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BINDING ENERGY OF A HYDROGENIC DONOR IN A GaAs QUANTUM-WELL WIRE UNDER AN INTENSE LASER FIELD RADIATION

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The laser-field dependence of the donor binding energy in a GaAs quantum-well wire under an external laser radiation and a static magnetic field is calculated by a variational method and in the effective-mass approximation. Different geometries concerning the size of GaAs-AlGaAs quantum wires as well as the strength of the applied magnetic field were considered. We found that the electronic properties strongly depend not only on the "laser-dressed" Coulomb potential, but also on the quantum confinement and the external magnetic field.

In lucrare se calculează energia de legătură a unei impurităţi donoare într-un fir cuantic din GaAs, sub acţiunea simultană a unui fascicul laser şi a unui câmp magnetis static, paralel cu axa firului. Rezultatele obţinute arată că spectrul energetic al impurităţii depinde nu numai de potenţialul coulombian modificat de radiaţia laser, ci şi de dimensiunile firului cuantic şi de intensitatea câmpului magnetic aplicat.

Keywords: donor binding energy, quantum well wire; intense laser-field; magnetic field.

1. Introduction

With the advent of high-power, long-wavelength, linearly polarized laser source possibilities have arisen in the study of the interaction of intense laser fields with electrons in semiconductors [1-3]. In the case of semiconductor heterostructures, the situation is even more interesting due to the possibility of carrier confinement within more than nanometrical distance, thus reducing the dimensionality of the system. As a consequence, some important and distinctive phenomena associated with low-dimensional structures have been theoretical anticipated and observed [4-7].

In particular, changes on the binding energy of hydrogenic impurities in low–dimensional semiconductor heterostructures induced by an intense laser field radiation (LFR) have been studied. It was reported that the binding energy in low–dimensional systems decreases on increasing the laser field amplitude [8, 9].

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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 LFR. 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 [10].

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 this paper we present the results of the binding energy of a hydrogenic donor in a cylindrical GaAs QWWcalculation, 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 [15], the Schrödinger equation for a hydrogen atom interacting with an electromagnetic field,

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

can be recast in the equivalent form:

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

Here $\vec{A}(t)$ is the vector potential for a laser beam, $\vec{\delta}(t)=-\frac{e}{m}\int_0^t\vec{A}(t')\,\mathrm{d}t'$, and

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

in which

$$\eta(t) = -\frac{e^2}{2m}\int_0^t \vec{A}^2(t')\,\mathrm{d}t'. \tag{4}$$

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

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

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

The expansion (5) converges rapidly so that the binding potential is adequately described by the first term [15]:

$$V(r) \cong \frac{-e^2}{4\pi\varepsilon\left(r^2+a^2\right)^{1/2}}. \tag{6}$$

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 [15].

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:

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

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:

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

Using the variational method, the ground-state wavefunction of the impurity is given [19, 20]:

$$\Psi_{nlm}(\vec{r}) = N\,\Phi_0(\rho)\,\Gamma_{1s}(\rho,\varphi,z). \tag{9}$$

N 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 [21], and Γ_{1s} is the hydrogenic-wavefunction that correspond to 1*s*-like state:

$$\Gamma_{1s} = \exp\left[-\lambda \ \sqrt{\rho^2 + z^2}\right] \tag{10}$$

The ground-state impurity energy is evaluated by minimizing the expectation value of the Hamiltonian with respect to the variational parameter λ and the binding energy is given by:

$$E_b(B,a) = E_0(B) - \min_{\lambda}\langle \Psi(\vec{r}) | H \, \Psi(\vec{r})\rangle \tag{11}$$

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 energy for the ground state 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, $m^* = 0.0665 m_0$ (where m_0 is the free electron mass), $\varepsilon = 12.58\ \varepsilon_0$. The barrier height is taken as $V_0 = Q_e\left(1.155x + 0.37x^2\right)$ eV, where $Q_e = 0.57$ and x is the Al concentration in the barrier material.

In Fig. 1(a) we plot the binding energy 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. 1(b).

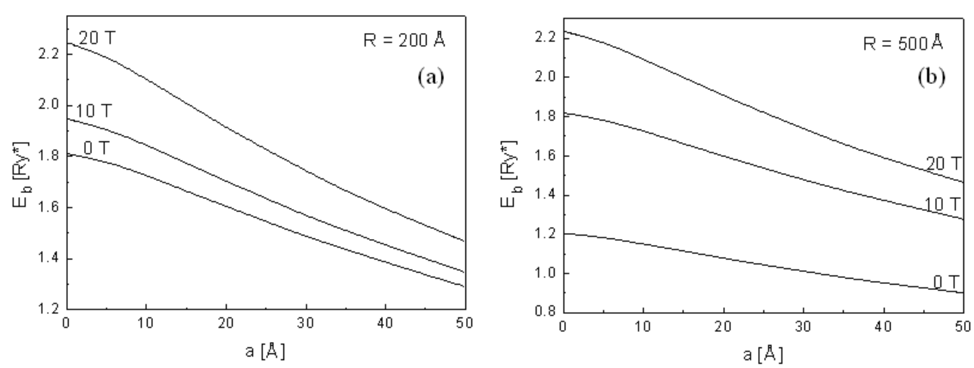

Fig. 1. Binding energy of a donor at the center of a GaAs QWW with (a) *R* = 200 Å and (b) *R* = 500 Å as a function of the laser–field amplitude *a*, for several values of the magnetic field *B*.

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 close to the Branis *et al* [21] 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 of the laser–dressed Coulomb potential with 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. Figure 1 also shows that the effect of the laser-field is more pronounced for small wire radius, *R*. This behaviour is due to the fact that the wave function for the 1*s*-like state has nonzero values at the origin and the corresponding density of the probability decays away from the impurity center. So, the binding energy is strongly dependent on the “dressed” Coulomb potential. As the wire radius is decreased, the electron wave function is more compressed. Thus, the binding energy of the impurity for the narrow wire is very 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. In addition to the effect of quantum confinement, the magnetic field determines the behavior of the binding energy. As expected, the energy increases 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, $l_c = \sqrt{\frac{\hbar}{eB}}$, is smaller than *R*. As Fig. 1 shows, the binding energy 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 Fig.2 where we plotted the corresponding dressed Coulomb potential).

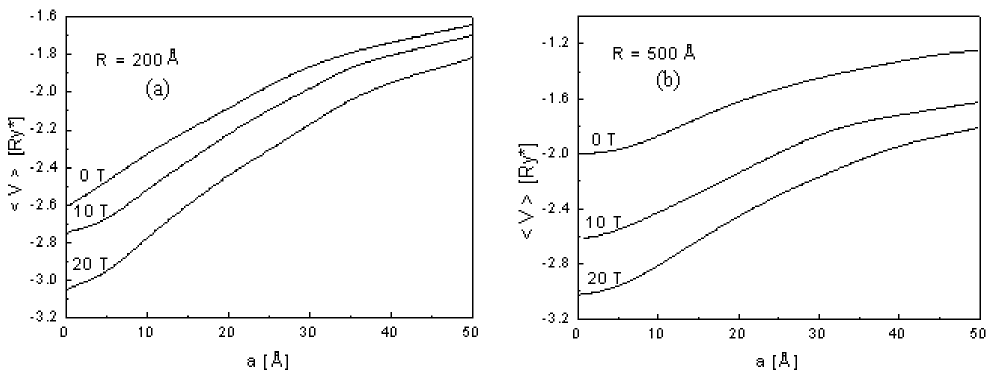

Fig.2. The “dressed” Coulomb potential as a function of the laser-field amplitude *a*, for a donor impurity in a GaAs-$Al_{0.3}Ga_{0.7}As$ QWW under an axial magnetic field. (a): R=200 Å; (b): R=500 Å

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. We also note 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.

The average electron-ion Coulomb interaction as a function of the laser field amplitude is shown in Fig. 2, for three magnetic field values. From these figure we see that the dependence of the “dressed” potential is physically consistent with the variation of the binding energy with *a.* As the laser field amplitude increases, the electronic orbital is weaker localized around the impurity and the average donor ion-electron separation increases. As expected, for wider QWW’s where the geometric confinement is reduced a weaker dependence of the Coulomb potential with *a* is found.

Further insight can be obtained from the lateral width of the wave function, which is given by $\left\langle \rho^2 \right\rangle^{1/2} = \left\langle \Psi \middle| \rho^2 \Psi \right\rangle^{1/2}$. The calculated results are shown in Fig. 3. It is seen that in the absence of the magnetic field the wave function extension is controlled by the lateral quantum confinement. At high magnetic fields, the width of the wave function is independent on the laser-field amplitude for the large well, but as R decreases it becomes sensitive to the laser field. This behaviour is consistent with the results of the impurity binding energy obtained from Fig. 1.

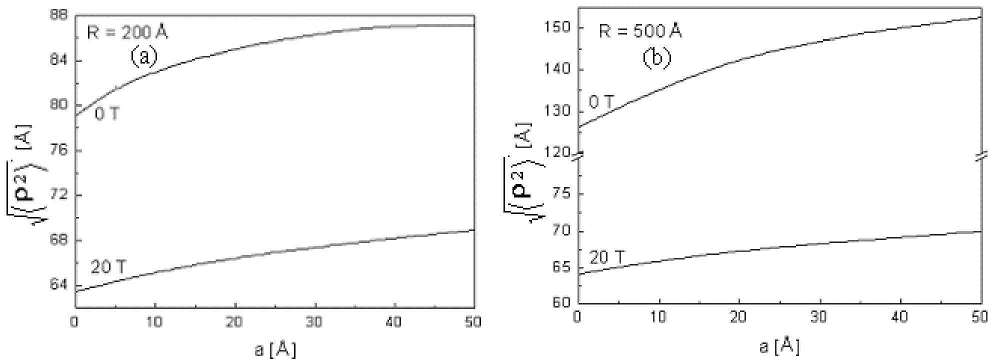

Fig. 3. Lateral width of the ground state wave function for a hydrogenic donor in a cylindrical GaAs–$Al_{0.3}Ga_{0.7}As$ QWW vs. the laser-field amplitude. (a): R=200 Å; (b): R=500 Å.

Because the magnetic field strength, the size of the quantum wire, and the laser field amplitude can strongly change the energy levels, one can obtain the desired tunability in the optical emission of QWW's by playing with such parameters.

As a summary, we have studied the effect of the high-frequency laser field on the binding energy 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 for the QWWs the laser-field amplitude provides an important effect on the electronic properties. Our results suggest that the optical properties of the quantum well wires can be tuned by changing the laser intensity, the wire radius, and the magnetic applied field. This gives a new degree of freedom in various optoelectronic devices applications based on low-dimensional structures.

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