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Linear and nonlinear optical properties in a semiconductor quantum well under intense laser radiation: Effects of applied electromagnetic fields

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ABSTRACT

In this work we are studying the intense laser effects on the electron-related linear and nonlinear optical properties in GaAs–$Ga_{1-x}Al_xAs$ quantum wells under applied electric and magnetic fields. The calculated quantities include linear optical absorption coefficient and relative change of the refractive index, as well as their corresponding third-order nonlinear corrections. The nonlinear optical rectification and the second and third harmonic generation coefficients are also reported. The DC applied electric field is oriented along the hererostructure growth direction whereas the magnetic field is taken in-plane. The calculations make use of the density matrix formalism to express the different orders of the dielectric susceptibility. Additionally, the model includes the effective mass and parabolic band approximations. The intense laser effects upon the system enter through the Floquet method that modifies the confinement potential associated to the heterostructure. The results correspond to several configurations of the dimensions of the quantum well, the applied electric and magnetic fields, and the incident intense laser radiation. They suggest that the nonlinear optical absorption and optical rectification are nonmonotone functions of the dimensions of the heterostructure and of the external perturbations considered in this work.

1. Introduction

Nanoelectronics is an emerging area that has attracted increasing interest due to the possibilities it opens in applied physics [1]. As it is well known, the application of either an electric or a magnetic field, among other external perturbations, changes the quantum states of carriers confined in nanostructures [2]. For this reason, the understanding of the effects of external electromagnetic fields on the optical and transport properties of low-dimensional systems—e.g., electrons confined in semiconductor nanostructures such as quantum wells (QWs), quantum-well wires (QWWs), and quantum dots (QDs)—is crucial for the evolution of such research area.

Recently, the development of high-power tunable laser sources, such as free electron lasers, has fueled the realization of a number of studies about the interaction of intense laser fields (ILF) with carriers in semiconductor low-dimensional systems [3]. This has allowed the discovery of interesting physical phenomena. We can mention, for instance, the presence of changes in the electron density of states in QWs and QWWs [4,5], the measurement of zero-resistance states in two-dimensional electron gases under microwave radiation [6], terahertz resonant absorption in QWs [7], and Floquet–Bloch states in single-walled carbon nanotubes [8], among others.

It is possible to find in the literature some discussion and analysis on the effect of an intense high-frequency laser field on the physical properties of bulk semiconductors [9–12]. In recent years, several works report investigations on the effect of laser fields on low dimensional heterostructures [13–28]. More specifically, Brandi et al. [13,14] extended the so-called dressed atom approach to treat the influence of the laser field upon a semiconductor system. In the model, the interaction with the laser is taken into account through the renormalization of the semiconductor effective mass. Niculescu et al. [15] have developed a theoretical study of the combined effects of intense high frequency laser and static magnetic fields on the binding and transition energies associated with the ground and some excited states of an on-center hydrogenic donor in a cylindrical GaAs QWW. They found that the effect of the laser field is more pronounced for s-like states, whereas for 2p-like states the binding energy is weakly dependent on the laser dressing parameter. With the use of the same calculation scheme, López et al. [16] have considered

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the laser-dressing effects on the electron g-factor in GaAs–$Ga_{1-x}Al_xAs$ QWs and QWWs under applied magnetic fields. Their work indicates the possibility of manipulating and tuning the conduction-electron g-factor in heterostructures by changing the detuning and laser field intensity.

Kasapoglu and Sökmen [17] studied the ILF dependence of intersubband absorption coefficient for 1–2 transitions in GaAs–$Ga_{1-x}Al_xAs$ double-graded QW under electric field. Taking into account a non-perturbative theory, they have obtained that the interband transitions may be tuned by changing the laser intensity together with the electric field and the well parameters. On the other hand, Diniz and Fanyao [18] have studied the effects of an ILF radiation on the optical properties of semiconductor QWs. Within the frame of the non-perturbative theory and variational approach, they have included the laser effects via laser-dressing QW potentials for both conduction and valence bands. They theoretically predicted a novel approach to build GaAs–$Ga_{1-x}Al_xAs$ lasers, by tailoring the semiconductor parameters and the external long-wavelength laser field radiation. This kind of non-perturbative calculations have been extended to investigate the effects of an ILF on the intersubband transitions in QWs [19]. The study uses the effective mass approximation as well as a variational calculation procedure. These works conclude that the intersubband optical transitions and energy levels in QWs can be significantly modified and controlled by means of an ILF.

In addition, the ILF effects on the density of impurity states of shallow donors in a square, V-shaped, and inverse V-shaped QWs have been studied by Niculescu et al. [20,21] and concluded that a proper consideration of the density of impurity states may be relevant in the interpretation of the optical phenomena related to shallow impurities in QWs; where the effects of an ILF compete with the applied electric field and the quantum confinement.

It is possible to mention the inclusion of the laser effects in calculations of a donor-impurity polarizability in a QW under an applied electric field. This study finds that the polarizability is a nonmonotonic function of the external perturbations like the applied electric field and the incoming laser radiation [22]. A theoretical study from Lima et al. [23] puts forward the appearance of a rather unexpected transition from a single to a double QW potential profile, induced by the ILF in a semiconductor double heterostructure. This feature allows the possibility of generating resonant states into the channel and of controlling the population inversion in QW lasers operating in the optical pumping scheme. Finally, the study of ILF effects has been extended to another heterostructures such as QWWs and QDs with several configurations of the quantum confinement, stoichiometry of the well and barrier regions, geometries of the systems, and external perturbations like applied electric and magnetic fields and hydrostatic pressure [24–28].

In recent years, the nonlinear optical properties of semiconductor QWs, QWWs, and QDs have been investigated experimentally and theoretically (see for instance Ref. [29] and references therein). The reason for this lies in the fact that the large optical nonlinearities associated with the intersubband transitions are very attractive for applications in the area of integrated optics and optical communications. Most of the studies performed are related to second-order nonlinear optical properties such as nonlinear optical rectification (NOR) and second harmonic generation (SHG). However, there are also reports on third-order nonlinear optical properties such as nonlinear optical absorption (NOA) and third harmonic generation (THG). It is well known that if the symmetry of a QW structure is broken anyhow, it is possible to obtain significant second-order susceptibilities. There are reports about theoretical predictions of large second-order susceptibilities associated with the intersubband transitions in low dimensional non-symmetric heterostructures. Very strong second-order nonlinear effects have been observed in step QWs, asymmetric coupled QWs and square QWs under an applied electric field. External applied electric fields can be used with the aim of obtaining asymmetric QWs that can be tuned to desirable conditions of confinement for correlated and noncorrelated carriers inside the well regions. Results reveal that the second-order susceptibilities are much larger than their values in bulk semiconductors.

We can mention theoretical calculations concerning the effects of external perturbations like applied electric and magnetic fields on the NOR in one-dimensional and zero-dimensional heterostructures [30,31]. There are also reports of the NOR in double triangular QWs and asymmetrical semiparabolic QWs [32,33] in which it is shown that the NOR susceptibility obtained in this kind of coupled well systems it can reach values 2–3 orders of magnitude higher than those obtained in single quantum systems.

Calculations of the SHG and THG coefficients in low dimensional systems have been put forward by some authors [34–36]. They included the hydrostatic pressure effects in asymmetric rectangular QWs [34], the electric field effects in parabolic and semiparabolic QWs [35], and the excitonic effects in small QDs—where the semiparabolic confining potential is dominant over the Coulomb interaction [36,37]. Intersubband optical absorption has been also studied in many theoretical reports in a V-groove QWW, in (CdS/ZnSe)/BeTe QWs, in quantum rings, and in spherical QDs with parabolic potential [38–41], and it has been concluded that the optical absorption coefficients are strongly affected by the incident optical intensity, the relaxation time, the confinement potential, and the structural dimensions of the heterostructures. Finally, it is important to notice that all the nonlinear properties cited above have been also studied in systems with an adjustable asymmetry such as the Pöschl–Teller QWs [42].

There is a recent report on the ILF effects on the nonlinear optical properties of a square QW under applied electric field [43]. The calculations performed there were carried out in the saturation limit using the density matrix formalism and the effective mass approach. The outcome shows that the laser field considerably affects the nonlinear optical properties. The inclusion of laser effects goes via the appropriate modification of the quantum confinement by means of step functions in the interfaces between the well and barrier materials. The present work is an extended form of such a previous report. We theoretically study the effects of ILF on the relative change of the refractive index, the NOR, the SHG, and the THG in single QWs under the combined effects of the electric field applied through the growth direction and the magnetic field applied in-plane. In Section 2 we describe the theoretical framework. Section 3 shows the results and discussion. We give our conclusions in Section 4.

2. Theoretical framework

Here we are dealing with the intense laser effects on the electron states in single GaAs–$Ga_{1-x}Al_xAs$ QW grown along the z-axis, in the presence of crossed electric and magnetic fields. The theoretical approach assumes the envelope-function and parabolic-band approximations for the determination of single electron states. We choose the electric field oriented along the growth direction, $\vec{\boldsymbol{F}} = -F\hat{z}$. The magnetic field is in-plane-oriented, and taken along the x-direction, $\vec{\boldsymbol{B}} = B\hat{x}$, within the Landau gauge; $\vec{\boldsymbol{A}}(\vec{\boldsymbol{r}}) = -Bz\hat{y}$. Then, the Hamiltonian for the confined electron has the following form [44–46]:

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