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Spin Transport through a Quantum Dot under Magnetic Field in the Presence of Spin and Charge Bias

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***Abstract**: In this work , we study the transport properties for a quantum dot under magnetic field, embedded between two normal leads in the presence of spin and charge bias .We use the theory of Keldysh non-equilibrium Green's functions technique when the correlation energy on the quantum dot is in the strong interaction limit. We derive model calculation to calculate the occupation numbers on the quantum dot , the spin and charge currents following through it and the differential charge and spin conductance as a function of spin bias. All the spin transport properties are discussed as a function of spin bias. We conclude that the spin transport properties of the device considered in our work are determined by the magnetic field and the spin bias.*
***Keyword** :Spin transport; Quantum Dot; Correlation interaction; magnetic field.*

I. Introduction

A portmanteau meaning "Spintronics electronics" is an emerging technology exploiting both the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid-state devices. Spintronics differs from the older Magnetoelectronics, in that the spins are not only manipulated by magnetic fields, but also by electrical field[1,2]. Spintronics emerged from discoveries in the 1980 concerning spin-dependent electron transport phenomena in solid-state devices. This includes the observation of spin-polarization electron injection from a ferromagnetic metal to a normal metal by Johnson and Silsbee[3] and the discovery of giant magnetoresistance independent by Albert Fert [4]and peter Grunberg [5].The origins of Spintronics can be traced back even further to the ferromagnet/superconductor tunneling experiments pioneered by Meservey and Tedrow, and initial experiments on magnetic tunnel junctions by Julliere in the 1970 [6]. The use of semiconductors for Spintronics can be traced back at least as far as the theoretical proposal of a spin field-effect-transistor by Datta and Das in 1990[7]. A spintronics device requires generation or manipulation of a spin –polarization of any spin dependent property[8].

Generation of spin polarization usually means creating a nonequilibrium spin population. This can beachievedin several ways. While traditionally spin has been oriented using optical techniques in which circularly polarized photons transfer their angular momenta to electrons, for device applications electrical spin injection is more desirable. In electrical spin injection a magnetic electrodeis connected to the sample[9].A net spin polarization can be achieved either through an equilibrium energy splitting between spin up and spin down such as putting a material in a large magnetic field (Zeeman effect) or the exchange energy present in a ferromagnet, or forcing the system out of equilibrium. We focus on the case when the correlation interaction U on the quantum dot be very stronge i.e.$U \rightarrow \infty$, since by the spin bais we mean that the chemical potential of the leads are spin dependent[10].

II. The Model Calculation

The model Hamiltonian for a quantum dot coupled to two leads is given by [11,12]:

$$H = \sum_{\sigma} E_d^{\sigma} n_d^{\sigma} + \mathrm{U} n_d^{\sigma} n_d^{-\sigma} + \sum_{\alpha}\sum_{\sigma}\sum_{k_\alpha} E_{k_\alpha} C_{k_\alpha}^{\sigma +} C_{k_\alpha}^{\sigma} + \sum_{\alpha}\sum_{\sigma}\sum_{k_\alpha} \left(V_{dk_\alpha} C_d^{\sigma +} C_{k_\alpha}^{\sigma} + h.c \right) \qquad (1)$$

The first and the second terms represent the Hamiltonian for the interacting quantum dot, with U is the correlation energy on the quantum dot . The strong correlation limit is considered and due to magnetic field the quantum dot energy level E_d will be splitted to E_d^{σ} and $E_d^{-\sigma}$ for spin up and spin down respectively . n_d^{σ} is the occupation number of the energy level E_d^{σ} and it is given by [13]:

$$n_d^{\sigma} = C_d^{\sigma +} C_d^{\sigma} \qquad (2)$$

The third term represents the conduction electrons in the left(L) and right(R) leads. $C_d^{+\sigma}$ and C_d^{σ} are the creation and the annihilation operators for electrons with spin σ on the quantum dot respectively . The last term describes the tunneling between the quantum dot and the leads with the coupling interacting V_{dk_α} . $C_{k_\alpha}^{+\sigma}$ and $C_{k_\alpha}^{\sigma}$ are the creation and annihilation operators for the electrons with momentum k_α and spin σ in the lead $\alpha(\alpha = R, L)$.

The magnetic field effect on the quantum dot is incorporated through adding the spin Zeeman splitting (which will be denoted by 2h) [8,14],with

$$E_d^\sigma = \quad E_d + \sigma h \tag{3}$$

In this relation σ takes positive sign for spin up and negative sign for spin down , so the energy splitting between $E_d^{-\sigma}$ and E_d^σ is equal to 2h [15] .When the charge bias $V_{cb}$is applied on the leads, this will lead to the variation in the chemical potentials of the left lead μ_L and the right lead μ_R ,

$$\mu_L = -\mu_R = V_{cb} \tag{4}$$

In the presence of spin bias V_{sb}, the chemical potentials will be spin dependent ,

$$\left.\begin{aligned} \mu_L^\sigma = \mu_R^{-\sigma} = V_{sb} \\ \mu_L^{-\sigma} = \mu_R^\sigma = -V_{sb} \end{aligned}\right\} \tag{5}$$

According to the theory of Keldysh non-equilibrium Green's functions technique, the current from the lead α flowing into the quantum dot for the spin channel σ is given by [16,17]:

$$I_\alpha^\sigma = \frac{i}{\hbar}\int \frac{dE}{2\pi}\Gamma_\alpha(E)[f_\alpha^\sigma(E,T)\{G_\sigma^r(E) - G_\sigma^a(E)\} + \ G_\sigma^<(E)] \tag{6}$$

The function $\Gamma_\alpha(E)$ is the line-width which represents the broadening function in the quantum dot levels due to the lead α [18]:

$$\Gamma_\alpha(E) = 2\pi \sum_{k_\alpha} \left|V_{dk_\alpha}\right|^2 \delta\left(E - E_{k_\alpha}\right) \tag{7}$$

The Fermi-Dirac distribution function for electrons in the lead α with spin σ at temperature T is given by [19]:

$$f_\alpha^\sigma(E) = \frac{1}{e^{\frac{(E-\mu_\alpha^\sigma)}{K_B T}} + 1} \tag{8}$$

The functions $G_\sigma^a(E)$ and $G_\sigma^<(E)$ are the Fourier transformation of the retarded , advanced and lesser Green's function $G_\sigma^r(t)$, $G_\sigma^a(t)$ and $G_\sigma^<(t)$ in the quantum dot respectively [16]. In our study , the case of strong correlation interaction is considered , i. e. U→ ∞ [2, 20] in the low temperatures, so the Fourier transform of the Green's functions $G_\sigma^{r,a}(E)$ is given by [21] :

$$G_\sigma^{r,a}(E) = \frac{1 - n_d^{-\sigma}}{E - E_d^\sigma - \sum_{0,\sigma}^{r,a}(E) - \sum_{1,\sigma}^{r,a}(E)} \tag{9}$$

The function $\sum_{0,\sigma}^{r,a}(E)$ is non-interacting tunneling self-energy and $\sum_{1,\sigma}^{r,a}(E)$ is the electron correlation and the tunneling self-energy.

The non-interacting tunneling self-energy is given by [22-24]:

$$\sum\nolimits_{0,\sigma}^{r.a}(E) = \sum_\alpha \sum_{k_\alpha} \frac{\left|V_{dk_\alpha}\right|^2}{E - E_{k_\alpha} \pm i0^+} \tag{10}$$

And by getting use of Plemelj's formula [25] , we get ,

$$\sum\nolimits_{0,\sigma}^{r}(E) = \sum_\alpha \left[\frac{-i}{2}\int_{-\infty}^{\infty} \Gamma_\alpha(\acute{E})\,\delta(E - \acute{E})d\acute{E} + \frac{1}{2\pi}P\int_{-\infty}^{\infty} \frac{\Gamma_\alpha(\acute{E})}{E - \acute{E}}d\acute{E}\right] \tag{11}$$

Then by using the wide band approximation [18] , $\Gamma_\alpha(E) \equiv \Gamma_\alpha$, then the quantum shift represented by the second term in eq. (11) will be equal to zero, so one cam write :

$$\sum\nolimits_{0,\sigma}^{r} = \frac{-i}{2}(\Gamma_\alpha + \Gamma_\alpha) \tag{12}$$

We also get,

$$\sum\nolimits_{0,\sigma}^{a} = \frac{i}{2}(\Gamma_\alpha + \Gamma_\alpha) \tag{13}$$

The electron correlation and tunneling self-energy $\sum_{1,\sigma}^{r,a}(E)$ is given by [26]:

$$\sum\nolimits_{1,\sigma}^{r,a}(E) = \sum_\alpha \sum_{k_\alpha} \frac{\left|V_{dk_\alpha}\right|^2 f_\alpha^\sigma\left(E_{k_\alpha}, T\right)}{E - E_{k_\alpha} + E_d^{-\sigma} - E_d^\sigma \pm i0^+} \tag{14}$$

and according to eq(3), we have ,

$$E_d^{-\sigma} - E_d^\sigma = \ -2h \tag{15}$$

So we can rewrite eq. (14) as follows ,

$$\sum\nolimits_{1,\sigma}^{r}(E) = \sum_\alpha \sum_{k_\alpha} \frac{\left|V_{dk_\alpha}\right|^2 f_\alpha^\sigma\left(E_{k_\alpha}, T\right)}{(E - 2h) - E_{k_\alpha} + i0^+} \tag{16}$$

Then by following the same procedure , we get ,

$$\sum\nolimits_{1,\sigma}^{r}(E) = \frac{-i}{2}\sum_{\alpha} \Gamma_\alpha f_\alpha^\sigma(E-2h,T) \tag{17}$$

and

$$\sum\nolimits_{1,\sigma}^{a}(E) = \frac{i}{2}\sum_{\alpha} \Gamma_\alpha f_\alpha^\sigma(E-2h,T) \tag{18}$$

Now, According to the theory of Keldysh , the occupation number n_d^σ of the quantum dot energy level E_d^σ is given by [27]:

$$n_d^\sigma = \frac{-1}{2\pi}\int dE\, ImG_\sigma^r(E)\sum_{\alpha} f_\alpha^\sigma(E,T) \tag{19}$$

So , we can calculate $n_{d\alpha}^\sigma$ by using the following relation [28]

$$n_d^\sigma = \sum_{\alpha} n_{d\alpha}^\sigma \tag{20}$$

$$n_{d\alpha}^\sigma = \frac{1}{2}(1-n_d^{-\sigma})\int dE \frac{\Delta_d^\sigma(E,h,T)}{(E-E_d^\sigma)^2 + \left(\Delta_d^\sigma(E,h,T)\right)^2} f_\alpha^\sigma(E,T) \tag{21}$$

Where

$$\Delta_d^\sigma(E,h,T) = \frac{i}{2}\sum_{\alpha} \Gamma_\alpha \{1 + f_\alpha^\sigma(E-2h,T)\} \tag{22}$$

$\Delta_d^\sigma(E,h,T)$ represents the broadening function of the quantum dot energy level with spin σ , which depends on the magnetic field and the leads temperature .

Now, in order to formulate the charge and the spin currents , we rewrite eq. (6) by getting use of eq.(19) in the following form :

$$I_\alpha^\sigma = \frac{1}{\pi}\Gamma_\alpha \int dE f_\alpha^\sigma(E)\left\{\frac{i}{2}\left(G_\sigma^r(E) - G_\sigma^a(E)\right)\right\} - \Gamma_\alpha n_d^\sigma \tag{23}$$

By using the over mentioned self-energies relations , we obtain,

$$I_\alpha^\sigma = 2\Gamma_\alpha n_{d_\alpha}^\sigma - \Gamma_\alpha n_d^\sigma \tag{24}$$

So the charge current flows from the lead α will be given by ,

$$I_{C,\alpha} = e(I_\alpha^\sigma + I_\alpha^{-\sigma}) \tag{25}$$

And the spin current flows from the lead α , in the case where there is no spin flip process in the system , will be given by

$$I_{s,\alpha} = \frac{\hbar}{2}(I_\alpha^\sigma - I_\alpha^{-\sigma}) \tag{26}$$

Finally ,the differential charge and spin conductance can be calculated by using the following relations [29,30]:

$$G_C = \frac{dI_C}{dV_{Sb}} \tag{27}$$

$$G_S = \frac{dI_S}{dV_{Sb}} \tag{28}$$

III. Results and Discussion

The occupation numbers formula given by eq. (20) must be solved self-consistently to get all the spin transport properties which depend on the spin and charge bias, the tunneling rates , the leads temperature and the magnetic field effect . All the spin transport properties will be presented as a function of spin bias. The leads electro-chemical potential –spin dependence, in the presence of charge, bias takes the following relations[31],

$$\left.\begin{array}{l} \mu_L^\sigma = V_{sb}+V_{cb} \\ \mu_L^{-\sigma} = -V_{sb}+V_{cb} \\ \mu_R^\sigma = -V_{sb} \\ \mu_R^{-\sigma} = V_{sb} \end{array}\right\} \tag{29}$$

The parameters that used to accomplish our calculations are T=300K , $E_d = 0.25eV$ and for the magnetic field h=0.1, 0.3,0.5 *eV*. Notably we take this symmetric case for the tunneling rates , where $\Gamma_R = \Gamma_L = \Gamma = 0.05eV$, Which means that all calculation will be in the regime $K_BT < \Gamma < 2h$. The calculated occupation numbers $n_{L,R}^{\pm\sigma}$ are presented in fig.(1) as a function of spin bias where $K_BT = 0.024eV$ and $V_{cb} = 0.2eV$. The n_L^σ and n_R^σ curves and also $n_L^{-\sigma}$ and $n_R^{-\sigma}$ curves do not show symmetry about the y-axis $V_{sb} = 0$, and all their values increase as $|V_{sb}|$ increasing.

$n_L^{-\sigma}$ increases for negative values of V_{sb} and it be maxima when $n_R^\sigma = n_L^{-\sigma}$ for all h values. The values of V_{sb} and $-V_{sb}$ at which $n_L^\sigma = n_L^{-\sigma}$ and $n_R^\sigma = n_R^{-\sigma}$ when h=0.5eV are equal to +h and –h respectively. While

$n_L^\sigma = n_R^{-\sigma}$ as well as $n_L^{-\sigma}$ and n_R^σ are nearly equal at V_{sb}= ±1eV. In general the values of V_{sb}, at which $n_{L,R}^{\pm\sigma}$ are equal, are magnetic field dependent.

The values of V_{sb} at which the curves in fig.(1) intersect , at which there is no role for spin (i. e. $n_\alpha^\sigma = n_\alpha^{-\sigma}$) or there is no role for the leads (i. e . $n_R^\sigma = n_L^\sigma$), can be controlled by the tunneling rates , the Zeeman splitting as well as the quantum dot and leads properties. Fig.(2) illustrates the total occupation numbers n_d^σ and $n_d^{-\sigma}$, where $n_d^{-\sigma} > n_d^\sigma$ for all V_{sb} values . Itis shown that n_d^σ and $n_d^{-\sigma}$ are equal at $V_{sb} = \pm 1.0eV$ where $V_{sb} > \Gamma > K_B T$ for all h values .

The different spin channels current components for the leads R and L are presented in fig.(3), at equilibrium in the spin bias , not all of them equal to zero. The currents I_L^σ and I_R^σ show inverse symmetry with the spin bias about the x-axis where the current equals zero . One can also write similar notes about the current $I_R^{-\sigma}$ and $I_L^{-\sigma}$, while $I_L^\sigma = I_R^{-\sigma}$and $I_L^{-\sigma} = I_R^\sigma$ at $V_{sb} = \pm 1.0eV$ and all the currents are equal to zero when $V_{sb} = V_{cb}$, i.e. the device is at equilibrium . The I_L^σ and I_R^σ curves exhibit "spin bias gap" , at which all the currents are nearly equal to zero. Thin gap increases as Zeeman energy increases.

The currents $I_L^{-\sigma}$ and $I_R^{-\sigma}$ show linear behavior as the spin bias varies from $V_{sb} = -(h + V_{cb})$ to $V_{sb} = h - V_{cb}$. while the currents $I_{L,R}^{\pm\sigma}$ show different behavior for $V_{sb} < -(h + V_{cb})$,$V_{sb} > (h - V_{cb})$ for all h values.

Fig.(4) represents the charge current as a function of spin bias for different value of h . The figure shows dip and peak nearly at $V_{sb} = h$ and $V_{sb} = -h$ respectively for $h \geq 0.3eV$ .The over mentioned notes are not true for h=0.1eV , since the charge bias effect becomes more obvious at relatively weak magnetic field . Our calculations make it sure that the presence of spin bias may allow for the charge current to be flow . One can get use of fig. (4) to determine the negative differential resistance regions, which takes the following role $-h < V_{sb} < h$ for $h \geq 0.3eV$. Notably, the position of E_d with respect to the energy reference (E=0) and the magnetic field effect both are important to determine the values of spin bias at which the device acts as resistor.
The charge differential conductance which may called the mixed charge /spin differential conductance is also calculated numerically by using finite differences method . The calculations are presented in fig.(5), in which the general features are varied with spin bias polarity .

The curves show also plateau at about $V_{sb} = V_{cb}$, which becomes more obvious as h increases. There are also certain values for the spin bias at which $\frac{dI_C}{dV_{sb}} = 0$, there values are nearly $|V_{sb}| = h$ for $h \geq 0.3eV$.

Fig.(6) shows certain steps in the spin current curve. The Number of these steps is related to the value of h . For h=0.5eV, these steps are lying at about $V_{sb} = -h$, $V_{sb} = 0$ and $V_{sb} = h$. This means that the spin current is quantized. For $h \leq 0.3eV$, the I-V characteristic is ohmic for $0 < V_{sb} < h$, this may be attributed to the bias in charge . Then , as the polarity is changed , the curves show certain step at nearly $V_{sb} = -(h + V_{cb})$.
The spin differential conductance is also calculated numerically (see fig.(7)). Fig(7c) shows peaks lying at $V_{sb} = E_d^{-\sigma}$, $V_{sb} = -E_d^\sigma$ and at $V_{sb} = h$. For h=0.3eV , the peaks are Located at $V_{sb} = h$, $V_{sb} = E_d^{-\sigma}$ and $V_{sb} = -E_d^\sigma$, while for h=0.1eV , the peaks are Located at $V_{sb} = h$ and $V_{sb} = -(h + V_{cb})$. The values of V_{sb}, at which the spin conductance is peaked , are determined by the magnetic field.

IV. Conclusions

According to our calculations, one can conclude that the position of peaks and dips at V_{sb} values are determined by the magnetic field and the bias in the charge which can be employed to determine the functional properties .The charge differential conductance-spin bias dependence shows nonmonotonic relation which comprises peaks and troughs , so there curves have negative slope at certain values of V_{sb} , at which the device acts as negative differential resistance. It is well known that nanodevices that show negative differential can be used as amplifiers and oscillators. The values of V_{sb} at which the device shows certain spin dependent functional properties may be differ with spin channel for certain lead. All the over mentioned spin transport properties can be tuned to control all the features by making the incoming and outgoing tunneling rates less than the thermal energy $K_B T$, this features are well investigated in reference[28].

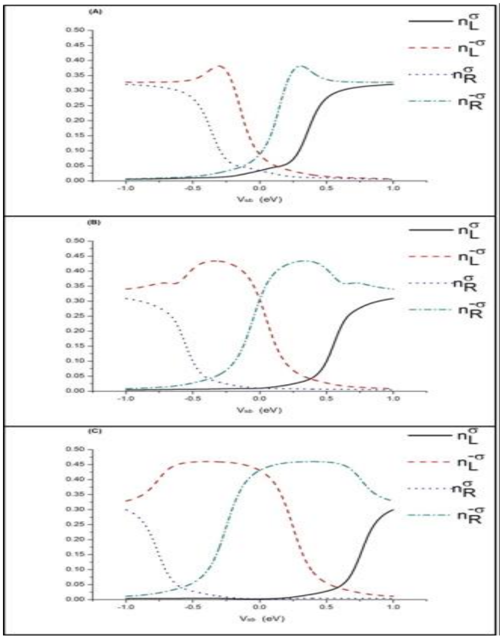


Fig.(1) represents the occupation numbers $n_{L,R}^{\pm\sigma}$ as a function of spin bias when $E_d = 0.25eV$, T=300K ,$V_{cb} = 0$ and $\Gamma_{L,R} = 0.05eV$ for the magnetic field A) $h = 0.1eV$, B) $h = 0.3eV$, C) $h = 0.5eV$.

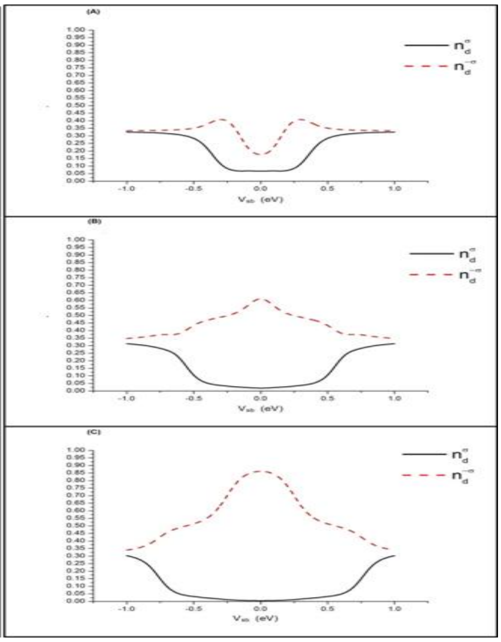


Fig.(2) represents the total occupation numbers $n_d^{\pm\sigma}$ as a function of spin bias when $E_d = 0.25eV$, T=300K , $V_{cb} = 0$ and $\Gamma_{L,R} = 0.05eV$ for the magnetic field A)$h = 0.1eV$, B) $h = 0.3eV$, C) $h = 0.5eV$.

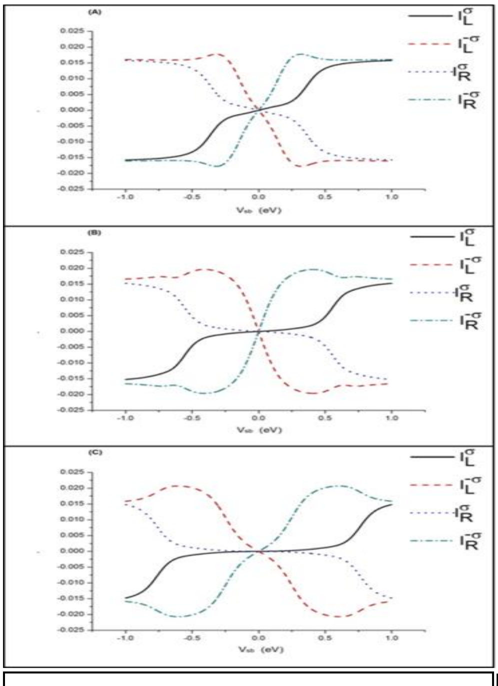


Fig.(3) represents the current components for the spin channels as a function of spin bias when $E_d = 0.25eV$, T=300K , $V_{cb} = 0$ and $\Gamma_{L,R} = 0.05eV$ for the magnetic field : A) $h = 0.1eV$, B) $h = 0.3eV$, C) $h = 0.5eV$

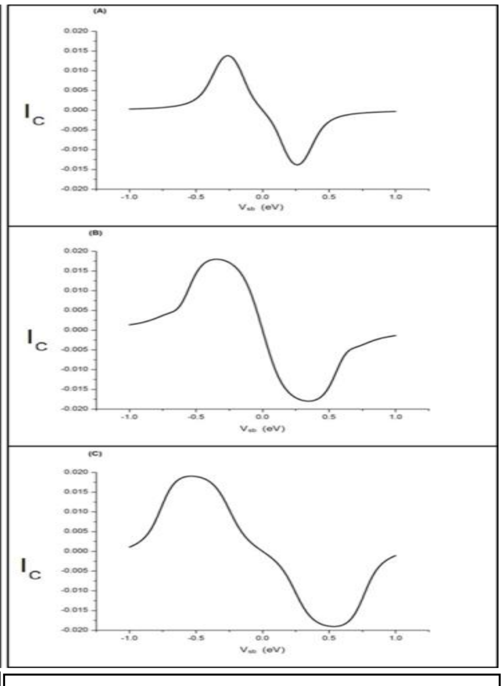
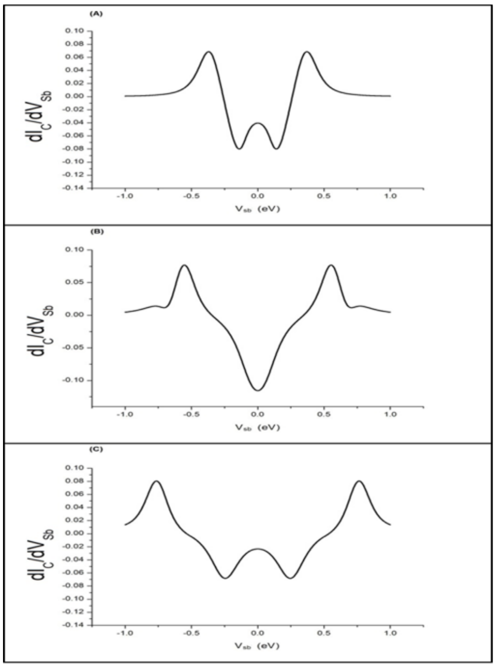


Fig.(4) represents the charge current as a function of spin bias when $E_d = 0.25eV$, T=300K , $V_{cb} = 0$ and $\Gamma_{L,R} = 0.05eV$ for the magnetic field : A) $h = 0.1eV$, B) $h = 0.3eV$, C) $h = 0.5eV$.



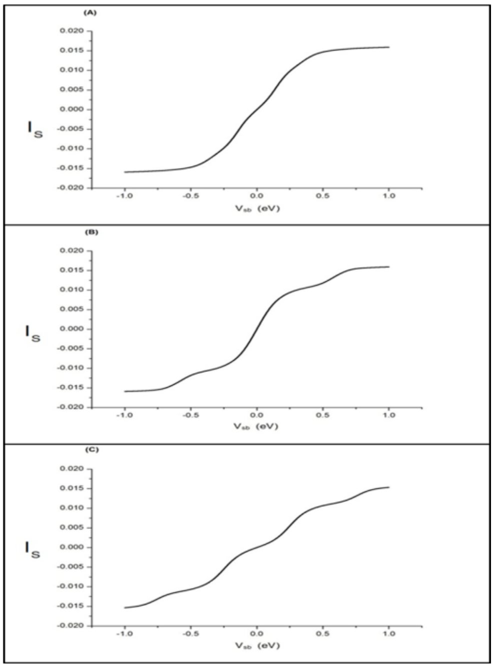


Fig.(5) represents the charge differential conductance as a function of spin bias when $E_d = 0.25eV$, T=300K , $V_{cb} = 0$ and $\Gamma_{L,R} = 0.05eV$ for the magnetic field A) $h = 0.1eV$, B) $h = 0.3eV$, C) $h = 0.5eV$.

Fig.(6) represents the spin current as a function of spin bias when $E_d = 0.25eV$, T=300K , $V_{cb} = 0$ and $\Gamma_{L,R} = 0.05eV$ for the magnetic field : A) $h = 0.1eV$, B) $h = 0.3eV$, C) $h = 0.5eV$

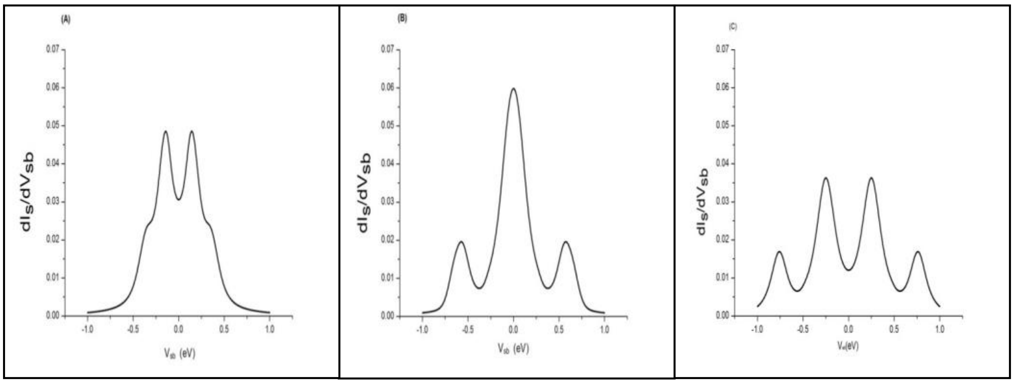


Fig.(7) represents the spin differential conductance as a function of spin bias when $E_d = 0.25eV$, T=300K , $V_{cb} = 0$ and $\Gamma_{L,R} = 0.05eV$ for the magnetic field : $A) h = 0.1eV$, B) $h = 0.3eV$, C) $h = 0.5eV$.

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