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The effects of hydrostatic pressure on the nonlinear intersubband transitions and refractive index changes of different QW shapes

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ABSTRACT

In this study, the effects of hydrostatic pressure on the linear and nonlinear intersubband transitions and the refractive index changes in the conduction band of different quantum well shapes are theoretically calculated within framework of the effective mass approximation. Results obtained show that intersubband properties and the energy levels in different QWs can be modified and controlled by the hydrostatic pressure. The modulation of the absorption coefficients and the refractive index changes which can be suitable for good performance optical modulators and various infrared optical device applications can be easily obtained by tuning the hydrostatic pressure strength.

1. Introduction

There has been an increasing interest, both experimentally and theoretically, in the investigation of low-dimensional semiconductor heterostructures due to their intrinsic physical properties and technological applications in electronic devices. The studies on quantum heterostructures open a new field in fundamental physics, and also offer a wide range of potential applications for optoelectronic devices. The advances in sophisticated methods of semiconductor structures growth have enabled the fabrication of devices carefully tailored to a particular application. By varying the profile of a semiconductor quantum well (QW), both the subband state energies and their wave functions changes, and so do various physical properties depending on them. Due to a large variety of technological applications, single and multiple semiconductor quantum-well structures have been extensively studied in different situations including external perturbations, such as pressure, magnetic and electric fields and distinct doping processes. Hydrostatic pressure is a thermodynamic variable for the solid state, which provides a useful tool to control and investigate the electronic, the excitonic, the impurity states as well as optical, device and transport properties of semiconductor materials and low-dimensional systems [1–5]. The application of hydrostatic pressure significantly affects the electronic properties of the semiconductor systems due to mainly the changes that it induces in quantities such as the energy band gap, effective mass, and the dielectric constant [6,7].

Intersubband transition in quantum wells (QWs) has unique properties such as a large dipole moment, an ultra-fast relaxation time, and a large tunability of transition wavelength. Not only the physical interests but also novel device applications are expected from these unique properties. Because of the possibility for novel devices, the optical properties of the quasi-two dimensional electron gas (2DEG) in a semiconductor structure has been investigated both theoretically and experimentally, and many new GaAs/$Ga_{1-x}Al_xAs$ quantum well photodetectors based on intersubband absorption has been proposed to replace the conventional detectors [8–14]. A number of device applications based on the intersubband transition, for example, far-infrared photodetectors [15–19], electro-optical modulators [20–22], all optical switch [23], and infrared lasers [24,25], have been proposed and investigated.

The nonlinear effects in the semiconductor quantum nanostructures are much stronger than the bulk materials due to the existence of a strong quantum confinement effect. Among the optical properties of low dimensional semiconductor systems, linear and nonlinear intersubband optical absorption coefficients and refractive changes have drawn more attention at theoretical and experimental investigations [26–29]. Linear and nonlinear optical properties in nano-structure semiconductors, such as

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quantum wells (QWs), quantum well wires (QWWs) and quantum dots (QDs), strongly depend on symmetrical and asymmetrical situations of the quantum system. These conditions can be obtained by geometrical features, which are realized using material-growing technologies like square quantum well (SQW) or graded quantum well (GQW) or parabolic quantum well (PQW). Theoretical studies show that the optical properties of quantum wells mainly depend on the asymmetry of the confining potential. Such an asymmetry in potential profile can be obtained either by applying an electric field to a symmetric quantum well or by compositionally grading the QW [30–32]. The application of an electric field in the growth direction of the system gives rise to a polarization of the carrier distribution and to an energy shift of the quantum states, which may be used to control and modulate the intensity output of photonic devices.

It is well known that for pressures $P \leq 10$ kbar a Γ-like electron is confined in GaAs layer by the Γ barriers of constant height while for $10 < P \leq 30$ kbar the X-minima of the barrier layers drop below the Γ-minimum of these layers and pass through the energies of the confined electron states. For $P > 30$ kbar the X-minima of the $Ga_{0.7}Al_{0.3}As$ layers become the minimum of the conduction-band states of the system and electrons are no longer confined to the GaAs layer. For $P \geq 40$ kbar the X-minima are the lowest energy states in the GaAs layer and both the barrier and well materials become indirect. As different from previous studies [33–36], in this study for $P=20$ kbar we investigate the effect of the hydrostatic pressure on the linear and nonlinear optical absorptions associated with intersubband transitions within the conduction band for different quantum well shapes.

2. Theory

In the effective mass approximation, the total Hamiltonian for an electron in a QW, having the z-axis as the growth direction under the hydrostatic pressure is given by

$$H = \frac{P_\perp^2}{2m^*(P)} + \frac{P_Z^2}{2m^*(P)} + V(z,P) \tag{1}$$

where, $P_\perp^2/2m^*(P)$ is the kinetic energy operator in the $(x–y)$ plane, m^* is the effective mass of the electron in the conduction band, P is the hydrostatic pressure in kbar. The pressure dependence of the effective mass of the electron in GaAs is determined from expression [37–38]

$$m^*(P) = \frac{m_0}{1+E_P^\Gamma[(2/E_g^\Gamma(P))+(1/E_g^\Gamma(P)+\Delta_0)]} \tag{2}$$

where m_0 is the free electron mass, $E_P^\Gamma = 7.51$ eV is the energy related to the momentum matrix element, $\Delta_0=0.341$ eV is the spin–orbit splitting, and $E_g^\Gamma(P)$ is the variation of the energy gap (in eV) for a GaAs semiconductor at Γ-point with the hydrostatic pressure in units of kbar, which in turn is expressed [37–40] as

$$E_g^\Gamma(P) = a + bP + cP^2 \tag{3}$$

where $a=1.519$ eV, $b=1.26\times10^{-2}$ eV/kbar and $c=-3.77\times10^{-5}$ eV/kbar^2.

The confinement potential which is given by

$$V(Z,P) = \begin{cases} \frac{V_0(P)z}{2L(P)}g & |z| \leq \frac{L(P)}{2} \\ V_0(P) & |z| > \frac{L(P)}{2} \end{cases} \tag{4}$$

and the barrier height is given by [41–43]

$$V_0(P) = Q_C\, \Delta E_g^\Gamma(X,P) \tag{5}$$

where $Q_C=0.6$ is the conduction band offset parameter, $\Delta E_g^\Gamma(X,P)$ is the band gap difference between QW and the barrier matrix at the Γ-point as a function of P, which for an aluminum fraction $X=0.3$ is given by [38,40,42]

$$\Delta E_g^\Gamma(X,P) = \Delta E_g^\Gamma(X) + PD(X) \tag{6}$$

where $\Delta E_g^\Gamma(X) = (1.155X + 0.37X^2)$ eV the variation of the gap is difference and $D(X)=[-(1.3x10^{-3})X]$ eV/kbar is the pressure coefficient of band gap. In Eq. (4)

$$L(P) = L[1-(S_{11}+2S_{12})P] \tag{7}$$

where $S_{11}=1.16\times10^{-3}$/kbar and $S_{12}=-3.7\times10^{-4}$/kbar are the elastic constants of the GaAs [37–40] and L is the original width of the confinement potentials in z-direction.

After the energies and their corresponding wave functions is obtained, the first-order linear absorption coefficient $\beta^{(1)}(\omega)$ and the third-order nonlinear absorption coefficient $\beta^{(3)}(\omega,I)$ for the intersubband transitions between two subbands can be clearly calculated as [44],

$$\beta^{(1)}(\omega) = \omega\sqrt{\frac{\mu}{\varepsilon_r}}|M_{21}|^2 \frac{\sigma_v\hbar/\tau_{in}}{(E_2-E_1-\hbar\omega)^2+(\hbar/\tau_{in})^2} \tag{8}$$

$$\beta(3)(\omega,I) = -\omega\sqrt{\frac{\mu}{\varepsilon_r}}\left(\frac{I}{2\varepsilon_0 n_r c}\right)|M_{21}|^2 \frac{\sigma_v\hbar/\tau_{in}}{\left\{(E_2-E_1-\hbar\omega)^2+(\hbar/\tau_{in})^2\right\}^2} \times\left[4|M_{21}|^2 - \frac{|M_{22}-M_{11}|^2\left\{(E_2-E_1-\hbar\omega)^2-(\hbar/\tau_{in})^2+2(E_2-E_1)(E_2-E_1-\hbar\omega)\right\}}{(E_2-E_1)^2+(\hbar/\tau_{in})^2}\right] \tag{9}$$

and the linear and the third-order nonlinear refractive index changes can be expressed as [45], respectively.

$$\left(\frac{\Delta n^{(1)}(\omega)}{n_r}\right) = \frac{\sigma_v|M_{21}|^2}{2n_r^2\varepsilon_0}\frac{(E_2-E_1-\hbar\omega)}{(E_2-E_1-\hbar\omega)^2+(\hbar/\tau_{in})^2} \tag{10}$$

$$\left(\frac{\Delta n^{(3)}(\omega,I)}{n_r}\right) = -\frac{\mu c}{4n_r^3\varepsilon_0}|M_{21}|^2\frac{\sigma_v I}{[(E_2-E_1-\hbar\omega)^2+(\hbar/\tau_{in})^2]^2} \times\left[4(E_2-E_1-\hbar\omega)|M_{21}|^2 - \frac{(M_{22}-M_{11})^2}{(E_2-E_1)^2+(\hbar/\tau_{in})^2} \left\{(E_2-E_1-\hbar\omega)[(E_2-E_1)(E_2-E_1-\hbar\omega)-(\hbar/\tau_{in})^2] -(\hbar/\tau_{in})^2[2(E_2-E_1)-\hbar\omega]\right\}\right] \tag{11}$$

Here I is the optical intensity of incident electromagnetic wave (with the angular frequency ω) that excites the structure and leads to the intersubband optical transition, μ is the permeability,

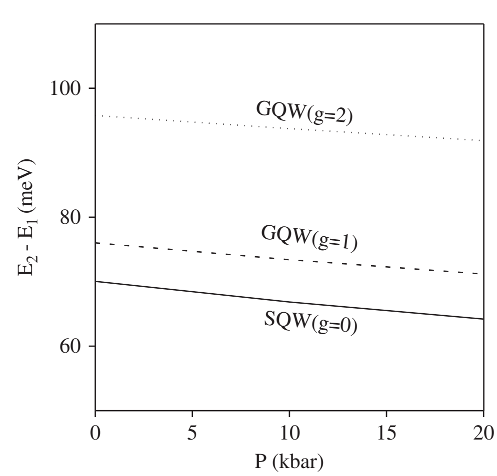

Fig. 1. For different QW shapes, the variations of the energy difference between the ground state and first excited state as dependent on the hydrostatic pressure.