Influence of Magnetic Field on Energy Spectra of a Nano Dot

T.Mugesh, T.Prem kumar, T. Chitravel, S.Saravanakumar

Abstract— We present a theoretical study on donor binding energies of GaAs / $Ga_{1-x}In_xSb$ nano dot as a strength of magnetic field along Z direction. Calculations are carried out by using the technique of variational ansatz with in the frame work of effective mass approximation. Our results shows that (i) wave function is unbound for most of the radii of interest and have negative binding energy for lower dot radius (ii) binding energy is increased while increasing the magnetic field as expected.

Index Terms— binding energy, magnetic field, effective mass approximation, unbound, variational ansatz.

1 INTRODUCTION

LOW- dimensional nanometer-sized system have defined a new research area in condensed matter physics within the last 20 years. Modern semiconductor processing techniques allowed the artificial creation of quantum confinement of only a few electrons. Recently, there has been much work devoted to the study of the states of hydrogenic impurities in low dimensional semiconductor heterostructures such as quantum wells (QW's), quantum-well wires (QWW's), and quantum dots (QD's) [1], [2], [3]. They pay the way to fabricate many quantum well structures with dimensions comparable to the electronic de-Broglie wavelength. Due to their reduced dimensionality, these structure exhibit some physical properties such as optical and electrical transport characteristics that are more pronounced than those of bulk semiconductor constituents [4], [5]. Theoretical studies for the binding energy of the ground state in GaAs QW's[1] infinite QWW's, [6] and QD's [7] have shown that for an infinite confinement potential the binding energy increases monotonically as the finite dimension (length or radius) is reduced, whereas for finite confinement potential the binding energy increases up to a maximum and then begins to decrease. Studies for donor-doped QW's [1] and infinite QWW's [6] have shown that the binding energy present a maximum when the impurity is located at the center of the structure and decreases for positions close to the edges. It is anticipated that the fabrication of semiconductor quantum structures with zero dimensions will show exotic electronic behaviour such as the observation of discrete electronic states in due to the electronic confinement [8]. The most widely investigated quantum dot system is the GaAs/ $Ga_{1-x}Al_x$ as system. But in our problem we have chosen to investigate GaAs/ $In_{1-x}Ga_xSb$ quantum dot. The quantum dot occurs in the GaAs region with InGaSb providing the barrier. If a donor is introduced in the GaAs region we have a simple hydrogenic donor, since GaAs is a direct gap material and the effective mass theory works well. However, if the size of the dot is small (~ 50 Å) the use of the effective mass theory is questionable. Effective mass theory is valid and usually employed in the studies of these properties.

Quantum dot infrared detectors offer potential advantages over current technologies such as quantum well infrared detectors, HgCdTe detectors, and other emerging technologies such as strained superlattice GaSb based detectors with a Type II band structure. Another advantage of using quantum dots rather than quantum well based detectors is the expectation of a larger photoconductive gain based on a reduced capture probability [9], [10].

InAs/$Ga_{1-x}In_xSb$ (InAs/GaInSb) strained layer superlattices (SLSs) can be considered as an alternative to the HgCdTe and GaAs/AlGaAs IR material systems and as a candidate for third generation IR detectors [9]. In our work we introduced GaAs ND in $Ga_{1-x}In_xSb$. With our knowledge there is no work is available in literature for this system.

2 THEORETICAL FRAME

Our system consists of a parabolic nano dot (depth VD, and radius R) containing a donor impurity inside the ND of the magnetically non-uniform "spin-doping" type-II QD system with GaAs nano dot embedded in a $Ga_{1-x}In_xSb$ matrix with a finite barrier. Consider an electron is moving in a ND each having an effective mass m*, which is $0.067m_e$, for GaAs. The Hamiltonian in the system within the effective mass approach when the magnetic field (without considering the strain at the interface) is applied is given by

$$H = \frac{1}{2m^*}(\vec{P} + \frac{e}{C}\vec{A})^2 + V(\rho) + \frac{e^2}{\varepsilon_0 r} + g^*\mu_B BS_z \quad (1)$$

Where, ρ refers to the position vector of an electron in two dimensions, $\vec{P}$ is the corresponding momentum operator, m* is the electron effective mass and $\vec{A}$ is the vector potential corresponding to the magnetic field, which has been applied in the Z direction, g is the effective Lande factor; μ_B is the Bohr magnetron; S_Z is the Z componenet of the total spin, ε_0 is the effective dielectric constant of the ND, and $V_D = \frac{V_{OB} r^2}{R^2}$ for $|r| \le R$ and $V_D = V_{OB}$ for $|r| > R$ $V_{OB}(\vec{r})$ is the barrier height

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given by $V_{OB}(\vec{r}) = Q_c \Delta E_g(x).Q_c$ is the conduction band off set parameter, which is taken to be 0.6 and the band gap difference between GaAs and $Ga_{1-x}In_xSb$ is given by

$$\Delta E_g(x) = 0.235 + 1.653x + 0.413x^2 \quad eV \tag{2}$$

The units of length and energy used throughout the present paper are the effective Bohr radius $R^* = \frac{\hbar^2 \varepsilon_0}{m^* e^2}$ where ε_0 is the static dielectric constant of GaSb

$$H_D = -\nabla + \frac{\gamma^2}{4} r^2 \sin^2\theta + \gamma L_z + \frac{V_D}{R^*} + \frac{2}{r} + \frac{g^* \mu_B B S_Z}{R^*} \tag{3}$$

Where L_z is the total orbital angular momentum along in the z-direction and γ is the measure of magnetic field. The Eigen functions for the lowest states within the dot are given by

$$\psi_{1s}(\vec{r}) = \begin{cases} N_1 \dfrac{\sin(\alpha_1 r)}{r} e^{-\delta r^2}, & r \le R, \\ N_2 \dfrac{e^{-\beta_1 r}}{r} e^{-\delta r^2}, & r > R \end{cases} \tag{4}$$

Where N_1 and N_2 are normalization constants α_1 and β_1 are given by

$$\alpha_1 = \sqrt{2m^* E_1} \text{ and } \beta_1 = \sqrt{2m^*(V_D - E_1} \tag{5}$$

Matching the wave functions and their derivatives at the boundary r = R, the energy eigen values are determined by imposing the boundary conditions,

$$-\frac{i\hbar}{m^*}\frac{\partial \psi}{\partial r}(r \le R)\Big|_{r=R} = -\frac{i\hbar}{m^*}\frac{\partial \psi}{\partial r}(r \ge R)\Big|_{r=R} \tag{6}$$

Using Eqn. (4) – (6), we obtain

$$\alpha_1 R + \beta_1 R \tan(\alpha_1 R) = 0 \text{ for S-states} \tag{7}$$

The ground state energy of the conduction electron in a parabolic QD in an external magnetic field, E_D, is obtained by minimizing the expectation value of H_D with respect to the trial wave functions given in Eq. (4). 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, in the unit of effective Rydberg and effective Bohr radius, is

$$H_{ID} = -\nabla^2 + \frac{\gamma^2}{4} r^2 \sin^2\vartheta + \gamma L_z + \frac{V_D}{R^*} - \frac{2}{r} + \frac{g^* \mu_B B S_z}{R^*} \tag{8}$$

The ground state energy of the donor in the presence of magnetic field is obtained by the variational method using the trial wave functions, Eqn.(4) with $e^{-\alpha r}$, where α is the variational parameter. The ground state energy is estimated by minimizing the expectation value of H_{ID} with δ and α as the variational parameters with respect to the above trial wave functions.

$$\psi_{1s}(\vec{r}) = \begin{cases} N_3 \dfrac{Sin(K_1 r)}{r} e^{-\delta r^2} e^{-\alpha r}, & r \le R \\ N_4 \dfrac{e^{-K_2 r}}{r} e^{-\delta r} e^{-\alpha r}, & r \ge R \end{cases} \tag{9}$$

Where, N_3 and N_4 are Normalization Constants

The ionization energy is obtained by

$$E_{ion} = E_D + \gamma - \langle \psi | H_{ID} | \psi \rangle_{\min} \tag{10}$$

The confining potential energies of a donor is calculated using the Hamiltonian (Eq.(9)) and the wave functions Eqs.(4) for different concentrations.

3 Results And Discussion

The calculations were carried out for the type-II semiconducting material by considering ε_0 = 13.13 and m* = 0.067 m_e. Where, m_e is the single electron bare mass. In Fig 1, we observe that, the sub energy increases with reducing the radius of the dot and reaches the maximum for R=40A^0. The sub band energy decreasing below the dot radius R=40 A^0. The following results are observed (i) Sub band energy shows maximum value for R=40A^0 for all magnetic field. (ii) The Sub band energy value increases as the applied magnetic field increases.

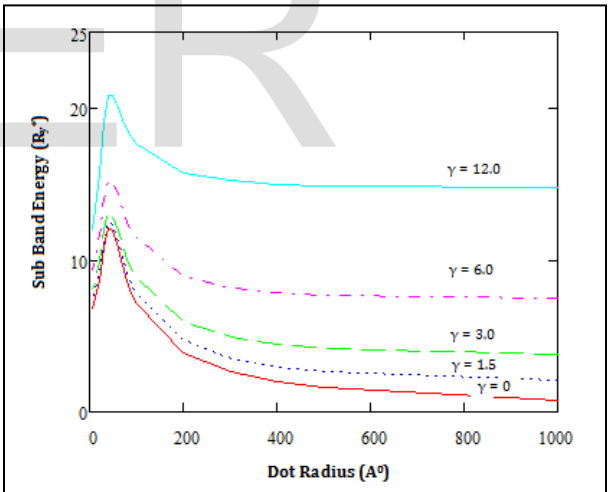

Fig. 1. Sub band energy as a function of dot radius with different magnetic field strength.

Fig 2 displays binding energy as a function of dot radius for different magnetic field strength. In the absence of magnetic field the binding energy shows positive value for R>800 A^0. Below that it shows negative value suggest the state of unbound [11]. We understood that, QD confinement at lower dot radius is achieved by increasing the magnetic field strength for this particular material was shown in the insert of fig.2. Very high magnetic field γ=12.0 the unbound state occurs below 83A^0 dot radius. The binding energy increases with Magnetic field strength suggest that the tunability of band gap is possible under strong magnetic field [12].

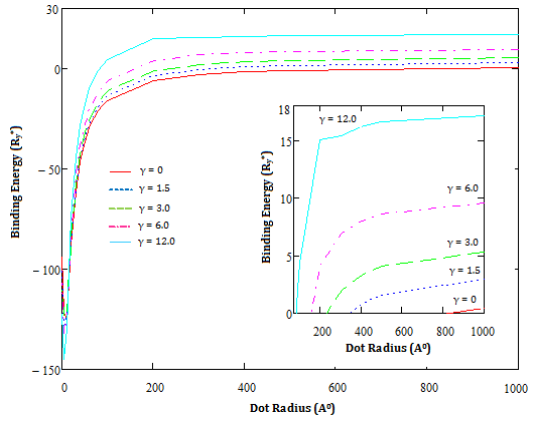

Fig.2. Binding energy as a function of dot radius with different magnetic field

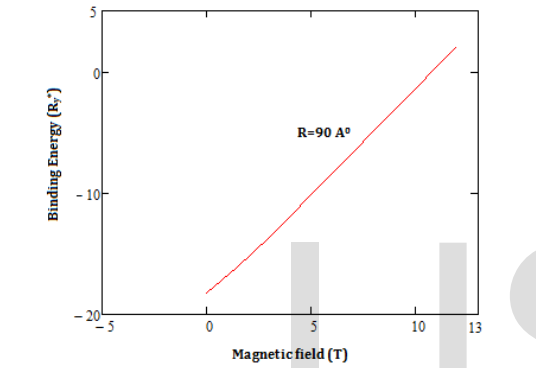

Fig.3. Binding energy as a function of applied magnetic field for dot radius R=90 A^0

The variation of binding energy for different magnetic field for the dot radius R=90 A^0 is displayed in fig 3. It shows linear variation with respect to the applied magnetic field.

4 Conclusion

We carried out the calculations for the energy levels of the nano dot system as a function of magnetic field. Calculations are done by using variational ansatz within the effective mass approximation. The peculiar behaviour of negative binding energy of our system arises due to the electron is too delocalized for lower dot radii, and staggered energy gap of the system which transcend this concept into tunnelling effect. Magnetic field has great influence on tuning the band gap of the system. Our Present work will hopefully stimulate the optoelectronic device fabrication in near future.

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