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Inverse parabolic quantum dot: The transition energy under magnetic field effect

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ABSTRACT

We present here, the evolution of the transition energy with a static magnetic field, when the electron and the hole are confined in inverse parabolic quantum dot (IPQD). The unexpected behavior is found, at the weak confinement regime the conduction band minimum and the top of valance band change from s-state to p-state or d-state for confined electron and hole inside IPQD, respectively. The strength of the inverse parabolic potential (potential hump) inside a quantum dot has the upper hand in tuning the ground state momentum for both electron and hole, and consequently their interband transition energy is changed. Knowing that this is not the case for the other types of potentials. The quantum size, the magnetic field and inverse potential hump effects on electron and hole ground and excited states are discussed.

1. Introduction

Recently, the extensive theoretical investigations have been focused on the subject of quantum dots (QDs) as low-dimensional quantum structures. Much of these study efforts have been devoted to understanding their electronic, optical and magnetic properties. Many studies considered a magnetic or an electric field effects to study quantum wells, quantum wires and QDs [1–6]. For practical and theoretical purposes, more works analyzing such structures have been concentrated on the magnetic properties with restricted geometries of spherical [7], parabolic, cylindrical and rectangular [8] QDs and other nanostructures such as super lattices, quantum wires, wells, anti dots, well wires and anti wells [9–11] with and without magnetic field [12,13].

The great progress in nanofabrication technology, makes it possible to manufacture high-controlled semiconductor quantum wells with the desired shape of the confinement potential [14]. Beside the well known and examined extensional types of quantum confinement, which are square and parabolic potential shape [15–17], the structures of quantum well hetero-structures with half parabolic [18], graded [19], V-shaped [20] and inverse parabolic quantum well (IPQW) potential shape [21–24] have been produced and studied.

Particularly, here we are concerned about inverse parabolic quantum confinement (IPQC) potential inside the QDs. Such confinement potential modulates the performance of the optoelectronic devices and quantum information. That is because in IPQC potential there is a great change in the electron and heavy hole wave functions and consequently in the ground-state energy and in the excited states compared with the other shapes of confinement potentials. As a result of that inter band

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transition energy of the particles inside IPQD is changed, and the normal selection rules for such transition is not applicable with the same common quantum numbers. Although IPQC potential has many important and exciting characteristics, still the existing literature which examined its fundamental physical properties is very limited [21–24].

Someone may ask, What is the feasibility of discussing the single particle system in such QD. We justify that to the fact of tuning single-particle wave functions in single semiconductor QDs is required to achieve solid-state quantum information processing. Normally, particle wave functions can be tuned transversely by a perpendicular magnetic field. Also in Ref. [25], they reported controlling of a longitudinal wave function in single quantum dots with a magnetic field. Therefore the charge distribution can be tuned with the magnetic field, consequently, the electron-hole interaction in single quantum dots can be controlled. Up to our knowledge, we believe this is the first time to treat the IPQC potential in QDs. In this paper an attempt is made to investigate the Schrodinger equation describing an electron and hole confined inside a cylindrical QD made of GaAs in the presence of a static magnetic field. We solve the time independent Schrodinger equation within the effective mass approximation, we obtain the energy spectra and wave functions of the confined single particle with an IPQC potential in the strong confinement regime of the dot radius ($R \leq$ Bohr radius (a_B)) and in the weak confinement regime ($R > 2a_B$) The paper is organized as: Next section, we present our theoretical model of calculation, in Section 3 we show our results with the discussion and in Section 4 we give our conclusion.

2. Theoretical model

Consider a charged particle electron or hole, e, h, with an electronic effective mass m_e^*, and m_h^* in the conduction band and in the valence band, respectively. The electron and the hole are confined to an inverse parabolic quantum confinement (IPQC) potential inside a quantum dot (QD). We will study the electronic states of the charged particles and their transition energy variation with the IPQC potential influenced by uniform and static magnetic field applied perpendicular to the QD in-plane. In cylindrical coordinates, the Schrodinger equation describing a spineless (spin-0) electron or hole in such a quantum system is usually written in the form.

$$\frac{1}{2\,m_i^*}\left(\overline{p}+\left(\frac{e}{c}\right)\overline{A}\right)^2\,\Psi(r,\phi,z)+V(r,z)\Psi(r,\phi,z)=E\,\Psi(r,\phi,z) \tag{1}$$

Where r, ϕ *and* z is the radial direction, azimuthal angle direction and the height direction in cylindrical coordinates, respectively. The chosen vector potential $\overline{A}=\frac{\overline{B}\times\overline{r}}{2}$ is a symmetric gauge within the perpendicular static magnetic field $\overline{B}=(0,0,B)$ therefor $\overline{A}=(0,A_\phi,0)$. Due to the symmetric in cylindrical quantum dot, the potential $V(r,z)$ can be separated into in-plane potential $V(r)$, written as symmetric inverse parabolic potential

$$V(r)=\begin{cases}V_i\left(1-\dfrac{r^2}{R^2}\right) & r\leq R\\[2ex] V_0^i & r>R\end{cases} \tag{2-a}$$

And the potential along growth direction (z-direction) present in the form of symmetric inverse parabolic potential as:

$$V(z)=\begin{cases}V_i\left(1-\dfrac{z^2}{L^2}\right) & z\leq L\\[2ex] V_0^i & z>L\end{cases} \tag{2-b}$$

Here 2L represents the height of the cylindrical QD with radius R. V_0^i is the barrier height and V_i is the potential strength inside a quantum dot (potential hump) [i stands for electron or hole]. The Schrodinger equation (1) with potential (2) in cylindrical coordinates has a form:

$$\frac{-\hbar^2}{2\,m_i^*}\left\{\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial\phi^2}+\frac{\partial^2}{\partial z^2}\right\}\Psi(r,z,\phi)+\left\{V(r)+V(z)+\frac{\boldsymbol{e^2B^2}}{\boldsymbol{8m_i^*c^2}}\boldsymbol{r^2}-\frac{j\hbar eB}{2\,m_i^*c}\frac{\partial}{\partial\phi}\right\}\Psi(r,z,\phi)=(E^r+E^z)\Psi(r,z,\phi) \tag{3}$$

We can write the wave function $\Psi(r,z,\phi)$ as two independent functions; $\Psi(r,z,\phi)=f(r,\phi)g(z)$, this leads to rewrite equation (3) in in-plane using the potential (2-a) inside quantum dot ($r\leq R$) as follows

$$-\frac{\hbar^2}{2m_i^*}\left\{\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial\phi^2}\right)f(r,\phi)\right\}-\frac{j\hbar eB}{2m_i^*c}\frac{\partial}{\partial\phi}f(r,\phi)+\left\{V_i-V_i\frac{r^2}{R^2}+\frac{e^2B^2}{8\,m_i^*c^2}r^2\right\}f(r,\phi)=E^rf(r,\phi) \tag{4-a}$$

And outside quantum dot ($r>R$)