Eur. Phys. J. B **80**, 89–93 (2011)
DOI: 10.1140/epjb/e2011-10902-y

THE EUROPEAN PHYSICAL JOURNAL B

Regular Article

The effects of the intense laser field on bound states in $Ga_xIn_{1-x}N_yAs_{1-y}/GaAs$ single quantum well

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Received 20 November 2010 / Received in final form 6 January 2011
Published online 1st March 2011 –

Abstract. We have investigated the effects of the intense laser field and nitrogen concentration on bound state energy levels in $Ga_xIn_{1-x}N_yAs_{1-y}/GaAs$ quantum well. The results show that both intense laser field and N-incorporation into the GaInNAs have strong influences on carrier localization. We hope that our results can stimulate further investigations of the related physics, as well as device applications of group-III nitrides.

1 Introduction

Dilute quaternary group-III arsenide nitride compounds $Ga_xIn_{1-x}N_yAs_{1-y}$ have been intensively studied in the past few years because of both their fundamental properties [1,2] and their potentials for 1.3 and 1.5 μm wavelength laser applications [3,4]. Adding small amounts of nitrogen to GaAs is found to decrease the lattice constant and band-gap which leads to long wavelength emission [5]. Addition of In to GaAs has the effect of increasing the lattice constant while decreasing the band-gap. For this reason GaInNAs can be lattice matched to GaAs with suitable material quality for the processing of long wavelength lasers [6]. When a thin layer of GaInNAs is sandwiched between GaAs layers, very deep quantum wells can be formed which strongly confine the electrons in the conduction band and thus improve the temperature characteristics of such devices.

As known, intense laser field (ILF) considerably affects the optical and electronic properties of semiconductors [7–13]. Because when an electronic system is irradiated by ILF, the potential of the system is modified which affects significantly the bound state energy levels, a feature that has been observed in transition energy experiments. So the effects of a high-frequency ILF on the confining potential and the corresponding bound state energy levels are a very important problem. This problem has been a subject of great interest and an enormous amount of literature has been devoted to this field [14–20]. Some of these studies are as follows: Enders et al. have investigated systematically the changes induced by intense, long wavelength, nonresonant laser fields on some electronic properties, namely the bound state energies and the electron density of states for quasi-2D electrons in a square quantum well (SQW) [14]. Their results showed that the effect of laser field on bound state energies is to induce blueshift, which depend on the laser intensity and frequency as well as on the polarization direction. The effects of the high frequency laser field on the subband structure and on polarizibilities of shallow donor in a GaAs/GaAlAs quantum well (QW) were investigated by Burileanu et al. [15]. Pérez-Maldonado et al. have considered an electron in a semiconductor nanostructure under a magnetic field perpendicular to its growth direction and monochromatic electromagnetic radiation, linearly polarized in a direction perpendicular to the magnetic field [16]. They have studied the time-dependent Schrödinger equation for a quantum Gaussian well. Quasi-energies are calculated in the Kramers-Henneberger approximation (KHA) as function of the cyclotronic orbit center position for different values of laser intensity. Varshni [17] has studied the effects of the laser-field and the quantum confinement on the ground and two excited states of an impurity located at the center of a spherical quantum dot confined by an infinite potential barrier. Radu et al. have investigated the effects of a laser field on subband energy levels in finite different shaped quantum wells such as V-shaped, parabolic and SQWs [18]. Neto et al. have derived the laser-dressed quantum well potential for an electron in a SQW [19]. Lima et al. have investigated how the potential and the corresponding bound states in a SQW are affected by a nonresonant intense laser field [20]. They derived an analytical expression valid for all values of the laser-dressing parameter.

The present work is concerned with the theoretical study of the effects of the intense laser field and nitrogen concentration on bound state energy levels in

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Table 1. Bowing parameters for relevant compounds in units of eV.

$C_{\text{In-Ga}}$ (InGaAs)	$C_{\text{In-Ga}}$ (InGaN)	$C_{\text{As-N}}$ (GaNAs)	$C_{\text{As-N}}$ (InNAs)
0.51[a]	1.4[b]	20[c]	4.22[d]

[a] Reference [21]; [b] reference [22]; [c] reference [23]; [d] reference [24].

$Ga_xIn_{1-x}N_yAs_{1-y}$/GaAs quantum well for a constant indium concentration. The paper is organized as follows. In Section 2, we described the theoretical framework. Section 3 is dedicated to the results and discussion, and finally, our conclusions are given in Section 4.

2 Theory

In the effective mass approximation, the Hamiltonian for the electron without the effect of intense laser field is given by

$$H = -\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial z^2} + V(z) \qquad (1)$$

where m^* is the effective mass of electron and $V(z)$ is the confinement potential in the z-direction. The functional form of the confinement potential is given by

$$V(z) = V_0\theta\left(|z| - L/2\right), \qquad (2)$$

where θ is the unit step function, L is the quantum well width and V_0 is the conduction band offset. Compositional dependence of the band gap energy in the bulk $Ga_xIn_{1-x}N_yAs_{1-y}$, including stress is given by [21]:

$$\begin{aligned} E_g(x,y) &= xyE_g(\text{GaN}) + (1-x)yE_g(\text{InN}) \\ &\quad + x(1-y)E_g(\text{GaAs}) + (1-x)(1-y)E_g(\text{InAs}) \\ &\quad + x(x-1)\left[yC_{\text{In-Ga}}(\text{InGaN}) + (1-y)C_{\text{In-Ga}}(\text{InGaAs})\right] \\ &\quad + y(y-1)\left[xC_{\text{As-N}}(\text{InNAs}) + (1-x)C_{\text{As-N}}(\text{GaNAs})\right] \end{aligned} \qquad (3)$$

where $C_{\text{A-B}}$ (ABC) is the bowing parameter of ABC. The relevant bowing parameters are listed in Table 1 [21–24]. The conduction band offset (V_0) was taken to be 80% of the total discontinuity between the band gap of GaAs and $Ga_xIn_{1-x}N_yAs_{1-y}$ materials [25] (from a theoretical fit to the experimental data, a type-I band alignment for the heavy holes with a strained conduction-band offset ratio of about 80% is obtained) and the values of the parameters such as the effective mass and dielectric constant for $Ga_xIn_{1-x}N_yAs_{1-y}$ material were obtained using a linear interpolation between parameters of relevant binary semiconductors [26]:

$$\begin{aligned} P(Ga_xIn_{1-x}N_yAs_{1-y}) &= xyP(\text{GaN}) + (1-x)(1-y)P(\text{InAs}) \\ &\quad + (1-x)yP(\text{InN}) + x(1-y)P(\text{GaAs}). \end{aligned} \qquad (4)$$

The physical parameters for binary semiconductors used in the calculation are listed in Table 2 [27–29].

When the intense laser effects are considered (the polarization of the laser radiation is parallel to the z-direction), the confinement potential in the equation (2) takes the following form [20]

Table 2. Parameters for GaAs, InGa, GaN and InN materials used in this calculation.

Material	GaAs[a]	InAs[a]	GaN[a]	InN
E_g(eV)	1.519	0.417	3.299	1.94[b]
Electron effective mass (m_0)	0.067	0.022	0.15	0.14[c]

[a] Reference [27]; [b] reference [28]; [c] reference [29].

$$\begin{aligned} \langle V\rangle(z;\alpha_0) &= \frac{V_0}{\pi}\left[\theta(\alpha_0 - z - L/2)\arccos\left(\frac{L/2+z}{\alpha_0}\right)\right. \\ &\quad \left. + \theta\left(\alpha_0 + z - L/2\right)\arccos\left(\frac{L/2-z}{\alpha_0}\right)\right] \end{aligned} \qquad (5)$$

where $\alpha_0 = eF_0/m^*\omega^2$ is laser-dressing parameter and F_0 is the field strength. Extended details about dressed potential in equation (5) and the nonperturbative theory developed to describe the atomic behavior in intense high frequency laser field can be find in references [20] and [30,31], respectively.

Taking into account the dressed-potential in equation (5), we obtain the quasi-stationary energy levels by solving the Schrödinger equation:

$$-\frac{\hbar^2}{2m^*}\frac{\partial^2\psi(z)}{\partial z^2} + \langle V\rangle(z;\alpha_0)\psi(z) = E\psi(z) \qquad (6)$$

where E is the energy eigenvalue under the ILF. To solve the Schrödinger equation in equation (6), we take as base the eigenfunction of the infinite potential well with L_b width. L_b is well width of the infinite well at the far end of SQW with L width ($L_b \gg L$) and its value is determined according to the convergence of the energy eigenvalues. These bases are formed as [32]

$$\psi_n(z) = \sqrt{\frac{2}{L_b}}\cos\left[\frac{n\pi}{L_b}z - \delta_n\right], \qquad (7)$$

where

$$\delta_n = \begin{cases} 0 & \text{if } n \text{ is odd,} \\ \frac{\pi}{2} & \text{if } n \text{ is even,} \end{cases}$$

and so, the wave function in the z-direction is expanded in a set of basis function as follows:

$$\psi(z) = \sum_{n=1}^{\infty} c_n\psi_n(z). \qquad (8)$$

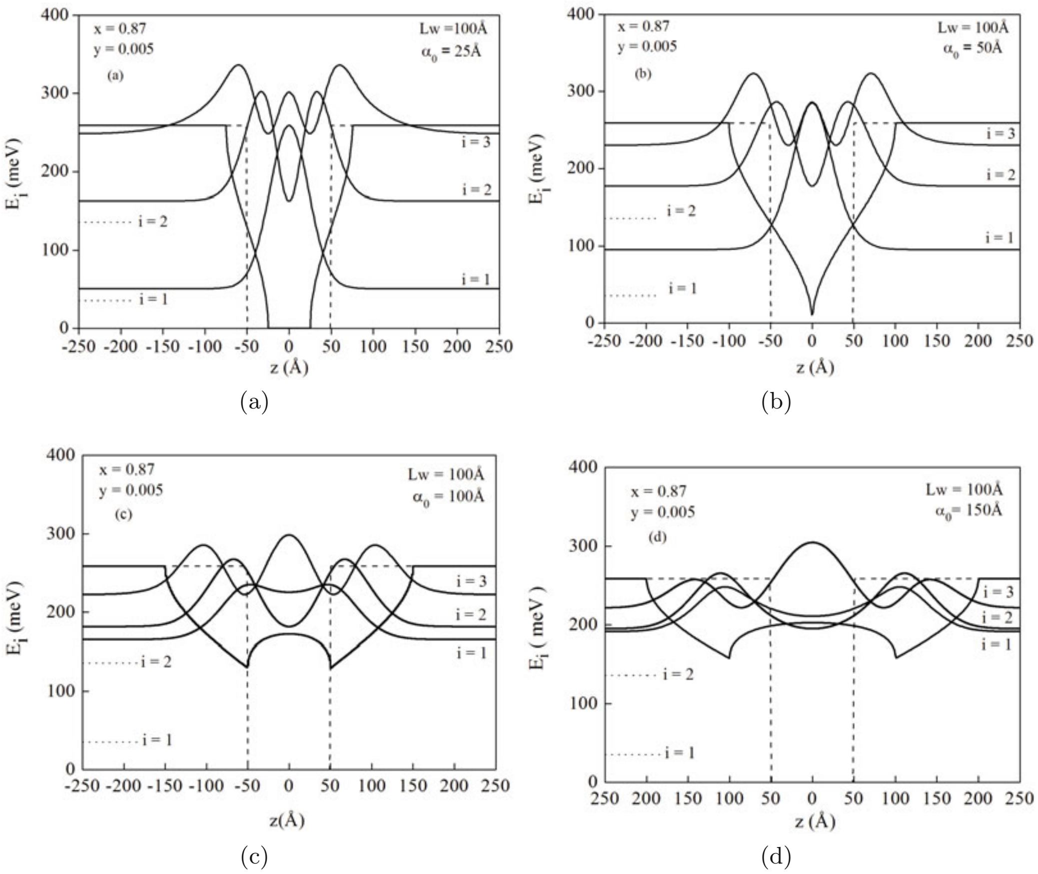


Fig. 1. The variation of the laser-dressed potential, bound states and squared wave functions related to these bound states in $Ga_xIn_{1-x}N_yAs_{1-y}$/GaAs quantum well which has the width $L = 100$ Å as a function of the position. In and N concentrations are $x = 0.87$ and $y = 0.005$, respectively. The results are for (a) $\alpha_0 = 25$ Å, (b) $\alpha_0 = 50$ Å, (c) $\alpha_0 = 100$ Å and (d) $\alpha_0 = 150$ Å. Dashed (solid) line corresponds to $\alpha_0 = 0$ ($\alpha_0 \neq 0$).

In calculating the wave function $\psi(z)$, we ensured that the eigenvalues are independent of the chosen infinite potential well width L_b and that the wave functions are localized in the well region of interest. This method which gives accuracies greater than 0.001 meV, is well controlled, gives the SQW eigenfunctions, and is easily applied to situations of varying potential and effective mass. This technique allows one to follow the development of SQW eigenstate outside the well and to determine the validity of quasi-bound state approximation. As with many numerical approaches, the algorithm can only be applied over a finite region of space, which means that we must place arbitrary boundaries and boundary conditions on the solution. For states that are sufficiently quasi-bound, then if the boundary is sufficiently far away from the quantum well, it should have no effect on the eigenstates. In fact, this can be used as reasonable criteria for having a well-defined quasi-bound state. For detailed information please check reference [33].

3 Results and discussion

In our calculations, equations (3) and (4) were used to determine the physical parameters ($V(z)$ and m^*) of $Ga_xIn_{1-x}N_yAs_{1-y}$ material according to nitrogen and indium concentrations, respectively. The electron effective mass was assumed to be same in the well and barrier regions.

In Figures 1a–1d and 2a–2d, we show the laser-dressed potential, bound states and squared wave functions related to these bound states in $Ga_xIn_{1-x}N_yAs_{1-y}$/GaAs single quantum well (SQW) which has the width $L = 100$ Å for a constant indium (In) concentration ($x = 0.87$) and different laser-dressing parameters (α_0) as a function of the position for two different nitrogen (N) concentrations $y = 0.005$ (Fig. 1) and $y = 0.05$ (Fig. 2), respectively. Dashed (solid) line corresponds to $\alpha_0 = 0\,(\alpha_0 \neq 0)$. There are two bound states in QW for $\alpha_0 = 0$, while there are three bound states for $\alpha_0 \neq 0$. Because as ILF increases the width of the well bottom decreases by $L-2\alpha_0$, while the top width increases by $L+2\alpha_0$. Energy levels are closer to each other since ILF creates an additional geometric confinement on the electronic states in the QW. Furthermore, for α_0 values which satisfy the condition $\alpha_0 > L/2$ SQW potential turns into double quantum well (DQW) potential [20] (we have observed in our previous study that DQW turns into triple

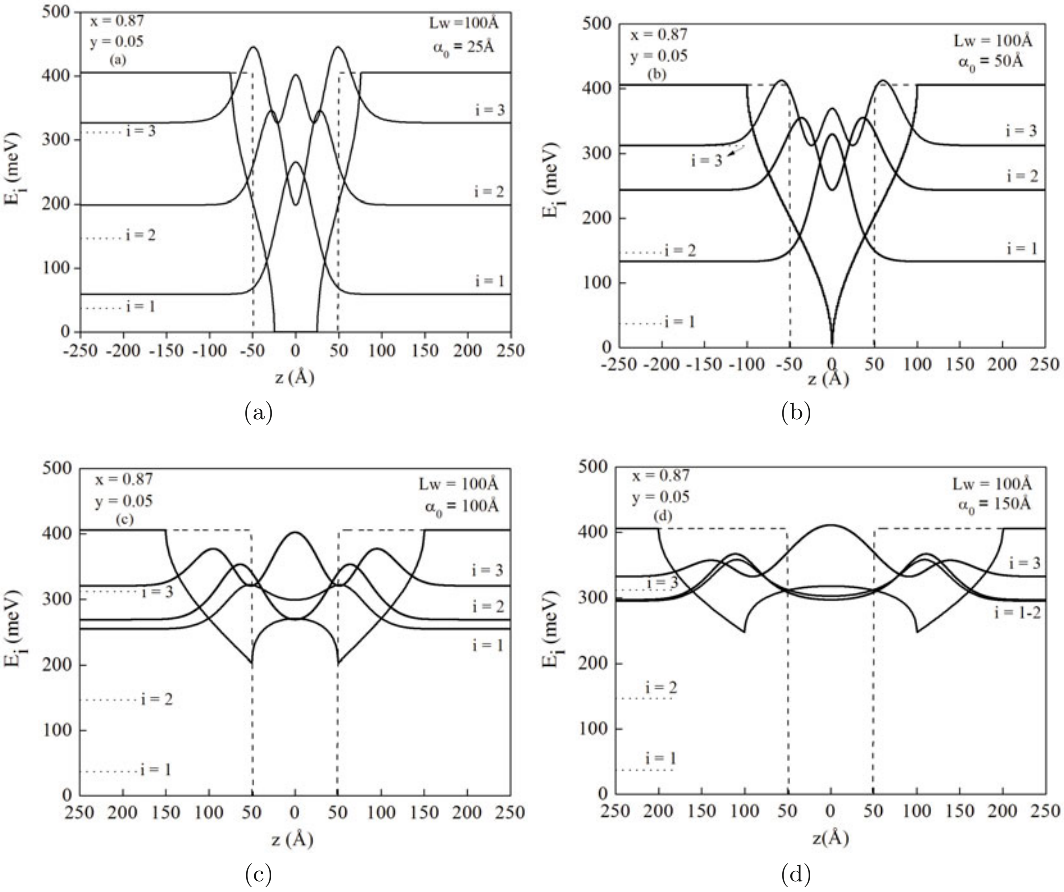


Fig. 2. The variation of the laser-dressed potential, bound states and squared wave functions related to these bound states in $Ga_xIn_{1-x}N_yAs_{1-y}/GaAs$ quantum well which has the width $L = 100$ Å as a function of the position. In and N concentrations are $x = 0.87$ and $y = 0.05$, respectively. The results are for (a) $\alpha_0 = 25$ Å, (b) $\alpha_0 = 50$ Å, (c) $\alpha_0 = 100$ Å and (d) $\alpha_0 = 150$ Å. Dashed (solid) line corresponds to $\alpha_0 = 0\,(\alpha_0 \neq 0)$.

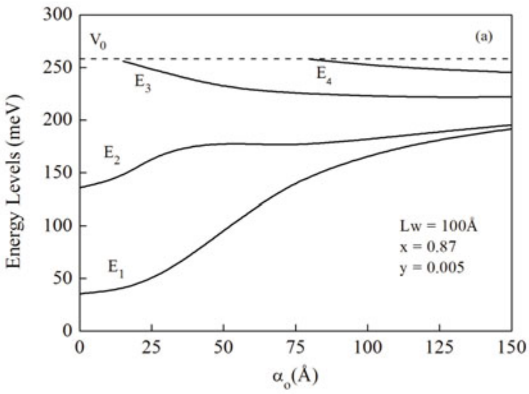
quantum well as α_0 increases [31]. The arising of a DQW enables one to create controllable resonant states located in the well material. This obviously does not need any growth of conventional DQWs, which are more difficult to tune to the desired resonance states.

As seen in Figure 2, higher N-concentration causes the deeper potential well which strongly confines the electrons in the conduction band and so even for $\alpha_0 = 0$, there are three bound states. N-incorporation into the GaInNAs has strong influence on carrier localization.

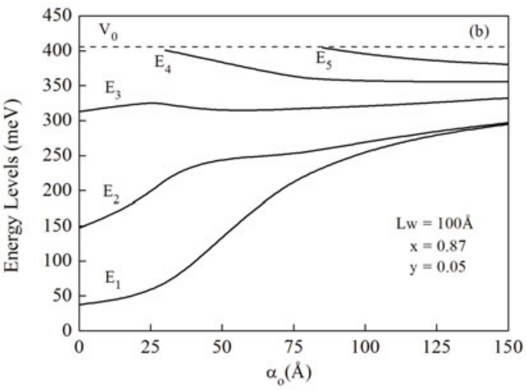
In order to see the effect of the ILF on the electronic states, the variations of energy levels for bound states in $Ga_xIn_{1-x}N_yAs_{1-y}/GaAs$ quantum well which has the width $L = 100$ Å as a function of the laser-dressing parameter for a constant In-concentration and two different N-concentrations are given in Figures 3a and 3b, respectively. As seen in these figures, as α_0 increases the lowest two energy levels increase while the bound state energies which are newly appeared with the effect of ILF decrease and this can be appreciated as an important factor in forming the population inversion in optical pumping laser systems. Change of energy spectrum with laser field provides a new freedom degree in optical systems based on interband and intersubband transitions and also important advantage in the field of application.

It should be noticed that when the energy of the electron is below the half-height of the QW the energy of the electron increases with growing laser-dressing parameter, i.e., E_1 and E_2 energy levels blue shifted with the α_0. At the same time, it implies a decreasing in the electron confinement with growing laser-dressing parameter if the energy of the electron is above the half-height of the well and than they are red shifted.

Furthermore, it should be noted that the range of laser intensities that are experimentally attainable is 10^3–10^{15} kW/cm^2. For $\alpha_0 = 100$ Å, output power of laser source with frequency $\nu = 30$ THz is $I \cong 6.8 \times 10^6$ kW/cm^2 (Intensity of laser source is given by $I = 0.0187\,\varepsilon_r^{5/2}\nu^4\alpha_0^2$ kW/cm^2, where $\varepsilon_r = 11.0274$ is the high-frequency dielectric permittivity of $Ga_{0.87}In_{0.13}N_{0.005}As_{0.995}$ and $a_B = 94.8781$ Å is effective Bohr radius under high-frequency AC fields). Therefore, our results are experimentally attainable.



(a)



(b)

Fig. 3. The variation of energy levels for bound states in $Ga_xIn_{1-x}N_yAs_{1-y}$/GaAs quantum well which has the width $L = 100$ Å for a constant In concentration as a function of the laser-dressing parameter. The results are for (a) $y = 0.005$ and (b) $y = 0.05$. Dashed line corresponds to V_0 level.

4 Conclusions

In this work, we have investigated the effects of the intense laser field, nitrogen and indium concentrations on energy levels for bound states in $Ga_xIn_{1-x}N_yAs_{1-y}$/GaAs quantum well within the effective mass and the spherical conduction band approximations. Our results reveal that: ILF creates an additional geometric confinement on the electronic states in the QW, the effect of the N concentration on the electronic states increases with the effect of ILF. We can tune the electronic structure and main optical properties of the system depend on intersubband transitions by changing the nitrogen concentration together with the laser field. We hope that our results can stimulate further investigations of the related physics, as well as device applications of group-III nitrides.

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