Manipulation of single electron spins through Landé g-factor in InAs quantum dots

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Abstract:- We study the variation in the Landé g-factor of electron spins induced by an anisotropic gate potential in InAs quantum dots for potential use as non-charge based logic devices. In this paper, we present the numerical simulations of such spins in an electrostatically confined two-dimensional asymmetric gate potential forming a quantum dot system in a 2DEG. Using numerical techniques based on finite element method, we show that the broken in-plane rotational symmetry, only due to Rashba spin orbit coupling in an asymmetric potential (induced by gate voltages) leads to cover wide range of E-field and B-field tunability of the electron g-factor.

1 Introduction

The notion of manipulating single electron spins through active modification of the spin-orbit interaction in a quantum dot formed in the plane of a two dimensional electron gas (2DEG) has received considerable attention for potential use in non charge-based logic devices and solid state quantum computing [1, 2]. Such research is of interest in that it might enhance the possibilities of next generation spintronic logic devices based on CMOS technology [3, 4].

Rashba [5] and Dresselhaus [6] spin orbit couplings are the key parameters in controlling the electron spins in a quantum dot. The Rashba spin orbit coupling arises from the structural inversion asymmetry of the quantum well confining potential along z-direction, while bulk inversion asymmetry gives rise to the Dresselhaus spin orbit coupling. The mathematical expressions for these interactions are given in Eqs. 4, 5 and 6 [7, 8].

It is also generally understood that the Zeeman spin splitting energy depends on the direction of an applied magnetic field and is described by the electron g-factor *tensor* [9, 10]. In the present work we only consider magnetic fields normal to the 2DEG, so the g-factor tensor reduces to a scalar. In several recent works, anisotropy effects in coupled quantum dot systems were explored [11, 12]. However, our methodology is different in such a way that we utilize the finite element method and study the g-factor in InAs quantum dots for both isotropic and anisotropic gate potentials.

We now turn to a discussion of our model, followed by a brief description of our computation method.

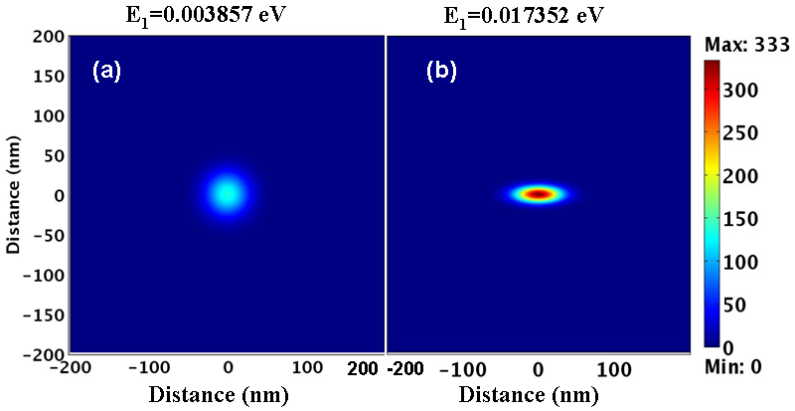

Figure 1: In plane wave functions for quantum dots formed by (a) symmetric quadratic potential with $\alpha = \beta = 1$, and (b) asymmetric quadratic potential with $\alpha = 1, \beta = 9$. In both cases, we choose $\ell_0 = 30$ nm, E = 10^5 V/cm, and B = 1 T.

2 Theoretical Model

We consider the motion of the electron in the $x-y$ plane of the quantum dot in the presence of a magnetic field oriented along z-direction. Thus the total Hamiltonian can be written as:

$$H = H_{xy} + H_z + H_{so}, \tag{1}$$

where H_z corresponds to the motion of the electron in a quantum dot normal to the interface, H_{so} is the spin-orbit interaction and the remaining term is given by:

$$H_{xy} = \frac{\vec{P}^2}{2m} + \frac{1}{2}m\omega_o^2(\alpha^2x^2 + \beta^2y^2) + \frac{1}{2}g_o\mu_B\sigma_z B, \tag{2}$$

where the kinetic momentum operator: $\vec{P} \equiv \vec{p} + \frac{e}{c}\vec{A}$ is the sum of the canonical momentum: $\vec{p} \equiv -i\hbar(\partial_x, \partial_y, 0)$, and the vector potential (in the symmetric gauge) $\vec{A} \equiv \frac{B}{2}(-y, x, 0)$.

The Hamiltonian associated with Rashba and Dresselhaus spin-orbit interactions can be written as: [7]

$$H_{so} = H_R + H_{D1} + H_{D2}, \tag{3}$$

where the *Rashba* interaction [5] is given by:

$$H_R = \frac{\alpha_R eE}{\hbar}\Big(\sigma_x P_y - \sigma_y P_x\Big), \tag{4}$$

and the linear and cubic *Dresselhaus* interactions [6, 13] are written as:

$$H_{D1} = \frac{0.7794\gamma_c k^2}{\hbar}\Big(-\sigma_x P_x + \sigma_y P_y\Big), \tag{5}$$

which is linear in components of the momentum operator $\vec{P}$ and

$$H_{D2} = \frac{\gamma_c}{\hbar^3}\Big(-\sigma_x P_x P_y^2 - \sigma_y P_y P_x^2\Big) + h.c., \tag{6}$$

which is cubic in components of the momentum operator. Here, *h.c.* denotes the Hermitian conjugate [7].

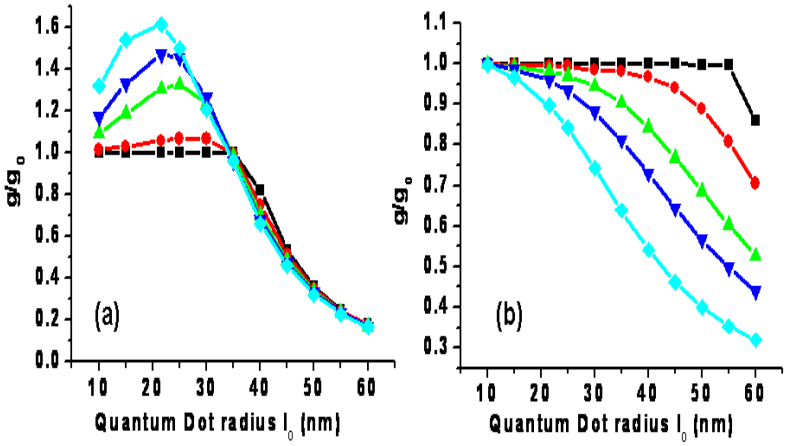

Figure 2: g-factor vs quantum dot radius for the potentials with (a) $\alpha = \beta = 1$ and (b) $\alpha = 1, \beta = 9$. In Fig(a), from bottom to top, the curves represent $E = (0.1, 2, 5, 7, 10) \times 10^5$ V/cm. In Fig(b), from top to bottom, the curves represent $E = (0.1, 2, 5, 7, 10) \times 10^5$ V/cm. In both cases, We choose $B = 1$ T.

The eigenvalue equation $H \mid \psi >= \epsilon \mid \psi >$, with H given by Eqs. 1 through 6, was solved numerically to obtain the lowest few eigenvalues and eigenstates versus the various parameters of the system. These parameters include the magnetic field strength B, the electric field E, and the strength of the quantum dot confinement potential as specified by the quantum dot radius $\ell_o = \sqrt{\frac{\hbar}{m^\star \omega_0}}$.

The electric field induced spin switching is quantified by defining an effective electron g factor by,

$$\epsilon = \frac{1}{2} g \mu_B \sigma_z B, \tag{7}$$

to describe the energy difference between the lowest energy up and down spin states. Thus, we consider the lowest two states (including spin) ϵ_2 and ϵ_1 and calculate the effective g factor as:

$$g = \frac{\epsilon_2 - \epsilon_1}{\mu_B B}. \tag{8}$$

3 Results and Discussions

The main observation is: the in-plane symmetry breaking in an anisotropic potential (i.e. $\alpha \neq \beta$) gives rise to qualitatively different behavior for the tunability of the electron g-factor with the application of electric and magnetic fields as compared to a symmetric potential (i.e. $\alpha = \beta = 1$).

In Fig.1, we illustrated isotropic and anisotropic effects in the quantum dot formed in the plane of 2DEG. These figures were obtained by using $\alpha = \beta = 1$ for the case of symmetric quantum dots (Fig.1 (a)) and $\alpha = 1$ and $\beta = 9$ for the case of asymmetric quantum dots (Fig.1 (b)). Here, we consider $\ell_o = \sqrt{\frac{\hbar}{m\omega_0}} = 30$ nm and $B = 1$ T. The in-plane symmetry breaking due to anisotropic gate potentials can be contrasted by comparing the wave function of the electron in symmetric and asymmetric potentials in the plane of 2DEG.

Figure 2 illustrates the g-factor tunability vs the strength of the applied electric field and confining potential (as parametrized by the quantum dot radius ℓ_o) for fixed magnetic field ($B = 1$ T) for both symmetric quantum dots ($\alpha = \beta = 1$ in Fig. 2(a)) and asymmetric quantum dots ($\alpha = 1, \beta = 9$ in Fig. 2(b)). We found that there is an abrupt change in the

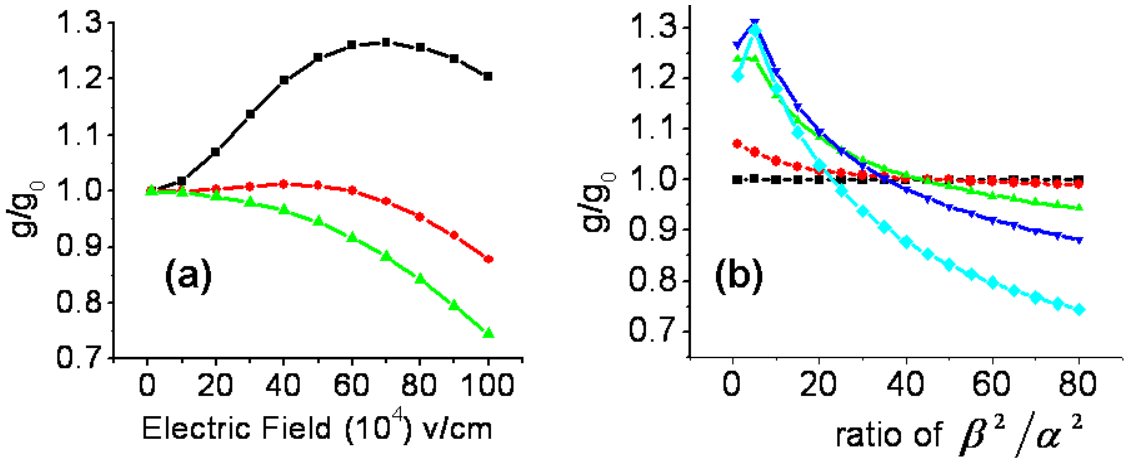

Figure 3: (a) g-factor vs electric fileds for quantum dots in the potential characterized by $\alpha = 1, \beta = 1$ (black), $\alpha = 1, \beta = 6.3$ (red)$\alpha = 1, \beta = 9$ (green). (b) g factor vs the degree of anisotropy of the quantum dot confinement potential for various electric field strengths $E = (0.1, 2, 5, 7, 10) \times 10^5$ V/cm. In both cases, we choose B=1 T and $\ell_0 = 30$ nm.

g-value due to level crossings (two eigenstates have the same spin) at near 35 nm quantum dot radius for the symmetric quantum dots. However, tunability of the g-factor or the level crossings point in the energy spectrum extends to the larger quantum dot radius for asymmetric quantum dots due to quenching in the orbital angular momentum. In Fig. 2(b), we found the level crossings point at near 55 nm quantum dot radius. Also, at very large anisotropic gate potentials (Fig. 2(b)), E-field tunability of the g-factor suppresses towards bulk crystal of InAs quantum dots mainly due to the increase in the area of the quantum dots.

In Fig.3, we compare the anisotropic effects in the variation of the g-factor with respect to the gate controlled electric fields. In Fig.3(a), g-factor for symmetric quantum dots ($\alpha = \beta = 1$, black curve) increases with the increase in gate controlled electric fields. However, anisotropic confining potential quenches the orbital angular momentum which reduces the variation in the g-factor. This gives the suppression of the E-field tunability of the g-factor towards bulk crystal. Rashba spin-orbit coupling is almost one order magnitude larger than the Dresselhaus spin-orbit coupling in the range of $E = 10^4 - 10^6$ V/cm in InAs quantum dots. It means, only Rashba spin-orbit coupling breaks the in-plane rotational symmetry in InAs quantum dots. In Fig.3(b), we plotted g-factor vs ratio of β^2/α^2. Again, we found that the quenching in the orbital angular momentum reduces the variation in the g-factor in asymmetric InAs quantum dots. In this paper, we choose InAs quantum dots which has quantitatively different behavior of the manipulation of the g-factor than GaAs quantum dots (see Ref.(8)). Manipulation of the effective g-factor is $-$ve in InAs quantum dots whereas, g-factor can be manipulated from $-$ve to +ve in GaAs quantum dots [7]. Usually, InAs quantum dots is epitaxially grown on GaAs material and both material have the same sign of bulk g-factor. It means, the penetration of the wavefunction from InAs dots to GaAs material follows the same sign of the g-factor. However, GaAs quantum dots is epitaxially grown on AlGaAs material which have different sign of bulk g-factor.

4 Conclusions

We have carried out a numerical simulation study of gate induced tunability of the electron g-factor in a prototype single electron spintronic device. We have considered symmetric and asymmetric quadratic potentials in the plane of 2DEG and employed a numerical approach based on the finite element method. We have shown that single electron spins in a quantum dot can be manipulated by gate controlled electric fields.

The key result of this work is illustrated in Figs. 2 and 3: E-field and B-field tunability is to cover the wide range of g-factor through strong Rashba spin-orbit coupling in InAs quantum dots. In asymmetric quantum dots, we have shown that anisotropic gate potential quenches the orbital angular momentum in the plane of 2DEG. This extends the tunability of the electron g-factor to the larger quantum dot radius.

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