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Donor bound polaron in a group III-V diluted magnetic quantum dot: the effect of Mn alloy content

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ABSTRACT

The effect of Mn content on donor binding energy of a hydrogenic donor as a function of dot radius in a GaAs diluted magnetic semiconductor quantum dot is investigated. The Mn based GaAs material is the most thoroughly studied ferromagnetic dilute magnetic semiconductor which brings out the relationship between magnetic and semiconducting properties. All the calculations include the exchange interaction of Mn alloy content with an itinerant carrier. The worked out computation are performed within a single band effective mass approximation using variational technique. The binding energy is calculated by varying its dot radius, for various Mn incorporation in Mn based GaAs inner quantum dot surrounded by the GaAlAs outer barrier material.

Introduction

The spin of charge carriers either electrons or holes in spintronic devices bring a new functionality in today's computer. The giant and tunneling magnetoresistance are exploited read/write heads in computer hard drives, magnetic sensors and magnetic random access memories [1,2]. These semimagnetic semiconductors bring out new classes of novel devices which include some ultra-dense nonvolatile semiconductor memory. In the present work, we investigate the donor binding energy in a semimagnetic semiconductor quantum dot as a function of dot radius. We include the exchange interaction of Mn ions with the donor electron.

Model

Within the effective mass approximation, the motion of a conduction-band electron confined in a parabolic quantum dot of $GaMnAs/Ga_{0.4}Al_{0.6}As$, is described by the following Hamiltonian,

$$H = -\frac{\eta^2}{2m_e^*}\nabla^2 - \frac{e^2}{\varepsilon r} + V_D + H_{zee} + H_{SP} \quad (1)$$

where

$$V_D = \frac{V_{0B}r^2}{R^2} \quad for \quad |r| \le R \quad and \quad V_D = V_{0B} \quad for \quad |r| > R \quad ,$$

V_{0B} is the barrier height of the parabolic dot, which is taken to be 60% of the difference in the band gap between the dot and the barrier. H_{zee} and H_{SP} refer the interaction of electron spin with the applied field (Zeeman effect) and the interaction between electron spin and Mn^{2+} ions respectively.

The ground state energy of the donor in the presence of is obtained by the variational method using the following trial wave functions:

$$\psi_{in}(r) = A\frac{\sin k_1 r}{r} e^{-\delta r^2} e^{-\alpha r} \qquad r < R$$

$$\psi_{out}(r) = B\frac{e^{-k_2 r}}{r} e^{-\delta r^2} e^{-\alpha r} \qquad r \ge R \quad (2)$$

The ground state energy is estimated by minimizing the expectation value of H with δ *and* α as the variational parameters with respect to the trial wave functions given in Eq. (2).

The binding energy is obtained by

$$E_b = E_D - \langle \psi | H | \psi \rangle_{\min} \quad (3)$$

where E_D is the ground state energy calculated without the Coulomb term.

Results and Discussion

We follow the atomic units to determine the electronic charges and the wave functions in which the electronic charge and the Planck's constant have been assumed as unity. The conduction band varies with the applied magnetic field eventually modifies the potential profile of the material. The height of the magnetic potential dot formed by the magnetic layer can be tuned by applying an external magnetic field separately in order to obtain barrier height. Hear, the barrier height of the conduction band is taken as 312 me Fig.1 displays the variation of binding energy of a hydrogenic donor impurity as a function of dot radius for different Mn content in a $GaMnAs/Ga_{0.4}Al_{0.6}As$ quantum dot . In all the cases, it is observed that the binding energy increases with decreasing dot radius and it reaches the maximum value for a critical dot radius and then rapidly decreases. It is because the contribution of confinement is dominant for smaller dot radii making the electron unbound with the spread of the wave function through the barrier. As the dot size approaches zero the confinement becomes negligibly small, and in the finite barrier problem the

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tunneling becomes huge. Further, it is found that the binding energy of the donor decreases with the Mn concentration in the GaMnAs/$Ga_{0.4}Al_{0.6}As$ quantum dot for all the dot radii. It is because the contribution of spin polaronic energy effect has been included in the Hamiltonian with increasing Mn alloy content. The Coulomb interaction between the Mn ions and the carrier increases when the radius of the quantum dot decreases, this eventually decreases the binding energy.

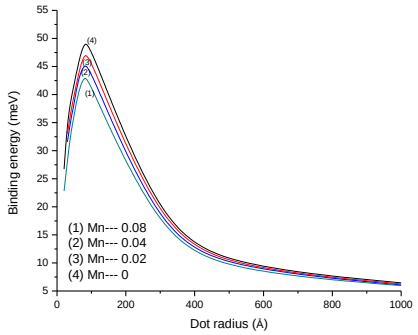

Fig.1 Variation of binding energy of a hydrogenic donor impurity as a function of dot radius for different Mn content in a GaMnAs/$Ga_{0.4}Al_{0.6}As$ quantum dot.

In Fig.2, we present the variation of binding energy as a function of Mn ions for three different dot radii. It is observed that the variation of binding energy is found to decrease sharply for smaller dots and this variation has less effect for larger dots. Hence, it is concluded that the effect of Mn content has more influence for smaller dots since the s-d interaction between the Mn^{2+} ions and the itinerant carrier has been included in the Hamiltonian with the geometrical confinement. The development of these diluted magnetic semiconductors leads to investigate novel devices which include spin transistors, nonvolatile semiconductor memory, magnetic sensors and magnetic random access memories.

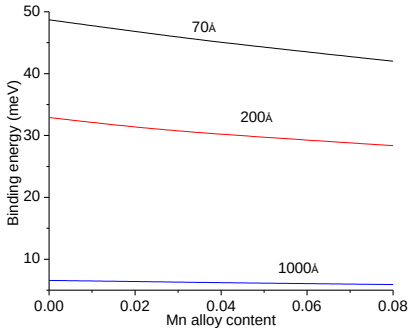

Fig.2 Variation of binding energy of a hydrogenic donor impurity as a function of Mn alloy content for different dot radii.

Conclusion

The hydrogenic donor binding energy as a function of dot radius in a GaMnAs/$Ga_{0.4}Al_{0.6}As$ quantum dot with the inclusion of s-d exchange interaction of Mn alloy content with the itinerant carrier has been computed. Calculations are performed by varying its dot radius for various Mn incorporation in GaMnAs material within a single band effective mass approximation using variational method. The spin polaronic energy of donor impurity for different Mn^{2+} is evaluated for different dot radii using a mean field theory. The development of these diluted magnetic semiconductors leads to investigate novel devices which include spin transistors, nonvolatile semiconductor memory, magnetic sensors and magnetic random access memories.

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