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Nonlinear intersubband absorption and refractive index changes in square and graded quantum well modulated by temperature and Hydrostatic pressure

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ABSTRACT

In this study, the effects of hydrostatic pressure and temperature on the linear and nonlinear intersubband transitions and the refractive index changes in the conduction band of square and graded quantum well (QW) are theoretically calculated within the framework of effective mass approximation. Results obtained show that the energy levels in different QWs and intersubband properties can be modified and controlled by the hydrostatic pressure and temperature. 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 temperature and the hydrostatic pressure.

1. Introduction

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. On varying the profile of a semiconductor quantum well (QW), both the subband state energies and their wave functions change, 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, temperature, 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, excitonic and 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 transitions within the conduction band of semiconductor quantum wells have been extensively studied from the viewpoints of both physical interest and novel device applications. Optical and transport properties have a strong relation with the degree of localization of the electronic states in the materials. In low-dimensional semiconductor structures, the electronic localization is in external fields, which is frequently used in applications to optoelectronic devices. 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 interest 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 have been investigated both theoretically and experimentally, and many new GaAs/$Ga_{1-x}Al_xAs$ quantum well photo-detectors based on intersubband absorption have been proposed to replace the conventional detectors [8–14]. A number of device applications based on the intersubband transition, for example, far-infrared photo-detectors [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 in the bulk materials due to the

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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 been drawn more attention in theoretical and experimental investigations [26–31].

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 [32–34]. As different from previous studies [35–38], in this study we investigate the effect of the hydrostatic pressure and temperature on the linear and nonlinear optical absorptions associated with intersubband transitions within the conduction band for square quantum well (SQW) and graded quantum well (GQW). Significant changes in the magnitude and position of absorption peaks are obtained when the pressure and temperature increase.

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

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

where $(P_{\perp}^{2})/(2m^{*}(P,T))$ 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, and T is temperature. The temperature and pressure dependence of the effective mass of the electron in GaAs is determined from the expression [39,40]

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

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 $E_g^{\Gamma}(P,T)$ is the variation of the energy gap (in eV) for a GaAs semiconductor at Γ-point with the temperature and hydrostatic pressure in units of kbar, which in turn is expressed [39–42] as

$$E_g^{\Gamma}(P,T)=E_g^{\Gamma}(0,T)+bP+cP^{2} \tag{3}$$

where $E_g^{\Gamma}(0,T)=1.519-(5.405\times10^{-4}\ \mathrm{K}^{-1})T^{2}/(T+204\ \mathrm{K})$ eV, $b=1.26\times10^{-2}$ eV/kbar and $c=-3.77\times10^{-5}$ eV/kbar^2.

The confinement potential is given by

$$V(z,P,T)=\begin{cases}0 & |z|\le\frac{L(P)}{2} \quad \text{for SQW}\\ \frac{V_0(P,T)}{L(P)}z & |z|\le\frac{L(P)}{2} \quad \text{for GQW}\\ V_0(P,T) & |z|>\frac{L(P)}{2}\end{cases} \tag{4}$$

and the barrier height is given by [43–45]

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

where $Q_C=0.6$ is the conduction band offset parameter, $\Delta E_g^{\Gamma}(X,P,T)$ 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 [40,42,44]

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

where $\Delta E_g^{\Gamma}(X)=(1.155X+0.37X^{2})$ eV is the variation of the gap difference, $D(X)=[-(1.3\times10^{-3})X]$ eV/kbar, and $G(X)=[-(1.11\times10^{-4})X]$ eV/K [46].

In Eq. (4)

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

where $S_{11}=1.16\times10^{-3}$ kbar^{-1} and $S_{12}=-3.7\times10^{-4}$ $kbar^{-1}$ are the elastic constants of GaAs [39–42] and L is the original width of the confinement potentials in z-direction.

After the energies and their corresponding wave functions are 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 [47]

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

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

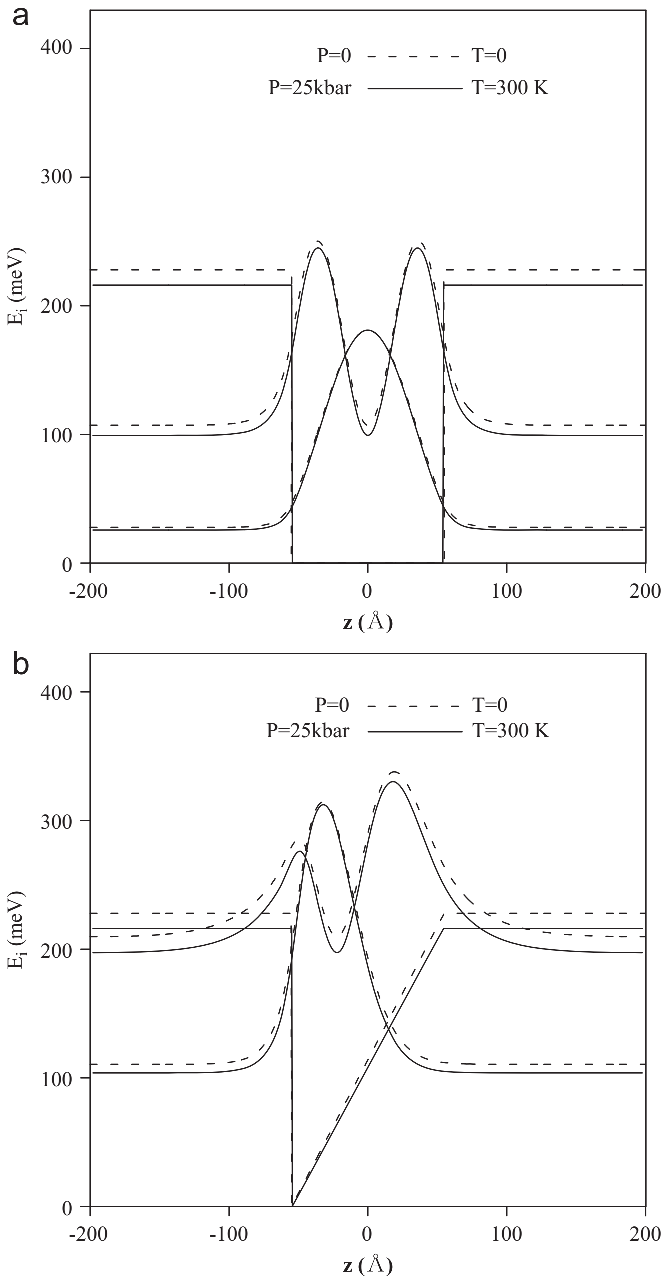

Fig. 1. Change of the potential profile and the energies with their squared envelope wave functions of the first and the second subband under temperature and pressure for (a) SQW and (b) GQW.