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The effects of the electric and magnetic fields on the nonlinear optical properties in the step-like asymmetric quantum well

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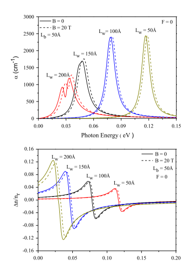
HIGHLIGHTS

- Absorption coefficients (AC) and refractive index (RI) change are sensitive to the well dimension.
- With the increase of well dimension, total AC and RI change shift to the lower photon energies.
- The electric and magnetic fields induce a blue shift on AC and RI changes.

GRAPHICAL ABSTRACT



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ABSTRACT

In the present work, total optical absorption coefficient (the linear and third-order nonlinear) and total refractive index change for transition between two first lower-lying electronic levels in the step-like $GaAs/Ga_{1-x}Al_xAs$ quantum well under the electric and magnetic fields are investigated and also the effect of relaxation time on saturation is investigated. A compact density-matrix approach is applied to investigate optical properties. The obtained results show that both total absorption coefficient and refractive index change are sensitive to well dimensions more than external fields. With the increase of quantum well width, total absorption coefficient and refractive index change shift to lower photon energies (red shift), the magnitude of total refractive index increases significantly while total absorption coefficient is reduced. Furthermore, the electric and magnetic fields induce a blue-shift on absorption coefficient and refractive index change.

1. Introduction

The linear and nonlinear properties in low-dimensional semiconductor quantum systems have attracted much attention both in theoretical and in practical applications. These strong nonlinear optical properties, such as the electro-optic effect [1,2], harmonic generation [3–17], refractive index changes (RICs) [18–22], and optical absorption effects [23–25], have a great potential in several device applications, such as far-infrared laser amplifiers [26], photodetectors [27], and high-speed electro-optical modulators [28].

There is a considerable interest in the optical phenomena based on intersubband transitions (ISBTs) in low-dimensional semiconductor quantum systems. Due to the generally larger values of dipole matrix

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elements and the possibility of achieving the resonance conditions, both the linear and nonlinear optical processes in these structures are investigated [29–31]. In two-dimensional (2D) semiconductor heterostructures, optical nonlinearities associated with ISBTs are known to be greatly enhanced as compared with those for the bulk semiconductors [32,33].

Apart from the traditional quantum well heterostructures such as square [34,35] and parabolic [32,36–39], quantum wells with shape of the half parabolic [40], graded [41], V-shaped [42], inverse parabolic and Posch–Teller [43–51] have been produced and studied. Furthermore, it is well known that the nonlinear optical properties of semiconductor quantum well (QW) mainly depend on the asymmetry of the confining potential. Such as asymmetry in a potential profile can be obtained, for example either by applying an electric field to a symmetric QW or by compositionally grading the QW. Therefore, several studies were pointed out on the theoretical analysis of linear and third-order nonlinear optical absorption in asymmetric QW [51–53] and also, the electric field effects on these properties are examined.

In this work, we have investigated the effects of the magnetic and electric fields on the nonlinear optical absorption and refractive index change of step-like GaAs/$Ga_{1-x}Al_xAs$ QW. This paper is organized as follows: we present the theoretical framework in Section 2, the numerical results and discussion in Section 3 and also the conclusions in Section 4.

2. Theory

We consider a step-like GaAs/$Ga_{1-x}Al_xAs$ QW. Within the framework of the effective mass approximation, the Hamiltonian of electron in the step-like QW under the magnetic field (B) which is applied perpendicular to the growth direction i.e. $\vec{B}=(B,0,0)$ and the electric field (F) which is applied to the growth direction (z-direction) is given by

$$H=\frac{1}{2m^*}\left[\vec{P}+\frac{e}{c}\vec{A}(\vec{r})\right]^2+V(z)+eFz \tag{1}$$

where m^* is the electron effective mass, e is the elementary charge, $\vec{P}$ is the momentum, $\vec{A}(\vec{r})$ is the vector potential and it is written in the form $\vec{A}=(0,-Bz,0)$ to describe the applied magnetic field and $V(z)$ is the confinement potential. The functional form of the confinement potential is given by

$$V(z)=\begin{cases} V_0, & z<-a, \\ 0, & -a\le z\le a, \\ V_0/2, & a<z\le b, \\ V_0, & z>b \end{cases} \tag{2}$$

where a and b is as $|a|=L_w/2$ and $b=L_w/2+L_b$ and chosen as the origin of the center of well with L_w width. To solve the Scrodinger equation of the system, we take as base the eigenfunctions of the infinite potential well with the L width. L ($\gg L_w+L_b$) is the well width of the infinite well at the end of step-like QW with (L_w+L_b) width and its value is determined according to the convergence of the energy eigenvalues. These bases are formed as

$$\psi_n(z)=\sqrt{\frac{2}{L}}\cos\left[\frac{n\pi}{L}z-\delta_n\right] \tag{3}$$

where

$$\delta_n=\begin{cases} 0 & \text{if } n \text{ is odd} \\ \frac{\pi}{2} & \text{if } n \text{ is even} \end{cases} \tag{4}$$

and so, the wave function is expanded in a set of basis function as follows:

$$\Psi(z)=\sum_{n=1}^{\infty} c_n\psi_n(z). \tag{5}$$

In calculating the wave function $\Psi(z)$, we ensured that the eigenvalues are independent of the chosen infinite well width L and that the wave functions are localized in the well region. We have also used the technique in our previous studies [54]. This method, which gives accuracies lesser than 0.001 meV, is well controlled, gives the QW eigenfunctions, and is easily applied to the situation of varying potential and effective mass. This technique allows one to follow the development of the QW eigenstate outside the well and to determine the validity of quasi-bound state approximation. For states that are sufficiently quasi-bound, if the boundary is sufficiently far away from the QW, then it should have no effect on the eigenstates. In fact, this can be used as reasonable criteria for having a well defined quasi-bound state. For detailed information refer to Ref. [55].

After the energy levels and corresponding wave functions are obtained, the linear and nonlinear refractive index (RI) changes and absorption coefficient (AC) for the ISBTs can be calculated. By using the density matrix formalism, the linear and third-order nonlinear ACs, related with the ISBT $1\rightarrow 2$, are given as follows [56,57]:

$$\alpha^{(1)}(\omega)=\omega\sqrt{\frac{\mu}{\varepsilon_R}}\frac{|M_{21}|^2\sigma_V\hbar\Gamma_{12}}{(\Delta E-\hbar\omega)^2+(\hbar\Gamma_{12})^2}, \tag{6}$$

$$\alpha^{(3)}(\omega,I)=-2\omega\sqrt{\frac{\mu}{\varepsilon_R}}\left(\frac{I}{\varepsilon_0 n_r c}\right)\times\frac{|M_{21}|^4\sigma_V\hbar\Gamma_{12}}{[(\Delta E-\hbar\omega)^2+(\hbar\Gamma_{12})^2]^2}\times\left(1-\frac{|M_{22}-M_{11}|^2}{|2M_{21}|^2}\cdot\frac{(\Delta E-\hbar\omega)^2-(\hbar\Gamma_{12})^2+2(\Delta E)(\Delta E-\hbar\omega)}{(\Delta E)^2+(\hbar\Gamma_{12})^2}\right), \tag{7}$$

where $\varepsilon_R=n_r^2\varepsilon_0$ is the real part of the permittivity. In addition, the total AC is given by

$$\alpha(\omega,I)=\alpha^{(1)}(\omega)+\alpha^{(3)}(\omega,I). \tag{8}$$

The linear and third-order nonlinear IR changes, related with the ISBT $1\rightarrow 2$, are given as follows:

$$\frac{\Delta n^{(1)}(\omega)}{n_r}=\frac{\sigma_V|M_{21}|^2}{2n_r^2\varepsilon_0}\frac{\Delta E-\hbar\omega}{(\Delta E-\hbar\omega)^2+(\hbar\Gamma_{12})^2} \tag{9}$$

$$\frac{\Delta n^{(3)}(\omega,I)}{n_r}=-\frac{\mu c|M_{21}|^2}{4n_r^3\varepsilon_0}\frac{\sigma_V I}{[(\Delta E-\hbar\omega)^2+(\hbar\Gamma_{12})^2]^2}\cdot\times\left\{4|M_{21}|^2-\frac{|M_{22}-M_{11}|^2}{(\Delta E)^2+(\hbar\Gamma_{12})^2}\cdot\left[\Delta E(\Delta E-\hbar\omega)-(\hbar\Gamma_{12})^2-\frac{(\hbar\Gamma_{12})^2(2\Delta E-\hbar\omega)}{\Delta E-\hbar\omega}\right]\right\}, \tag{10}$$

where σ_V is the carrier density in the system, μ is the permeability of the system, $\Delta E=E_2-E_1$ is the energy difference between two electronic states, $M_{ij}=|\langle\Psi_i|ez|\Psi_j\rangle|$ $(i,j=1,2)$ is the matrix elements of the dipole moment for z-polarization of the incident radiation, Γ_{12} is the relaxation rate which is equal to the inverse relaxation time T_{12}, c is the speed of light in the free space and I is the incident optical intensity which is defined as $I=(2n_r/\mu c)|E(\omega)|^2$. The total change of the RI can be written as

$$\frac{\Delta n(\omega,I)}{n_r}=\frac{\Delta n^{(1)}(\omega)}{n_r}+\frac{\Delta n^{(3)}(\omega,I)}{n_r}. \tag{11}$$