-order perturbation theory, the change in energy of a level is given by

$$\Delta E = \langle \Psi_0(x,y) | V'(x,y) | \Psi_0(x,y) \rangle \tag{3}$$

where $V'(x, y)$ is the perturbation term. For a square cross-sectional wire we obtain

$$\Delta E = -4V_0 \int_{L_x/2}^{+\infty} \psi^*(x)\psi(x)dx \int_{L_y/2}^{+\infty} \psi^*(y)\psi(y)dy \tag{4}$$

Califano and Harisson [16] have demonstrated that this can be a quite useful approach to the solution of finite barrier quantum wires and dots.

2.1. Laser-dressed potential

We assume the presence of an intense high-frequency laser field with the polarization direction along the x-axis. In the high-frequency limit ($\omega\,\tau >> 1$, with τ the transit time of the electron in the well region [8]) the x-direction laser "dressed" potential is given by [7]

$$V_{xd}(x,\alpha_0)=\frac{\omega_R}{2\pi}\int_0^{2\pi/\omega_R} V_x(x+\alpha(t))dt \tag{5}$$

Here

$$\alpha(t)=\alpha_0\sin(\omega t),\qquad \alpha_0=\frac{e\,A_0}{m^*\omega_R} \tag{6}$$

describes the motion of the electron with charge e in the laser field and α_0 is the laser-dressing parameter.

For parabolic confinement the expression of the "laser-dressed" potential [11] is

$$V_{xd}(x,\alpha_0)=\begin{cases}\dfrac{V_0}{2b^2}\left[2x^2+\alpha_0^2\right], & |x|\in D_1;\\ V_0+\dfrac{V_0}{2\pi b^2}\left[\begin{array}{l}\left(2x^2+\alpha_0^2-2b^2\right)\arccos\dfrac{|x|-b}{\alpha_0}\quad -\\ -\alpha_0\left(3|x|+b\right)\sqrt{1-\left(\dfrac{|x|-b}{\alpha_0}\right)^2}\end{array}\right], & |x|\in D_2;\\ V_0, & |x|\in D_3.\end{cases} \tag{7}$$

where $b=L_x/2$, $D_1=[0,b-\alpha_0)$, $D_2=[b-\alpha_0,b+\alpha_0]$, and $D_3=(b+\alpha_0,+\infty)$.

2.2 Effect of hydrostatic pressure

The application of hydrostatic pressure p modifies the barrier height V_0 and the effective masses $m^*_{w,b}$. For the hydrostatic pressure dependence of the electron effective mass and the potential barrier we refer, for example, to the work of Raigoza *et al*. [17].

The total Hamiltonian for the system is given by

$$H_0(\alpha_0, p) = H_x(\alpha_0, p) + H_y(p) \tag{8}$$

where

$$H_x(\alpha_0, p) = -\frac{\hbar^2}{2m^*_{w,b}(p)}\frac{d^2}{dx^2} + V_{xd}(x, \alpha_0, p) \tag{9}$$

and

$$H_y(p) = -\frac{\hbar^2}{2m^*_{w,b}(p)}\frac{d^2}{dy^2} + V_y(y, p) \tag{10}$$

The eigenvalue problems of Eqs. (8-9) must be solved numerically. The corresponding eigenfunctions $\psi_{n_x}(x)\psi_{n_y}(y)$ can be used to obtain the first-order corrections $\Delta E_{n_x,n_y}$ and the subband energies are given by

$$E_n = E^0_{n_x,n_y} + \Delta E_{n_x,n_y} \tag{11}$$

3. Numerical results and discussion

In our study for numerical calculations we consider a $\mathrm{GaAs/Al}_{x_b}\mathrm{Ga}_{1-x_b}\mathrm{As}$ PC-QWW with the Al concentration at the barriers x_b =0.3 and m_w = 0.0665m_0.

Fig.2 shows the laser-dressed potential energy of a wire with $L_x = L_y$ =100 Å for $\alpha_0 = 20$ Å.

In the presence of the laser one notice two effects:

(i) the effective well width of the wire (lower part of the confinement potential), which affects the carrier localization decreases

(ii) the barrier height is reduced.

Thus, the laser dressed energy levels must be pushed to the upper part of the well. Consequently, since the laser emission of the dressed wire occurs at higher energies, a decrease of the electron-hole recombination is expected [18].

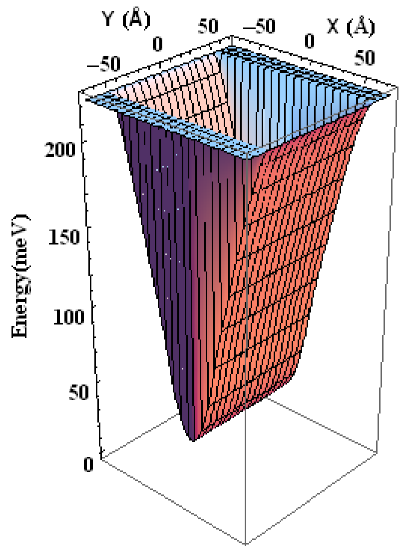

Fig.2. Laser-dressed potential energy of a PC-QWW

For this structure, the dependence of the single electron bound-state energy on the laser parameter is presented in Table I. The first-order corresponding corrections ΔE_1 are also given.

Table 1. Energy level and first-order correction for a 100Å×100Å QWW

α_0 [Å]	0		10		20		30	
p [kbar]	0	13.5	0	13.5	0	13.5	0	13.5
E_1 [meV]	143.39	139.96	146.16	144.54	159.01	156.01	174.70	172.06
ΔE_1 [meV]	0.1045	0.0971	0.1190	0.1092	0.1588	0.1138	0.2375	0.2297

As expected, a strong blue shift of energy with increasing α_0 is observed. Due to the variation of electron effective mass with the change in pressure, the subband energy decreases when the pressure increases for all laser parameters. As seen in Table I, the energy corrections are small, so that the perturbation theory remains valid for intense laser fields.

The dependence of the subband energy levels in a QWW with lateral widths L_x=200 Å and L_y=100 Å on the laser parameter and the corresponding behavior of the corrections ΔE are shown in Fig.3 for two values of the hydrostatic pressure.

(a) (b)

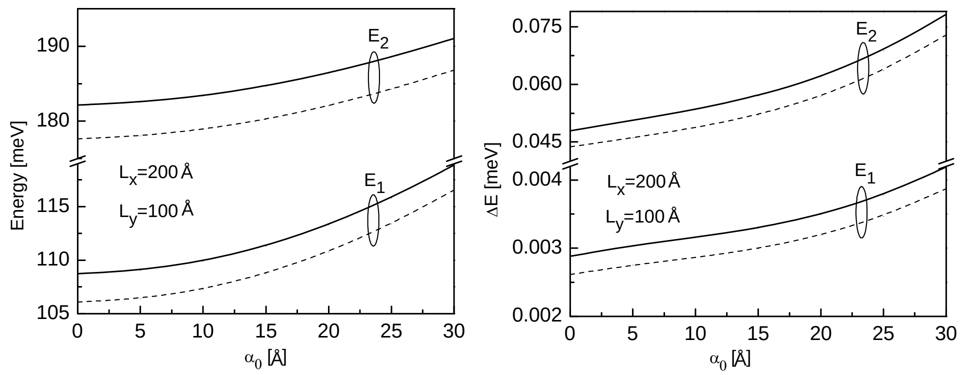

Fig.3. Subband energies (a) and first-order corrections (b) vs. α_0 for a 200 Å×100 Å QWW for p = 0 (solid lines) and p = 13.5 kbar (dashed lines)

Our calculations show that as the wire widths increases, the effect of the laser field is less pronounced, and the first order perturbation corrections decreases. This is also observed for a wider PC-QWW with L_x =200 Å, L_y =200Å presented in Fig.4. In this last case four subband energies are obtained. Higher energy levels are almost independent on the laser intensity due to the wave functions penetration into the barriers. As expected, the degeneracy of E_2 and E_3 levels is removed as the laser parameter increases (see Fig. 4b).

(a) (b)

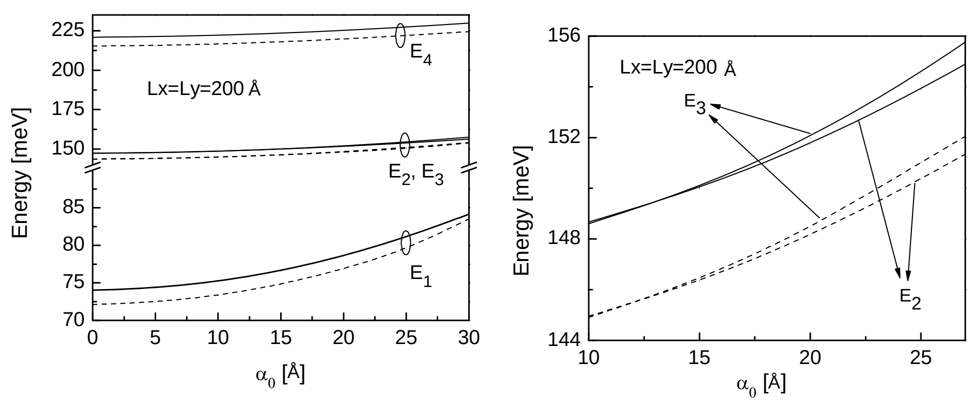

Fig.4. (a): Subband energies vs. α_0 for a 200 Å×200 Å QWW for p = 0 (solid lines) and p = 13.5 kbar (dashed lines). (b) Zoom of Fig. (a) for large laser parameters.

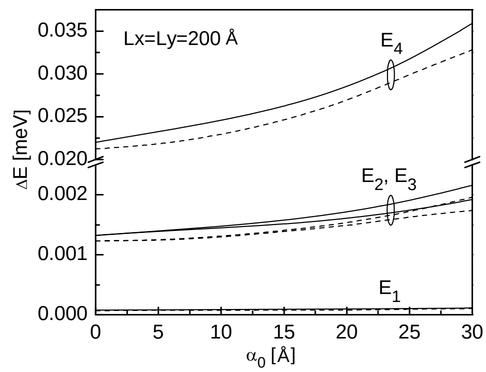

Fig.5 First-order corrections vs. α_0 for a 200 Å×200 Å QWW for p = 0 (solid lines) and p= 13.5 kbar (dashed lines)

In summary, the interaction of a non-resonant high-frequency laser field with a semiconductor QWW under hydrostatic pressure is investigated. The blue shift of the subband energies depends not only upon the lateral widths but also upon the laser field parameter. Our calculations show that the optical emission of GaAs/AlGaAs wires can be easily tuned by changing the hydrostatic pressure.

R E F E R E N C E S

[1]. *A. Montes, C.A. Duque, A.L. Morales, N. Porras-Montenegro*, J. Appl. Phys. 84 (1998) 1421.
[2]. *A. Montes, C.A. Duque, N. Porras-Montenegro*, J. Appl. Phys. 81 (1997) 7890.
[3]. *S. Aktas, A. Bilekkaya, S. E. Okan*, Physica E 40 (2008) 2703.
[4]. *A. Bilekkaya, S. Aktas, S. E. Okan, F. K. Boz*, Superlatt. Microstr. 44 (2008) 96.
[5]. *E. Ozturk, H. Sari, and I. Sokmen*, Solid State Commun. 132 (2004) 497.
[6]. *E.C.Niculescu, L. Burileanu, and M.Cristea*, U.P.B. Sci. Bull., Series A, Vol. 69,(4) (2007) 81.
[7]. *O. O. Diniz Neto, and Fanyao Qu*, Superlatt. Microstr. 35 (2004) 1.
[8]. *H. S. Brandi, and G. Jalbert*, Solid State Commun. 113 (2000) 207.
[9]. *E. Ozturk, and I. Sokmen*, Solid State Commun. 126 (2003) 605.
[10]. *E. Ozturk, H. Sari, and I. Sokmen*, J. Phys. D: Appl.Phys. 38 (2005) 935.
[11]. *A. Radu, E. Niculescu, and M. Cristea*, J. Optoelectr. Adv. Mat. 10 (2008) 2555.
[12]. *L. M. Burileanu, E. C. Niculescu, N. Eseanu, A. Radu*, Physica E (2009) 856.
[13]. *H.O. Oyoko, N. Parras-Montenegro, S.Y. Lopez, and C.A. Duque*, Phys. Status Solidi C 4 (2) (2007) 298.
[14]. *A. John Peter, and K. Navaneethakrishnan*, Superlatt. Microstr. 43 (2008) 63.
[15]. *E. Kasapoglu*, Phys. Lett. A 373 (2008) 140.
[16]. *M. Califano and P. Harisson*, J. Appl. Phys. 86 (1999) 5054.
[17]. *N. Raigoza, A.L. Morales, A. Montes, N. Porras-Montenegro, and C.A. Duque*, Phys. Rev. B 69 (2004) 045323.
[18]. *F. Qu, and P. C. Morais*, Phys. Lett. A 310 (2003) 460.