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Intraband optical absorption in a single quantum ring: Hydrostatic pressure and intense laser field effects

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ABSTRACT

The intraband optical absorption in GaAs/$Ga_{0.7}Al_{0.3}As$ two-dimensional single quantum ring is investigated. Considering the combined effects of hydrostatic pressure and intense laser field the energy of the ground and few excited states has been found using the effective mass approximation and exact diagonalization technique. The energies of these states and the corresponding threshold energy of the intraband optical transitions are examined as a function of hydrostatic pressure for the different values of the laser field parameter. We also investigated the dependencies of the intraband optical absorption coefficient as a function of incident photon energy for different values of hydrostatic pressure and laser field parameter. It is found that the effects of hydrostatic pressure and intense laser field lead to redshift and blueshift of the intraband optical spectrum respectively.

1. Introduction

Self-assembled semiconductor quantum nanostructures, such as quantum dots (QDs) and quantum rings (QRs) have been investigated extensively given their potential as building blocks for a broad range of novel optoelectronic devices, e.g. nanoemitters, and for quantum information technologies [1–4]. The potential of these nanostructures is based on their remarkable similarity to atomic systems. Furthermore, what makes these nanostructures so attractive is the ability to tune their optoelectronic properties by carefully designing their size, composition, strain and shape. These parameters set the confinement potential of the charge carriers, thus determining the electronic and optical properties of a nanostructure.

It is well known that external perturbations are useful tools to manipulate the electronic and optical properties of low-dimensional semiconductor nanostructures. In particular, it was theoretically proved that the nanostructures irradiated by intense laser field (ILF) exhibit characteristics very different from those of a bulk semiconductor and the radiation effects are more pronounced as the carriers' confinement is increased by dimensionality reduction [5–11]. In addition, studies of the influences of the hydrostatic pressure on the electronic and impurity states have proven to be invaluable in the context of the optical properties of semiconductor heterostructures [12,13]. For a given structure, the difference in energy between the type-I and type-II transitions can be tuned with external hydrostatic pressure in the continuous and reversible manner. This makes possible an elucidation of the properties of various interband transitions.

Simultaneous effects of hydrostatic pressure and ILF on electronic, impurity states and optical properties of semiconductor quantum wells and QDs have been investigated in Refs. [10,14–18]. The studies have shown that the electronic, impurity and optical properties of quantum wells and dots are strongly affected by the mentioned influences. Having this in motivation, the present work aims at the theoretical investigation of the combined influences of the hydrostatic pressure and ILF on one-electron states and intraband optical absorption coefficient in GaAs/$Ga_{0.7}Al_{0.3}As$ two-dimensional QR. The paper is organized as follows: in Section 2 we describe the theoretical framework. Section 3 is dedicated to the results and discussion, and our conclusions are given in Section 4.

2. Theoretical framework

Without loss of generality, our system can be considered two-dimensional, with the electron confined in the plane $z=0$ [19]:

$$V(x\mathbf{i}+y\mathbf{j},P)=\begin{cases}0, & \text{if } R_1(P)\le\sqrt{x^2+y^2}\le R_2(P),\\ V(\tilde{X},P), & \text{if } \sqrt{x^2+y^2}<R_1(P), \text{ or } \sqrt{x^2+y^2}>R_2(P).\end{cases} \quad (1)$$

where $\mathbf{i}$ and $\mathbf{j}$ are the unit vectors along the x-axis of laser

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Table 1
The parameters considered in the description of the Γ and X energy gap functions.

Γ-minimum	X-minimum
$a_\Gamma = 1519.36$ *rmmeV*	$a_X = 1981$ *rmmeV*
$b_\Gamma = 1360$ *rmmeV*	$b_X = 207$ *rmmeV*
$c_\Gamma = 220$ *rmmeV*	$c_X = 55$ *rmmeV*
$\alpha_\Gamma = 10.7$ *rmmeV*/kbar	$\alpha_X = -1.35$ meV/kbar

polarization and y-axis respectively, $\tilde{X}$ is the aluminum concentration, $R_1(P)$ and $R_2(P)$ are the pressure dependent inner and outer radii respectively of the QR given by [20]:

$$R_{1,2}(P) = R_{1,2}(0)[1 - 2(S_{11} + 2S_{12})P]^{1/2}, \tag{2}$$

where S_{11} and S_{12} are the components of the compliance tensor of GaAs [21] ($S_{11} = 1.16 \times 10^{-3}$ kbar^{-1} and $S_{12} = -3.7 \times 10^{-4}$ kbar^{-1}). $R_1(0)$ and $R_2(0)$ are the dimensions of the structure at zero hydrostatic pressure. In Eq. (1) $V(\tilde{X}, P)$ is given by

$$V(\tilde{X}, P) = r\begin{cases} E_g^\Gamma(\tilde{X}, P) - E_g^\Gamma(0, P), & \text{if } P \le P_1(\tilde{X}), \\ E_g^X(\tilde{X}, P) - E_g^\Gamma(0, P) + S_{\Gamma X}(\tilde{X}, P), & \text{if } P_1(\tilde{X}) < P \le P_2(\tilde{X}). \end{cases} \tag{3}$$

Here, $r\,(=0.6)$ is the fraction of the band gap discontinuity, $\tilde{X}$ is the aluminum concentration. The energy gap function at the i-point $(i = \Gamma, X)$ of the conduction band is given by

$$E_g^i(\tilde{X}, P) = a_i + b_i\,\tilde{X} + c_i\tilde{X}^2 + \alpha_i P. \tag{4}$$

The values of the parameters a_i, b_i, c_i, and α_i are shown in the Table 1 [22].

The pressure $P_1(\tilde{X})$ is the value corresponding to the crossover between the Γ and X bands minima in $Ga_{1-\tilde{X}}Al_{\tilde{X}}As$, and the pressure $P_2(\tilde{X})$ is its equivalent with respect to the crossover between the Γ-band minimum at the GaAs well and the X-band minimum at the $Ga_{1-\tilde{X}}Al_{\tilde{X}}As$ barrier, and the expressions of pressure and aluminum concentration dependent band gaps at Γ and X minima can be found in [21]. Besides,

$$S_{\Gamma X}(\tilde{X}, P) = S_0\frac{P - P_1(\tilde{X})}{P}\,\tilde{X} \tag{5}$$

is the $\Gamma - X$ mixing strength coefficient and S_0 is the adjustable parameter which fits the experimental measurements [23,24].

We assume the system to be under the action of laser radiation represented by a monochromatic plane wave of frequency ω_0. The laser beam is non-resonant with the QR structure, and linearly polarized along a radial direction (oriented along the x-axis). In the high-frequency regime the particle is subjected to the time-averaged potential [5,25]

$$V_d(x, y, P) = \frac{\omega_0}{2\pi}\int_0^{2\pi/\omega_0} V((x + \alpha_0\,sin(\omega_0 t))\mathbf{i} + y\mathbf{j}, P)dt \tag{6}$$

where α_0 is the laser field parameter.

Taking into account (Eqs. (1), 3) and (5) one may obtain a closed analytical form of $V_d(x, y, P)$, as in [26]. Taking for simplicity the same effective mass of the electron inside and outside the QR, the laser-dressed energies are obtained from the time-independent Schrödinger equation [27–29]

$$\left[-\frac{\hbar^2}{2m(P)}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + V_d(x, y, P)\right]$$
$$\Phi_d(x, y, P) = E_d(P)\Phi_d(x, y, P), \tag{7}$$

where $m(P)$ is the pressure dependent effective mass of the electron [21]. The laser-dressed energy eigenvalues $E_d(P)$ and eigenfunctions $\Phi_d(x, y, P)$ may be calculated by solving Eq. (6) with a 2D diagonalization technique [30–32].

The light absorption process can be described as an optical transition that takes place from an initial state to a final one assisted by a photon. The optical absorption calculations for the intraband transitions are based on Fermi's golden rule derived from time-dependent perturbation theory [33,34]:

$$\alpha(\hbar\omega) = \frac{16\pi^2\beta_{FS}\hbar\omega}{\varepsilon(P)^{1/2}V}N_{if}|M_{fi}|^2\delta(E_f - E_i - \hbar\omega), \tag{8}$$

where $\varepsilon(P)$ is the pressure dependent static dielectric constant of the material [35], V is the volume of the sample per QR (in this work $V = 6 \times 10^{-18}$ cm^3) [36], β_{FS} is the fine structure constant, $\hbar\omega$ is the incident photon energy and E_f and E_i are the energies of the final and initial states, respectively. $N_{if} = N_i - N_f$ is the difference between the number of electrons in the initial and final states. Since we consider a one-particle problem, we assume $N_i = 1$ for the ground state and $N_f = 0$ for all upper states. M_{fi} is the matrix element of coordinate and the δ-function is substituted by a Lorentzian profile with a full width at half maximum of 0.8 meV [34,37,38].

3. Results and discussion

In the calculations the aluminum concentration has been taken as $\tilde{X} = 0.3$. It is worth to note that the appropriate choices of pressure-dependent energy gaps, structure dimensions, electron effective mass and static dielectric constant of the structure used in numerical calculations in this work, guarantee good agreement between theoretical calculations and experimental measurements [22,24]. In Figs. 1(a)–(c) are shown the dependencies on hydrostatic pressure of the ground and few excited state energies for different values of the laser field parameter α_0. We see that all energies are decreasing functions of pressure and such a behavior can be explained as follows: for $P \le P_1$ the radial-confining potential height is constant (see Ref. [21]) and the energy decrease is only due to the increase of the electron effective mass with pressure, but if $P_1 < P < P_2$ there will be a faster decrease in the electron energy with pressure, since in addition to the decrease associated to the growth in the value of the electron effective mass, now there is an extra reduction in the energy, that is associated with the fall in the radial-potential barrier height.

On the other hand, Fig. 1(a) shows that in the absence of the laser field $(\alpha_0 = 0)$, the first two excited levels are twice degenerated. The laser field removes this degeneracy by breaking the initial axial symmetry (see Figs. 1(b) and (c)). It should be mentioned that with the increase of laser field the effective length (the dressing effect of the laser "reshapes" the confinement potential by enlarging the QR) of the confinement potential (for low lying states) along the laser field polarization (x-direction) decreases. For this reason, in all investigated cases the laser field brings the increment of the dressed energies.

Fig. 2(a)–(c) contains the threshold energy associated with the transition between the ground state and excited states varying as a function of hydrostatic pressure, for different values of the laser field parameter α_0. We can see that the threshold energy is a decreasing function of the hydrostatic pressure for all transitions except for $1 \to 2$ transition in the case of $\alpha_0 = 5$ nm, where it has both decreasing and increasing behaviors. This is associated with the change in the rate of decreasing of the ground and first excited state energies, which can be seen in Fig. 1(c). Meanwhile, the threshold energy of $1 \to 3$ transition increases with the augment of the laser field parameter, which can also be understood from the energy spectrum shown in Fig. 1.

Note that, by analysing the parities of the laser dressed wave