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ELECTRIC FIELD AND INTENSE LASER RADIATION EFFECTS ON THE INTERBAND TRANSITIONS IN QUANTUM WELLS

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Se studiază dependenţa de intensitatea câmpului laser a tranziţiei optice interbandă într-o groapă cuantică rectangulară sub efectul unui câmp electric static, în aproximaţia masei efective. La valori mici ale intensităţii radiaţiei laser se constată o dependenţă pătratică a energiei de tranziţie de parametrul laser, în timp ce pentru valori mari ale intensităţii, această dependenţă devine cvasiliniară. Rezultatele obţinute demonstrează că sursele laser cu gropi cuantice pot fi acordate în frecvenţă cu ajutorul câmpurilor externe.

The laser field dependence of the interband optical transition in a square quantum well (SQW) under an applied electric field is evaluated in the effective mass approximation. At weak laser field a quadratic dependence of the transition energy as a function of laser parameter is found, while for higher values of the parameter this dependence becomes cvasilinear. These results show that the emission frequencies associated with quantum well lasers can be tuned by external fields.

Key words: square quantum well, laser field, recombination rate, photoluminiscence.

1. Introduction

Strong laser driven semiconductor heterostructures have received much attention in recent years, with the availability of intense THz laser sources [1-5]. 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. The effect of an intense laser radiation on the linear optical absorption spectra of semiconductor structures was theoretically studied by Johnsen and Jauho [6]. The solution of the time dependent Schrödinger equation for an electron confined in the potential well created by a semiconductor heterostructure in the presence of an in-plane magnetic field and a laser radiation, as studied by Perez-Maldonado *et al*. [7] and Osario *et al*. [8]**,** has presented the

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electric field direction dependence of the binding energy and the polarizability of donor impurities in GaAs-AlGaAs quantum wires.

A simple scheme taking into account the effect of the laser interaction with the semiconductor through the renormalization of the electron effective mass has been proposed by Bradi and Jalbert [9]. The laser field dependence of the intersubband optical absorption in a graded quantum well under an applied electric field has been calculated by Ozturk *et al*. [10]. Using a nonperturbative theory and the variational approach, Neto and Fanyao [11] have derived the laser-dressed quantum well fundamental absorption edge, when an intense laser field radiation is applied.

In this paper we investigate the effects of the laser field on the electronic levels and the optical transitions in a square GaAs-$Al_xGa_{1-x}As$ quantum well (SQW) under an external static electric field.

2. Theory

The method used in the present calculation is based on a nonperturbative theory that has been developed in order to describe the atomic behavior in intense laser fields [12].

For a particle moving in a quantum well under the combined forces of high-frequency laser and static electric fields, the Hamiltonian is given by:

$$H = \frac{\left(\vec{p} + q\vec{A}\right)^2}{2m^*} + V(z) - qFz \,. \tag{1}$$

Here q and m^* are the electron (hole) electric charge and the electron (hole) effective mass, respectively, and F is the strength of the external electric field applied along the growth direction. $V(z)$ is the carrier confinement potential of the quantum well:

$$V(z) = V_0 \; \theta\left(|\, z\,| - \frac{L}{2} \right), \tag{2}$$

where V_0 is the conduction (valence) band offset, L is the quantum well's thickness, and $\theta(x)$ is the step function.

We assume that the laser field can be represented by a monochromatic plane wave of frequency ω. For a linear polarization along the z-direction, the vector potential of the laser field is $\vec{A}(t) = A_0 \cos(\omega\, t)\vec{u_z}$.

After a nontrivial algebra calculation [13], the one-electron Schrödinger equation becomes:

$$\left[-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2} + V_d(z, a_0) - qFz \right]\psi(z) = E(\alpha, F)\psi(z), \tag{3}$$

where $V_d(z,a_0)$ is the laser "dressed" potential:

$$V_d(z,a_0)=\sum_k V_k J_0(k\,a_0)\,e^{ikz} \ . \tag{4}$$

$a_0=\dfrac{q\,A_0}{m^*\omega}$ is laser dressing parameter, V_k is the k-th Fourier component, and $J_0(x)$ is a zero order Bessel function. In the absence of the electric field, in equation (3), the subband wave functions are taken as the linear combinations of the eigenfunctions χ_n of the square potential well, i.e., $\phi_k(z)=\sum_n c_n^k \chi_n(z)$, where $\sum_n$ is extended over all bound states in the quantum well.

To account for the redistribution of the electronic charge density under an electric field, we treat the qFz term of the Hamiltonian in a variational manner and we choose the wave functions as [14]:

$$\psi_k(z)=\phi_k(z)e^{-\lambda_k z} \ , \tag{5}$$

where λ_k denotes the variational parameters. Note that in the presence of an electric field there is no true bound state for a finite QW of depth V_0, since the potential energy is negative and large in absolute value, for large, negative value of z. If, however, the field is not excessively large, so that:

$$F<\frac{\sqrt{2m^*}}{\hbar\,q}\left(V_0-E_k^0(a_0)\right)^{3/2} , \tag{6}$$

where $E_k^0(a_0)$ represents the zero-field energy related to the $\phi_k(z)$ wave function, the states will have a long lifetime and can therefore be considered as quasibound states. [14] In the following we will consider the values of F such that Eq. (6) holds.

In the presence of the electric field, energy levels of the electron in the laser "dressed" potential are given by:

$$E_k(a_0,F)=\min_{\lambda_k}\frac{\langle\psi_k(z)|H\,\psi_k(z)\rangle}{\langle\psi_k(z)|\psi_k(z)\rangle} \ . \tag{7}$$

3. Results and discussion

In the above calculations, we will consider a square GaAs-$Al_xGa_{1-x}As$ quantum well. We take $m_e^*=0.0665m_0$, $m_h^*=0.36m_0$ and an aluminum concentration in the barrier material $x=0.30$. For the electron (hole) states the barrier height V_0 is obtained from the 60% (40%) rule of the band gap discontinuity $\Delta E_g=1247x$ (meV).

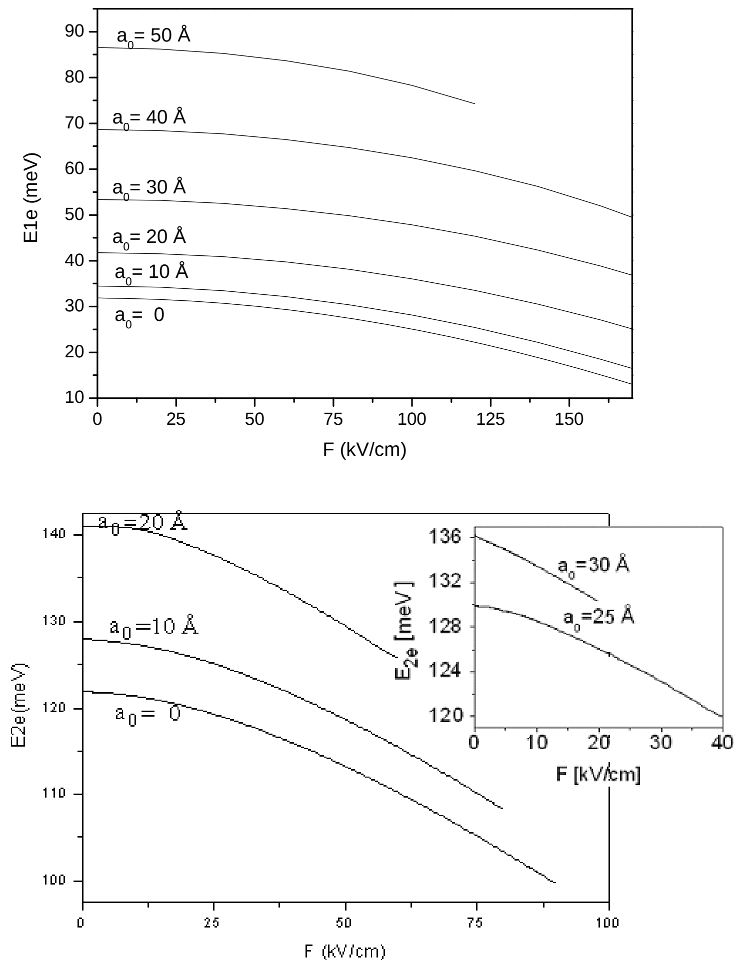


Fig. 1. Subband energy levels of an electron confined in a 100 Å thick SQW as functions of the electric field for different laser field parameter values

Fig. 1 shows the variation of the two first electron subband energies E_1 and E_2 as functions of the electric field F for various values of the laser field parameter a_0, in a GaAs QW with a thickness of 100 Å. As expected, the Stark effect is more important in the high lying energy level case than in the low energy level. We also observed the blue shifts in each bound state energy level with respect to laser parameter increase. The shifts are greater for the higher level, which for $a_0 > 40$ Å becomes unbound even for a weak electric field $F \cong 1$ kV/cm (as shown in the inset of Fig.1.).

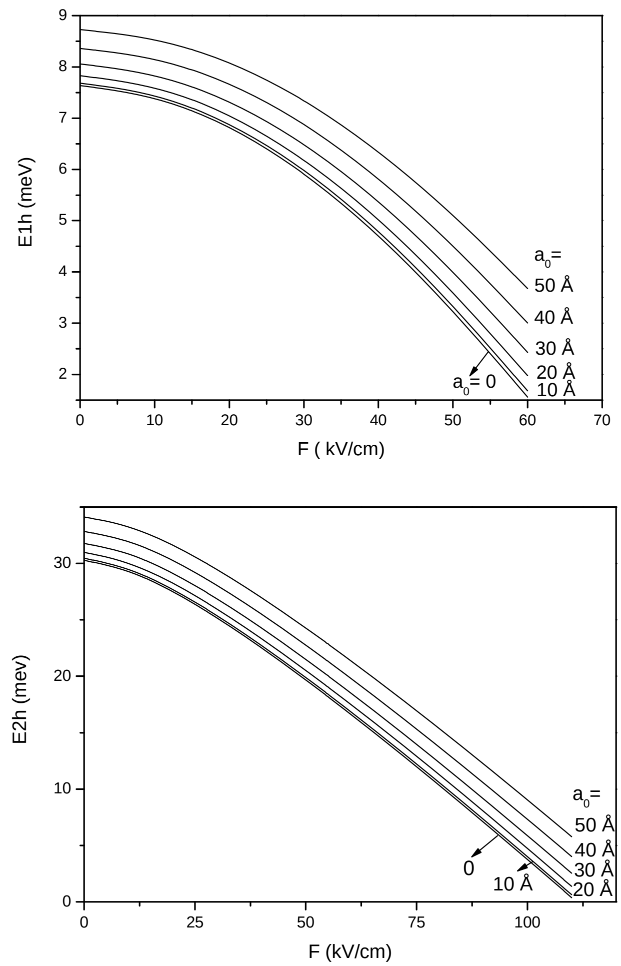


Fig. 2. Energy of the first and the second heavy-hole subband levels as functions of the electric field for different laser field parameter values

It is also found that the polarization effect is more pronounced in the heavy-hole case, because the valence-band QW barrier is quite small and the effective mass is larger. This is illustrated in Fig. 2, which shows the dependence of the first and the second hole subband energies on the laser field parameter. Notice that for the conduction electrons in the ground state the Stark shift quadratic dependence on *F*, typical for weak fields, is observed up to 100 kV/cm even for a_0 =50 Å. The second energy level dependence with respect to the strong electric field ($F > 30$ kV/cm) is a cvasilinear decrease. On the other hand, for valence electrons, the shift is quadratic only up to 35 kV/cm for the first energy level and up to 25 kV/cm for the second energy level.

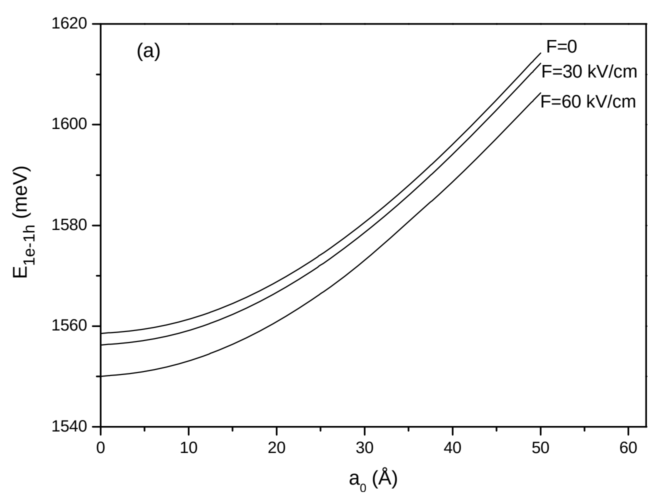
We have also studied the change of the fundamental absorption edge induced by the laser field. Fig. 3(a) presents the calculated two-dimensional band gap $E_g^{'}$, defined as:

$$E_g^{'} = E_{1e} + E_{1h} + E_g , \quad (8)$$

where E_g is the optical absorption edge of bulk GaAs, $E_g(4K) = 1519$ meV. For small values of a_0 ($a_0 < 30$ Å, in this calculation), we obtained a quadratic laser field dependence. As a_0 increases, an almost linear blue shift of $E_g^{'}$ with respect to the laser-dressing parameter is observed.

The fundamental absorption edge can be tuned by laser parameter, a_0, and static applied electric field, *F*. For instance, for F=60 kV/cm and a_0=0, $E_g^{'}$ is located in the infrared region of the spectrum while, for the studied GaAs-$Ga_{0.7}Al_{0.3}As$ SQW, it moves into the visible region for F=0 and a_0=50 Å.

In the presence of the electric field, the interband transition $2c \rightarrow 2v$ are observed only for $a_0 \leq 20$ Å, (fig. 3(b)), because for the higher laser parameter values, the second conduction subband becomes unbound in the intense laser field.



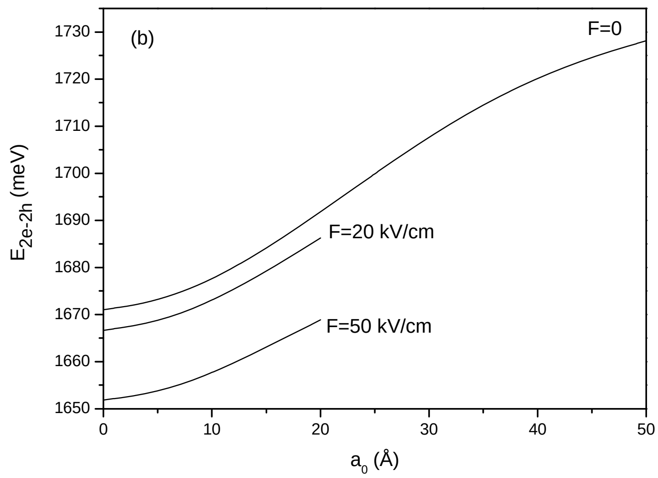


Fig. 3. The interband transition energies as functions of the laser field parameter for different electric field strengths. (a): 1e→1h transition; (b): 2e→2h transition.

In order to systematically study the effects of an intense laser field, we calculated the overlap integral S_{cv}, defined as

$$S_{cv}(a_0, F) = \int \psi_c^*(z)\,\psi_v(z)\,dz\,. \tag{9}$$

The recombination rate of electrons and holes is proportional to the S_{cv}^2, so that this quantity, plotted in fig. 4 versus the laser-dressing parameter for several electric field values, is significant in photoluminescence (PL) experiments.

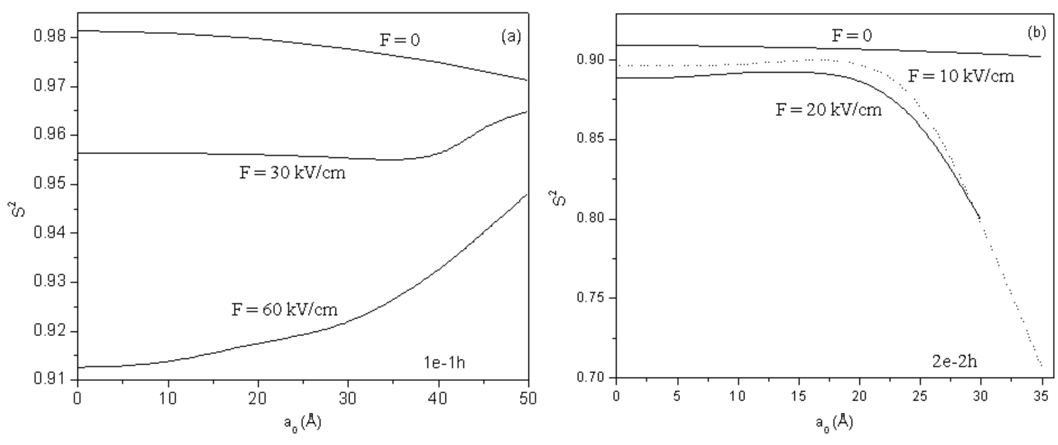


Fig.4. Square of the overlap integral between electron and heavy-hole states as a function of the laser field parameter for different electric field values

As expected, our results showed a decrease of PL signal as the static field increases, due to the spatial separation of the carriers. Fig. 4(a) shows that in the absence of an electric field the recombination rate monotonically decreases with the increase of the laser field parameter. This is an understandable result, because as the laser field increases, the conduction electron wave function becomes more delocalized in the QW, while the valence electron function, less affected by the laser field, remains localized near the center of the well. The presence of a static electric field induces a spatial shift of the hole (electron) wave function along (opposite) to the field direction. As a result, the recombination rate decreases with increasing values of the electric field. This effect is compensed for large values of the laser parameter, when the delocalization of the electron inside the QW leads to a reoverlap of the electron and hole wave functions. Fig. 4(b) shows that for quantum wells under an external electric field the higher subband wave functions are more sensitive to laser-dressing parameter and, as one may expect, there is a critical laser parameter value $a_0 > a_{0c}(L)$ above which the emission 2c$\rightarrow$2v will be eliminated from the recombination spectrum.

4. Conclusions

We have studied the effects of the high-frequency laser field on the intersubband transitions in a GaAs-Ga_{1-x} Al_xAs quantum well in the presence of an external electric field. Our results show that the emission frequencies associated with the GaAs-AlGaAs quantum well lasers can be tuned by an external intense laser field. Such an effect provides a novel strategy to drive tunable semiconductor laser, which can be tailored by quantum wells parameters and by external applied fields.

R E F E R E N C E S

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