Coherent Spin Polarization in an AC-Driven Mesoscopic Device

Mina Danial Asham*, Walid A. Zein†, and Adel H. Phillips†
*Faculty of Engineering, Benha University, Benha, Egypt
E-mail: minadanial@yahoo.com
†Faculty of Engineering, Ain-Shams University, Cairo, Egypt
E-mail: adel.phillips@gmail.com

The spin transport characteristics through a mesoscopic device are investigated under the effect of an AC-field. This device consists of two-diluted magnetic semiconductor (DMS) leads and a nonmagnetic semiconducting quantum dot. The conductance for both spin parallel and antiparallel alignment in the two DMS leads is deduced. The corresponding equations for giant magnetoresistance (GMR) and spin polarization (SP) are also deduced. Calculations show an oscillatory behavior of the present studied parameters. These oscillations are due to the coupling of photon energy and spin-up & spin-down subbands and also due to Fano-resonance. This research work is very important for spintronic devices.

1 Introduction

The field of semiconductor spintronics has attracted a great deal of attention during the past decade because of its potential applications in new generations of nanoelectronic devices, lasers, and integrated magnetic sensors [1, 2]. In addition, magnetic resonant tunneling diodes (RTDs) can also help us to more deeply understand the role of spin degree of freedom of the tunneling electron and the quantum size effects on spin transport processes [3–5]. By employing such a magnetic RTD, an effective injection of spin-polarized electrons into nonmagnetic semiconductors can be demonstrated [6]. A unique combination of magnetic and semiconducting properties makes diluted magnetic semiconductors (DMSs) very attractive for various spintronics applications [7, 8]. The II-VI diluted magnetic semiconductors are known to be good candidates for effective spin injection into a non-magnetic semiconductor because their spin polarization can be easily detected [9, 10]. The authors investigated the spin transport characteristics through mesoscopic devices under the effect of an electromagnetic field of wide range of frequencies [11–14].

The aim of the present paper is to investigate the spin transport characteristics through a mesoscopic device under the effect of both electromagnetic field of different frequencies and magnetic field. This investigated device is made of diluted magnetic semiconductor and semiconducting quantum dot.

2 The Model

The investigated mesoscopic device in the present paper is consisted of a semiconducting quantum dot connected to two diluted magnetic semiconductor leads. The spin-transport of electrons through such device is conducted under the effect of both electromagnetic wave of wide range of frequencies and magnetic effect. It is desired to deduce an expression for spin-polarization and giant magnetoresistance. This is done as follows:

The Hamiltonian, H, describing the spin transport of electrons through such device can be written as:

$$\begin{aligned} H = & -\frac{\hbar^2}{2m^*}\frac{d^2}{dx^2} + eV_{sd} + eV_g + E_F + V_b \\ & + eV_{ac}\cos(\omega t) \pm \frac{1}{2}g\mu_B\sigma B + \frac{N^2e^2}{2C} \pm \sigma h_o, \end{aligned} \tag{1}$$

where m^* is the effective mass of electron, $\hbar$ is the reduced Planck's constant, V_{sd} is the source-drain voltage (bias voltage), V_g is the gate voltage, E_F is the Fermi-energy, V_b is the barrier height at the interface between the leads and the quantum dot, V_{ac} is the amplitude of the applied AC-field with frequency ω, g is the Landé factor of the diluted magnetic semiconductor, μ_B is Bohr magneton, B is the applied magnetic field, σ-Pauli matrices of spin, and h_o is the exchange field of the diluted magnetic semiconductor. In eq. (1), the term $(N^2e^2/2C)$ represents the Coulomb charging energy of the quantum dot in which e is the electron charge, N is the number of electrons tunneled through the quantum dot, and C is the capacitance of the quantum dot. So, the corresponding Schrödinger equation for such transport is

$$H\psi = E\psi, \tag{2}$$

with the solution for the eigenfunction, $\psi(x)$, in the corresponding regions of the device can be expressed as [15]:

$$\psi(x) = \begin{cases} \left[A_1 e^{ik_1x} + B_1 e^{-ik_1x}\right] J_n\left(\frac{eV_{ac}}{\hbar\omega}\right) e^{-in\omega t}, x < 0 \\ \left[A_2 Ai(\rho(x)) + B_2 Bi(\rho(x))\right] J_n\left(\frac{eV_{ac}}{\hbar\omega}\right) \\ \times e^{-in\omega t}, 0 < x < d \\ A_3 e^{ik_2x} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right) e^{-in\omega t}, x > d \end{cases} \tag{3}$$

where $Ai(\rho(x))$ is the Airy function and its complement is $Bi(\rho(x))$ [16]. In eqs. (3), the parameter $J_n(eVac/\hbar\omega)$ represents the n^{th} order Bessel function of the first kind. The solutions of eqs. (3) must be generated by the presence of the different side-bands "n" which come with phase factor $e^{-in\omega t}$ [11–14], and d represents the diameter of the quantum dot. Also, the parameters k_1, k_2 and $\rho(x)$ in eqs. (3) are:

$$k_1 = \sqrt{\frac{2m^*}{\hbar^2}\left(E + n\hbar\omega + V_b + \sigma h_o\right)}, \tag{4}$$

n = 0, ± 1, ± 2, ± 3 ...

$$k_2 = \sqrt{\begin{array}{l}\frac{2m^*}{\hbar^2}(V_b + eV_{sd} + eV_g + E_F + \frac{N^2e^2}{2C} + \\ n\hbar\omega \pm \frac{1}{2}g\mu_B B\sigma \pm \sigma h_o)\end{array}} \tag{5}$$

and

$$\begin{array}{rcl}\rho(x) & = & \dfrac{d}{eV_{sd}\Phi}\left(E_F + V_b + eV_{sd}\left(\dfrac{x}{d}\right) + eV_g + \right. \\ & & \left. \dfrac{N^2e^2}{2C} + \dfrac{1}{2}g\mu_B B\sigma + E \right)\end{array} \tag{6}$$

in which Φ is given by

$$\Phi = \sqrt[3]{\frac{\hbar^2 d}{2m^* eV_{sd}}}. \tag{7}$$

Now, the tunneling probability, $\Gamma(E)$, could be obtained by applying the boundary conditions to the eigenfunctions (eq. (3)) and their derivative at the boundaries of the junction [11–14]. We get the following expression for the tunneling probability, $\Gamma(E)$, which is:

$$\Gamma(E) = \sum_{n=1}^{\infty} J_n^2\left(\frac{eV_{ac}}{\hbar\omega}\right)\cdot\left\{\frac{4k_1k_2}{\pi^2\Phi^2}\left[\alpha^2k_1^2k_2^2 + \beta^2 m^{*2} k_1^2\right]^{-1}\right\}, \tag{8}$$

where α and β are given by:

$$\alpha = Ai\left(\rho(0)\right)\cdot Bi\left(\rho(d)\right) - Bi\left(\rho(0)\right)\cdot Ai\left(\rho(d)\right), \tag{9}$$

and

$$\beta = \frac{1}{\Phi m^*}\left[Ai\left(\rho(0)\right)\cdot Bi'\left(\rho(d)\right) - Bi\left(\rho(0)\right)\cdot Ai'\left(\rho(d)\right)\right], \tag{10}$$

where $Ai'(\rho(x))$ is the first derivative of the Airy function and $Bi'(\rho(x))$ is the first derivative of its complement. Now, the conductance, G, of the present device is expressed in terms of the tunneling probability, $\Gamma(E)$, through the following equation as [11–14, 17]:

$$G = \frac{2e^2}{h}\sin(\varphi)\int_{E_F}^{E_F+n\hbar\omega} dE\left(-\frac{\partial f_{FD}}{\partial E}\right)\cdot\Gamma(E), \tag{11}$$

where ϕ is the phase of the scattered electrons and the factor $(-\partial f_{FD}/\partial E)$ is the first derivative of the Fermi-Dirac distribution function and it is given by:

$$\left(-\frac{\partial f_{FD}}{\partial E}\right) = (4k_BT)^{-1}\cosh^{-2}\left(\frac{E - E_F + n\hbar\omega}{2k_BT}\right), \tag{12}$$

where k_B is the Boltzmann constant and T is the absolute temperature. The spin polarization, SP, and giant magnetoresistance, GMR, are expressed in terms of the conductance, G, as follows [18]:

$$Sp = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\uparrow} + G_{\uparrow\downarrow}}, \tag{13}$$

and

$$GMR = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\uparrow}}, \tag{14}$$

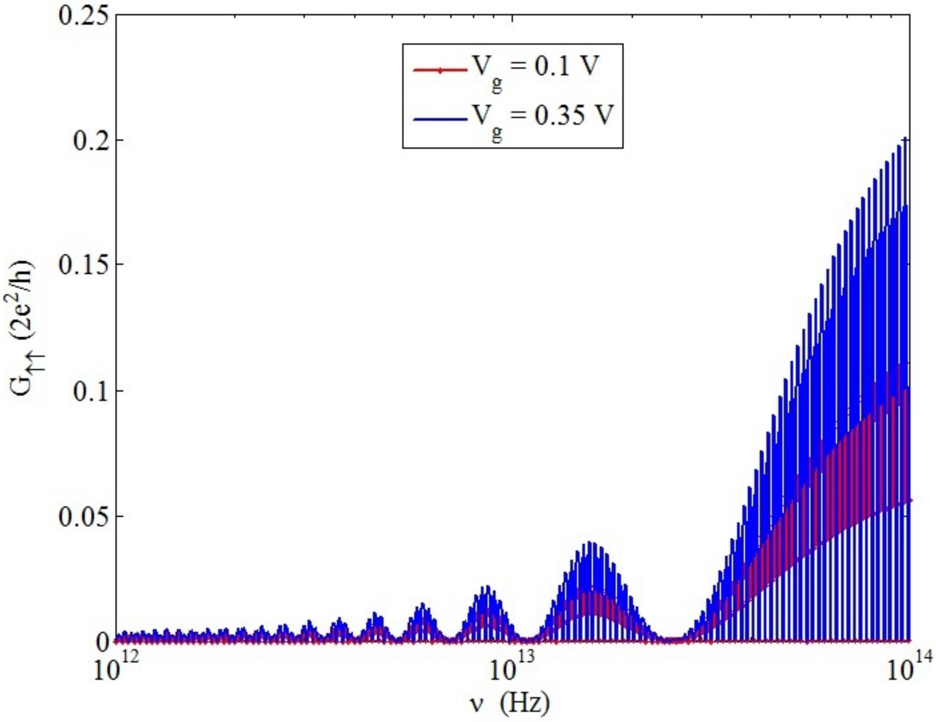
where $G_{\uparrow\uparrow}$ is the conductance when the magnetization of the two diluted magnetic-semiconductor leads are in parallel alignments, while $G_{\uparrow\downarrow}$ is the conductance for the case of antiparallel alignment of the magnetization in the leads. The indicator ↑ corresponds to spin up and also ↓ corresponds to spin down.

3 Results and Discussion

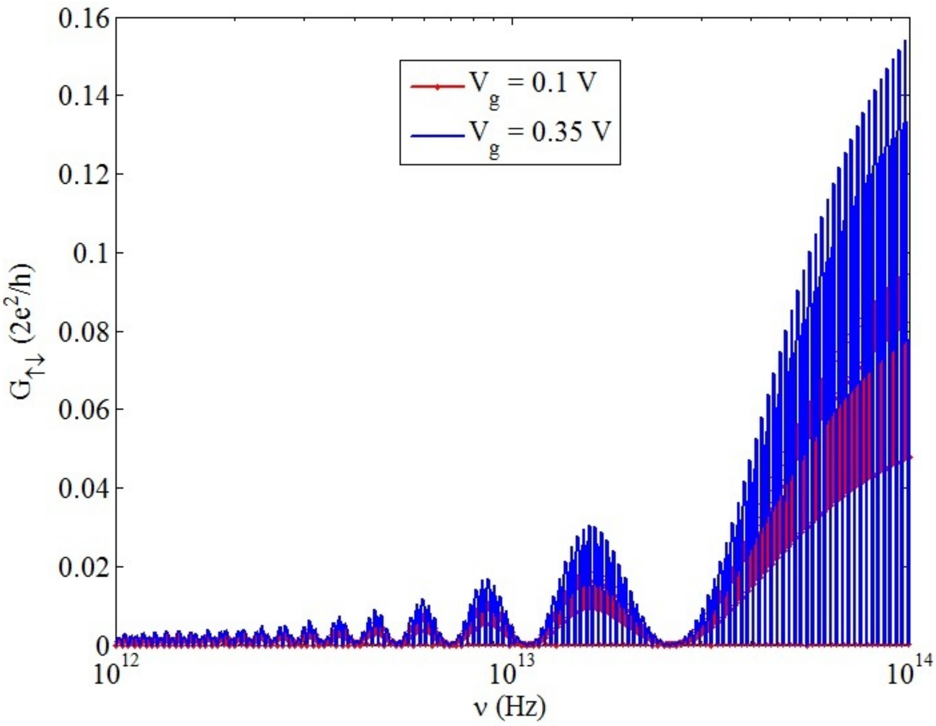
Numerical calculations to eqs. (11, 13 and 14), taking into consideration the two cases for parallel and antiparallel spins of quasiparticles in the two leads. In the present calculations, we take the case of quantum dot as GaAs and the two leads as diluted magnetic semiconductors GaMnAs. The values for the quantum dot are [11–14, 19–21]: E_F = 0.75 eV, C = 10^{-16} F and d = 2 nm, V_b = 0.3 eV. The value of the exchange field, h_o, for GaMnAs is -1 eV and g = 2 [18–22].

The features of the present results:

1. Figs. 1a, 1b show the variation of the conductance with the induced photon of the frequency range $10^{12} - 10^{14}$ Hz. The range of frequency is in the infra-red range at different values of gate voltage, V_g. Fig. 1a is for the case of the parallel alignment of spin in the two diluted magnetic semiconductor leads, while Fig. 1b for antiparallel case. As shown from these figures that an oscillatory behavior of the conductance with the frequency for the two cases. It must be noted the peak height of the conductance (for the two cases) increases as the frequency of the induced photons. Also, the trend of the dependence is a Lorentzian shape for each range of frequencies. These results are due to photon-spin-up and spin-down subbands coupling. This coupling will be enhanced as the frequency of the induced photon increases.
2. Fig. 2a shows the variation of the giant magnetoresistance, GMR, with the frequency of the induced photon at different values of gate voltage, V_g. As shown from the figure, random oscillations of GMR with random peak heights. GMR attains a maximum value ∼ 30%

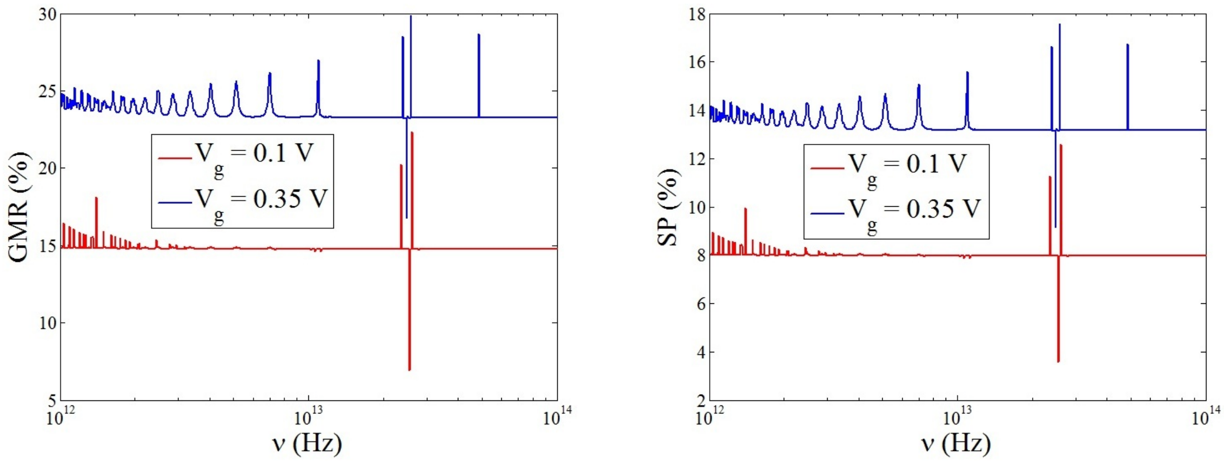


(a)



(b)

Fig. 1: The variation of conductance with frequency at two different gate voltages for (a) parallel spin alignment and (b) antiparallel spin alignment.



(a) (b)

Fig. 2: The variation of (a) GMR and (b) SP with frequency at two different gate voltages.

at $\nu = 2.585\times10^{13}$ Hz ($V_g = 0.35$ V) and GMR attains a maximum value ~ 22% at $\nu = 2.615\times 10^{13}$ Hz ($V_g = 0.1$ V).

3. Fig. 2b shows the variation of the spin polarization, SP, with the frequency of the induced photon at different values of gate voltage, V_g. As shown from the figure, random oscillations of spin polarization with random peak heights. SP attains a maximum value ~ 17.6% at $\nu = 2.585\times10^{13}$ Hz ($V_g = 0.35$ V), and also SP attains a maximum value ~ 12.6% at $\nu = 2.615\times10^{13}$ Hz ($V_g = 0.1$ V).

These random oscillations for both GMR & SP might be due to spin precession and spin flip of quasiparticles which are influenced strongly as the coupling between the photon energy and spin-up & spin-down subbands in quantum dot.

Also, these results show that the position and line shape of the resonance are very sensitive to the spin relaxation rate of the tunneled quasiparticles [23,24] through the whole junction.

In general, the oscillatory behavior of the investigated physical quantities might be due to Fano-resonance as the spin transport is performed from continuum states of dilute magnetic semiconductor leads to the discrete states of non-magnetic semiconducting quantum dots [14, 25].

So, our analysis of the spin polarization and giant magnetoresistance can be potentially useful to achieve a coherent spintronic device by optimally adjusting the material parameters. The present research is practically very useful in digital storage and magneto-optic sensor technology.

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