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Effects of an intense, high-frequency laser field on the binding energy of excitons confined in a GaInNAs/GaAs quantum well

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ABSTRACT

The effects of an intense, high-frequency laser field linearly polarized along the growth direction on the binding energy of excitons confined in a GaInNAs/GaAs quantum well is computed for different nitrogen and indium mole fractions by means of a variational technique within the effective-mass approximation. Our results show that such laser field creates an additional geometric confinement on the electronic and exciton states in the quantum well and the exciton binding energy depends on both the nitrogen and indium concentrations.

1. Introduction

In recent years, the quaternary alloy GaInNAs has been emerged as a subject of considerable theoretical and experimental research interest due to their very unique physical properties and a wide range of possible device applications. GaInNAs exhibits interesting new properties and differs considerably from the conventional III–V alloys. Significant changes occur in the electronic band structure compared to GaInAs with incorporation of only a small fraction of nitrogen into GaInAs. These include a large red-shift of the band gap [1–5], an increase in the electron effective mass [6–8], a highly nonlinear pressure dependence of the band gap [6,9,10] and the N-induced formation of new bands [4,5,7,8].

In addition, these new materials have received considerable attention due to the growing interest in its basic physical properties [11–15]. Shan et al. [16] showed that interaction between the conduction band and a narrow resonant band formed by nitrogen states in $Ga_{1-x}In_xN_yAs_{1-y}$ alloys leads to a splitting of the conduction band into two subbands and a reduction of the fundamental band gap. Polimeni et al. [17] estimated this interaction energy. The electronic structures of strained $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs quantum wells (QWs) have been investigated by Fan and Yoon [12] using a 6×6 Hamiltonian model. A large number of papers concern on detailed optical characterization of $Ga_{1-x}In_xN_yAs_{1-y}$. These papers include low temperature photoluminescence [14], absorption spectrum [18], the temperature dependence of photoluminescence [15,19,20]. Mair et al. [13] used time-resolved photoluminescence spectroscopy to study carrier dynamics in a $Ga_{1-x}In_xN_yAs_{1-y}$ epilayer. Those results show that the low-temperature photoluminescence emission is dominated by localized exciton recombination, and the measured recombination lifetimes are shorter than the corresponding GaAs exciton lifetime.

The study of semiconductor heterostructures, particularly under the action of external fields, has attracted the attention of many researchers in the last decades. These studies have been extended to semiconductor heterostructures under intense electric fields created by an applied ac voltage or high-intensity THz laser [21–24]. It has become possible to measure the effect of an intense laser radiation on ionization and perturbation of dopants in different semiconductor systems [25,26] with development and application of coherent, high-power, long-wavelength, frequency-tunable and linearly polarized radiation sources such as THz or far infrared free electron lasers.

In the present paper, we have investigated effects of an intense, high-frequency laser field and both the nitrogen (N) and indium (In) concentrations on exciton binding energy in a $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs QW using a variational technique within the effective-mass approximation. Despite considerable progress in the development of devices based on the $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs heterostructures, many fundamental physical properties of these materials are still unknown, such as the binding energy of the excitons and impurities in these systems. To the best of our knowledge, this is the first study for exciton binding energy in such a QW material under intense, high-frequency laser fields.

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2. Theoretical

In the effective mass approximation, the Hamiltonian for the electron–hole pair without laser field is given by

$$H=\frac{1}{2m_e^*}\mathbf{p}_e^2+V(z_e)+\frac{1}{2m_h^*}\mathbf{p}_h^2+V(z_h)-\frac{ke^2}{\varepsilon_r|\mathbf{r}_e-\mathbf{r}_h|} \tag{1}$$

where $m^*_{e(h)}$ is the effective mass of the electron (hole), $\mathbf{r}_e(\mathbf{r}_h)$ is electron (hole) position in the laboratory frame, $\mathbf{p}_e(\mathbf{p}_h)$ is the electron (hole) momentum operator, $k\equiv 1/(4\pi\varepsilon_0)$ is the Coulomb constant, ε_r is the relative dielectric constant of the semiconductor material (see Table 1) and $V(z_{e(h)})$ is the confinement potential profile for the electron (hole) in the z-direction.

The functional forms of the confinement potentials for electron and hole are given as

$$V(z_{e(h)})=V_0^{e(h)}\theta(|z_{e(h)}|-L/2) \tag{2}$$

where θ is the unit step function, L is the well width, $V_0^{e(h)}$ is the conduction band offset and taken to be 80 (20) percent of the total discontinuity between the band gap of GaAs and $Ga_{1-x}In_xN_yAs_{1-y}$ grown on GaAs [27]. The band gap energy in the bulk $Ga_{1-x}In_xN_yAs_{1-y}$ in Ref. [28] is as follows:

$$E_g(Ga_{1-x}In_xN_yAs_{1-y})=E_g(Ga_{1-x}In_xAs)-69\,\mathrm{eV}\times\Delta e(x,y) \tag{3}$$

where $\Delta e(x,y)=e(x,y)-e(x,0)$ is the difference between the strain computed for $Ga_{1-x}In_xN_yAs_{1-y}$ and $Ga_{1-x}In_xAs$, $e(x,y)=[a(0,0,)-a(x,y)]/a(x,y)$, and $a(x,y)$ is the lattice constant of $Ga_{1-x}In_xN_yAs_{1-y}$. The electron effective mass is given as [28]

$$m^*(Ga_{1-x}In_xN_yAs_{1-y})=m^*(Ga_{1-x}In_xAs)+18.1667m_0\Delta e(x,y) \tag{4}$$

The heavy hole effective mass and the static dielectiric constant of $Ga_{1-x}In_xN_yAs_{1-y}$ materials are obtained using a linear interpolation between the parameters of the relevant binary semiconductors [29]

$$P(Ga_{1-x}In_xN_yAs_{1-y})=P(\mathrm{InN})xy+P(\mathrm{InAs})x(1-y)+P(\mathrm{GaN})(1-x)y+P(\mathrm{GaAs})(1-x)(1-y) \tag{5}$$

where the relevant physical parameters for the above binary semiconductors are listed in Table 1.

It is convenient to introduce the center of mass coordinate $\mathbf{R}=(m_e^*\mathbf{r}_e+m_h^*\mathbf{r}_h)/(m_e^*+m_h^*)$ and the relative coordinate $\mathbf{r}=\mathbf{r}_e-\mathbf{r}_h$ (see Ref. [31] and references therein). In cylindrical coordinates $(x=\rho\cos\phi,\quad y=\rho\sin\phi,\quad z=z)$, the Hamiltonian for a confined exciton reads

$$H=-\frac{\hbar^2}{2\mu}\left(\frac{\partial^2}{\partial\rho^2}+\frac{1}{\rho}\frac{\partial}{\partial\rho}+\frac{1}{\rho^2}\frac{\partial^2}{\partial\phi^2}\right)-\frac{\hbar^2}{2m_e^*}\frac{\partial^2}{\partial z_e^2}-\frac{\hbar^2}{2m_h^*}\frac{\partial^2}{\partial z_h^2}-\frac{ke^2}{\varepsilon_r\sqrt{\rho^2+(z_e-z_h)^2}}+V(z_e)+V(z_h) \tag{6}$$

where the term $\rho=\sqrt{(x_e-x_h)^2+(y_e-y_h)^2}$ is the relative distance between the electron and hole in the $(x–y)$ plane, $\mu=m_e^*m_h^*/(m_e^*+m_h^*)$ being the reduced mass.

When irradiated by an intense, high-frequency laser field polarized perpendicularly to the QW interfaces, the confinement potential is distorted, taking the form described in Ref. [30]

$$V(z_{e(h)})=\frac{V^0_{e(h)}}{\pi}\left[\theta(\alpha_0-L/2-z_{e(h)})\arccos\left(\frac{L/2+z_{e(h)}}{\alpha_0}\right)+\theta(\alpha_0-L/2+z_{e(h)})\arccos\left(\frac{L/2-z_{e(h)}}{\alpha_0}\right)\right] \tag{7}$$

where $\alpha_0=(eF_0/m^*\omega^2)$ and F_0 is the field strength. The Coulombian potential is also changed by the laser fields, becoming (see Ref. [31] and references therein)

$$V_C=-\frac{ke^2}{2\varepsilon_r}\left\{\frac{1}{\sqrt{\rho^2+(z_e+\alpha_0-z_h)^2}}+\frac{1}{\sqrt{\rho^2+(z_e-\alpha_0-z_h)^2}}\right\} \tag{8}$$

Our trial wave-function of the electron–hole system was chosen as (see Ref. [32] and references therein)

$$\psi(\rho,z_e,z_h;\alpha,\beta)=N\varphi(z_e)\varphi(z_h)\exp\left[-\sqrt{\frac{\rho^2}{\alpha^2}+\frac{(z_e-z_h)^2}{\beta^2}}\right] \tag{9}$$

where N is the normalization constant, α and β are the variational parameters, $\varphi(z_e)$ and $\varphi(z_h)$ represent the motions of electron and hole in the z-direction, respectively.

The Schrödinger equation of the excitonic structure is

$$H\psi(\rho,z_e,z_h;\alpha,\beta)=E\psi(\rho,z_e,z_h;\alpha,\beta) \tag{10}$$

where E is the total energy.

The ground state exciton binding energy is obtained as follows:

$$E_b=E_z^e+E_z^h-Min_{(\alpha,\beta)}\langle\psi|H|\psi\rangle \tag{11}$$

where E_z^e and E_z^h are the lowest electron and hole subband energies corresponding to the quantum confinement along the z-axis direction.

3. Result and discussion

In our calculations, Eqs. (3)–(5) were used to determine the physical parameters (ε, m_e^*, m_h^*, $V(z)$) of $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs material according to nitrogen and indium concentrations. As seen in Table 2 for a constant indium concentration, as nitrogen concentration increases both the electron effective mass (hole effective mass) and the band discontinuity increase while dielectric constant decreases. Furthermore, the band discontinuity and dielectric constant increases while the electron effective mass (hole effective mass) decreases with increasing indium for a constant nitrogen concentration.

The effect of intense, high-frequency laser field on the confinement potential profile in a $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs QW, which has the width $L=100$ Å, for constant In and N concentrations is

Table 1
Parameters of the binary compounds used for the calculation.

Material	GaAs[a]	InAs[a]	GaN[b]	InN[b]
Lattice constant a_0 (Å)	5.6533	6.0584	4.50	4.98
Heavy hole effective mass $m_h(m_0)$	0.350	0.333	0.855	0.833[c]
Dielectric constant	12.53	14.55	10.69[d]	7.46[e]
$In_xGa_{1-x}As$ band gap at 300 K (eV)[f]	$E_g=1.424-1.53x+0.45x^2$			

[a] Ref. [35].
[b] Ref. [36].
[c] Ref. [40].
[d] Ref. [38].
[e] Ref. [39].
[f] Ref. [37].

Table 2
Physical parameters of $Ga_{1-x}In_xN_yAs_{1-y}$ material according to nitrogen and indium concentrations.

x	y	$m_e(m_0)$	$m_h(m_0)$	V_e (meV)	V_h (meV)	ε_r
0.35	0.002	0.0553	0.3441	407.36	101.84	13.22
0.35	0.005	0.0656	0.3447	438.83	109.70	13.21
0.35	0.01	0.0829	0.3458	491.35	122.83	13.20
0.15	0.005	0.0770	0.3481	231.68	57.92	12.81
0.25	0.005	0.0713	0.3464	339.06	84.76	13.01
0.35	0.005	0.0656	0.3447	438.83	109.70	13.21