

Intense laser radiation and magnetic field effects on the electronic states in quantum well wires

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A systematic study of the binding and transition energies associated with the ground and some excited states of a hydrogenic on-center donor in a cylindrical GaAs quantum-well wire, in the simultaneous presence of intense high-frequency laser and static magnetic fields is performed. We use a variational procedure within the effective-mass approximation. The results show that the electronic and optical properties strongly depend not only on the "laser-dressed" Coulomb potential, but also on the quantum confinement and the applied magnetic field.

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1. Introduction

Recently, there has been much interest in the study of intense laser-field radiation (LFR) effects on the optical and the electrical properties of nanostructures [1-7]. In particular, changes of the binding energy of hydrogenic impurities in low-dimensional semiconductor heterostructures induced by an intense LFR have been studied. It was reported that the binding energy in low-dimensional systems decreases while the laser field amplitude increases [8,9].

Fanyao *et al.* have used a nonperturbative theory that "dresses" both the potential of impurity and the confinement potential in the structure to study the binding energy of a donor impurity in quantum wires [10], and quantum dots [11], placed in an intense laser-field. They have also calculated the ground-state binding energy of an on-center hydrogenic impurity in the presence of intense high-frequency laser and static electric fields [1].

Sari *et al.* [12] have studied the laser-field dependence of the binding energy and the polarizability of shallow-donor impurities in graded quantum wells under an external electric field.

Varshni [13] has investigated the laser-field and quantum confinement effects on the ground and two excited states of an impurity located at the center of a spherical quantum dot confined by an infinite potential barrier.

Recently, Kasapoglu *et al.* [14] have discussed the laser-field dependence of the photoionization cross-section and binding energy of shallow donor impurities in graded quantum-well wire (QWW) under an electric field. A nonperturbative theory under variational approach was used for this study.

In a previous paper [15] we have studied the electrical field effects on the exciton bound to anionized donor in parabolic quantum wells.

In this paper we investigate the binding and the allowed transition energies associated with the ground and some excited states of a hydrogenic donor in a cylindrical GaAs QWW, in the simultaneous presence of intense high-frequency laser and static magnetic fields.

2. Theory

To describe the atomic behaviour in the presence of the laser field we assume that the radiation can be represented by a monochromatic plane wave of frequency ω . Following the approach proposed by Lima and Miranda [16], the Schrödinger equation for a hydrogen atom interacting with an electromagnetic field,

$$i\hbar \frac{\partial \psi(\vec{r}, t)}{\partial t} = \left[\frac{1}{2m} (\vec{p} + e\vec{A}(t))^2 - \frac{e^2}{4\pi\epsilon r} \right] \psi(\vec{r}, t) \quad (1)$$

can be recast in the equivalent form:

$$i\hbar \frac{\partial \phi(\vec{r}, t)}{\partial t} = \left[\frac{\vec{p}^2}{2m} - \frac{e^2}{4\pi\epsilon |\vec{r} - \vec{\delta}|} \right] \phi(\vec{r}, t). \quad (2)$$

Here $\vec{A}(t)$ is the vector potential for a laser beam,

$$\vec{\delta}(t) = -\frac{e}{m} \int_0^t \vec{A}(t') dt', \text{ and}$$

$$\psi(\vec{r}, t) = \exp \left[i\vec{\delta}(t) \cdot \frac{\vec{p}}{\hbar} \right] \cdot \exp \left[i\frac{\eta(t)}{\hbar} \right] \phi(\vec{r}, t) \quad (3)$$

in which

$$\eta(t) = -\frac{e^2}{2m} \int_0^t \vec{A}^2(t') dt'. \quad (4)$$

Expanding the laser-dressed binding potential $-\frac{e^2}{4\pi\epsilon |\vec{r} - \vec{\delta}|}$, one gets:

$$V = -\frac{e^2}{4\pi\epsilon (r^2 + a^2)^{1/2}} \left\{ 1 + \frac{\vec{r} \cdot \vec{\delta}}{r^2 + a^2} + \dots \right\} \quad (5)$$

where $a = |\vec{\delta}(t)| = \frac{eA}{m\omega}$ is the amplitude of the electron oscillation in the radiation field.

The expansion (5) converges rapidly [16] so that the binding potential is adequately described by the first term:

$$V(r) \cong \frac{-e^2}{4\pi\epsilon(r^2 + a^2)^{1/2}}. \quad (6)$$

This potential has been used in atomic and molecular problems [16-18] and for the study of the impurity states associated with shallow donors in spherical quantum dots [13]. It is important to emphasize that this approximation is valid for the description of an atom under either a strong or a weak laser field [19].

Under these conditions, the Hamiltonian of a hydrogenic on-center donor in a cylindrical QWW in the presence of an intense laser field and a static magnetic field applied along the wire axis can be written as:

$$H = -\frac{\hbar^2}{2m^*} \left[\frac{1}{\rho} \frac{\partial}{\partial \rho} \left(\rho \frac{\partial}{\partial \rho} \right) + \frac{\partial^2}{\partial z^2} + \frac{1}{\rho^2} \frac{\partial^2}{\partial \varphi^2} \right] + \frac{1}{8} \frac{e^2 B^2}{m^*} \rho^2 - \frac{ie\hbar B}{2m^*} \frac{\partial}{\partial \varphi} - \frac{e^2}{4\pi\epsilon\sqrt{\rho^2 + z^2 + a^2}} + V_c(\rho) \quad (7)$$

Here B is the external magnetic field, and $V_c(\rho)$ is the potential-energy barrier that confines the carriers within the wire of radius R :

$$V_c(\rho) = \begin{cases} 0 & \text{if } \rho < R \\ V_0 & \text{if } \rho > R \end{cases} \quad (8)$$

Using the variational method, the trial wave functions of the impurity are given by [19, 20]:

$$\Psi_{nlm}(\vec{r}) = N_{nlm} \Phi_0(\rho) \Gamma_{nlm}(\rho, \varphi, z) \quad (9)$$

N_{nlm} is the normalization factor, $\Phi_0(\rho)$ is the eigenfunction of the electron in a cylindrical wire in the presence of an axial magnetic field [22], and Γ_{nlm} are hydrogenic-like functions that correspond to nlm states. In Eq. (9), the variational envelope-wave functions are taken as:

$$\begin{aligned} \Gamma_{1s} &= \exp\left[-\lambda_{1s}\sqrt{\rho^2 + z^2}\right] \\ \Gamma_{2s} &= \left(1 - \sigma\sqrt{\rho^2 + z^2}\right) \exp\left[-\lambda_{2s}\sqrt{\rho^2 + z^2}\right] \\ \Gamma_{2p_0} &= \rho \cos\varphi \exp\left[-\lambda_{2p_0}\sqrt{\rho^2 + z^2}\right] \\ \Gamma_{2p_{\pm}} &= \rho \exp[\pm i\varphi] \exp\left[-\lambda_{2p_{\pm}}\sqrt{\rho^2 + z^2}\right] \end{aligned} \quad (10)$$

where σ is the orthogonality parameter and λ_k ($k = 1s, 2s, 2p_0, 2p_{\pm}$) are the variational parameters.

The impurity energies are obtained variationally as a function of the magnetic and laser fields and the binding energies are given by:

$$E_{b,nlm}(B, a) = E_0(B) - \min_{\lambda_k} \langle \Psi_{nlm}(\vec{r}) | H | \Psi_{nlm}(\vec{r}) \rangle \quad (11)$$

where E_0 is the ground-state energy of the electron in the absence of the Coulomb term.

3. Results and discussion

We have calculated the binding energies for the ground ($1s$) and low lying excited states ($2s$, $2p_0$, and $2p_{\pm}$) of a hydrogenic on-center donor in a cylindrical GaAs-Al_{0.3}Ga_{0.7}As QWW. For numerical calculation we assume that the electron mass and the dielectric constant are constant across the barrier, $m^* = 0.0665m_0$ (where m_0 is the free electron mass), $\epsilon = 12.58 \epsilon_0$. The barrier height is taken as $V_0 = Q_e(1.155x + 0.37x^2)$ eV, where $Q_e = 0.57$ and x is the Al concentration in the barrier material.

In Fig. 1 we plot the binding energies as a function of the laser-field amplitude, a , for several values of the external magnetic field B and a wire radius of $R = 200$ Å. The corresponding results of $R = 500$ Å are shown in Fig. 2.

We see that for a given value of R the binding energies of the impurity decrease as the parameter a increases, in agreement with the zero-dimensional case [13]. In the case of $a = 0$ (i.e., no laser field applied) our calculation for the ground-state binding energy gives results remarkably closed to the Branis *et al.* [22] ones. Notice that the energy first weakly depends upon the laser field, but for large values of a , an almost linear decrease of E_b is found.

For $B = 0$, this behaviour is the result of the coupling and competition between the laser-dressed Coulomb potential and the barrier confining potential, V_c . Initially the geometric confinement of the electron around the impurity ion is predominant but for large values of a the spread of the electron wave function weakens the Coulomb interaction, and, as a consequence, the impurity binding energy decreases.

Figs. 1 and 2 show also that the effect of the laser-field is more pronounced for s -like states and small wire radius, R . Only wave functions for the s -like states have nonzero values at the origin and the corresponding density of the probability decays away from the impurity center. So, the “dressed” Coulomb potential has greater influence on s -like states than on the others. As the wire radius is decreased, the electron wave function is strongly compressed. Thus, the binding energy of the impurity for the narrow wire is more sensitive to the laser-field amplitude. This is in agreement with the results obtained for the two- [12]-and one-dimensional [10] cases in the absence of the magnetic field.

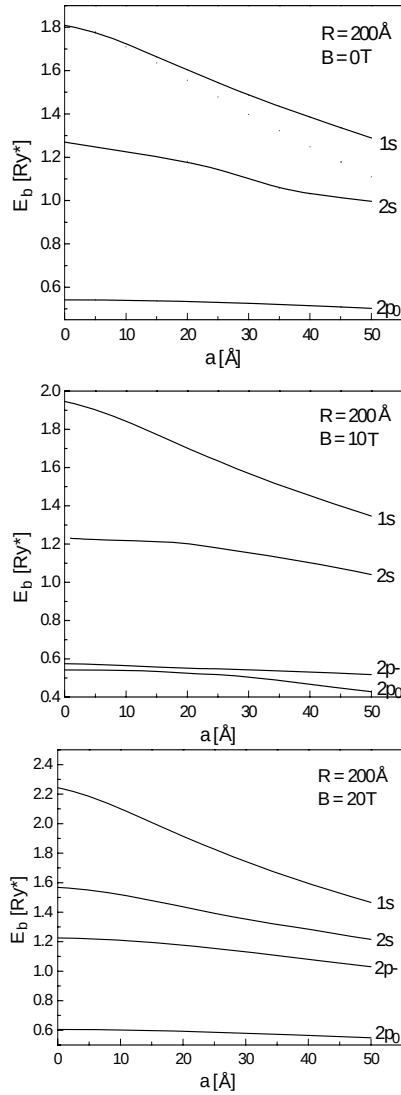


Fig. 1. Binding energy of the ground and low lying excited states for a donor at the center of a GaAs QWW with $R = 200 \text{ Å}$ as a function of the laser-field amplitude, a , for several values of the magnetic field B .

Notice that, for $B = 0$ and small values of wire radius ($R < 300 \text{ Å}$), the $2p_-$ -like state of on-center donor in a cylindrical GaAs QWW is unbounded, as has already been pointed out [21,23]. The $2p_-$ -like state becomes bound at high magnetic fields that confine the electron wave function and (or) at large R , when the ground subband energy, E_0 , is small. Also, as seen in Figs. 1 and 2, the curves of the binding energy of the $2p$ states are weakly dependent on the laser-dressing parameter. The reason is that the electron density for these states is peaked away from the origin. Due to the extension of the wave function in the x - y plane (measured, for example, by $\langle \rho^2 \rangle$) the electron becomes weakly localized to the impurity and the Coulomb interaction slightly decreases with a .

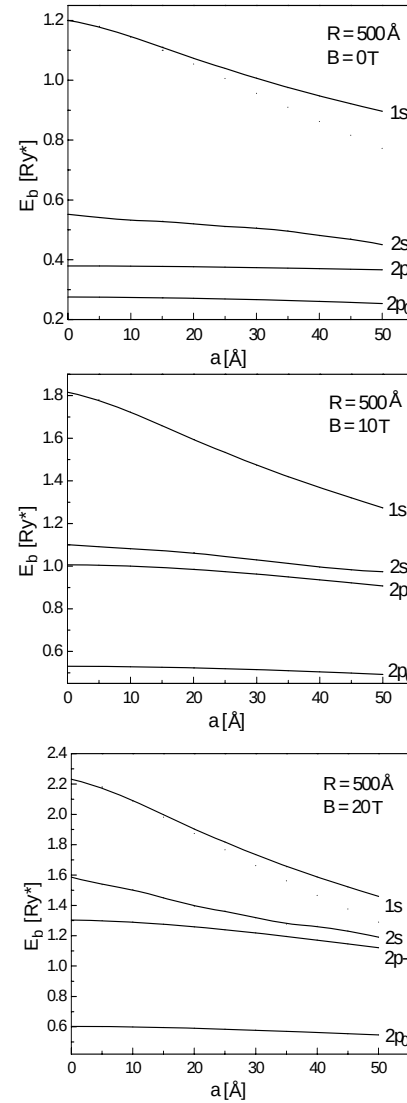


Fig. 2. Same as Fig. 1, but for $R = 500 \text{ Å}$.

In addition to the effect of quantum confinement, the magnetic field determines the behavior of the binding energy for all the analyzed states. As expected, the energies increase with B because the magnetic field gives an additional lateral confinement of the electron near the wire axis. The effect is more pronounced for large values of the wire radius R so that the cyclotron length

$$l_c = \sqrt{\frac{\hbar}{eB}} < R.$$

As Figs. 1 and 2 show, the binding energy of the ground state is more sensitive to the laser-field amplitude at higher magnetic fields. This is a consequence of the fact that in the magnetic field the electron becomes more closely localized to the impurity. An increase of the laser field leads to a reduction of the attractive potential seen by the electron (see also Figs. 4 and 5 where we plotted the corresponding dressed Coulomb potential). As a result, the effect of the laser field on the ground state binding energy is more drastically in devices with

narrower quantum wells in the presence of the applied magnetic field. For all studied states we observe that at high magnetic fields, where the confining potential V_c is a small perturbation on the magnetic energy, the binding energies very weakly depend on the wire radius. For the studied structures, this high magnetic field limit is effectively reached at $B = 20$ T.

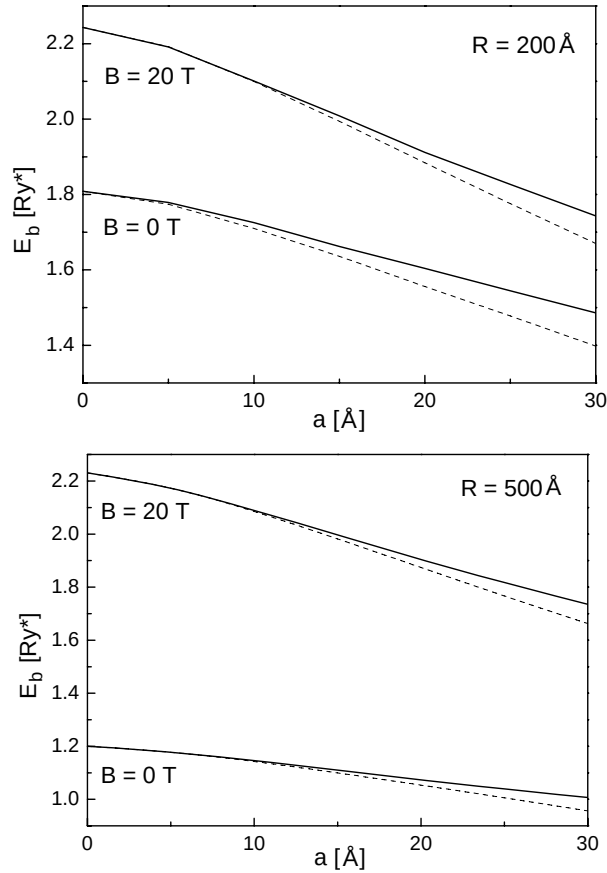


Fig. 3. The ground state binding energy as a function of the laser field amplitude, a , calculated using the variational approach (solid lines) and the perturbation approach (dashed lines), respectively.

We would like to mention that we have tested the accuracy of our variational approach by considering the case in which the laser-field amplitude a is small and using a first-order perturbation approach. The unperturbed wave function corresponds to $a = 0$ (no laser field applied) and the perturbing Hamiltonian is

$$W(r) \cong \frac{-e^2}{4\pi\epsilon} \left[\frac{1}{\sqrt{\rho^2 + z^2 + a^2}} - \frac{1}{\sqrt{\rho^2 + z^2}} \right] \quad (12)$$

The results for the ground state binding energy are shown in Figure 3. We observe that for $a \leq 30$ Å the

change in the energy thus obtained is within a few percent of that calculated using our variational approach. Also, we note that for $B = 0$ the curves of Fig. 3 agree well with the results of Fanyao *et al.* [10].

The average electron-ion Coulomb interaction as a function of the laser field amplitude is plotted in Figs. 4 and 5, for three magnetic field values. From this figures we see that the dependence of the “dressed” potential on a is physically consistent with the variation of the binding energy with a . As the laser field amplitude increases, the electronic orbital is more weakly localized around the impurity and the average donor ion-electron separation increases. As expected, for wider QWWs where the geometric confinement is reduced a weaker dependence of the Coulomb potential on a is found.

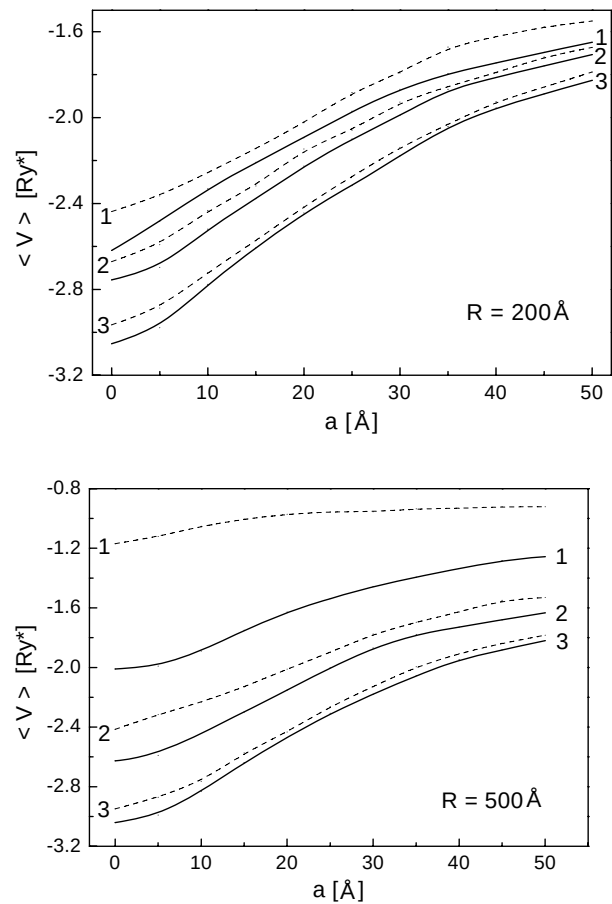


Fig. 4. The “dressed” Coulomb potential as a function of the laser-field amplitude, a , for the s -like states in a $\text{GaAs-Al}_{0.3}\text{Ga}_{0.7}\text{As}$ QWW with the axial magnetic field. Solid lines: 1s-state; dashed lines: 2s-state. The magnetic fields $B = 0, 10$ and 20 T are indicated by 1, 2 and 3 on the lines, respectively.

The effect is most clearly seen for the s -like states, which have a smooth and monotonic decrease of the Coulomb interaction with the laser field. Again, the dressed potential for the $2p$ -like states is only slightly

influenced by the laser field due to the absence of a concentration of the electron density near the well center.

In Figure 6 the $1s-2p$ transition energies of a donor impurity are plotted as a function of the magnetic field for different values of the parameter a . These energies are given by:

$$E_T(nlm \rightarrow n'l'm') = E_{b,nlm}(B,a) - E_{b,n'l'm'}(B,a) \quad (13)$$

and the selection rules used for the allowed transition are: $\Delta l = \pm 1$; $\Delta m = 0, \pm 1$.

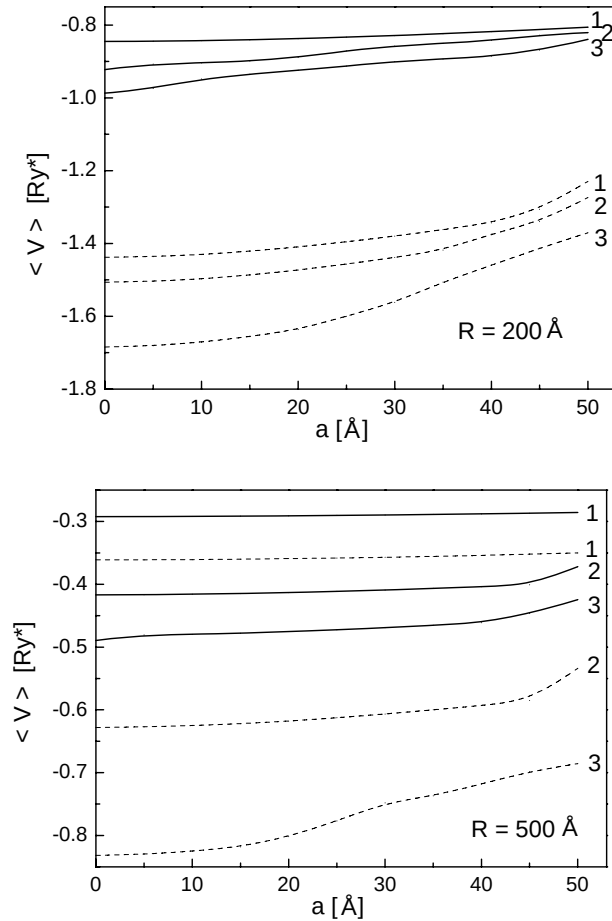


Fig. 5. The “dressed” Coulomb potential as a function of the laser-field amplitude a , for the $2p$ -like states in a GaAs- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ QWW with the axial magnetic field. Solid lines: $2p_0$ -state; dashed lines: $2p_-$ -state. The magnetic fields $B = 0, 10$ and 20 T are indicated by 1, 2 and 3 on the lines, respectively.

From this figure we can see that for a given value of a , dependence of the $1s-2p_-$ transition energies on the magnetic field is very weak, but the $1s-2p_+$ transition energies rapidly increase with B . In the zero-laser field case our results agree with those of Villamil *et al.* [21].

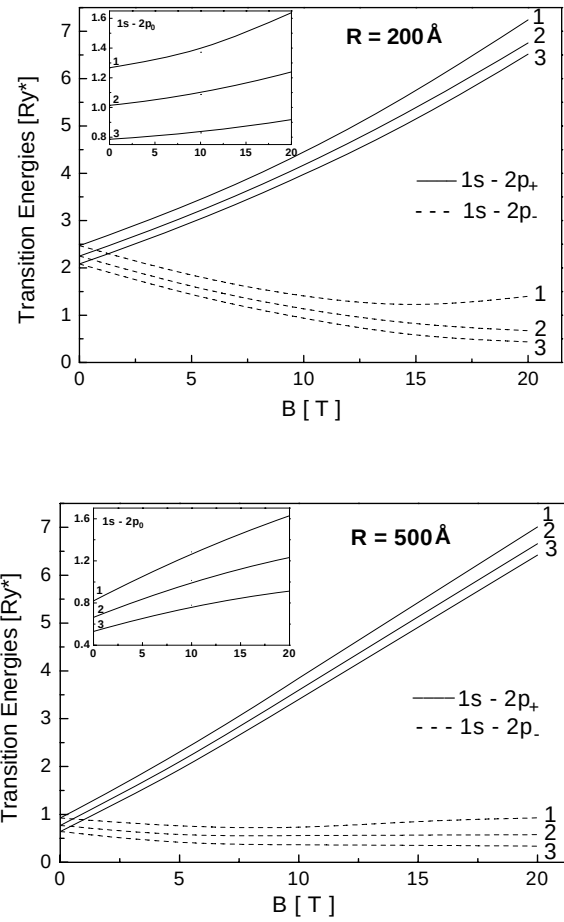


Fig. 6. On-center intradonor $1s-2p_{\pm}$ transition energies for GaAs-AlGaAs QWW as function of the magnetic field: The laser field amplitudes $a = 0$ Å, 25 Å and 50 Å are indicated by 1, 2 and 3 on the lines, respectively. The inset shows $1s-2p_0$ transition energy vs. the magnetic field.

Also, it is important to observe that for the geometry we are using, a red shift in the transition energies with increasing the laser-dressing parameter a is found.

Because the magnetic field strength, the size of the quantum wire, and the laser field amplitude can strongly change the transition energies, one can obtain the desired tunability in the optical emission of QWWs by playing with such parameters.

4. Conclusions

We have studied the effect of the high-frequency laser field on the ground and some low lying excited states of a hydrogenic donor placed in a QWW heterostructure in the presence of an external magnetic field. The calculation were performed within the effective mass approximation and using a variational method. We found that the binding

and the transition energies strongly depend not only on the “dressed” Coulomb potential, but also on the confinement potential, and the strength of the applied magnetic field. Also, our results pointed out that in QWWs the intense laser radiation produces an important effect on the electronic and optical properties. This kind of optical control may be of great interest for some optoelectronic devices based on low-dimensional structures in the presence of the laser and magnetic fields.

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