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Short Communication

Correlation Effect of Two Donors in a Nano Dot under the Influence of Magneticfield

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Magnetic field induced binding energy of two donors in a parabolic GaAs/AlGaAs nano dot is reported. The calculations are carried out using variation ansatz within the single band effective mass approximation. The binding energy is estimated for different inter-impurity distances in the presence of magnetic field. The correlation effect of two donors is introduced through the wave function. It is found that inter-impurity distance, correlation of donors and the magnetic field strength make the electron more binding.

Keywords: Nano dot, Binding energy, Variational method.

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1. INTRODUCTION

Quantum dots containig one,two and more electrons can be fabricated with the recent advances in nanofabrication technology such as Molecular beam epitaxy, chemical vapour deposition and lithography. The energy levels with and without correlation have been intensively investigated experimentally [1, 2] and theoretically [3, 4]. In these quasi zero dimensional systems in which the carrier motion is restricted to a narrow region of a few nanometers in dimension, the correlation among the electrons are shown to be appreciable [5]. The effect of electron-electron interaction has shown a great importance in these systems [6, 7]. The interaction and correlation of two electrons are useful in optical applications because there appear additional spectral lines. Moreover, the positions of these lines can be altered by selecting different inter-impurity distances through the technological advances. The positions of these lines can be altered by choosing different inter-impurity distances through technological processes [8].

In this calculation we investigate the binding energy of shallow-donor impurity states in a symmetrical GaAs-$Ga_{1-x}Al_xAs$ quantum dot in the influence of magnetic field. Numerical calculations are carried out within the single band effective-mass approximation variationally. Binding energy is calculated for different inter-impurity distances in the presence of magnetic field. Magnetic field induced binding energy with and without the correlation is studied.

2. THEORY AND MODEL

The Hamiltonian consists of two donors in a parabolic QD in the presence of a magnetic field B and it is given by

$$H_D = \sum_{j=1}^{2}\left[\frac{1}{2m^*}\left(\bar{p}_j - \frac{e}{c}\bar{A}_j\right)^2 + V_D(\bar{r}_j)\right] + \frac{e^2}{\varepsilon_o r_{12}} - g^*\mu_B{}^* BS_z \quad (1)$$

where

$$V_D(\bar{r}_j) = \frac{V_0(B)r^2}{R^2} \quad \text{for} \quad |r| \le R \quad \text{while}$$
$$V_D(\bar{r}_j) = V_0(B) \quad \text{for} \quad |r| > R ,$$

and $V_0(B)$ is the barrier height of the parabolic dot given by $V_D(\bar{r}) = Q_c \Delta E_g(x)$.

Q_c is the conduction band off-set parameter, which is taken to be 0.658 and the band gap difference between GaAs and $Ga_{1-x}Al_xAs$ is given by

$$\Delta E_g(x) = 1.155x + 0.37x^2 \text{ eV}. \quad (2)$$

The ground state energy of a donor in a parabolic quantum dot with magnetic field is estimated by variational method. We have assumed the trial functions as

$$\psi_{in}^{(0)}(r) = A_{in} e^{-\xi r 2} \quad r < R$$
$$\psi_{out}^{(0)}(r) = -A_{out}\frac{e^{-\delta r}}{r} \quad r \ge R \quad (3)$$

Here A_{in} and A_{out} are normalization constants. By matching the wave functions and their derivatives at the boundaries of the QD, and along with the normalization, we fix the values of A_{in}, A_{out}, and $\xi = \frac{1}{R}\left(\frac{1}{R} + \delta\right)$.We take δ as the variational parameter. By introducing the effective Rydberg $Ry^* = m^* e^4 / 2\hbar^2\varepsilon^2$ (5.3meV) as the unit of energy and the effective Bohr radius $a^* = \hbar^2\varepsilon / m^* e^2$ (103 Å) as the length unit, the Hamiltonian given in Eq.(1) becomes

$$H_D = -\nabla^2 + \frac{\gamma^2}{4} r^2 \sin^2\theta + \gamma L_z + \frac{V_D}{Ry^*} - g^*\mu_B{}^* BS_z \quad (4)$$

where V_D is the parabolic confinement, μ_B^*,is an effective Bohr magneton and g^* is an effective Lande factor

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of GaAs. The ground state energy of the conduction electron in a parabolic QD in the external magnetic field, E_D, is obtained by minimizing the expectation value of H_D with respect to the variational parameter δ, which minimizes H_D for various magnetic fields.

The Hamiltonian for a donor situated at the center of the parabolic dot in the presence of external magnetic field applied along the growth direction is

$$H_{ID} = H_D - \frac{2}{r} \qquad (5)$$

The ionization energy of the donor in the presence of magnetic fields, $E_{ion}(B) = E_D + \gamma - \langle \psi | H_{ID} | \psi \rangle_{\min}$, is obtained by variational method using the following trial wave functions with β, λ as the variational parameters

$$\begin{aligned} \psi_{in}(r) &= \psi_{in}^{(0)} e^{-\beta(r_1+r_2)} e^{-\lambda(r_1 r_2)} \quad r < R \\ \psi_{out}(r) &= \psi_{out}^{(0)} e^{-\beta(r_1+r_2)} e^{-\lambda(r_1 r_2)} \quad r \ge R \end{aligned} . \qquad (6)$$

3. RESULTS AND DISCUSSION

Numerical calculations have been carried out to investigate the effects of magnetic field strength on donor impurity states in semiconductor quantum states in a $GaAs/Ga_{1-x}Al_xAs$ quantum dot is reported. The units of length and energy used throughout are the effective Bohr radius $R^* = \hbar^2 \varepsilon / m^* e^2$ and the effective Rydberg $R_y^* = m^* e^4 / 2\varepsilon^2 \hbar^2$ where ε is the dielectric constant and m^* is the effective mass of electron in the conduction band minimum of GaAs. The barrier height is taken to be 195 meV which corresponds to the $Ga_{1-x}Al_xAs$ quantum dot, for which $R_y^* = 5.3$ meV and $R^* = 103$ Å.

The magnetic field strength $\gamma = 1$ equals to 6.12 tesla. Fig. 1 shows the variation of binding energy as a function of dot radius for different inter-impurity distances. In all the cases, the binding energy decreases with an increase of dot size, reaching the bulk value for large dot radius. Also we observe an increase in binding energy in a magnetic field. In general, in all quantum nano structures without magnetic elements (eg. GaAs / GaAlAs systems) the magnetic field increases with the binding energy [9]. As the dot size approaches zero the confinement becomes negligibly small, and in the finite barrier problem the tunneling becomes huge. The binding energy again approaches the bulk value. This is a well known result in all quantum nano structures [10]. We notice that as inter-impurity distance decreases the binding energy increases. This is due to the reduction of distance causes the increase of coulomb interaction energy which ultimately increases the binding energy.

We present the variation of magnetic field as a function of measure of magnetic field strength for two different dot sizes with and without the correlation effect as shown in in Fig. 2. The binding energy increases with the magnetic field strength also the binding energy increases with the dot size due the confinement. The electron-electron correlation effect makes the binding energy to increase further. Also it is

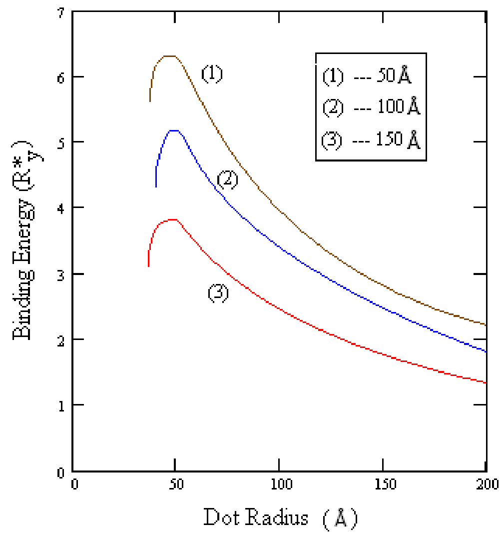

Fig. 1 – Variation of binding energy as a function of dot radius for different inter-impurity distances

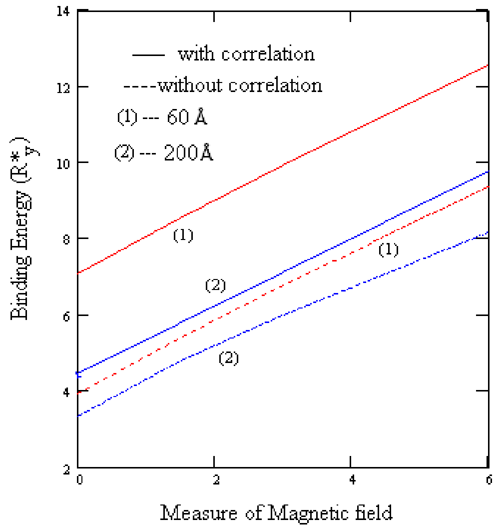

Fig. 2 – Variation of magnetic field as a function of measure of magnetic field strength for two different dot sizes

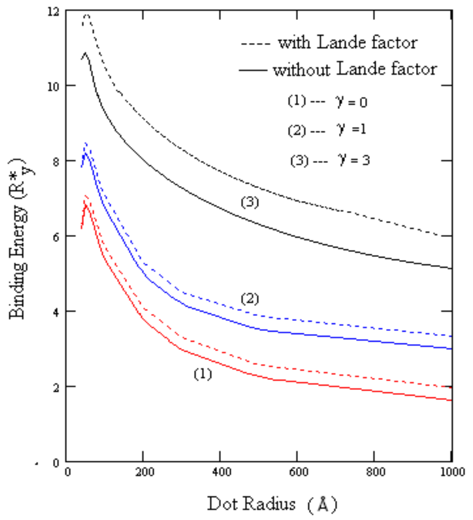

Fig. 3 – Variation of binding energy with the dot radius for different magnetic field strengths with and without the Lande factor

observed that binding energy increases as the dot radius decreases due to the confinement in all the magnetic field strengths. Also the binding energy increases with the magnetic field for all the dot radii.

Moreover, Fig. 3 displays the variation of binding energy with the dot radius for different magnetic field strengths with and without the Lande factor. It is observed that binding energy increases as the dot radius decreases due to the confinement in all the magnetic field strengths. Also the binding energy increases with the magnetic field for all the dot radii. Moreover, the binding energy still increases when the Lande factor is included in the Hamiltonian.

4. SUMMARY

In conclusion, the effects of magnetic field on the binding energy of shallow-donor impurity states in a symmetrical GaAs-$Ga_{1-x}Al_xAs$ quantum dot have been found. Binding energy has been computed for different inter-impurity distances in the presence of magnetic field. The effect of magnetic field on the binding energy with and without the correlation has been investigated. The results show that inter-impurity distance, correlation of electrons and the magnetic field strength make the electron more binding. The present results are useful to understand the optical and magnetic properties of quantum dot materials.

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