Spin Thermoelectric Effect of Diluted Magnetic Semiconductor Nanodevice

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***Abstract* — A spin thermoelectric effect in diluted magnetic semiconductor nanodevice is investigated. This nanodevice is modeled as a semiconducting quantum dot is connected to two diluted magnetic semiconductor leads. The spin transport of electrons through such nanodevice is conducted under the effect of an ac-field with frequency in the mid-infrared range and magnetic field. The thermoelectric parameters are expressed in terms of the photon-assisted tunneling probability, which has been derived by solving the Schrodinger equation of the present studied nanodevice. Results show that both Seebeck and Peltier coefficients together with figure of merit have high values. Also, the value of thermoelectric efficiency of this nanodevice is quit high. These results indicate that the present diluted magnetic semiconductor nanodevice is promising thermoelectric nanodevices for spin caloritronics applications that is for energy harvesting (Seebeck coefficient) and as coolers (Peltier coefficients) for nanoelectronics devices such as nanocontrollers and computer CPUs.**

Keywords— spin thermoelectric effect; diluted magnetic semiconductor; quantum dot; spin transport

I. INTRODUCTION

Advances in nanoscience and nanotechnology critically depend on the development of nanostructures whose properties are controlled during synthesis. The electronic properties of these nanostructured materials are dominated by quantum effects [1]. Spin-polarized injection of electrons into semiconductor has attracted a rapidly growing interest due to its potential application in spintronics devices recently. Operation of a spintronic device requires efficient spin injection into a semiconductor, spin manipulation, control and transport, and spin detection [2, 3]. Controlling the spin state of electrons provides an important versatility for future nanoelectronics [4, 5].

Diluted Magnetic semiconductors (DMSs) has been attracting researchers due to their wide range of applications like spintronics devices such as spin-FET, spin-LED, nanoscale integrated magnetic memories & sensors etc. [6, 7]. Diluted Magnetic semiconductors have been studied by the researchers for identifying DMSs which have strong ferromagnetism at room temperature. Initially II-VI semiconductor alloys [8, 9] like Zn_{1-x} Mn_xTe and Cd_{1-x} Mn_xTe were studied [10, 11] but they showed very weak ferromagnetism and low Curie temperature (Tc). More recently, the Mn-doped III–V semiconductors [12, 13] like In_{1-x} Mn_xAs [14] and Ga_{1-x} Mn_xAs [15-18] has been studied and they have shown ferromagnetism at higher Curie temperature.

Thermoelectric materials can be used to convert heat to electricity, through the Seebeck effect or can be used for cooling or refrigeration through the converse Peltier effect [19, 20]. The recent discovery of both the Spin-Seebeck [21 - 23] and Peltier effect [24, 25] is at the core of spin-caloritronics [26, 27], an emerging field where the generation and control of spin currents by a thermal gradient in nanoelectronics devices is in focus. Spin caloritronics is the field of combining thermoelectric effects with spintronics and nanomagnetism [26, 27].In recent years, this field has been the object of intense investigation, yielding promising opportunity in energy efficient spintronics devices. The coupling of heat transport with spintronics has generated novel ideas such as innovative spin sources [21, 23, 28 - 30], thermal spin-transfer torque [31, 32], magnetic heat valves [33] and magnetically switchable cooling [34, 35]. Driven by the downscaling of nanoelectronic components, the development and understanding of new and local refrigeration concepts is essential [36]. A thermo-spin effect in a mesoscopic device consisting of a ferromagnetic graphene coupled to normal graphene is investigated [37]. Also, the spin-thermoelectric effect in ferromagnetic graphene/ superconducting graphene junction with Schottky barrier of delta type at the interface of the junction is investigated [38, 39].

The purpose of the present paper is to investigate spin-dependent thermoelectric transport in nanoelectronics device under the effect of both ac-field of frequency in the mid-infrared range and magnetic field.

II. THE MODEL

The investigated nanoelectronics device is modeled in the present paper as follows: a semiconducting quantum dot is connected to two diluted magnetic semiconductor leads. The spin transport of electrons through such nanodevice is conducted under the effect of an ac-field with frequency in the mid-infrared range and magnetic field. The thermoelectric parameters are expressed in terms of the tunneling probability, which has been derived by solving the Schrodinger equation [17, 18] of the present studied nanodevice. The thermopower (Seebeck coefficient), S, Peltier coefficient, Π, and the electronic thermal conductance, κ_e, are expressed in terms of the function, $L_m(\mu)$, respectively as follows [37-40]:

$$|S| = \frac{1}{eT} \cdot \frac{L_1}{L_0} \tag{1}$$

and

$$\Pi = \frac{L_1}{e L_0} \tag{2}$$

and

$$\kappa_e = \frac{1}{T}\left(L_2 - \frac{L_1^2}{L_0}\right) \tag{3}$$

where e is the electronic charge and T is the absolute temperature. The function, L_m, (for the cases m = 0, 1, 2) is defined [37- 40] in terms of the tunneling probability, $\Gamma_{with\ photons}(E)$, as follows:

$$L_m(\mu) = \frac{2}{h} \int_{E_F}^{E_F+\hbar\omega} dE\, \Gamma_{withPhoton}(E).(E-\mu)^m . \left(-\frac{\partial f_{FD}(E)}{\partial E}\right) \tag{4}$$

where h is Planck's constant, μ is the electrochemical potential and $\left(-\partial f_{FD}(E)/\partial E\right)$ is the first derivative of the Fermi-Dirac distribution function and it is given by:

$$\left(-\frac{\partial f_{FD}}{\partial E}\right) = \left(4k_B T\right)^{-1} .\cosh^{-2}\left(\frac{E-E_F+n\hbar\omega}{2k_B T}\right) \tag{5}$$

In which k_B is Boltzmann's constant, T is the absolute temperature, E is the energy of the tunneled electrons, E_F is the Fermi-energy, and ≅ω is the photon energy of the induced ac-field. In Eq.(4), $\Gamma(E)$ is the tunneling probability which has been calculated in details by the authors [17, 18] by solving the Schrodinger equation and applying the boundary conditions to the obtained eigenfunctions, and its expression is given by:

$$\Gamma(E) = \sum_{n=1}^{\infty} J_n^2\left(\frac{eV_{ac}}{n\hbar\omega}\right). \left\{\frac{4k_1k_2}{\pi^2\Phi^2}\left[\alpha^2 k_1^2 k_2^2 + \beta^2 m^{*2} k_1^2\right]^{-1}\right\} \tag{6}$$

The tunneling through such device is induced by an external ac-field of different frequencies of the form $V=V_{ac}\cos(\omega t)$ where V_{ac} is the amplitude of the field and ω is its angular frequency that is the photon-assisted tunneling process is achieved. The parameter $J_n\left(\frac{eV_{ac}}{n\hbar\omega}\right)$ represents the nth order Bessel function of the first kind , m* is the effective mass of electron and ħ is the reduced Planck's constant. The solution of Schrodinger equation [17, 18] must be generated by the presence of the different side-bands, n, which come with the phase factor $e^{-i n \omega t}$ (n=0, ±1,±2,….) [17,18, 37-41]. The parameters k1, k2, Φ , α and β are expressed as:

$$k_1 = \sqrt{\frac{2m^*}{\hbar^2}\left(E + n\hbar\omega + V_b + \sigma h_0\right)} \tag{7}$$

and

$$k_2 = \sqrt{\frac{2m^*}{\hbar^2}\left(\begin{matrix} eV_{sd} + eV_g + E_F + V_b + \\ n\hbar\omega \pm \frac{1}{2} g\,\mu_B \sigma B + \frac{N^2e^2}{2C} \pm \sigma h_0 \end{matrix}\right)} \tag{8}$$

where V_{sd} is the source-drain voltage (bias voltage), Vg 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. 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. Also, the expressions for parameters α and β (Eq. (6)) are respectively 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

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

where Ai(ρ(x)) is the Airy function & its complement is Bi(ρ(x)) and Ai′(ρ(x)) is the first derivative of the Airy function and Bi′(ρ(x)) is the first derivative of its complement. The expression of the parameter ρ(x) (Eqs.9, 10) is given by:

$$\rho(x) = \frac{d}{eV_{sd}\Phi}\left(\begin{matrix} eV_{sd}\left(\frac{x}{d}\right) + eV_g + E_F + V_b + \\ \frac{1}{2} g\,\mu_B \sigma B + \frac{N^2e^2}{2C} + E \end{matrix}\right) \tag{11}$$

In which Φ is given by:

$$\Phi = \sqrt[3]{\frac{\hbar^2 d}{2m^* eV_{sd}}} \tag{12}$$

where d is the diameter of the semiconducting quantum dot. The thermoelectric figure of merit of the present device is expressed as [37 - 40]:

$$ZT = \frac{S^2 GT}{\kappa_{ph} + \kappa_e} \quad (13)$$

where κ_{ph} is the phonon contribution to thermal conductance. In the present paper, we might neglect the phonon contribution to thermal conductance (Eq.13). This is because our calculations will be performed at very low temperature. It can be taken into consideration when we consider electron-phonon interaction and phonon drag. So, Eq. (13) will take the following form as:

$$ZT = \frac{S^2 GT}{\kappa_e} \quad (14)$$

The electrical conductance, G, (see Eq.14) of the present device could be calculated using the following Landauer-Buttiker formula [17, 18]:

$$G = e^2 L_0 \quad (15)$$

The ideal efficiency of a thermoelectric device for electricity generation η_{max} is given by [40, 42, 43]:

$$\eta_{\max} = \frac{T_H - T_L}{T_L} \cdot \left(1 - \frac{1 + \frac{T_L}{T_H}}{\sqrt{1+ZT} + \frac{T_L}{T_H}} \right) \quad (16)$$

where T_H is the temperature of the heat source (hot side of the present nanodevice) and T_L is the temperature of the heat sink or cold side of the present nanodevice. Eq. (16) relates the device efficiency to the figure of merit which is a materials property and therefore most of the effort in the thermoelectric field is focused on materials development to improve the thermal to electrical conversion efficiency.

III. RESULTS AND DISCUSSION

Numerical calculations are performed to the thermoelectric parameters (see Eqs.1, 2, 3, 13). Results for the conductance, G, have been calculated previously [18]. The calculations are performed for the cases of parallel and antiparallel spins alignments of quasiparticle 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 parameters of the considered quantum dot are the following [17, 18]:

E_F = 0,75 eV, C = 10^{-16} F, d = 2 nm, B = 0.5 T and V_b = 0.3 eV. The value of the exchange field energy h_o for GaMnAs is -1 eV and g=2 [17, 18, 44].

The features of the results are:

-Fig. (1) shows the variation of Seebeck coefficient, S, with the gate voltage, V_g, for both cases of parallel and antiparallel spin alignments. The value of the frequency of the induced ac-field is f = $3x10^{12}$ Hz.

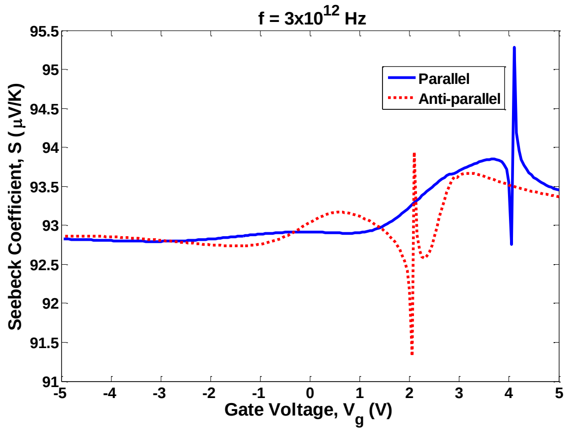

Fig. 1 The variation of Seebeck coefficient, S, with gate voltage, V_g, for both cases of spin alignment.

-Fig. (2) shows the variation of Peltier coefficient, Π, with the gate voltage, V_g, for both cases of parallel and antiparallel spin alignments. The value of the frequency of the induced ac-field is f=$3x10^{12}$ Hz.

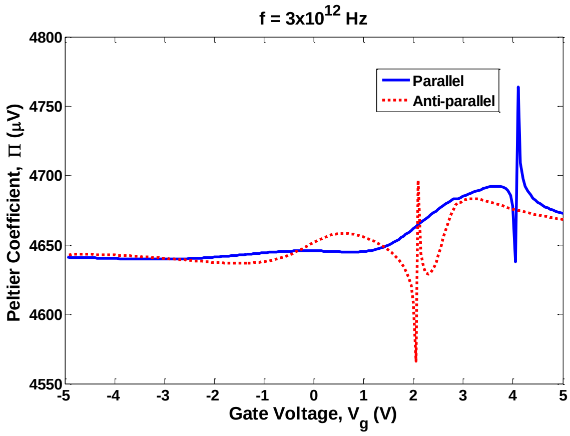

Fig. 2 The variation of Peltier coefficient, Π, with the gate voltage, V_g, for both cases of spin alignment.

As shown from fig.(1) that the Seebeck coefficient, S, increases, for the case of parallel spin alignment, when the gate voltage increases from -5 V to +3.75 V and then it has a dip peak at gate voltage, V_g, equals 4.1 V ($S_{max.}$=95.28 μV/K). While for the case of antiparallel spin alignment, the Seebeck coefficient, S, increases when the gate voltage increases from -5 V to

+0.85 V and it has a dip peak at gate voltage, V_g, equals 2.1 V ($S_{max.}$= 93.94 μV/K). Now concerning fig. (2), the variation of the Peltier coefficient, Π, with the gate voltage is similar to the variation of Seebeck coefficient, S, with gate voltage, that is, for the case of parallel spin alignment the Peltier coefficient attains a maximum value equals 4764 μV when V_g=4.1 V. While for antiparallel spin alignment, the maximum value of Peltier coefficient is 4697 μV, when the gate voltage equals 2.1 V. The Peltier coefficient increases when the gate voltage increases from -5 V to 3.75 V, for the parallel spin alignment case, and this increase for Peltier coefficient is when the gate voltage increases from -5 V to 0.7 V for the antiparallel spin alignment case. These variations of both Seebeck and Peltier coefficients ((Figs.1 & 2) might be explained as follows: The spin polarized carriers are injected into the conducting channel from the source and driven towards and detected by the collector. The carriers can flow freely through the drain ("on" state) if their spins are parallel to that of drain or are blocked ("off" state) if anti-parallel. Similar to the traditional field-effect-transistor, the on/off states of spin field-effect-transistor are switched by the gate voltage which controls the spin direction of the passing carriers via the Rashba spin-orbit coupling acting as an effective magnetic field, with its strength controlled by the gate voltage. It is believed that spin field-effect-transistor has the advantages of low energy consumption and fast switching speed since it does not involve creating or eliminating the electrical conducting channel during the switching like the traditional field effect transistor [45, 46]. Also the induced far-infrared radiation ($f = 3x10^{12}$Hz) introduces new photon-mediated conduction channels in the present nanodevice [17, 18, 41]. Also, we notice from these figures that the values of both Seebeck and Peltier coefficients are high. This is might be due to the applications of magnetic field, B, (see Eqs. 8, 11) which causes Zeeman splitting of the energy levels of the semiconducting quantum dot [2, 3, 17, 18].

-Fig.(3) shows the variation of the electronic thermal conductivity, κ_e , with gate voltage, V_g, for both parallel and antiparallel spin alignment cases. As shown from this figure that for the case of parallel spin alignment, the electronic thermal conductivity, κ_e, decreases as the gate voltage increases in the range investigated. While for the case of antiparallel spin alignment, the electronic thermal conductivity decreases with the gate voltage except it has two maxima, $\kappa_{emax} = 1.67x10^{-12}$ W/K at V_g= - 0.4V and $\kappa_{emax} = 2.555x10^{-13}$ W/K at V_g=2.5V.

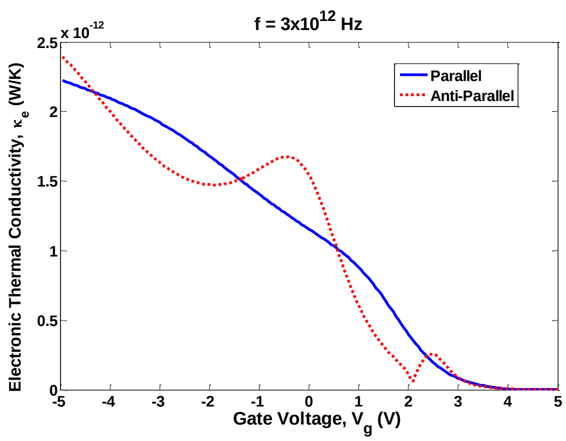

Fig. 3 The variation of the electronic thermal conductivity, κ_e, with the gate voltage, V_g, for both cases of spin alignment.

-Fig. (4) shows the variation of the figure of merit, ZT, with the gate voltage, V_g, for both cases of parallel antiparallel spin alignments.

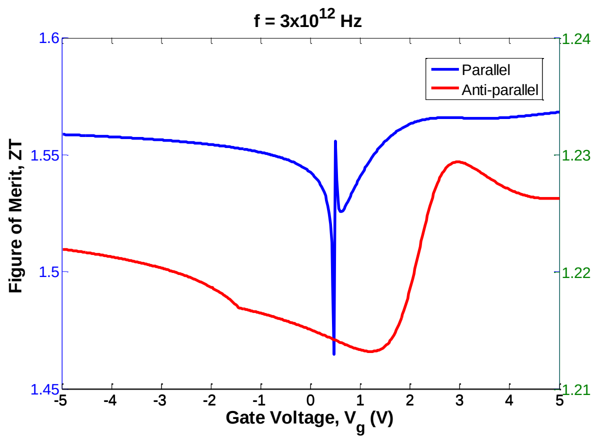

Fig. 4 The variation of the figure of merit, ZT, with the gate voltage, V_g, for both cases of spin alignment.

As shown from this figure that for the case of parallel spin alignment, the figure of merit, ZT, decreases slightly and attains a dip minimum (ZT_{min} = 1.464) at V_g = 0.475 V and a dip maximum (ZT_{max} = 1.556) at V_g = 0.5 V. Then it highly increases till V_g=2.325V and then it slightly increases. While for the case of antiparallel spin alignment, the figure of merit, ZT, decreases until it attains a minimum value equals 1.213 at V_g = 1.3 V and after that it increases sharply until it attains a maximum value equals 1.229 at V_g = 2.325V and then decreases. In general the large value of the figure of merit, ZT, is a consequence of the large values of Seebeck coefficients which in turn give high values of the efficiency power, S^2G, (see Eq.14) and small values of the electronic thermal conductivity, κ_e, (see Fig.3). Table (1) shows the efficiency, η, of this investigated thermoelectric nanodevice calculated from Eq.(16) in case of parallel and anti-parallel spin alignments as a function of the figure of merit at two different values of temperature 50 K and 150 K respectively.

TABLE I THE EFFICIENCY, η, OF THE PRESENT NANODEVICE

Spin alignment	ZT	η (%)
Parallel	2.9871	85.57
Anti-parallel	2.987	85.56

IV. CONCLUSION

In this paper, a spin thermoelectric effect in the present nanodevice is investigated. This nanodevice is modeled as: a semiconducting quantum dot is connected to two diluted magnetic semiconductor leads. The spin transport of electrons through such nanodevice is conducted under the effect of an ac-field with frequency in the mid-infrared range and magnetic field. Results show large values of figure of merit, ZT, as a result of the combined effect of external magnetic fields, spin polarization and appropriate tuning of the semiconducting quantum dot energy level. Also the thermoelectric efficiency, η, of the present nanodevice attains a high value (see table (1)). So, the present nanodevice with its structure is the most promising thermoelectric nanodevices for spin caloritronics applications.

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