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The effect of hydrostatic pressure, temperature and magnetic field on the nonlinear optical properties of asymmetrical Gaussian potential quantum wells

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HIGHLIGHTS

- Optical properties of asymmetrical Gaussian potential QWs are discussed with multiple effects.
- The new and reliable results are obtained via the fine difference method.
- The influence of applied magnetic field is significant with respect to other effects.

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ABSTRACT

In this study, simultaneous effects of hydrostatic pressure, temperature and magnetic field on the linear and nonlinear intersubband optical absorption coefficients (OACs) and refractive index changes (RICs) in asymmetrical Gaussian potential quantum wells (QWs) are theoretically investigated within the framework of the compact-density-matrix approach and iterative method. The energy eigenvalues and their corresponding eigenfunctions of the system are calculated with the differential method. Our results show that the position and the magnitude of the resonant peaks of the nonlinear OACs and RICs depend strongly on the hydrostatic pressure, temperature and external magnetic field. This gives a new degree of freedom in various device applications based on the intersubband transitions of electrons.

1. Introduction

With recent rapid advances of modern technology, such as molecular beam epitaxy and metal-organic chemical vapour deposition [1,2], it has become possible to produce a variety of dimensionality semiconductor nanostructures [3–5], which offer a wide range of potential applications for optoelectronic devices. Some of these applications include semiconductor lasers [6], single-electron transistors [7], quantum computing [8], optical memories [9] and infrared photodetectors [10]. To fully understand and predict experimental phenomenon, the nonlinear optical properties in these semiconductor structures have been intensively studied theoretically. Especially, much attention has been paid to the larger-band-gap low-dimensional semiconductor QWs structure because they are more advantageous to grow, process, and fabricate into devices than are small-band-gap semiconductors.

Recently, there is a considerable interest in the optical phenomena based on semiconductor QWs nanostructure in the presence of some external perturbations, such as electric field, magnetic field, hydrostatic pressure and temperature. It is because its band gap can be tuned and thereby the change in property may be applied for the electro and opto-electronic devices. In particular, by means of the applied hydrostatic pressure one may generate indirect transitions in the energy-space. This transitions come from the appearance of the hydrostatic pressure-induced conduction band minimum at the *X* point of the Brillouin zone of the materials that make up the potential barriers. Ungan et al. have investigated the effects of hydrostatic pressure and doping concentration on subband structure and optical transitions in modulation-doped $GaAs/Al_xGa_{1-x}As$ QW. The obtained results show that by changing the doping concentration, the hydrostatic

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pressure and the structure parameters change further the separation between the subbands, which gives a new degree of freedom in device applications [11]. Hakimyfard et al. have studied the simultaneous effects of pressure and magnetic field on intersubband optical transitions in Pöschl–Teller QW [12]. Karabulut et al. have theoretically studied the simultaneous influences of applied electric field, magnetic field and hydrostatic pressure on the nonlinear optical rectification and OACs in $GaAs/Al_xGa_{1-x}As$ asymmetric double QWs. They have given the optimizing nonlinear OACs using adjustable the geometry of the structure. Besides, the combination of hydrostatic pressure and electric field provide a way of tuning the position of the maxima and minima of the nonlinear optical properties [13]. Dakhlaoui et al. analyzed the intersubband transitions and OACs in GaAs QW under the effects of hydrostatic pressure, the position and the concentration of Si δ-doped layer [14]. Oubram et al. investigated the hydrostatic pressure on intersubband transitions of n-type doped GaAs QW [15]. Majority of provided results indicate that the various factors such as temperature, applied electric and magnetic field, and hydrostatic pressure affect the electronic and optical properties of these semiconductor materials. Particularly, the manipulation of hydrostatic pressure leads to change in the confinement of electrons and in different transitions, which is very useful to fabricated optoelectronics devices.

In the present work, we present a numerical study of the linear and nonlinear OACs and RICs in an asymmetrical Gaussian potential QWs. In Section 2, the eigenfunctions and eigenenergies of electron states are obtained using finite difference method, and the analytical expression for the OACs and RICs are derived by means of the compact-density-matrix approach and an iterative method. In some investigation, the Gaussian shape QWs have been widely studied. But we find both energy and wavefunction for the low-lying state in this model are wrong to applied in these works [16–18]. Therefore, we have written a comment for pointing out the incorrect [19]. In Section 3, the numerical results and discussions are presented for asymmetrical Gaussian potential QWs under the simultaneous effects of hydrostatic pressure, temperature, applied magnetic field and the fixed applied electric field. Because of the electric field effect and structural parameters on the nonlinear optical properties in asymmetrical Gaussian potential QWs have been discussed in our previous paper [20]. A brief summary is given in Section 4.

2. Theory

The Hamiltonian for an electron confined in the asymmetrical Gaussian potential QWs under the influence of applied electric and magnetic and the hydrostatic pressure (electric field oriented in the growth direction and magnetic field perpendicularly to the growth direction). Within the effective-mass approximation, the Hamiltonian of this system can be written as [21]

$$\left(-\frac{\hbar}{2}\frac{d}{d_z}\left[\frac{1}{m^*(P,T)}\frac{d}{d_z}\right]+V(z,P,T)+\frac{e^2B^2}{2m^*(P,T)c^2}\right)\varphi(z)=E\varphi(z), \tag{1}$$

where z represents the growth direction of the QWs. B is the external magnetic field, and T is the temperature. $m^*(P,T)$ is the pressure- and temperature-dependent conduction effective mass in the well region, given by the expression [22,23]

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

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 pressure- and temperature-dependent energy gap for the GaAs semiconductor at the Γ-point, given by [22]

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

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

And the confinement potential $V(z,P,T)$ is given by

$$V(z,P,T)=\begin{cases}-V_0(P,T)\exp(-z^2/2L(P)^2), & z\ge 0\\ \infty, & z<0,\end{cases} \tag{4}$$

here the barrier height is given by [24]

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

where Q_c=0.6 is the conduction band offset parameter, X=0.3 is the mole fraction of aluminum in $Ga_{1-x}Al_xAs$, and $\Delta E_g^{\Gamma}(X,P,T)$ is the band gap difference between QW and barrier matrix at the Γ-point as a function of P and T, which is given by [25]

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

where $\Delta E_g^{\Gamma}(X)=(1.55X+0.37X^2)$ eV the variation of the gap is difference and $D(X)=[-(1.3\times10^{-3})X]$ eV/kbar, $G(X)=[-(1.11\times10^{-4})X]$ eV/K. The pressure-dependent width of the QWs and barrier layer is given by

$$L(P)=L(0)(1-(S_{11}+2S_{12})P). \tag{7}$$

where $S_{11}=1.16\times10^{-3}$ kbar^{-1} and $S_{12}=3.7\times10^{-4}$ kbar^{-1} are the elastic constants of the GaAs and $L(0)$ is the original width of the layers.

Due to the presence of the applied electric and magnetic fields and hydrostatic pressure in the Hamiltonian (Eq. (1)), it is impossible to find self-energy analytic eigenfunctions that correspond to the exact solution of one electron confined in asymmetrical Gaussian potential QWs. To obtain the eigenvalues and eigenvectors of the time-independent Schrödinger equation, we have adopted the finite difference method. Next we will derive the OACs and RICs in asymmetrical Gaussian potential QWs by the compact-density-matrix method and the iterative procedure. The analytical expressions of the linear and the third-order nonlinear susceptibilities for a two-level quantum system are given as follows [26–28]. First, for the linear term,

$$\varepsilon_0\chi^{(1)}(\omega)=\frac{N|M_{21}|^2}{E_{21}-\hbar\omega-i\hbar\Gamma_{12}}. \tag{8}$$

For the third-order term,

$$\varepsilon_0\chi^{(3)}(\omega)=-\frac{N|M_{21}|^2}{E_{21}-\hbar\omega-i\hbar\Gamma_{12}}\times\left[\frac{4|M_{21}|^2}{(E_{21}-\hbar\omega)^2+(\hbar\omega)^2}-\frac{(M_{22}-M_{11})^2}{(E_{21}-\hbar\omega-i\hbar\Gamma_{12})}\right]. \tag{9}$$

The susceptibility $\chi(\omega)$ is related to the change in the refractive index as follows:

$$\frac{\Delta n(\omega)}{n_r}=Re\frac{\chi(W)}{2n_r^2}, \tag{10}$$

where n_r is the refractive index. By using Eqs. (8)–(10), the linear and the third-order nonlinear refractive index changes are obtained by

$$\frac{\Delta n^{(1)}(\omega)}{n_r}=\frac{1}{2n_r^2\varepsilon_0}|M_{21}|^2N\left[\frac{E_{21}-\hbar\omega}{(E_{21}-\hbar\omega)^2+(\hbar\Gamma_{12})^2}\right] \tag{11}$$

and