Spin Polarized Current through Serially coupled Double Quantum Dots with Rashba Spin- Orbit Interaction

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Abstract

In this paper, a physical model is introduced for studying the Spin polarized electron current in the presence of Rashba spin-orbit effect (RSO) through a serially (one level) coupled double quantum dots made of different semiconductor material that give different Zeeman splitting for the two dots under the influence of an external magnetic field.

The transport properties and the factors effecting it such as the energies ($E_{i\sigma}$) for the two dots, Rashba spin-orbit interaction energy, tunneling energy, the tunneling spin polarized current and polarization are all calculated as a function of the detuning energy (ϵ). Finally, we explain and give some analyzation to the effect of Rashba spin-orbit interaction in a double quantum dots system.

Keywords: DQD, Rashba Spin Orbit Effect, Spin Polarized Current

1- Introduction

Control and discover of spin polarized current though nanostructures has attracted a lot of attention theoretically [1, 2] and experimentally [3] over the past and recent few years, because it worth in our understanding of fundamental quantum physics and has several applications, such as Nano-electronics, the field of spintronic and quantum computation scheme, etc.… [4-6].

In information devices there are two types of flow carried by electrons (charges and spin) since an electron carry both charge and spin then the existence of a charge current naturally implies the existence of passing of spin current.

Efforts to improve computational power and speed have led researchers to explore the possibility to use electron spin, rather than its charge as the basis of new electronic devices called- a "spintronics".

One interesting way to create a spin polarized current is through a system of double quantum dots connecting to two ferromagnetic metals or magnetic semiconductors [7].

In semiconductor devices the most important interaction which causes spin relaxation is the spin-orbit (SO) interaction. The spin-orbit interaction couples the spin degree of freedom to the spatial motion of the electron, which significantly influences the transport properties of solids [8-10].

Recently, many experiments have been carried out to study the properties of another effect called Rashba-spin orbit in different material double quantum dots and in the presence of magnetic fields [11-13].

In this work, the spin- polarized current which related to the tunneling through a double quantum-dot system attached to leads in the presence of the Rashba spin-orbit interaction and Zeeman splitting is explored. For different Zeeman splitting we use different dots materials (different g -factors).

The spin –polarized current with the presence of Rashba spin-orbit interaction (RSO) are obtained by solving the master equation in the Born-Markov approximation.

In the next section and by following the work of Li Zhen-Shan et al. [14], we will present the theoretical treatment to formulate an expression for realizing spin-related currents and polarization in DQD-system.

2-Model and Hamiltonian

With the existing of the Rashba spin-orbit interaction (t_{so}) and the different Zeeman splitting for each dot ($\Delta_i = g_i\mu B$), We use a system consist of two tunnel- coupled quantum dots (each with different material) sandwiched between two leads $\propto = L, R$ with their chemical potentials μ_L , μ_R , connected with DQD by the rates Γ_L and Γ_R (see Fig.(1)), while we neglected the interactions between the left lead and right leads.

By including the interaction term between the two dots t_{12} , then the Hamiltonian of the quantum junction is described by the sum of the Hamiltonian for isolated system (H^o_{dots} , H_{leads}) and the dots –leads coupling (H_T).

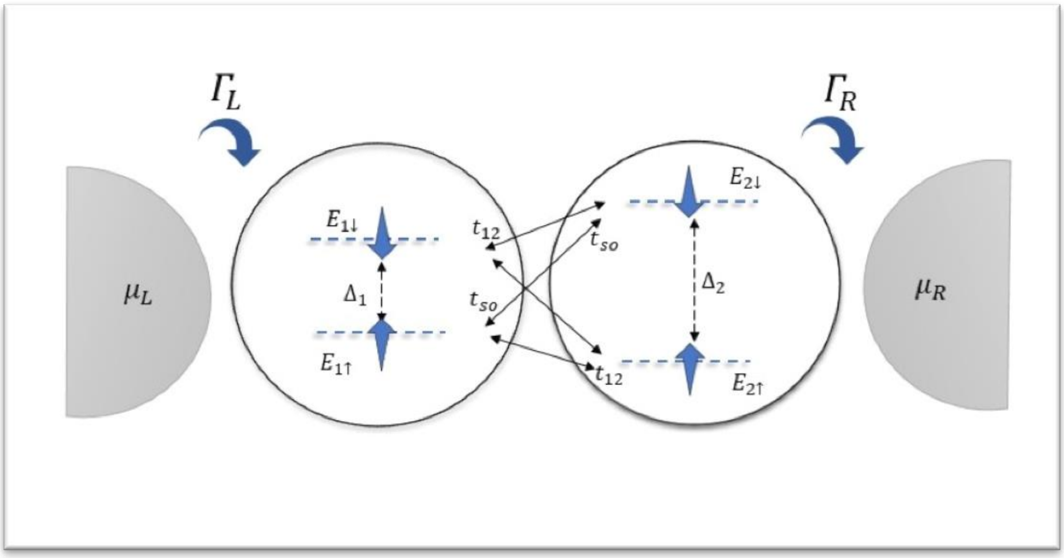

Fig.1: Schematic diagram described the system under consideration

The total Hamiltonian of the system is described by Anderson Hamiltonian;

$$H = H^{o}_{dots} + H_{Leads} + H_{T} \quad (1)$$

Where,

$$H^{o}_{dots} = \sum_{\sigma,i=1,2} \xi_{i\sigma} d^{\dagger}{}_{i\sigma} d_{i\sigma} - t_{12} \sum_{\sigma} (d^{\dagger}{}_{1\sigma} d_{2\sigma} + H.c.) + \sum_{i=1,2} \Delta_i S_{zi}$$
$$+ t_{so} (d^{\dagger}{}_{1\uparrow} d_{2\downarrow} - d^{\dagger}{}_{2\uparrow} d_{1\downarrow} + H.c.) \quad (2)$$

Assuming that DQD occupied by one electron, then four basis states are available for this electron; $|\uparrow,0\rangle, |\downarrow,0\rangle, |0,\uparrow\rangle, |0,\downarrow\rangle$ and by including all the interaction that exist between the two dots then, the Hamiltonian matrix elements of H^{o}_{dots} in eq. (1) will be[14].

$$H^{0}_{dots} = \begin{pmatrix} -\frac{\Delta_1}{2} & 0 & -t_{12} & t_{so} \\ 0 & -\frac{\Delta_1}{2} & -t_{so} & -t_{12} \\ -t_{12} & -t_{so} & -\frac{\Delta_2}{2} - \varepsilon & 0 \\ t_{so} & -t_{12} & 0 & -\frac{\Delta_2}{2} - \varepsilon \end{pmatrix} \quad (3)$$

ε is the detuning energy and could be taken to adjust the energies at the two dots.
In the physical model that we pended on, many points are taken into consideration:

1- The effect of the regular magnetic field (B) is to remove the degeneracy of quantum dots level and existing four energy levels ($E_{i\sigma}$) (i=1,2)

2- The tunneling coupling t_{12} couples the energy levels of electrons in the two dots with the same spin.

3- Rashba Spin –orbit coupling t_{so} couples the energy levels of electrons in the two dots with the opposite spin.

4- To ensure that the spin current flows in one direction we assume that the chemical potential for leads $\mu_L > \mu_R$.

5- Assuming that $\Delta_2 > \Delta_1$ where Δ_1 , Δ_2 are the Zeeman splitting fordots1 and 2 respectively.

6- We take the broadening in dots energy levels due to the coupling with the leads $\Gamma_{R,L} = 2\pi\Omega_{L,R} |\gamma_{L,R}|^2$ and we assume that $\Omega_{L,R}$ is the density of states and it will be taken as a Lorentzian shape and tunneling couplings $\gamma_{L,R}$ are energy independent, then

$$\Gamma_R = \Gamma_L = \Gamma_\alpha \quad (4)$$

3- Calculation of DQD Energies ($E_{i\sigma}$)

In order to calculate the energy levels of the two dots, we use the eigen value equation

$$[H_{Dots} - IE] = 0 \qquad (5)$$

Where I is the unitary matrix, so we get

$$E^4 + E^3(\Delta_1 + \Delta_2) + E^2\left(\Delta_1\Delta_2 + \frac{\Delta_2^2}{4} + \frac{\Delta_1^2}{4} + \Delta_2\varepsilon + \varepsilon^2 - 2t_{so}^2 - 2t_{12}^2\right) + E\left(\frac{\Delta_1\Delta_2^2}{2} + \frac{\Delta_2\Delta_1^2}{4} + \Delta_1\Delta_2\varepsilon + \Delta_1\varepsilon^2 - t_{so}^2\Delta_2 - t_{so}^2\Delta_1 - 2t_{12}^2\varepsilon - 2t_{so}^2\varepsilon - t_{12}^2\Delta_1 - t_{12}^2\Delta_2\right) + \left(\frac{\Delta_2^2\Delta_1^2}{8} + \varepsilon\frac{\Delta_2\Delta_1^2}{4} + \varepsilon^2\frac{\Delta_1^2}{4} - t_{so}^2\frac{\Delta_1\Delta_2}{2} - t_{12}^2\frac{\Delta_1\Delta_2}{2} - t_{so}^2\Delta_1\varepsilon - t_{12}^2\Delta_1\varepsilon + t_{12}^4 + t_{so}^4 + 2t_{so}^2t_{12}^2\right) = 0 \qquad (6)$$

Equation (6) can be calculated numerically.

The results are presented as a function of the detuning energy (ε) in figs.(2) for $\Delta_2 = 0.1\text{meV}$, $\Delta_1 = 0.02\text{meV}$, $\Gamma = 0.001\text{meV}$, $t_{12} = 0.005\text{meV}$ and for $t_{so} = 0.005\text{meV}$ *and* for different Rashba spin-orbit interaction

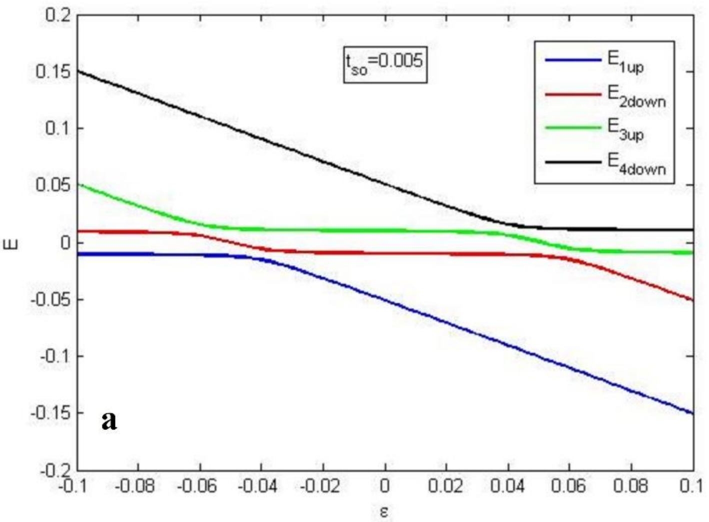

Fig.2: $E_{i\sigma}$ for the two dots as a function of the detuning energy

We noticed here, that the behavior of the four energies spectrum are the same for different t_{so} .And it's clearly seen in figs.(2) that $E_{1\downarrow}(E_{2\downarrow})$, $E_{1\uparrow}(E_{2\uparrow})$, $E_{1\downarrow}(E_{1\uparrow})$ and $E_{2\downarrow}(E_{2\uparrow})$ first decreases and then increased in the range of $\varepsilon = (-0.1 \rightarrow 0.1)\text{meV}$ and the effect of large t_{so} is a small gap between $E_{1\uparrow}(E_{2\uparrow})$ and $E_{1\downarrow}(E_{2\downarrow})$ these energy spectra at $\varepsilon = (\pm 0.05)\text{meV}$.

In order to represent the effect of Rashba spin-orbit interaction on the energy levels we choose $E_{2\downarrow}$ as shown in fig. (3).

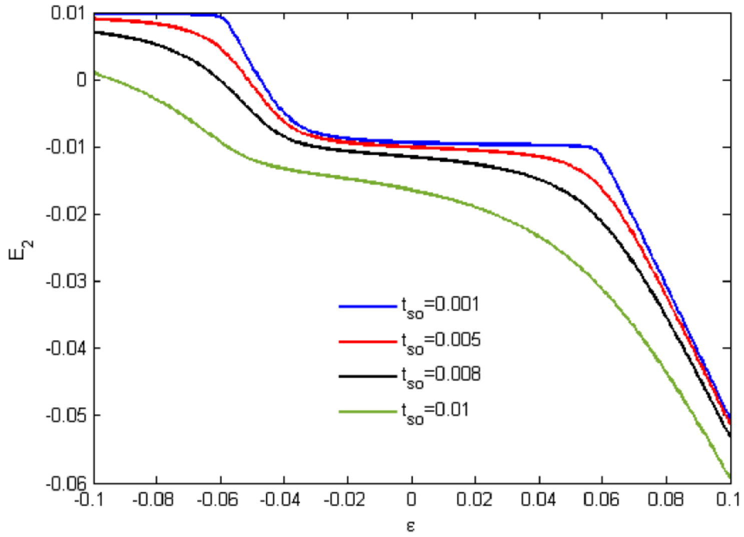

Fig.3: $E_{2\downarrow}$ spectrum as a function of detuning energy for different values of t_{so}

Fig. (4) shows the energy difference for electrons have the same spin $\Delta E_{\uparrow} = (E_{1\uparrow}$ - $E_{2\uparrow})$ and $\Delta E_{\downarrow} = (E_{1\downarrow} - E_{2\downarrow})$ as a function of (ε), we can see a minimum value for ($\Delta E_{\uparrow}$) difference at $\varepsilon = -0.05$, at this point the levels with the same spin become very close to each other and open a channel for electrons at $E_{1\uparrow}$ in QD1 to passed into $E_{2\uparrow}$ at the QD2 and a spin- up current is tunnel from left QD to right QD. In the same way a polarized spin–down current also appears at $\varepsilon = 0.05eV$ for ($\Delta E_{\downarrow}$) minimum value

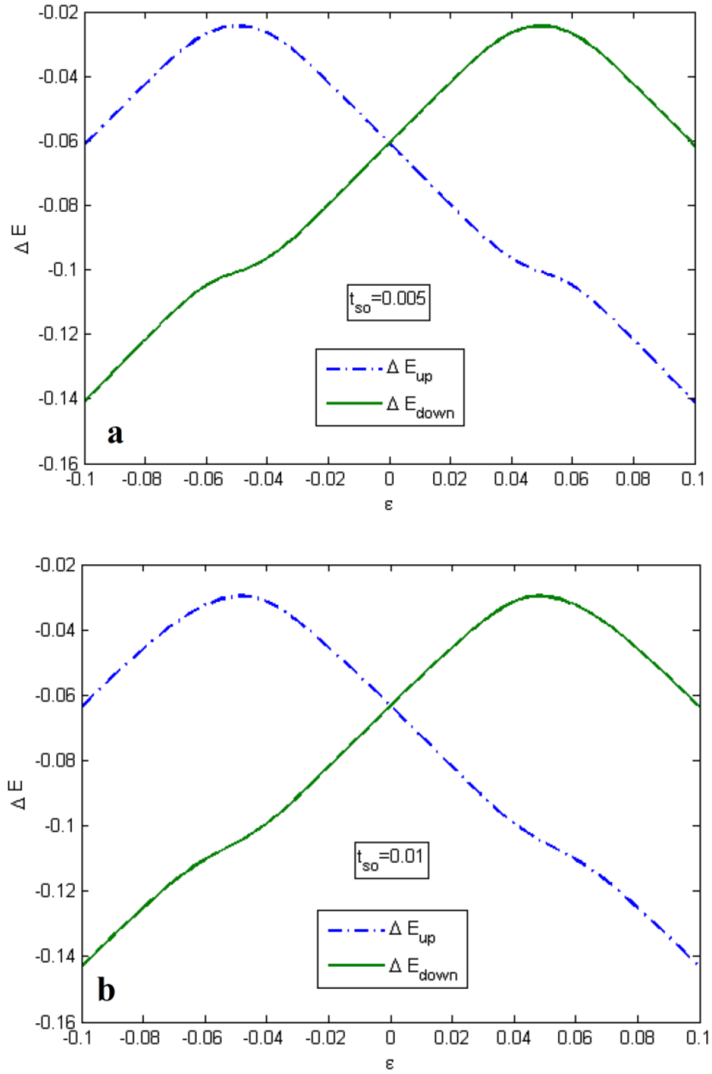

Fig.4: Energy level difference between electrons have the same spin in the two dots (a) For $t_{so} = 0.005$ (b) for $t_{so} = 0.01$

4-The spin polarized current calculation

To study the tunneling current through the double quantum dots, it is very convenient to characterize this dynamic using the equation of motion for the time evolution of density matrix $\rho(t)$ of the quantum system.

Within the Born-Markov approximation [15], the dynamics equation of motion can be written as follow [16];

$$\dot{\rho}_{mn}(t) = -i\langle m|[H^0_{dots},\rho]|n\rangle + \sum_{k\neq n}(\Gamma_{nk}\rho_{kk} - \Gamma_{nk}\rho_{kk})\,\Delta_{mn} - \Lambda_{mn}\rho_{mn}(1-\Delta_{mn}) \tag{7}$$

Γ_{nk} describe the transition rate from the state $\langle n|$ to the state $|k >$ and the non-adiabatic parameter whose real part is responsible for the time decay of the off-diagonal matrix elements (coherence);

$$\Lambda_{mn} = \frac{1}{2}\sum_k(\Gamma_{km} + \Gamma_{kn}) \tag{8}$$

one can calculate the transition rates using the Fermi Golden rule approximation;

$$\Gamma_{mn} = \sum_{\alpha=L,R}\Gamma_\alpha\{f(E_m - E_n - \mu_\alpha)\delta_{N_m,N_n+1} + [1 - f(E_n - E_m - \mu_\alpha)\delta_{N_m,N_n-1}]\} \tag{9}$$

N_m is the number of electrons in the system when it is in state $\langle m|$.

with $f(E_m - E_n - \mu_\alpha)$ is the Fermi distribution function at $\alpha = L, R$ lead and δ_{N_m,N_n} is the delta function.

The four basic states of the DQD are defined bellow;

$\|1\rangle$	$\|2\rangle$	$\|3\rangle$	$\|4\rangle$
$\|\uparrow,0\rangle$	$\|\downarrow,0\rangle$	$\|0,\uparrow\rangle$	$\|0,\downarrow\rangle$

The available transitions that take place between the stats n = 1,2,3,4 and the states m = 1,2,3,4 reduced the solution of equation (7) at the steady states $\dot{\rho}_{mn}(t) = 0$ to;

$$\rho_{11} = \frac{\Gamma_{12}\rho_{22}+\Gamma_{13}\rho_{33}+\Gamma_{14}\rho_{44}}{x} \tag{10}$$

$$\rho_{22} = \frac{\Gamma_{21}\rho_{11}+\Gamma_{23}\rho_{33}+\Gamma_{24}\rho_{44}}{y} \tag{11}$$

$$\rho_{33} = \frac{\Gamma_{31}\rho_{11}+\Gamma_{32}\rho_{22}+\Gamma_{34}\rho_{44}}{z} \tag{12}$$

$$\rho_{44} = \frac{\Gamma_{41}\rho_{11}+\Gamma_{42}\rho_{22}+\Gamma_{43}\rho_{33}}{D} \tag{13}$$

Where,

$$x = (\Gamma_{21} + \Gamma_{31} + \Gamma_{41})$$

$$y = (\Gamma_{12} + \Gamma_{32} + \Gamma_{42})$$

$$z = (\Gamma_{13} + \Gamma_{23} + \Gamma_{43})$$

$$D = (\Gamma_{14} + \Gamma_{24} + \Gamma_{34})$$

The total current that tunnels through the system I_{tot} is considered as the summation of the spin- up current $I_{\uparrow}$ and the spin- down current $I_{\downarrow}$ as [17],

$$I_{tot} = I_{\uparrow} + I_{\downarrow} = \Gamma \, [\, \rho|0,\uparrow\rangle + \rho|0,\downarrow\rangle] \tag{14}$$

by represented that $\rho|0,\uparrow\rangle = \rho_{33}$ and $\rho|0,\downarrow\rangle = \rho_{44}$,so the total current in eq. (14) is taken the form;

$$I_{tot} = \Gamma(\rho_{33} + \rho_{44}) \tag{15}$$

In order to calculate I_{tot} it is convenient to reduced ρ_{33} , ρ_{44} in terms of ρ_{22} such that,

$$\rho_{33} = [\frac{(x1x6 - x3x4)}{x3x5 + x2x6}]\rho_{22} \tag{16}$$

$$\rho_{44} = \left[\frac{(\Gamma_{31}D + \Gamma_{41}\Gamma_{34})(z\Gamma_{41} + \Gamma_{31}\Gamma_{43})(x1x6 - x3x4)}{(x3x5 + x2x6)} + \frac{(\Gamma_{31}\Gamma_{42} - \Gamma_{41}\Gamma_{32})}{(\Gamma_{31}D + \Gamma_{41}\Gamma_{34})}\right]\rho_{22} \tag{17}$$

Where;

$$\begin{aligned} &x1 = (xy - \Gamma_{21}\Gamma_{12}) && x4 = (\Gamma_{31}\Gamma_{42} - \Gamma_{41}\Gamma_{32}) \\ &x2 = (x\Gamma_{23} + \Gamma_{21}\Gamma_{13}) && x5 = (z\Gamma_{41} + \Gamma_{31}\Gamma_{43}) \\ &x3 = (\Gamma_{21}\Gamma_{14} + x\Gamma_{24}) && x6 = (\Gamma_{31}D + \Gamma_{41}\Gamma_{34}) \end{aligned} \tag{18}$$

By substituting the values of ρ_{33} and ρ_{44} defined in eq. (16), (17) and get

use of the definitions in eq. (18), then an expression for I_{tot} will be,

$$I_{tot} = \Gamma\left\{\left[\frac{(x1x6 - x3x4)\rho_{22}}{x3x5 + x2x6}\right] + \left[\frac{(\Gamma_{31}D + \Gamma_{41}\Gamma_{34})(z\Gamma_{41} + \Gamma_{31}\Gamma_{43})(x1x6 - x3x4)}{(x3x5 + x2x6)} + \frac{(\Gamma_{31}\Gamma_{42} - \Gamma_{41}\Gamma_{32})}{(\Gamma_{31}D + \Gamma_{41}\Gamma_{34})}\right]\rho_{22}\right\} \tag{19}$$

In order to study the effect of Rashba spin-orbit interaction on the spin current in the DQD system , $I_{\uparrow}, (I_{\downarrow})$ is calculated numerically from eq.(16) and eq. (17) as a function of the detuning energy (ε) for different t_{so} and at fixed values for other system parameters , these results are presented in fig. (5).

From fig. (5), we clearly seen that the spin polarized current increased as t_{so} increased and the current maximum is shifted towards the $\varepsilon = 0$.

the spin-up polarized currents fig.(5a) for all values of t_{so} first increased and then increased between $\epsilon = (-0.1 - 0)$ and spin- down polarized currents, fig.(5b) have the same behavior at $\epsilon = (0 - 0.1)$ and the polarization stopped at $\epsilon = 0$ where no spin-up or spin –down polarized currents exist.

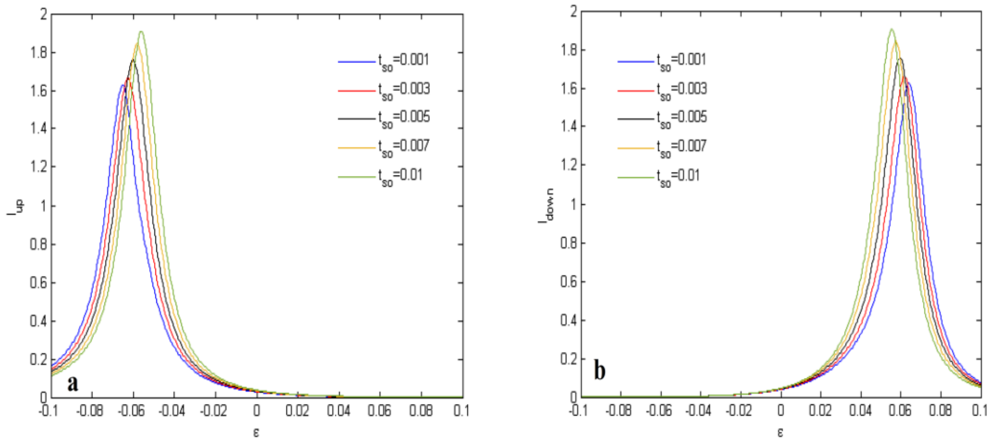

Fig.5: Spin –polarized currents, $I_{\uparrow}, (I_{\downarrow})$ for different t_{so} and at fixed other parameters $\Delta_2 = 0.1\mathrm{meV}$, $\Delta_1 = 0.02\mathrm{meV}$, $\Gamma = 0.001\mathrm{meV}$, $t_{12} = 0.005\mathrm{meV}$.

And I_{tot} that define in equation (14) are show in fig. (6) for different t_{so}

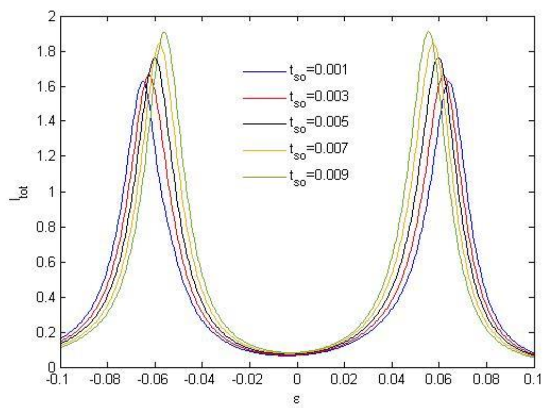

Fig.6: Spin –polarized currents for different t_{so} and at fixed other

parameters $\Delta_2 = 0.1\text{meV}$, $\Delta_1 = 0.02\text{meV}$, $\Gamma = 0.001\text{meV}, t_{12} = 0.005\text{meV}$

5-the polarization calculation

The electron polarization in DQD system is always define as [18];

$$P = \frac{I_\uparrow - I_\downarrow}{I_\uparrow + I_\downarrow} \tag{20}$$

Our numerical results for P are shows in fig. (7), we see here a peak at $\epsilon = -0.005$ where the spin-up current is totally polarized ($P = 1$) and the spin-down current equal zero. But at $\epsilon = +0.005$ the spin-up current equal zero and the spin-down current is totally polarized ($P = -1$). Also, the two polarization peaks are symmetric around $\epsilon = 0$

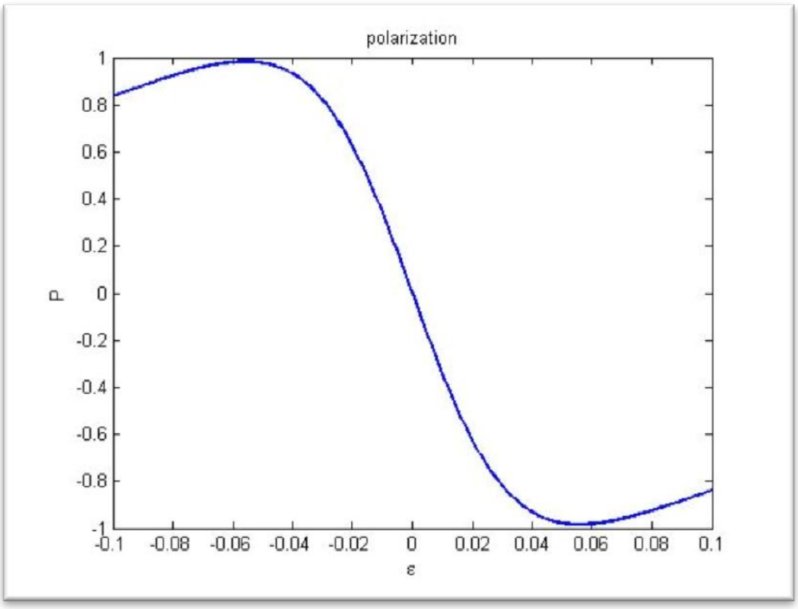

Fig.7: the polarization at fixed parameters $\Delta_2 = 0.1\text{meV}$, $\Delta_1 = 0.02\text{meV}$, $\Gamma = 0.001\text{meV}, t_{12} = 0.005\text{meV}$

6- The magnetic field effect

The spin-polarized current also calculated at different values of applied magnetic field (B), where different B introduced different Zeeman splitting (Δ_i) ($i = 1,2$) for the two dots.

Fig. (8) shows that the spin-up (down) polarized current are decrease with increasing B, this behavior is attributed to the large different between levels (large Δ_i) have the opposite spin and no probability for these levels to be in resonance to each other and no spin current is passed as a result.

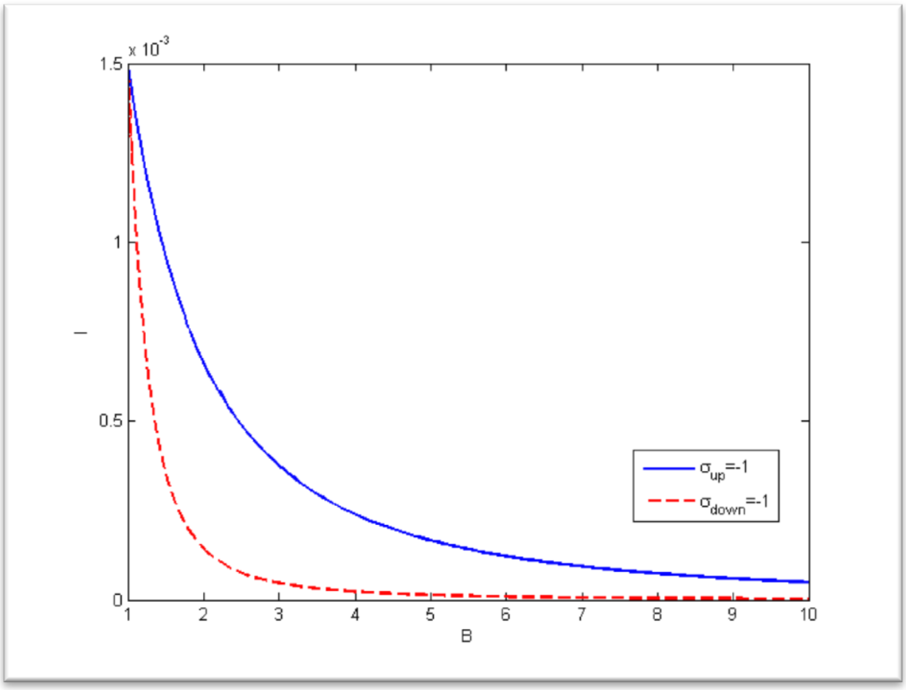

Fig.8: the magnetic effect on the DQD

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تيار البرم المستقطب خلال نقطتين كميتين بشكل سلسلة مع تأثير تفاعل البرم والمدار لراشبا

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المستخلص

في هذا المنشور، تم وضع انموذج فيزيائي لدراسة تيار الالكترونات مستقطبة البرم بوجود تأثير اقتران البرم والمدار لراشبا والمار خلال نقطتين كميتين (ذات مستوي طاقة واحد) مربوطتين على شكل سلسلة ومصنوعتين من مادتين شبه موصلة مختلفتين لكي توفر فاصلة زيمان مختلفة عند وضعها تحت تأثير مجال مغناطيسي ثابت.

كل خصائص النقل والعوامل المؤثرة عليه مثل الطاقة $(E_{i\sigma})$ للنقطتين الكميتين، طاقة تفاعل البرم والمدار لراشبا t_{so} ، طاقة النفق t_{12} وتيار الالكترونات مستقطبة البرم الذي تم حسابه كدالة لطاقة الموائمة ε واخيراً تمت مناقشة وتحليل تأثير تفاعل البرم والمدار لراشبا في نظام النقطتين.