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INVESTIGATION OF INTERNAL MAGNETIC FIELD IN DEFECTED SINGLE-ELECTRON SEMICONDUCTOR QUANTUM DOT

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ABSTRACT

In addition to the Zeeman magnetic field, there will be created another magnetic field due to the spin orbit interaction in the structure; converting the up and down spin states to each other. The intensity of the magnetic field caused by the spin interaction depends on the spin orbit (SO) coupling. In this article, we have investigated the internal electric and magnetic fields in a single electron defect quantum dot. Moreover, we have demonstrated that the magnitudes of the above mentioned internal fields depend on the size and the position of the defect inside the quantum dot. Therefore, by changing the position and the size of the defect in the quantum dot, we can control the effects caused by the interface inside the structure. Also, without any external electric fields application, we can reset the internal magnetic field to zero and thereby prevent the spin flipping.

Keywords: Quantum dot (QD), Spin orbit interaction, internal magnetic field, internal electric field.

I. INTRODUCTION

One of the best options to realize a single qubit is a confined electron in a semiconductor quantum dot, whose spin states will represent the logical states of a qubit [1]. The electron inside the quantum dot and its peripheral environment are not isolated and there exists a coupling between them which limits life time of the stored information accordingly. Therefore, it's possible to increase the lifetime of any stored information, by controlling the spin-qubit interaction, until the quantum gates are capable of performing the information processing tasks.

The spin orbit interaction can be the main reason for the spin flips in GaAs-type crystal; in which there exists a strong interaction between the electrons and acoustic phonons. The combination of the two interactions gives rise to a spin relaxation mechanism [2].

If the Zeeman magnetic field is the only effective magnetic field in the structure nothing happens to the spin up and down in Zeeman energy levels and the electron remains in its initial spin state. Also, because of the spin orbit interaction there will be a magnetic field in the x-y plane that causes the spin up to deviate from the z-axis. On the other hand, because of the acoustic phonons existence in the GaAs structure, the magnetic field due to the spin orbit interaction in the x-y plane, will be rotating with a constant magnitude. This rotating field causes the angle of the deviation from z-axis continuously increase compared to the previous moment until the spin up changes to the spin down state [3].

In this article, we have discussed quantum system model and SO interaction in the defected quantum dot, next, we have found the intensity of the magnetic field due to the spin orbit interaction and internal electrical field of a defected single-electron GaAs QD, assuming equal electron confinement in x, y and z directions. Then we have introduced the simulation outcomes and ultimately in the last part we have introduced a summary of the paper.

II. RESULTS AND DISCUSSION

II.1 Model

In this part, we study the confined electron in a quantum dot whose harmonic oscillator potential in the x and y direction has a frequency of ω_0 and a confinement radius of *l*, while in the z direction is in the form of an infinitive square quantum well with a width of L. We have considered the quantum dot in the presence of a 1T magnetic field perpendicular to the x-y plane, by writing the Hamiltonian of x-y, in the phase coordinate (p_2, p_1, q_1, q_2), the total Hamiltonian of the system will be as follows [4]

$$H_0 = \frac{p_1^2 + p_2^2}{2m^*} + \frac{1}{2}m(\omega_1^2 q_1^2 + \omega_2^2 q_2^2) + \frac{1}{2}g\mu_B\sigma_z B_z + H_z, \quad (1)$$

H_z, suggests the confinement, in z (growth) direction with the following ground state

$$\psi_{0z} = \sqrt{\frac{2}{L}}\sin\frac{\pi z}{L} \quad . \quad (2)$$

II.2 Spin orbit interaction

A kind of SO interaction called Bychkov-Rashba will appear, due to the structure inversion asymmetry, in solid state system [5]. Another type is due to bulk inversion asymmetry known as Dresselhaus; [6], the sum of the two Hamiltonians will be as follows

$$H_{so} = \alpha(\sigma_x k_y - \sigma_y k_x) + \beta\ (\sigma_x k_x - \sigma_y k_y), \quad (3)$$

where, α and β are respectively the coefficients of Bychkov-Rashba and Dresselhaus interaction by the following relations [7]

$$\alpha(z) = \alpha_{\text{int}}(z) + \alpha_{ext}(z) \quad , \quad (4)$$

the first term is due to the internal electric field of the structure, defined as follows, while the second term is caused by applying an external electric field.

$$\alpha_{\text{int}}(z) = \frac{d}{dz}[\alpha_1\,(u(-z) + u(z-L)) + \alpha_2(u(z) - u(z-L)) + \alpha_3(u(z-d_1) - u(z-d_2))], \quad (5)$$

and β coefficient with considering interface effects of defect,

$$\beta = (\gamma(z)\frac{d^2}{dz^2} + \gamma_{\text{int}}(z)\frac{d}{dz}) \quad , \quad (6)$$

where, Dresselhaus parameter is defined as follows

$$\gamma(z) = \gamma_1[u(-z) + u(z-L)] + \gamma_2\,[u(z) - u(z-L)] + \gamma_3[u(z-d_1) - u(z-d_2)] \quad , \quad (7)$$

also the Dresselhaus parameter associated with the interface can be obtained as follows

$$\gamma_{\text{int}}(z) = \gamma_1[\delta(z-L^+) - \delta(z)] + \gamma_2[\delta(z) - \delta(z-L^-)] + \gamma_3[\delta(z-d_1^+) - \delta(z-d_2^-)] \quad , \quad (8)$$

and as a result we have obtained $\alpha_3 = 3.041$ mevA°^{2}, $\gamma_{1,2} = 14.86$ mevA°^{3} and $\gamma_3 = 20.25$ mevA°^{3}, regarding band structure parameters, will be obtained.

The average of electrical field has been calculated:

$$\langle E\rangle = -(1/e)\left\langle\frac{d}{dz}(V_{ext} + E_c)\right\rangle \quad , \quad (9)$$

where in this equation V_{ext}, is the applied electrostatic potential energy and since no external electric field is applied to the structure it'll be equal to zero, and E_c is the conduction-band-edge profile

$$E_c(z) = \Delta E_c(u(-z) + u(z-L) + (u(z) - u(z-L)) + \Delta E_{cd}(u(z-d_1) - u(z-d_2)) \quad , \quad (10)$$

the last term of the above equation is caused by placing a square defect as wide as (d_1-d_2) inside the confining potential in the z direction and as wide as 2*l* in the x and y directions.

The average built-in electric field will be obtained

$$\langle E\rangle = (-1/e)\Delta E_{cd}\,\langle(\delta(z-d_1) - \delta(z-d_2))\rangle \quad , \quad (11)$$

as we can see, in the above equation without a defect, the average internal electric field will be zero due to the symmetry in the structure.

On the other hand, rotating the equation (3) by 45° we obtain the spin orbit Hamiltonian as follows [4]

$$H_{so} = \frac{1}{\hbar}[(\beta+\alpha)\sigma_+ p_- + (\beta-\alpha)\sigma_- p_+] \quad , \quad (12)$$

and then applying Aleiner transformation [8] to the equation (12) and using the second quantization we have the following Hamiltonian [4]

$$H_{so} = i\gamma_y\left[\hat{a}a_x^+\hat{a}a_x^+\hat{a}a_y + \hat{a}a_y^+(1-\hat{n}_x) - a_y\hat{n}_x - \hat{a}a_y^+a_xa_x\right]\sigma_x - i\gamma_x\left[\hat{a}a_y^+\hat{a}a_y^+a_x + \hat{a}a_x^+(1-\hat{n}_y) - a_x\hat{n}_y - a_x^+a_ya_y\right]\sigma_y \quad , \quad (13)$$

where in this equation γ_x, γ_y that could be defined as

$$\gamma_y = m^*(\beta-\alpha)^2(\beta+\alpha)\sqrt{\frac{2m^*}{\hbar\omega_1}}, \qquad \gamma_x = m^*(\beta+\alpha)^2(\beta-\alpha)\sqrt{\frac{2m^*}{\hbar\omega_2}} \quad , \quad (14)$$

comparing equation (14) with the equation (15), that represents the interaction of a magnetic field with spin, we may come to the conclusion that because of the spin orbit interaction there will exist a magnetic field in the x-y plane

$$H_{int} = \frac{1}{2} g \mu_B B_{int} . \sigma \quad , \tag{15}$$

$$B_{so} = \frac{4 \times B_z \times [\gamma_y{}^2 + \gamma_x{}^2]^{1/2}}{g \hbar \omega_c} \quad ,$$
$$\omega_c = |e| B_z / m^* c. \tag{16}$$

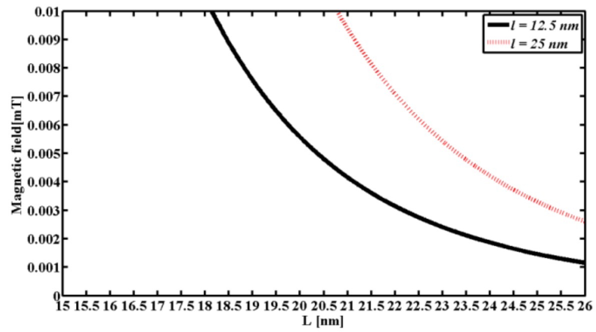

Fig. 1: The, without defect, quantum dot magnetic field vs the confinement width in the z direction for two different confinement radius in x-y plane.

As it could be seen in the Figure 1 without defect, the internal magnetic field in the quantum dot for L=25 nm and l=12.5 nm will be approximately 0.001 mT, and by increasing the confinement radius in x-y plane the internal magnetic field will also be increased.

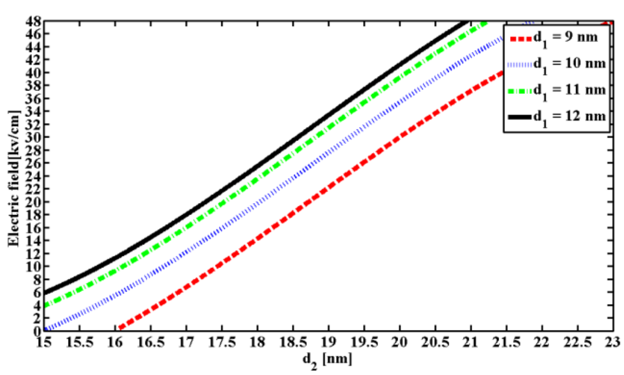

Fig. 2*:* The effect of the size and the position of the defect on the electric field due to the interface caused by the defect. It could be seen that in a quantum well of 25 nm with a square defect in the position of d_1=12nm and d_2=16nm there will be created an electric field with a magnitude of 12 kv/cm.

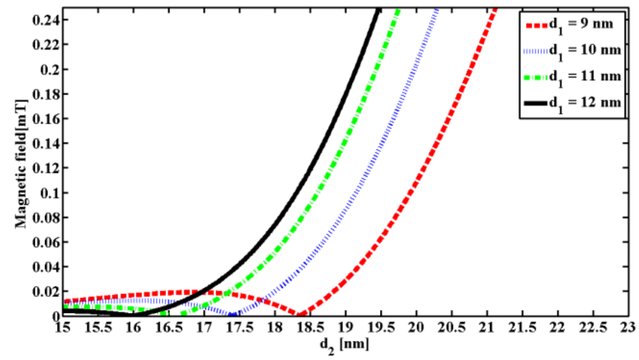

Fig. 3: The effect of the size and the position of the defect on the magnetic field due to the spin orbit interaction, it could be seen that in a quantum well of 25 nm with a square defect in the position of d_1=12nm and d_2=16nm, the magnitude of the created magnetic field would be zero.

III. Summary

In this article we have examined the magnetic and electric fields created inside the single electron quantum dot of $Al_{0.41}Ga_{0.59}As/GaAs$ in which the potential confinement in the x-y direction is parabolic and in the z direction is square with an approximately infinite barrier and in which we have inserted a square defect of $Al_{0.1}Ga_{0.9}As$. It should be noted that the only applied field to this structure will be the Zeeman magnetic field. without a defect because of the symmetry inside the structure and because the internal electric field is zero, the Rashba interaction will be zero and the Dresselhaus interaction will be the only spin orbit interaction in the structure and so the internal magnetic field will be only due to the Dresselhaus interaction and the internal magnetic field is shown in Figure 1. But placing a square defect will disturb the symmetry of the structure giving rise to an internal electric field and Rashba interaction accordingly. since changing the size and the position of the defect in the quantum dot affects the magnitude of the internal electric field (Refer to Figure 2) and as a result the intensity of the Rashba interaction, by setting the size and the position of the defect we can reset the magnitude of the magnetic field due to both spin orbit interactions to zero (Refer to Figure 3). As it could be seen in Figure 2 inside the quantum well of 25 nm in the z direction placing a defect in d_1=12nm and d_2=16 nm can accomplish the mentioned objective.

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