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Linear and nonlinear optical properties in a double inverse parabolic quantum well under applied electric and magnetic fields

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ABSTRACT

In the present work, the effects of electric and magnetic fields on the optical absorption coefficient and refractive index changes associated with intersubband transitions in a GaAs/$Al_xGa_{1-x}As$ double inverse parabolic quantum well are theoretically calculated within the effective-mass approximation. The expressions for the linear and third-order nonlinear absorption coefficients and refractive index changes are those obtained by using the compact density-matrix approach and iterative method. The results are presented as functions of the incident photon energy for different values of the applied electric and magnetic fields. It is found that the optical absorption coefficient and refractive index changes are strongly affected by the applied electric and magnetic fields.

1. Introduction

In the last years, the linear and nonlinear optical properties related to intersubband transitions (ISBTs) in low-dimensional semiconductor systems in which the carriers are confined into one, two, and three dimensions such as quantum wells (QWs), quantum well wires (QWWs), and quantum dots (QDs) have been extensively studied from the viewpoints of both physical interests and novel

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optoelectronic device applications. The nonlinear effects in these low-dimensional quantum systems are much stronger than in the bulk materials due to the existence of a strong quantum-confinement effect. Furthermore, these nonlinear properties have the potential for device application in semiconductor lasers [1], single-electron transistors [2], quantum computing [3], optical memories [4], far-infrared laser amplifiers [5], photo-detectors [6,7], and high-speed electro-optical modulators [8].

The development of material growth techniques, such as molecular beam epitaxy (MBE) and metal–organic chemical vapor deposition (MOCVD), makes possible to manufacture high-quality semiconductor QWs with desired profiles of the confinement potential. It is well known that the shape of the QW confining potential significantly affects the nonlinear optical properties. Therefore, the linear and nonlinear optical properties of these structures, with different confining potential functions have been intensively studied both theoretically and experimentally [9–23]. West and Eglash [9] and Levine et al. [10] reported their experimental results for the linear ISB optical absorption within the conduction band of a GaAs QW. The effects of applied electric fields on ISB transitions in modulation-doped single QW structures are studied experimentally by Mathur et al. [11]. Zhang and Xie [12] studied the electric field effect on the second-order nonlinear optical properties of parabolic and semi-parabolic QWs. They found that the second-harmonic generation susceptibility sensitively depends on the relaxation rate of the systems. The THz nonlinear absorption of asymmetric double QWs is calculated by Bedoya and Camacho [13]. Yildirim and Tomak [14] studied the effects of the asymmetry and the electric field on the nonlinear ISB optical absorption in GaAs QWs. Chen et al. [15] discussed the linear and nonlinear ISB optical absorption in triangular QWs. Karabulut and Duque [16] calculated the nonlinear optical rectification and optical absorption in GaAs/$Al_xGa_{1-x}As$ double QWs under applied electric and magnetic fields. The polaron effects on the optical absorption coefficient and refractive index changes in a square QW were calculated by Li et al. [17]. In addition, Keshavarz et al. [18–20] have investigated the linear and nonlinear ISB optical absorption in symmetric and asymmetric double semi-parabolic QWs, with and without applied electric field. Baskoutas et al. [21] reported the linear and nonlinear optical absorption coefficients in inverse parabolic QWs under static external electric field. Unal et al. [22] theoretically examined the electric field effect on the refractive index changes in a Modified-Pöschl–Teller QW. Recently, the effects of geometry, hydrostatic pressure, and aluminum concentration on the donor-impurity-related linear and nonlinear optical absorptions in GaAs/$Al_xGa_{1-x}As$ concentric quantum rings were calculated by Baghramyan et al. [23]. In previous works, we have studied the features of ISB optical transitions in single QWs [24–28] and double QWs [29,30] in the presence of the intense laser field [24–27], hydrostatic pressure [26,27], and the electric field [28,29]. We found that the application of one, or several, of these external probes has important influences on the optical properties of QWs.

In the present article we investigate the linear and nonlinear optical absorptions associated with ISBTs within the conduction band of GaAs/$Al_xGa_{1-x}As$ double inverse parabolic quantum well (DIP-QW) under applied electric and magnetic fields. The paper is organized as follows: In Section 2, details of the calculations are presented. The numerical results are presented and discussed in Section 3. Finally, the conclusions are given in Section 4.

2. Theory

Within the framework of the effective-mass approximation, the Hamiltonian for an electron in DIP-QW in the presence of magnetic field **B**, applied perpendicular to the growth direction, and electric field **F** applied along the z-direction, can be written as

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

where z represents the growth direction, m^* is the electron effective mass, e is the elementary electron charge, c is the speed of light in the free space, $\mathbf{A} = \frac{1}{2m^*}(\mathbf{B} \times \mathbf{r})$ the vector potential of magnetic field **B** [we choose a vector potential $\mathbf{A} = (0, -Bz, 0)$ and magnetic field $\mathbf{B} = (B, 0, 0)$], and $V(z)$ is the finite confinement potentials in the z-direction. The functional form of the symmetric confinement potential is given by the expression