MAGNETIC AND ELECTRIC FIELD EFFECTS ON THE BINDING ENERGY OF A SHALLOW DONOR IN QUANTUM DOT–QUANTUM WELL

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We studied the simultaneous of the magnetic and electric field effects on the binding energy for a shallow donor confined to move in spherical Quantum Dot – Quantum Well (GaAs-GaAlAs). Calculations are performed in the framework of the effective mass approximation using the Hass variational approach. We describe the effect of the quantum confinement by a infinite deep potential. The result shows that the corrections due to the magnetic and electric field are very important and cannot be neglected or ignored. We have demonstrated the existence of a critical value $\left(\frac{a}{b}\right)_{cri}$ which can be used to distinguish the three dimensions confinement from the spherical surface confinement and it's may be important for the nanofabrication techniques.

• key words: Quantum Dot - Quantum Well, Magnetic Field, Electric Field

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I.Introduction

In the past ten years, studies on the impurity states in nanostructure semiconductors, such as quantum well (QW), quantum well wire (QWW) and quantum dots (QD), have become subjects of extensive investigations both in basic and applied researches [1-5]. Recently, a new class of quantum dots called quantum-dots quantum-well (QDQW) or Inhomogeneous quantum dots ''IQD'', have been studied both theoretically and experimentally [6-12]. QDQW are composed of two semiconductor materials one of which, with the smaller band gap, is embedded between a core and outer shell of the material with the larger band gap. We show in Fig.1 a schematic diagram of quantum dots – quantum well structure where a and b are the inner and the outer radius of the QDQW respectively. For more details on the chemical fabrication of this new artificial structure, we refer to references [13-22]: CdS/HgS/CdS [13, 15, 17], InAs/GaAs [16], CdSe/HgSe/CdSe [17], ZnS/CdS/ZnS [18, 21] and InAs/ZnSe [22]. These structures could exhibit somme remarkable and interesting phenomena.

The original characteristic of these structures is that their physical properties can be controlled and can be tuned by changing the core radius, the thickness of the well and the size of the outermost shell.

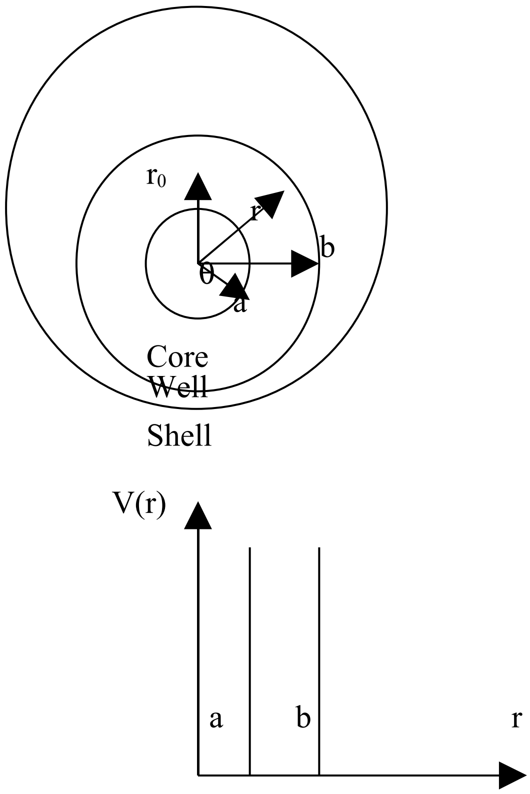

Fig.1 : Schematic diagram of quantum-dots quantum-well structure. a and b are the inner and the outer radius of the QDQW respectively

11

Understanding the Impurity states in these structures is an important problem in semiconductors technology. Many works have been devoted to the studies of impurity states in the quantum well, quantum wire and quantum dots [1-5]. Recently, J.Silva *et al* [2] have calculated the donor binding energy as a function of the donor position in QD with an infinite spherical well and for different radius of the structure. They found that the donor binding energy decreases when the donor position increases reaching a minimum, as the donor position is equal to the radius of the QD.

For QDQW, to the best of our knowledge no work has been done to treat the effect of the donor's position and magnetic field on the binding energy. Cheng-Ying Hsieh [6] have calculated the ground and excited states of hydrogenic impurity located at the center of a quantum-dots quantum-well of a spherical core (GaAs) coated by a spherical shell ($Ga_{1-x}Al_xAs$) and then embedded in a bulk material ($Ga_{1-y}Al_yAs$).

The quantum confined stark effect have been the subject of numerous experimental and theoretical investigations [3-5, 7, 10] which demonstrated that the binding energy are shifted to low energies in the presence of an uniform electric field. Recently, Asaid *et al* [4] have analyzed the effect of an uniform electric field on the energy of a shallow donor placed anywhere in quantum crystallite. They found that when the donor is placed at the center, the energy level is shifted to low energies, the energy shifted is proportional to the square of electric field. When the donor is placed anywhere, the energy level shift depends on the direction of the electric field. Khamkhami *et al* [7] have analyzed the uniform electric field effects on the excitons, in QDQW, they found that the stark effect appears even for very small size and the energy shift is more significant when the exciton is placed on the spherical surface.

In the present work, we use a variational method to calculate the hydrogenic donor binding energy in QDQW in the strong and the moderate confinement regimes. We will examine the effect of the magnetic and the electric field on the binding energy. This paper is organized as follows: in section 2, we present the general formalism, we deduce the expression of the donor binding energy in the presence of the uniform magnetic and electric field. The numerical results and discussions are presented in section 3.

II. General formalism

We consider a donor Impurity located at the position $\vec{r}_0$ of a quantum-dots quantum-well made out of [GaAlAs (Core) / GaAs (Well) / GaAlAs (Shell)]. The confining potential well is assumed to an infinitely deep well.

In the effective mass approximation, the Hamiltonien of the system is written as:

$$H = H_0 + V_w + W + M \qquad (1)$$

Where the unperturbed Hamiltonien is given by:

$$H0 = T + V = -\frac{\hbar^2}{2m^*}\Delta - \frac{e^2}{\varepsilon_0|\vec{r}-\vec{r}_0|} \qquad (2)$$

Where m* is the electron band effective mass and ε_0 is the dielectric constant. $\vec{r}$ is the electron position relative to the donor located at $\vec{r}_0$ position.

With :

$$|\vec{r}-\vec{r}_0| = \sqrt{r^2 + r_0^2 - 2rr_0 Cos\theta} \qquad (3)$$

We assumed that the confinement potential energy is modelized by:

$$V_w = \begin{cases} 0 & a\langle r \langle b \\ \infty & r\langle a \;\; and \;\; r\rangle b \end{cases} \qquad (4)$$

Where a and b denote the inner and outer radius of the QDQW, respectively (See Fig-1)

The energy due to the external electric field $\overrightarrow{F}$ is given by:

$$W = eF(r\cos\theta - r_0) \qquad (5)$$

In the present study, we do not take into account the possible spin-orbit coupling as well as the Zeeman effect, restricting ourselves to the diamagnetic contribution. Therefore, our result may be interpreted as “mean” result independently of a possible splitting. In these conditions, the diamagnetic contribution M due to the magnetic field B reads, using the coulomb gauge,

$$M = \frac{\hbar^2 e^2}{2m^* c^2} B^2 r^2 \sin^2\theta \qquad (6)$$

In the following, all expressions will be given in the effective units: $a^* = \frac{\hbar^2 \varepsilon_0}{m^* e^2}$ for length and $R^* = \frac{m^* e^4}{2\hbar^2 \varepsilon_0^2}$ for energy. Furthermore, we

introduce the dimensionless parameters $f = \frac{e a^* F}{R^*}$ and $\gamma = \frac{\hbar\omega_c}{R^*}$ characterizing the strength of the electric and magnetic fields. $\omega_c = \frac{eB}{m^* c}$ is the effective cyclotron frequency.

In order to solve numerically, the Schrödinger equation, we use a variational method. The wave function given by :

$$\psi = \psi_0 \, [1+\beta \, f \, (r \cos\theta - r_0)] \qquad (7)$$

Where β is a variational parameter (which takes into account the presence of the electric field) and ψ_0 is the wave function in the absence of the electric field (f = 0) given by:

$$\psi_0 = \frac{Sin[K(r-a)]}{r} e^{-\alpha |\vec{r}-\vec{r}_0|} \qquad (8)$$

α is a variational parameter and $K = \frac{\pi}{b-a}$.

The exponential factor exp-$\alpha \left|\vec{r} - \vec{r}_0\right|$ describes the coulomb spatial interaction.

The energy is obtained by the minimization with respect to the variational parameter α :

$$E_t = \min_{\alpha} \left\{ \frac{\langle \psi \,|H|\psi \rangle}{\langle \psi \,|\psi \rangle} \right\} \qquad (9)$$

The binding energy E_b of the Impurity is given by:

$$E_b = E_{Sub} - E_t \qquad (10)$$

Where E_t and E_{Sub} represents the state energy of an electron in QDQW with and without the impurity binding respectively.

III. Results and Discussion

We will examine the effect of the electric and magnetic fields.

Two extreme cases that present them selves : a = 0 (i.e homogeneous quantum dot ''HQD'' of b radius) and a $\rightarrow$ b for b fixed wich corresponds to an infinitely thin spherical layer.

III.1 Effect of the electric field

In fig.2, we present the binding energy E_b as a function of the ratio a/b for two different confinement regimes b = 1 a* and b = 2 a* and for two several values of the electric field f = 0, 0.4 and 0.8. We notice that when the electric field increases the binding energy decreases and we remark that the effect of the electric field becomes more important when the ratio a/b offers toward 1 or the outer radius of the QDQW increases.

We also remark that the binding energy E_b presents a minimum for a critical value of the ratio $(\frac{a}{b})_{crit}$ depending of the value of b. For a/b equal zero, E_b recovers the limit corresponding to a HQD.

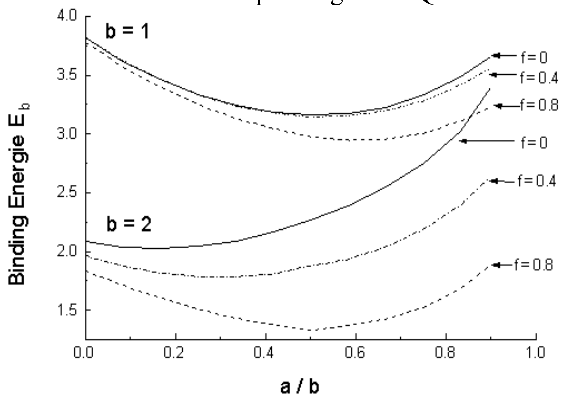

FIG. 2: Variations of the binding energy E_b as a function of the radio a/b for two different values of the outer radius of the QDQW, b = 1 a* and 2 a* and two values of the electric field f = 0.4 and 0.8. The solid curve corresponds to the binding energy variation in the absence of electric field.

In fig.3, we fix the outer and the inner radius of the QDQW respectively at b = 3 a* and a = 1 a* and we plot the binding energy E_b as a function of the donor position r_0 for two different values of the electric field f = 0 and 0.4. We remark that the electric field reduced the binding energy. Its effect is more pronounced when the impurity is placed to the center of the spherical layer ($r_0 = \frac{a+b}{2}$) and decreases when the donor moves toward extremities of the spherical layer.

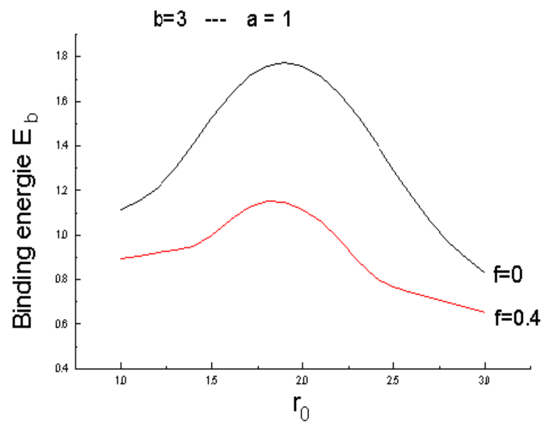

FIG. 3 : Variations of the binding energy as a function of the impurity position for two different values of the electric field.

III.2 Effect of the magnetic field

In fig.4, we present the binding energy E_b as a function of the ratio a/b for two different confinement regimes b = 1 a* and b = 2 a* and for various values of the magnetic field $\gamma = 0$, 0.4 and 0.8. We observe that the binding energy increases as the magnetic field increases.

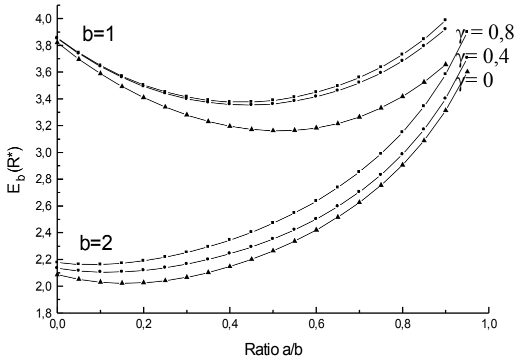

FIG. 4: Variations of the binding energy E_b as a function of the radio a/b for two different values of the outer radius of the QDQW, b = 1 a* and 2 a* and various values of the magnetic field γ =0, 0.4 and 0.8.

In fig.5, we fixed the outer and the inner radius of the QDQW respectively at b = 3 a* and a=1a* and we plotted the variation of the binding energy E_b associated to two different values of the magnetic field $\gamma = 1$ and 0.3 as a function of the impurity position r_0. We remark that when the magnetic field increases the binding energy increases too. Its effect is more pronounced when the impurity is placed to the center of the spherical layer ($r_0 = \frac{a+b}{2}$) and decreases when the donor moves toward extremities of the spherical layer. We can explain this result by the fact that the geometric confinement increases.

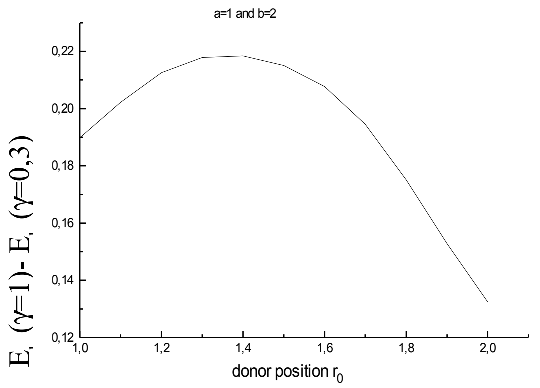

FIG. 5 : variation of the binding energy E_b associated to two different values of the magnetic field $\gamma = 1$ and 0.3 as a function of the impurity position r_0.

IV. Conclusion

In conclusion, we have studied the donor binding energy in QDQW. The calculation was performed within the effective mass approximation and using the variational method. An infinitely deep potential well have been used. The results show that the binding energy depends strongly on the core and the shell radius. We have demonstrated the existence of a critical value $(\frac{a}{b})_{crit}$ which may be important for the nanofabrication techniques. This value may also be used to distinguish the three dimensional confinement from the spherical surface confinement. In addition, we found that also the binding energy depends strongly on the donor position. We demonstrated that it is maximal when the donor is placed in the center of the ''HQD'' or QDQW.

We have shown that the effect of the electric field reduces the binding energy. When the magnetic field increases the binding energy increases. We notice that the stark and the magnetic effects are more pronounced when the donor is placed to the center of the QDQW and becomes less important when the impurity moves toward the extremities of the spherical layer. What proves that the QDQW is specific and confirm the fact that its physical properties differ of each constitutes.

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