The dependence of the intersubband transitions in square and graded QWs on intense laser fields

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Received 7 April 2004; received in revised form 13 May 2004; accepted 18 May 2004 by C. Tejedor
Available online 7 June 2004

Abstract

The intersubband absorption in square and graded quantum wells under a laser field is calculated within the framework of the effective mass approximation. We conclude that, for quantum wells with different shapes, the laser field amplitude induces an important effect on the electronic and optical properties of the semiconductor structure. This gives a new degree of freedom in various device applications based on the intersubband transition of electrons.

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PACS: 71.55.Eq; 73.21.Fg; 78.67.De

Keywords: A. Square and graded quantum wells; D. Optical transitions; D. Laser field

1. Introduction

Strongly laser-driven semiconductor heterostructures have received attention in the recent years, with the availability of intense THz laser sources [1–11]. In the last decade the studies have been extended to semiconductor nanostructures under intense electric fields, originated by an applied ac voltage or a high-intensity infrared laser. Recent experiments on the optical properties of electronic systems under an intense THz radiation have revealed interesting phenomena [12,13], including resonant absorption [12], THz photon assisted tunneling [13]. The effect of an intense high-frequency laser field on the physical properties of bulk semiconductors has been discussed and analyzed in the literature [14–17]. In recent years, a number of investigations have been published on the effect of the laser fields on low-dimensional heterostructures. The effect of intense THz radiation on the linear optical absorption spectra of semiconductor structures theoretically studied by Johnsen et al. [18]. The solution of the time-dependent Schrödinger equation for an electron confined in a potential well created by a semiconductor heterostructure in the presence of an in-plane magnetic field and laser radiation is studied by Perez-Maldonado et al. [19]. They have observed a symmetry breaking in the quasi-energy spectra for intensities greater than a critical value. Recently, a simple scheme based on the inclusion of the effect of the laser interaction with the semiconductor through the renormalization, or dressing, of the electron effective mass has been proposed by Bradi et al. [20].

Because of the possibility for novel devices, the optical properties of the quasi-two dimensional (2D) electron gas in a semiconductor structure have been investigated both theoretically and experimentally, and many new GaAs/Ga\textsubscript{1-x}Al\textsubscript{x}As quantum well photodetectors based on intersubband absorption have been proposed to replace the conventional detectors [21–26]. Not only the physical interests but also novel device applications are expected from these unique properties. One of the most remarkable features of 2DEG is the intersubband optical transitions between the sizes quantized subbands in the same band. A number of device applications based on the intersubband transition, for example, far-infrared photo-detectors [27–31], electro-optical modulators [32–34], all optical...
switch [35], and infrared lasers [36,37], have been proposed and investigated.

In asymmetric QW structures, the changes in the absorption coefficients were predicted theoretically and confirmed experimentally to be larger than the changes that occur in conventional square QWs [38–42]. In this study we investigate the effect of the laser field on the intersubband optical transitions for square quantum well (SQW) and graded quantum-well (GQW). These transitions are predicted to have a narrow bandwidth, and are of practical interest as tunable optical semiconductor devices.

2. Theory

The method used in the present calculation is based upon a nonperturbative theory that has been developed to describe the atomic behavior in intense high-frequency laser fields [43,44]. We consider the situation where a laser field with a vector potential \( A(t) \) is linearly polarized (real polarization vector \( e \)) along the \( z \) direction and the electrodynamics potentials in the dipole approximation \( A(t) = eA_0 \cos \Omega t \). It can be seen that due to the time-dependent nature of the radiation field, in principle, we have to solve the time dependent Schrödinger equation to obtain the energy spectrum of the electron bounded in the quantum well under the laser radiation. The key issue of this approach is to find the laser ‘dressed’ potential energy. By applying the time-dependent translation \( z \rightarrow z + \alpha(t) \) the semiclassical Schrödinger equation in the momentum gauge, describing the interaction dynamics in the laboratory frame of reference, was transformed by Kramers as follows [45],

\[
\frac{-\hbar^2}{2m'} \nabla^2 \psi(r, t) + \frac{m^*}{e} \mathbf{E} \cdot \mathbf{v} + V(z + \alpha(t))\psi(r, t) = i\hbar \frac{\partial \psi(r, t)}{\partial t}
\]

Here \( V(z) \) is the confinement potential in the \( z \)-direction and

\[
\alpha(t) = \alpha_0 \sin \Omega t, \quad \alpha_0 = \frac{eA_0}{m'c\Omega}
\]

represents the quiver motion of a classical electron in the laser field and \( V(z + \alpha(t)) \) is the ‘dressed’ potential energy. In this approximation, the influence of the high-frequency laser field is entirely determined by the ‘dressed potential’ \( V(z + \alpha(t)) \), which depends on \( \Omega \) and \( l \) (\( l \) being the average intensity of the laser) through \( \alpha_0 \) where [45],

\[
\alpha_0 = (\hbar^2/\Omega^2) \left( \frac{e}{m^*} \right) (8\pi\hbar^2/e)^{3/2}
\]

where \( e \) and \( m' \) are the charge and effective mass of an electron, \( c \) is the velocity of the light and \( A_0 \) is the amplitude of the vector potential.

3. ‘Dressed’ confinement potential for SQW and GQW

Following the Floquet approach [43,44], the space-translated version of the Schrödinger equation, Eq. (1), can be cast in the equivalent form of a system of coupled time independent differential equations for the Floquet components of the wave function \( \psi \), containing the (in general complex) quasi-energy \( E \). An iteration scheme was developed to solve this, for the zeroth Floquet component \( \psi_0 \), the system reduces to the time-independent Schrödinger equation [1,43,44]:

\[
\left[ -\frac{\hbar^2}{2m'} \nabla^2 + V(\alpha_0, z) + eFz \right] \psi_0 = E\psi_0,
\]

where \( V(\alpha_0, z) \) is the ‘dressed’ confinement potential which obtained by averaging \( V(z + \alpha(t)) \) over a period of the radiation field, and depends on \( \Omega \) and \( l \) only through \( \alpha_0 \) [20]. For SQW, the ‘dressed’ confinement potential is given by the following expression [2,46,47]:

\[
V(\alpha_0, z) = \frac{V_0}{2} \left( \Theta(|z| - (L/2 + \alpha_0)) + \Theta(|z| - (L/2 - \alpha_0)) \right)
\]

where \( V_0 \) is the conduction band offset at the interface, \( L \) is the well width, \( \Theta \) is the step function.

In this study, for numerical calculations, we have taken, \( m' = 0.0665m_0 \) (where \( m_0 \) is the free electron mass), the barrier height \( V_0 = 228 \text{ meV} \), and the well widths \( L = 120 \text{ Å} \). These parameters are suitable for square \( \text{Ga}_1-x\text{Al}_x\text{As/GaAs} \)SQW materials with an aluminum concentration \( x \approx 0.3 \). By changing the Al concentration \( x \) in the \( \text{Ga}_1-x\text{Al}_x\text{As} \) on obtains a linearly changing conduction band profile. For GQW the functional form of ‘dressed’ confinement potential is given by the following expression [46],

\[
V(\alpha_0, z) = \frac{V_0}{2} \left( \Theta(|z| - (L/2 + \alpha_0)) + \Theta(|z| - (L/2 - \alpha_0)) \right) + \Theta(|z| - (L/2 + \alpha_0)) + \Theta(|z| - (L/2 - \alpha_0))
\]

After the energies and their corresponding wave functions is obtained, the linear absorption coefficient for the intersubband transitions can be clearly calculated [47,48].

4. Results and discussion

We have theoretically investigated the linear intersubband optical absorption in SQW and GQW under intense laser field, at \( T = 300 \text{ K} \). In Fig. 1(a) and (b) for SQW and GQW we show the ‘dressed’ potential profile (dashed lines) and the energies with their squared envelope wave functions.
(solid curves) for different two laser field values ($\alpha_0 = 20$ and $45 \text{ Å}$). As seen in this figure, for both SQW and GQW while the effective ‘dressed’ well width (lower part of the confinement potential) decreases with the laser field, the width of the upper part of the ‘dressed’ confinement potential increases, thus in the presence of the laser field the subbands are mostly localized in upper part of the ‘dressed’ well. Whereas the electron wave function in a SQW has a symmetric character, in the GQW the electron wave function is asymmetric character. Also, due to the asymmetric character of the electron wave function in the GQW, the carrier confinement of GQW structure is smaller compared to that of the SQW. It should be pointed out that the particle is mostly confined on the left-hand side of the GQW whereas in the SQW it moves freely in the whole well. Consequently, due to the additional confinement of carriers the subband energy levels in GQW structure are larger than that of the SQW. As seen in Fig. 1 the laser field sensitivity of the electronic structure of GQW is quite different compared with results of SQW. The reason is that; by increasing the laser field the effective ‘dressed’ well width, which obviously affects the carrier confinement, decreases and the subbands tends to localize in the upper part of the ‘dressed’ well with wider width. We can say that, for GQW this behavior is faster for SQW, since in GQW the particles are more energetic and under the laser field they can easily be pushed up to the top of the well. For example, as seen from Fig. 1(a) for $\alpha_0 = 20 \text{ Å}$, while all subbands of GQW are mostly localized in the upper part of the ‘dressed’ well, the second and third subbands ($i = 2$ and $3$) of SQW are mostly localized in the upper part of the ‘dressed’ well with wider width, and the ground state is still localized in lower part of the ‘dressed’ well. For about $\alpha_0 \geq 30 \text{ Å}$, the ground state of SQW is pushed up to the top of the well so that it is no longer localized in the narrow lower part of ‘dressed’ well. Thus, we suggest that the quantum well type

![Fig. 1](image_url)

Fig. 1. The shape of the ‘dressed’ potential profile (dashed curves), the energies with their squared envelope wave functions (solid curves) of a square and graded GaAs/Ga$_{1-x}$Al$_x$As quantum wells for laser-field amplitudes (a) $\alpha_0 = 20 \text{ Å}$, and (b) $\alpha_0 = 45 \text{ Å}$. 


the energy difference that of (1–2) subbands. Since, firstly the third and second subbands $(2–3)$ is quite different when we compare with this figure, the variation of the energy difference between width, thus the energy levels get close to each other and the point out that by increasing the laser field the subbands tends effective narrow lower part of the ‘dressed’ well. We should the top of the well so that they are no longer localized in the excited subbands and later the ground state are pushed up to respectively. By further increasing the laser field, first, the critical laser field amplitude depends on the quantum well types, and for SQW and GQW this critical amplitude value is almost $a_0 = 30$ Å and $a_0 = 20$ Å, respectively. By further increasing the laser field, first, the excited subbands and later the ground state are pushed up to the top of the well so that they are no longer localized in the effective narrow lower part of the ‘dressed’ well. We should point out that by increasing the laser field the subbands tends to localize in the upper part of the ‘dressed’ well with wider width, thus the energy levels get close to each other and the energy difference between subbands decreases. As seen in this figure, the variation of the energy difference between $(2–3)$ subbands is quite different when we compare with that of $(1–2)$ subbands. Since, firstly the third and second subband energy levels get to be close to the top of the well, the energy difference $E_3 - E_1$ increases with the laser field. For SQW this energy difference $E_3 - E_1$ begins to increase whenever the laser field reaches a certain value ($a_0 \approx 50$ Å). Since all subbands are mostly localized in upper part of the ‘dressed’ well when the laser field increases up to the critical laser field, the energy difference $E_3 - E_2$ increases after this critical laser field value. Since the potential profile of the GQW structure changes faster than that of SQW by increasing the laser field, the subbands of GQW are faster localized in upper part of the ‘dressed’ well. Due to this behavior the subband energy difference $E_3 - E_2$ of GQW decreases rapidly even though at low laser field values ($a_0 < 30$ Å), and this energy difference decreases slightly at high laser field values ($a_0 > 30$ Å). As seen from Fig. 2, for both SQW and GQW the variation of the energy difference between $E_3 - E_1$ decreases with the laser field. Thus we can say that, in the presence of the laser field the energy difference between the subbands, $E_3 - E_1$, is different for different quantum well types. By considering the variation of the energy difference $E_3 - E_1$ in Fig. 2, it should be pointed out that by applying only the laser field we can obtain blue or red shift in the intersubband optical transitions.

For the $(1–2)$ intersubband transition in Fig. 3(a) and (b), we present the variation of the absorption coefficient as a function of incident photon energy for SQW and GQW, respectively. From Fig. 3, also it is seen that, while the intersubband absorption spectrum shows blueshifts up to the critical laser field value (for SQW $a_0 \approx 30$ Å and for GQW $a_0 \approx 20$ Å) for the $(1–2)$ transition, these spectrums show red shifts when the laser field values are grater than these certain values. This behavior in the absorption spectrum can be explained as; by increasing the laser field the effective ‘dressed’ well width decreases, which in turn increases the energy difference $E_3 - E_1$ and afterwards the energy difference begins to decrease when the laser field is further increased (see Fig. 2). The intersubband absorption coefficient is changed in energy with increasing laser-field amplitude over a wide range of the laser-field amplitude. Since in the GQW the particles are mostly confined in the left side of the well region, and by increasing the laser field the effective ‘dressed’ well width decreases, the geometric confinement of the electron increases thus it gets to be more energetic and it can penetrate into the potential barriers easily. This penetration modifies the subband dispersion relations and causes a reduction in the overlap function between the ground and second subband. Thus, for GQW the magnitude of the absorption coefficient becomes smaller than for SQW.

In Fig. 4(a) and (b), the optical absorption coefficient is given as a function of the photon energy for several laser field values for SQW and GQW, respectively. As seen in this figure, the variation of the absorption coefficient as a function of the incident photon energy for $(2–3)$ transition is quite different compared with that of $(1–2)$ transition. For SQW, Fig. 4(a) shows a red shift up to a critical laser-field amplitude value ($a_0 \approx 50$ Å) for the $(2–3)$ intersubband and when the laser field further increased this spectrum shows blue shifts. This behavior is similar to the behavior of the energy difference between the $(2–3)$ subbands given in Fig. 2. It is seen from Fig. 4(b) that, in contrast to the variation of the $(2–3)$ transition in resonant photon energy of SQW, there is no critical laser field value of the $(2–3)$ transition of GQW. For GQW case, the sensitivity to the laser field of the absorption coefficient in this curve can be explained as; by applying the laser field, firstly the third and second subband energy levels get to be close to the top of the

Fig. 2. The energy difference between subbands as a function of the laser field for SQW and GQW.
well and the energy difference $E_3 - E_2$ decreases and when the laser field is further increased, these subbands are mostly localized in the left-side of the upper part of the ‘dressed’ well, thus $E_3 - E_2$ decreases slightly with laser field. Due to this behavior for the (2–3) transition of GQW theintersubband absorption spectrum monotonically shows red shifts.

For GQW the variation of the absorption coefficient as a function of the photon energy is given in Fig. 5 for the (1–3) transition. In the SQW due to the symmetric character of the electron wave function the lateral confinement increases with laser field, but the parity which prohibits the (1–3) transition is zero. Whereas the electron wave function of GQW is asymmetric and the (1–3) transition becomes possible. Thus, it should be noticed that in asymmetric structures we have more subband transitions, and the (1–3) transition of GQW shows red shift under the laser field. As seen from this figure, while for small laser field range ($\alpha_0 < 30 \text{ Å}$) the absorption peak decreases in magnitude with increasing laser field, for high laser field range ($\alpha_0 > 30 \text{ Å}$) this peak increases in magnitude with increasing laser field. Because the low laser field pushes the electrons in the second and third states ($i = 2$ and 3) to the left-side of the well and pushes the electrons in the ground state to the

Fig. 3. For the (1–2) transition, the variation of the absorption coefficient as a function of the photon energy for intense laser field values $\alpha_0 = 0, 20, 30, 45, 60 \text{ Å}$ for (a) SQW and (b) GQW structure.

Fig. 4. For the (2–3) transition, the variation of the absorption coefficient as a function of the photon energy for intense laser field values $\alpha_0 = 0, 20, 30, 45, 60 \text{ Å}$ for (a) SQW and (b) GQW structure.
right-side of the well, thus the overlap function between the ground and third subbands decreases. The high laser field values push the electrons to the left-side of the well for all states, thus the overlap function between the ground and third subbands increases.

In conclusion, we have investigated mainly the effect of intense laser fields on the intersubband transitions in SQW and GQW. We have shown that by increasing the laser field intensity, the effective well width (‘dressed’ width) decreases, which in turn increases the spacing of the energy levels in the quantum well so that this mechanism can be used as a way to control the carrier confinement in these quantum well structures. We can observe that increasing the laser field amplitude changes the separation between subbands, thus the energy differences and the absorption peaks change in magnitude and position as laser-field amplitude increases.

References


Fig. 5. For the (1–3) transition, the variation of the absorption coefficient as a function of the photon energy for intense laser field values $a_0 = 0, 20, 30, 45, 60$ Å for GQW structure.