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Linear and nonlinear optical properties in an asymmetric double quantum well under intense laser field: Effects of applied electric and magnetic fields

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A B S T R A C T

In the present study, the effects of electric and magnetic fields on the linear and third-order nonlinear optical absorption coefficients and relative change of the refractive index in asymmetric GaAs/GaAlAs double quantum wells under intense laser fields are theoretically investigated. The electric field is oriented along the growth direction of the heterostructure while the magnetic field is taken in-plane. The intense laser field is linear polarization along the growth direction. Our calculations are made using the effective-mass approximation and the compact density-matrix approach. Intense laser effects on the system are investigated with the use of the Floquet method with the consequent change in the confinement potential of heterostructures. Our results show that the increase of the electric and magnetic fields blue-shifts the peak positions of the total absorption coefficient and of the total refractive index while the increase of the intense laser field firstly blue-shifts the peak positions and later results in their red-shifting.

1. Introduction

Recent developments in the manufacture of low-dimensional systems have made it possible to produce high-quality semiconductor quantum wells (QWs) with desired shape of the confinement potential [1–7]. The interest in these systems is due to the importance of understanding the basic processes in quantum structures as well as their potential applications in electro-optical devices.

The double quantum well (DQW) systems are very important for the future industrial applications. On the basis of DQW systems, several nanoelectronic devices have been suggested and already realized. DQWs based on various semiconductor materials appear frequently in lasers emitting light in a wide range of wave lengths including the region 1.3–1.5 μm that is of great importance in optical communications. Furthermore, DQWs are also considered as effective terahertz (THz) detectors. Therefore, DQW systems have been studied extensively in a wide range of fields such as physics and chemistry [8,9]. Dong and Makri [8] have investigated and optimized the THz radiation emitted from a DQW. The effect of coupling of subband wave functions on the multisubband electron mobility in a δ-doped barrier $GaAs/Ga_{1-x}Al_xAs$ asymmetric double quantum well (ADQW) structure was studied by Das et al. [9]. In many experiments, the asymmetry of the DQW potential can be varied by changing the external parameters. However, most theoretical studies have been made for symmetric DQW systems and asymmetric systems have seen less theoretical interest than symmetric ones [10–15].

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Many studies indicate that nonlinear optical properties of semiconductor quantum heterostructures significantly depend on asymmetries of confinement potential [16–20]. Such an asymmetry in the potential profile can be created by selecting different well width [21], by additionally selecting different well depths [22], by applying an electric field to the structure [23], or by doping the wells with different concentrations [24]. In these asymmetric systems, quite high magnitudes of oscillator strength in the QWs are responsible for the large expectation values of the dipole moment. Therefore, it is possible to expect obtaining significant value of the nonlinear optical properties. Taking into account quite extensively to the literature on the subject, we can refer to the experimental observations of the nonlinear optical absorption (NOA) and nonlinear optical rectification (NOR) [25], the second harmonic generation (SHG) [26,27], third harmonic generation (THG) [28], and the four-wave mixing [29]. These reports have motivated the authors to perform many theoretical studies on NOA, NOR, SHG, THG, and other optical nonlinearities in semiconductor heterostructures [30]. These works show that the nonlinear optical responses are closely related to the asymmetries in the spatial dependencies of the wave functions corresponding to the allowed energy states.

As it is known, applying an electric or a magnetic field changes the quantum states of the confined carriers in nanostructures [31]. Therefore, understanding the effects of external electric and magnetic fields on the optical and transmission properties of low-dimensional systems is crucial for the development of this field of research. Recently, the development of high-power tunable laser source, such as free electron lasers, has fueled the realization of numerous studies on the interaction of intense laser field (ILF) with carriers in semiconductor low dimensional systems [32]. In the literature, it is possible to find some discussion and analysis of the effect of an intense high-frequency laser field on the physical properties of bulk semiconductors [33–36]. For laser radiation propagating parallel to the magnetic field, Miranda [33] finds that multiphoton processes are dominant when the laser frequency is near the electron cyclotron frequency. The rate of change of the longitudinal optical (LO)-phonon population due to scattering by free carriers in the presence of two laser fields is calculated by Nunes [34]. The distortion of the optical-absorption coefficient of a direct-gap semiconductor is investigated by Galvao and Miranda [35] when the semiconductor is subjected to an additional infrared laser field. Sakai and Nunes [36] investigated the possibility of excitation and amplification of LO lattice vibrations by electrons due to interband absorption of a laser field in semiconductors. In recent years, many works have reported the research done on the effect of ILF in low-dimensional heterostructures [37–41].

In the present study, the low dimensional heterostructure under investigation is an ADQW model consisting of two quantum wells with different widths separated by a barrier. The effects of externally applied electric, magnetic, and ILF are considered in our analysis. After determining the electronic structure of ADQWs, the aim is the calculation of NOA and relative change of the refractive index (RI) in the system. This is done in the framework of a two-level approach and the density matrix theory. We studied the changes of NOA and relative change of the RI with the external fields as a function of the incident photon energy.

Our article is organized as follows. In Section 2, briefly presents the description of the theoretical model. In Section 3, we give the results and discussion. Finally, the conclusions are given in Section 4.

2. Theory

Here, we are interested in the effects of electric, magnetic, and ILF on electron states in the GaAs/GaAlAs ADQW grown along the z-axis. Theoretical approach assumes the effective mass approximation for the identification of single electron state. We chose the electric field as directed along the growth direction ($\vec{F} = F\hat{z}$). The magnetic field is in-plane and taken along the x-direction ($\vec{B} = B\hat{x}$) within the Landau gauge ($\vec{A} = Bz\hat{y}$). Finally, the ILF is polarized in the z-direction. Then, the Hamiltonian without ILF effects has the following format for a confined electron [42]:

$$H = \frac{1}{2m_e^*}\left[\vec{p}_e + \frac{e}{c}\vec{A}\right]^2 + V(z) + e\vec{F}\cdot\vec{r}, \tag{1}$$

where m_e^*, $\vec{p}_e$, e, c, $\vec{A}$ and $\vec{r}$ are the electron effective mass, the electron momentum operator, the electron charge, the speed of light in vacuum, the magnetic vector potential ($\vec{A} = \vec{A}(\vec{r})$), and the electron coordinate, respectively. $V(z)$ is the confinement potential and by choosing as the origin of the z-axis the left side of the central barrier, the potential energy function is given by

$$V(z) = \begin{cases} V_0, & z \le -Lw_1, z \ge L_b + Lw_2 \text{ and } 0 \le z \le L_b \\ 0, & -Lw_1 < z < 0 \text{ and } L_b < z < L_b + Lw_2 \end{cases} \tag{2}$$

where Lw_1 (Lw_2) is the left (right) well width and L_b is the central barrier width of the ADQW. V_0 is the band discontinuity and calculated by $V_0 = Q_c(1155x+370x^2)$ meV, where $Q_c = 0.6$ is the conduction band offset parameter for $GaAs/Ga_{1-x}Al_xAs$ QW and x is the Al concentration in the barrier regions.

To solve Eq. (1), we take as a basis the eigen functions of L_D-width infinite potential well. These functions are the following:

$$\phi_n(z) = \sqrt{\frac{2}{L_D}}\cos\left(\frac{n\pi z}{L_D} - \delta n\right), \tag{3}$$

where δn is;

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

and the wave function that describes the system is formed from the complete set as follows [43]:

$$\psi(z) = \sum_{n=1}^{\infty} c_n \phi_n(z), \tag{5}$$

where c_n are the corresponding expansion coefficients.

When the ILF effects are considered, the confinement potential in Eq. (2) takes the following form:

where $\alpha_0 = \frac{eF_0}{m^*\varpi^2}$ is the laser dressing parameter, F_0 is the field strength, ϖ is the non-resonant frequency of the laser field, Θ is the step function, and $L = L_b + Lw_1 + Lw_2$.

After obtaining the energy levels and corresponding wave functions of Hamiltonian in Eq. (1) with the modified potential by the effects of ILF, linear and third-order NOA and relative changes of the RI for the intersubband (ISB) transitions can be calculated. Using the density matrix formalism, linear and third-order NOA coefficients related with the ISB transitions are given as follows [44], respectively: