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Spin Dependent Peltier Effect in Ferromagnetic Graphene/Superconducting Graphene Junction

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Abstract

A spin dependent Peltier effect in graphene nanodevice is investigated. This nanodevice is modeled as ferromagnetic graphene/ superconducting graphene junction with Schottky barrier of delta-type at the interface of the junction. The Peltier coefficient is expressed in terms of spin-dependent Andreev reflection and normal reflection which will be deduced by solving Dirac-Bogoliubov-deGennes equation in one dimension. Numerical calculations are performed for two different superconducting layers under the effects of the induced ac-field and magnetic field. Results show that the present nanodevice operates only in narrow band of THz frequencies. Also, the present results might indicate that the present nanodevice is stable under the effect of magnetic field, which must be needed for quantum information processing. The present graphene nanodevice based on Peltier effect might be used as coolers for nanoelectronic devices such as nanocontrollers and computer CPUs. The present research is very important in the field of spin caloritronics on the nanoscale systems and at low temperatures.

Keywords

Spin-Caloritronics, Ferromagnetic Graphene, Superconducting Graphene, Spin Peltier Coefficient, Ac-field, Magnetic Field

1. Introduction

The desire to find nanomaterials with a high thermoelectric performance is the driving force of material science and nanotechnology [1, 2] and is vital for efficient energy harvesters or refrigerators. The coupling between spin and charge transport in condensed matter is studied in the lively field referred to as spintronics. Spintronics utilizes the electron spin degree of freedom for information storage and logic operations, which could decrease the power consumption, increase data processing speed, and increase integration densities [3]. Spin caloritronics is the field of combining thermoelectric effects with spintronics and nanomagnetism, which recently enjoys renewed attention [4]. The coupling of heat transport with spintronics has generated novel ideas such as innovative spin sources [5-9], thermal spin-transfer torque [10, 11], magnetic heat valves [12] and magnetically switchable cooling [13, 14]. Driven by the downscaling of nanoelectronic components, the development and understanding of new and local refrigeration concepts is essential [15]. The spin Peltier effect offers this possibility and pioneering experiments of the author [16] have reported field dependent magneto-thermo-galvanic voltage measurements in multiple Co/Cu multilayer nanowires, thereby indicating the existence of spin dependent Peltier coefficients. The semiconductor nanomaterials development extends applications concerning thermoelectric effects like Seebeck and Peltier, which are the basic phenomena among other non-equilibrium thermoelectric effects. Seebeck effect is the electric voltage generation in a conductor under a temperature gradient, and it is used in the heat sink applications. With the inverse effect, namely Peltier, an active cooling can be received [17]. Peltier effect of superconductor-semiconductor mesoscopic device has been investigated [19]. Two-dimensional (2D) nanomaterials, including graphene, hexagonal boron nitride and MoO_3 have attracted much attention recently due to their extraordinary structural, mechanical, electronic and thermal properties, with great interest in both fundamental science and engineering applications [19]. A thermo-spin effect in a mesoscopic device consisting of a ferromagnetic graphene coupled to normal graphene has been investigated [20]. The present authors [21] investigated the spin-thermoelectric effect in ferromagnetic graphene/ superconducting graphene junction with Schottky barrier of delta-type at the interface of the junction. The present paper is devoted to investigate the spin-Peltier effects in ferromagnetic grapheme / superconducting graphene junction. The investigation is conducted under the effect of induced ac-field and magnetic field.

2. The Model

The present investigated nanodevice is modeled as follows: ferromagnetic graphene/ superconducting graphene junction with Schottky barrier of delta-type at the interface of the junction (see Fig.1). The spin polarization transport is conducted under the effects of the induced ac-field and magnetic field.

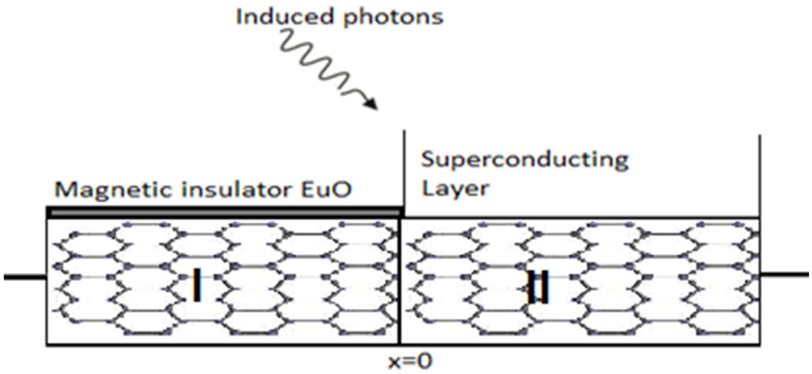

Fig. 1. *Region I is the ferromagnetic graphene, and region II is the superconducting graphene.*

In this section, the spin Peltier coefficientis expressed in terms of spin-dependent Andreev reflection and normal reflection which will derived by solving Dirac-Bogoliubov-deGennes equation in one dimension [22,23]:

$$\begin{pmatrix} -i\hbar v_F \sigma.\nabla - \varepsilon - \sigma h_o - E_F & \Delta \\ \Delta^* & i\hbar v_F \sigma.\nabla + \varepsilon - \sigma h_o - E_F \end{pmatrix} \Psi = E\Psi \quad (1)$$

where ħ is the reduced Planck's constant, v_F is the Fermi velocity, σ is Pauli matrix, h_0 is the exchange field energy of the ferromagnetic graphene and Δ is the superconducting order parameter which is expressed in terms of its phase ϕ as [24]:

$$\Delta = \Delta_0 \exp(i\phi) \quad (2)$$

The parameter Δ_0 is related to the critical temperature of superconductor graphene, T_c, as [25]:

$$\Delta(T) \simeq \Delta_0 \tanh\left(1.74\sqrt{\frac{T_c}{T} - 1}\right) \quad (3)$$

where T is the absolute temperature of the junction and Δ_0 is expressed in terms of the critical temperature, T_c, as [22]:

$$2\Delta_0 = 3.53\, k_B T_c \quad (4)$$

where k_B is Boltzmann constant. The parameter ε (Eq.1) is expressed in terms of the following parameters as follows:

$$\varepsilon = \Phi_{SB} + eV_{sd} + eV_g + eV_{ac}\cos(\omega t) + \frac{1}{2} g\mu_B B\sigma \quad (5)$$

where Φ_{SB} is Schottky barrier height, V_{sd} is the bias voltage, V_g is the gate voltage, V_{ac} is the amplitude of the induced ac-field with frequency, ω, μ_B is the Bohr magneton, B is the magnetic field and g is Lande g-factor of the ferromagnetic graphene.

$$\Psi_I(x \prec 0) = \sum_{n=1}^{\infty} \left[\begin{pmatrix} 1 \\ B_+ e^{i\theta} \\ 0 \\ 0 \end{pmatrix} e^{ik_+ x} + b \begin{pmatrix} 1 \\ -B_+^* e^{-i\theta} \\ 0 \\ 0 \end{pmatrix} e^{-ik_+ x} + a \begin{pmatrix} 0 \\ 0 \\ 1 \\ B_-^* e^{-i\theta} \end{pmatrix} e^{-ik_- x} \right] J_n\left(\frac{eV_{ac}}{n\hbar\omega}\right) e^{-in\omega t} \quad (6)$$

where Ψ_I (x< 0) is the eigenfunction in the ferromagnetic graphene (region I). The eigenfunction, Ψ_{II} in the superconducting graphene (region II) is given by:

$$\Psi_{II}(x \rangle 0) = \sum_{n=1}^{\infty} \left[c \begin{pmatrix} u \\ u A_+ \\ \mathrm{v} e^{-i\varphi} \\ \mathrm{v} e^{-i\varphi} A_+ \end{pmatrix} e^{ik'_+ x} + d \begin{pmatrix} \mathrm{v} \\ -\mathrm{v} A_-^* \\ u e^{-i\varphi} \\ -u e^{-i\varphi} A_-^* \end{pmatrix} e^{-ik'_- x} \right] J_n\left(\frac{eV_{ac}}{n\hbar\omega}\right) e^{-in\omega t} \quad (7)$$

where $k_\pm$ is the wave vector of quasiparticles in the ferromagnetic graphene (Eq.6) and $k'_\pm$ is the corresponding wave vector of quasiparticles in the superconducting graphene (Eq.7) and are given ,respectively, as:

$$k_{\pm} = \frac{\left(E - \varepsilon \pm E_{FI}\right)\cos\theta}{\hbar v_F} \tag{8}$$

and

$$k'_{\pm} = \frac{\left(\sqrt{\left(E_{FII} \pm \sqrt{\left(E-\varepsilon\right)^2 - \Delta^2}\right)^2 - \left(m v_F^2\right)^2}\right)\cos\theta'}{\hbar v'_F} \tag{9}$$

where E_{FI} is the Fermi-energy in the ferromagnetic graphene and θ is the Klein angle in ferromagnetic graphene (region I), J_n is the Bessel function of first kind, and the solutions of Eqs. (6, 7) must be generated by the presence of the different side-bands "n" which come with the phase factor exp(-inωt) [25,26]. The parameters E_{FII}, θ' and v'_F are respectively the Fermi energy, Klein angle and the Fermi velocity in the superconducting graphene (region II). For the coherence factors of electrons and holes u & v (Eq.7) are related as [27]:

$$u^2 = 1 - v^2 = \frac{1}{2}\left[1 + \frac{\sqrt{E^2 - \Delta^2}}{E}\right] \tag{10}$$

The parameters A in Eq.(7) and B in Eq. (6) are given as:

$$A_{\pm} = \left(\frac{E_{FII} \pm \sqrt{\left(\left(E-\varepsilon\right)^2\right) - \Delta^2} - m v_F'^2}{\hbar v'_F k'_{\pm}}\right) e^{i\theta'} \tag{11}$$

$$B_{\pm} = \left(\frac{E_{FI} - E + \varepsilon - m v_F^2}{\hbar v_F k_{\pm}}\right) e^{i\theta} \tag{12}$$

The parameters A* (Eq.7) and B* (Eq.6) are the complex conjugate of A (Eq.11) and B (Eq.12) respectively. Now, applying the boundary conditions at the interface of ferromagnetic graphene & superconductor graphene (the two regions I & II), we get the spin dependent Andreev reflection, a, and the normal reflection, b, coefficients respectively:

$$a = \sum_{n=1}^{\infty} J_n\left(\frac{eV_{ac}}{n\hbar\omega}\right) e^{-in\omega t}\left(2\cos(\theta)(B_+ + B_-^*)(A_+ + A_-^*)\, u\, v\, e^{-i\phi}\right) \tag{13}$$

and

$$b = \sum_{n=1}^{\infty} J_n\left(\frac{eV_{ac}}{n\hbar\omega}\right) e^{-in\omega t}\left[\left(u^2 A_-^* + v^2 A_+\right)\left(B_+ + B_-^*\right) 2\cos(\theta) - 1\right] \tag{14}$$

The Peltier coefficient, Π, is expressed in terms of the function, $L_m(\mu)$ as follows [17,28]:

$$\Pi = \frac{L_1}{e L_o} \tag{15}$$

where e is the electronic charge and T is the absolute temperature. The function, L_m, (for the cases m=0, 1) is given by [17, 21, 28]:

$$L_m(\mu) = \frac{2}{h}\int dE \int_0^{\pi/2} d\theta \cos(\theta)\left(1 + |a|^2 - |b|^2\right)\left(E - \mu\right)^m . \left(-\frac{\partial f_{FD}}{\partial E}\right) \tag{16}$$

where h is Planck's constant, μ is the electrochemical potential in the corresponding regions I & II (Fig. 1) and $\left(-\frac{\partial f_{FD}}{\partial E}\right)$ is the first derivative of the Fermi-Dirac distribution function which is expressed as:

$$\left(-\frac{\partial f_{FD}}{\partial E}\right) = \left(4 k_B T\right)^{-1} . \cosh^{-2}\left(\frac{E - E_F + n\hbar\omega}{2 k_B T}\right) \tag{17}$$

in which k_B is Boltzmann constant, T is the absolute temperature and E_F is the Fermi energy in the corresponding regions of the device.

3. Results and Discussion

Numerical calculations are performed for the spin dependent Peltier coefficient (Eq.15) for both cases of parallel and antiparallel spin alignment. There is a good possibility for developing novel electronic devices with graphene since it can be converted into a ferromagnetic graphene or a superconducting graphene. This can be achieved by depositing the magnetic insulator EuO on the top of the graphene; magnetic exchange energy of 5 meV can be induced into graphene sheet [29]. Also, superconducting graphene can be induced (via the proximity effect) in the graphene by placing a La-Ba-CuO of thickness equals approximately 10 nm, on top of graphene [30]. The critical temperature, T_c of this superconducting graphene was found to be ≅ 17.9 K [30]. The values of the following parameters are: The temperature T=10K, the exchange field energy h_0 = 5meV and the Lande g-factor for graphene g= 4 [31]. The amplitude of the induced ac-signal is V_{ac} = 0.25 V. The Fermi energy, E_F, is calculated according to the following equation [31]:

$$E_F = \hbar v_F k_F \tag{18}$$

where the value of Fermi velocity, v_F is taken to be 10^6 m/S and the Fermi wave vector, k_F, is calculated in terms of charge-carrier concentration, N, via the following equation [31]:

$$k_F = \left(\pi N\right)^{0.5} \tag{19}$$

where N≅ 0.36x1012 cm^{-2} [31]. It must be noted that the value of the Fermi energy, E_F, (Eq. 18) must be modulated by the exchange energy of the ferromagnetic graphene (region I). Also, the value of Fermi energy, E_F, (Eq. 18) must be modulated by the order parameter, Δ, of the superconducting graphene [24, 30] which is simulated as random number in order to be optimized. Also, the Klein angles through the ferromagnetic graphene and superconductor graphene are varies randomly in order to be optimized. Now, the features of the present results are:

-Fig.2 shows the variation of the total Peltier coefficient, Π, that is the sum of the values for both parallel and antiparallel spin alignments with the gate voltage at different values of the frequency of the induced ac-field. We notice from this figure that the Peltier coefficient decreases as the gate voltage increases. The effect of the induced ac-field with certain frequency on the values of the Peltier coefficient might be due to the interplay of photon energy of the induced ac-field and the specular Andreev reflection of Dirac fermions. This interplay affects on the side-bands for spin flip in the corresponding region of the present graphene nanodevice and the tunneling rates [20, 21].

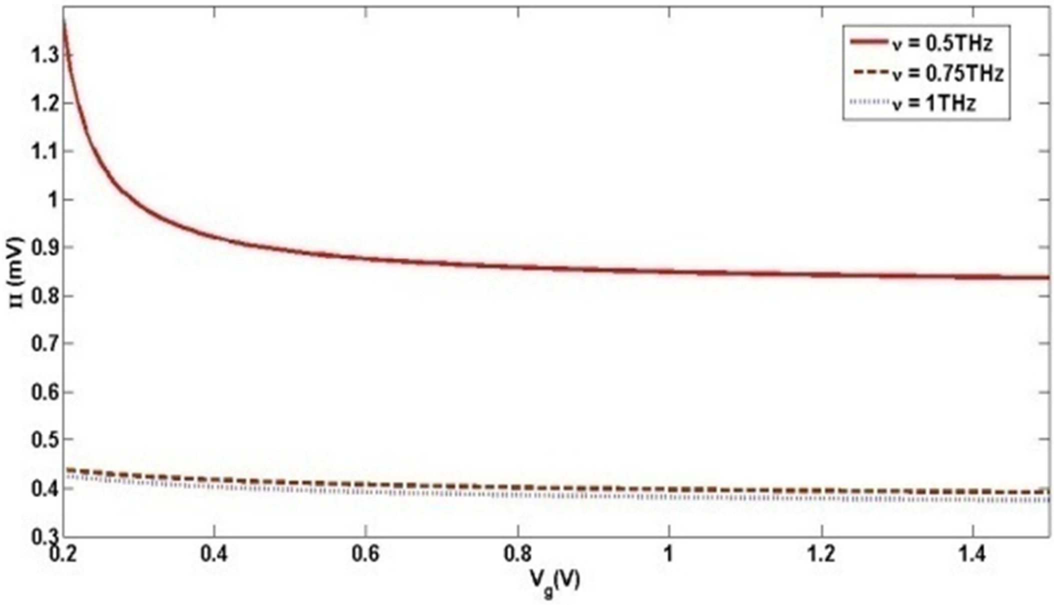

Fig. 2. *The variation of the Peltier coefficient with the gate voltage at different frequencies of the induced ac-field.*

-Fig.3 shows the variation of the Peltier coefficient, Π, with the giant magnetoresistance, GMR. Since the discovery of the giant magnetoresistance (GMR) effect [32, 33], the use of the intrinsic angular momentum of the electrons has opened up new spin based device concepts. The two channel model of spin-up and spin-down electrons with spin-dependent conductance very well describes spin and charge transport in such devices. Most recent work in spin caloritronics [4] aimed at spin-dependent thermoelectric effects led to the discovery of thermally driven spin sources [4] and the spin Peltier effect [16]. The giant magnetoresistance, GMR, was calculated in terms of the conductance for both the parallel and antiparallel spin alignments by the authors [34]. As shown from this figure that the Peltier coefficient increases with the giant magnetoresistance. The present result shows that the Peltier coefficient of the present investigated graphene nanodevice can be monitored by measuring the giant magnetoresistance.

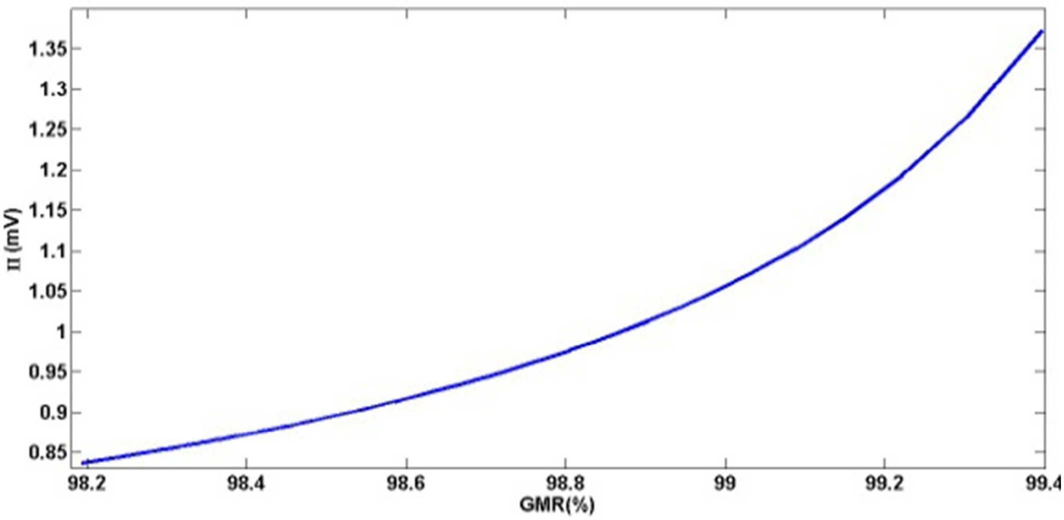

Fig. 3. *The variation of the Peltier coefficient with the giant magnetoresistance.*

It is interesting to consider another superconducting layer and its effect on the spin transport properties of the present investigated graphene nanodevice. So, the superconducting layer is Nb_3Ge (type II) [35] with critical temperature T_C = 23.2K and critical magnetic fields are B_{Co}= 37 T & B_C= 26.2T. The computation of the total sum of Peltier coefficient, for both parallel and antiparallel spin alignments, is performed at temperature, T equals 20K and the value of the frequency of the induced ac-field is 0.5 THz. So, Fig.4 shows the variation of the Peltier coefficient, Π, with the gate voltage, V_g, at different values of the magnetic field, B.

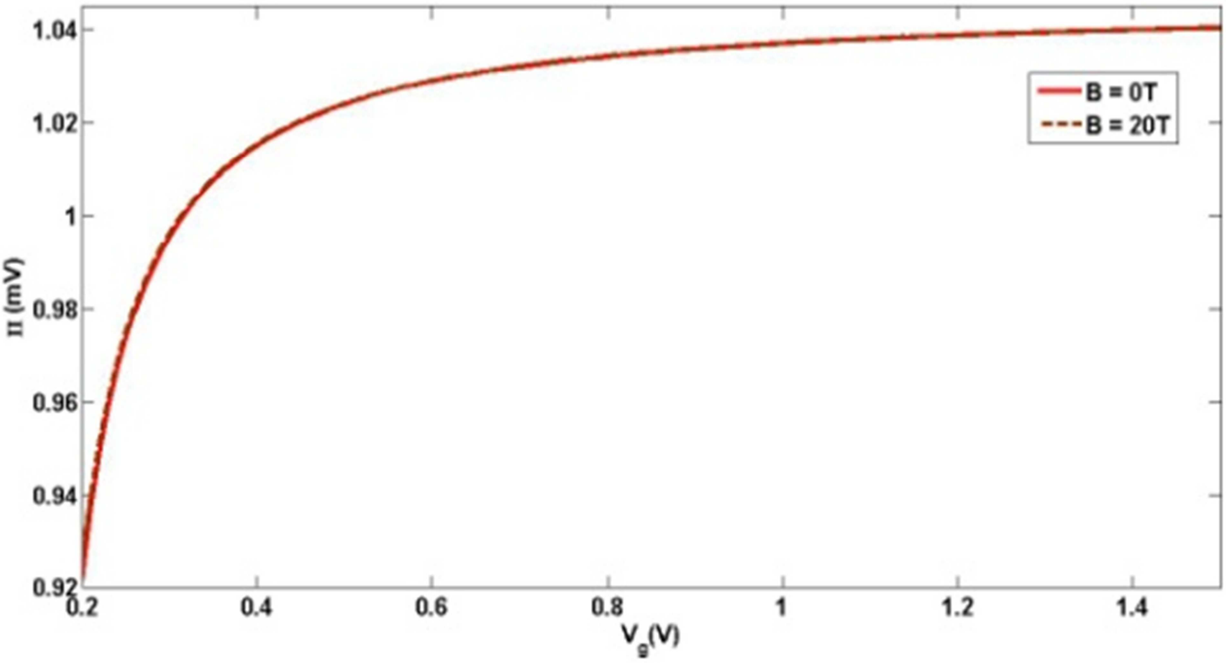

Fig. 4. *The variation of the Peltier coefficient with the gate voltage at different values of the magnetic fields.*

As shown from this figure that the Peltier coefficient increases with the increase of the gate voltage up to certain value, approximately, equal 0.93 V, and then the increase is slightly slow. As shown from this figure that the value of the calculated Peltier coefficient do not change with the variation of the magnetic field. This result might indicate that the present proposed graphene nanodevice is stable under the effect of the magnetic field, which is needed for magneto-thermoelectric nanodevices [21, 36].

-Fig.5 shows the variation of the total Peltier coefficient,Π, with the giant magnetoresistance, GMR.

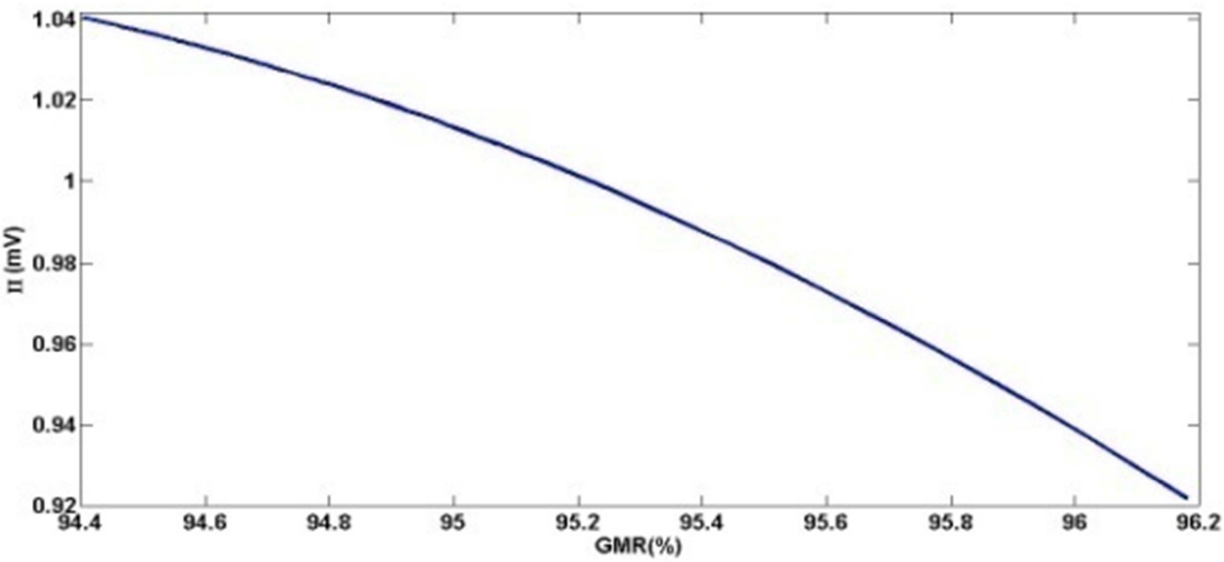

Fig. 5. *The variation of the Peltier coefficient with the giant magnetoresistance.*

As shown from this figure that the Peltier coefficient decreases as the giant magnetoresistance increases. The present result shows that the Peltier coefficient of the present investigated graphene nanodevice can be monitored by measuring the giant magnetoresistance.

4. Conclusion

In the preset paper, a spin dependent Peltier effect in graphene nanodevice is investigated. The graphene nanodevice is modeled as ferromagnetic grapheme / superconducting graphene junction with Schottky barrier at the interface between the two regions of the junction. Specular Andreev reflection plays an important role in tunneling Dirac fermions in the junction. The present paper shows that the spin Peltier effect is based on the assumption that spin-up and spin-down channels can transport heat independently. Also, with such present investigated graphene nanodevice the need for local and programmable refrigeration devices is growing and possibly the spin Peltier effect can fulfill this role. Also, spin dependent Peltier coefficient can be monitored by measuring the giant magnetoresistance. So, the present graphene nanodevice is promising for spin caloritronics applications.

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