Spin Coherent Transport in Graphene Superlattice Based Nanostructure

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Abstract— **Spin transport characteristics of single layer ferromagnetic graphene superlattice nanostructure is explored with application of external magnetic field and induced infrared (IR) ac-field with certain optimal value of frequency. The transfer matrix methods have been used to calculate the tunneling probability through the proposed nanostructure and Landuar Buttiker equation for conductance of both different spin alignments. Conductance of these spin alignments is used to declare the spin polarization and giant magneto-resistance. The Fano factor for the explored nanostructure has been computed for both spin alignments. Results show oscillatory manner with high selectivity form at certain ranges of transmission control parameters for the conductance and Fano factor for both spin alignments. These oscillations might be because of the induced proximity effect of gating of EuO which leads to spin filtering. Also results show that spin polarization attains 100% at certain value of gate voltage. So the present exploration of spin transport through single layer ferromagnetic graphene superlattice might have a scientific potential in the design and understanding of graphene superlattice based spin filters by optimizing the different parameters studied in this paper.**

Keywords— Spin polarization; graphene superlattice; ferromagnetic insulator EuO; giant magneto-resistance; magnetic field; ac-field

I. INTRODUCTION

Conventional electronics utilize the charge transport degrees of freedom only, while spintronics aims at utilizing the spin degrees of freedom alternative to or with the older degrees of freedom. The devices based on spintronics have merits over the conventional semiconductor devices in data processing speed, integration densities, nonvolatile data storage and power consumption [1-4]. The information technology field has been enhanced by a new era that opened up by the understanding of spin dependent electronic transport [5-10]. The basic code of data based on binary system ('1') 'ON' and ('0') 'OFF' for the logic gates, the spin state 'up' may be used for ('1') and the spin state 'down' may be used for ('0') in addition to the mixed states are promising in encoding, manipulating information and the new topics of quantum information applications.

One of the carbon allotropes is the graphene which is a single layer of carbon atoms arranged in a honeycomb like lattice that consists of two nonequivalent sublattice A and B with two atoms per unit cell [11, 12]. The half-integer quantum Hall effect [13], ultrahigh carrier mobility [14], optical effect [15,16], finite minimal electrical conductivity [13,17,18], special Andreev reflection [19] and some other properties are novel properties exhibited by graphene because of its special dispersion relation which makes its electrons behave like a massless relativistic particles. Recently, many systems of graphene have been investigated like effects of photon and phonon effects on different graphene nano-composites[20-23], the spin polarized transport in diluted magnetic semiconductors [24], ferromagnetic monolayer graphene barrier [25-27], a double ferromagnetic monolayer graphene barrier [28], and ferromagnetic monolayer graphene superlattice [29-31] have been explored which contribute to interesting results. Long spin lifetimes are expected in graphene because of its intrinsically low spin-orbit interaction and hyperfine couplings, also its adjustable carrier concentration make graphene a promising nanomaterial for spintronic applications [32-34].

The technique of superlattice is commonly used for modulation of band structures and some other physical properties of different materials [35-37]. Recently, graphene superlattices have been very interesting topic to explore a various quantum phenomena [38–41]. In the past few years, utilizing graphene-based magnetic superlattices [29-31, 42, 43] to enhance spin polarization became very attractive in spintronic applications.

The shot noise power which is the time-dependent current fluctuations due to the discreteness of the electrical charges, provides further information about the physics of an electronic system other than transport quantities such as the conductance [44,45]. The shot noise characterized by the dimensionless quantity Fano factor, *F*, defined as the ratio of the between noise power to average current [44]. Many authors investigated shot noise and Fano factor in different semiconductor, graphene and silicene superlattices [46-52].

This paper aims at the exploration of both the spin polarization transport characteristics and spin dependent Fano factor of single layer ferromagnetic graphene superlattice in the presence of both applied IR ac-field and external magnetic field. This paper is formed from four sections, first of all was the introduction, in Section 2, the proposed model and its theoretical formalism have been introduced. The numerical results for the spin transport characteristics of single layer graphene superlattice are presented in Section 3. Finally, the conclusion with a summary presented in Section 4.

II. THEORY OF THE PROPOSED MODEL

The next step is to deduce a formula for the conductance for the proposed spintronic nanostructure. This nanostructure is modeled based on the good possibility for developing novel spintronic nanostructure with single layer graphene superlattice above substrate (SiO_2) since it can be changed into a ferromagnetic graphene. This can be achieved by depositing a series of ferromagnetic insulator, EuO, strips on the top of the graphene superlattice sheet with metallic gate above it (Fig.1); magnetic exchange energy of 5 meV can be induced into this single layer graphene superlattice sheet [26, 27]. Also these strips cause a proximity effect splitting of the electronic states in graphene superlattice [29- 31, 53] which originates a superlattice with a spin-dependent potential profile. The two source and drain leads are normal single layer graphene.

The spin polarization transport is conducted in the presence of an induced IR ac-field and magnetic field, B. Photon-assisted conduction channels could be introduced by the oscillating ac-field that can be adjusted by the gate voltage to set it in the conduction window of that nanostructure [54,55]. The applied magnetic field produces Zeeman splitting with the contribution from the photon-assisted channels make the transport different for the different spin alignments resulting in photon-assisted spin polarized conductance.

Now starting derive the conductance, G, for both spin alignments also, the giant magneto-resistance (GMR) and the spin polarization (SP) corresponding to the conductance shall be derived as follows:

The proposed model of single layer graphene superlattice nanostructure designed as N superlattice period that consists of (2N-1) normal graphene strips with 2N ferromagnetic strips interlock.

Dirac equation is used to solve for Ψ with Hamiltonian H [28-31, 53] as:

$$H\Psi = E\Psi \qquad (1)$$

where,

$$H = -i\hbar v_F \hat{\sigma}.\nabla + \sigma_z h_0 + U + eV_{ac}\cos\omega t \qquad (2)$$

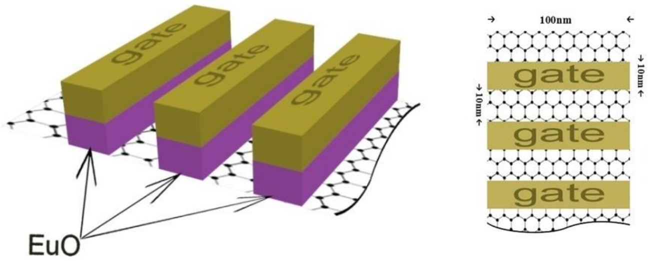


Fig.1.*Schematic diagram of graphene superlattice spintronic nanostructure.*

$$U = V_b + eV_{sd} + eV_g + \frac{1}{2} g\mu_B B\sigma \qquad (3)$$

where $\hbar$ is the reduced Planck's constant, v_F- Fermi velocity, $\sigma_{x,y,z}$ refer to Pauli matrices, h_0 is the exchange energy of the ferromagnetic graphene, V_{ac} and V_b represent the peak value of induced IR ac-field and the barrier height respectively, V_{sd} and V_g represent bias and gate voltages respectively, B represents the magnetic field strength, g - Lande g-factor and μ_B-Bohr magneton. Solving Eq.1, the following eigenfunctions are:

The eigenfunction in the left single layer graphene lead is:

$$\Psi_L(x) = \left[\left[\begin{pmatrix} 1 \\ \alpha\exp(i\theta) \end{pmatrix}\exp(ik_x x) + r\begin{pmatrix} 1 \\ -\alpha\exp(-i\theta) \end{pmatrix}\exp(-ik_x x)\right] e^{ik_y y}\right] J_{n'}\left(\frac{eV_{ac}}{n'\hbar\omega}\right)e^{-in'\omega t}. \qquad (4)$$

And the eigenfunction in the right single layer graphene lead is:

$$\Psi_R(x) = \left[t\begin{pmatrix} 1 \\ \alpha\exp(i\theta) \end{pmatrix} e^{ik_x x}.e^{ik_y y}\right] J\left(\frac{eV_{ac}}{n'\hbar\omega}\right)e^{-in'\omega t} \qquad (5)$$

And the eigenfunction for certain j^{th} strip of single layer ferromagnetic graphene is:

$$\Psi_j(x) = \left[\left[a_j\begin{pmatrix} 1 \\ \beta_j\exp(i\phi_j) \end{pmatrix}\exp(ik_{jx}x) + b_j\begin{pmatrix} 1 \\ -\beta_j\exp(-i\phi_j) \end{pmatrix}\exp(-ik_{jx}x)\right] e^{ik_y y}\right] J_{n'}\left(\frac{eV_{ac}}{n'\hbar\omega}\right)e^{-in'\omega t}. \qquad (6)$$

where, in Eq.(6) ϕ is the incident angle on certain j^{th} interface, θ (Eqs.(4,5)) is the incident angle on the left and right graphene leads and the parameters r and t (Eqs.(4,5)) are the reflection and transmission amplitudes. The parameter α (Eqs.(4,5)) is :

$$\alpha = \hbar v_F k_F \qquad (7)$$

where, k_F represents the Fermi wave vector. Also the parameter β_j is:

$$\beta_j = \frac{\left(E - E_{F_j} - U + \sigma h_j + n'\hbar\omega\right)}{\hbar v_{F_j}} \quad (8)$$

In Eqs. (4,5,6) $J_{n'}\left(\frac{eV_{ac}}{n'\hbar\omega}\right)$ is the n'^{th} -order of first kind Bessel function [45,46]. Eqs. (4, 5, 6) solutions have to be obtained by the existence of various minibands n' in a single layer graphene superlattice nanostructure, these solutions combined with $\exp(-in'\omega t)$ phase factor [54, 55]. Now applying boundary conditions at different interfaces using transfer matrix method [18, 19, 28-31]:

$$\begin{pmatrix} t \\ 0 \end{pmatrix} = \begin{pmatrix} e^{-ik_x.3L} & 0 \\ 0 & e^{ik_x.3L} \end{pmatrix} \begin{pmatrix} 1 & 1 \\ \alpha e^{i\theta} & -\alpha e^{-i\theta} \end{pmatrix}^{-1} T \begin{pmatrix} 1 \\ r \end{pmatrix} \quad (9)$$

In present nanostructure, the same length, L, for both normal and ferromagnetic strips is considered.
The parameter T (Eq.9) is:

$$T = \left(M_1 M_2 M_3 M_2\right)^N \begin{pmatrix} e^{-ik_x L} & e^{ik_x L} \\ \alpha e^{i\theta}.e^{-ik_x L} & -\alpha e^{-i\theta} e^{ik_x L} \end{pmatrix} \quad (10)$$

where, k_x is:

$$k_x = k_F \sin(\theta) \quad (11)$$

$$M_1 = \frac{1}{2\beta_j \cos(\phi)} \begin{pmatrix} \beta_j (e^{ik_x' L - i\phi} + e^{ik_x L + i\phi}) & (e^{ik_x' L} - e^{ik_x L}) \\ (e^{ik_x' L} - e^{ik_x L}) & \beta_j (e^{ik_x' L + i\phi} + e^{-i(k_x L + \phi)}) \end{pmatrix} \quad (12)$$

where, k_x' is:

$$k_x' = \sqrt{\beta_j^2 - k_F^2.\sin(\phi)} \quad (13)$$

$$M_2 = \frac{1}{2\alpha \cos(\theta)} \begin{pmatrix} \alpha (e^{ik_x' L - i\theta} + e^{-ik_x L + i\theta}) & (e^{ik_x' L} - e^{ik_x L}) \\ (e^{ik_x' L} - e^{-ik_x L}) & \alpha (e^{ik_x' L + i\theta} + e^{-i(k_x L + \theta)}) \end{pmatrix} \quad (14)$$

and,

$$M_3 = \frac{1}{2\beta_j \cos(\phi)} \begin{pmatrix} \beta_j (e^{ik_x' L - i\phi} + e^{-ik_x L + i\phi}) & (e^{ik_x' L} - e^{ik_x L}) \\ (e^{ik_x' L} - e^{ik_x L}) & \beta_j (e^{ik_x' L + i\phi} + e^{-i(k_x L + \phi)}) \end{pmatrix} \quad (15)$$

The tunneling probability, Γ(E), is given by the following equation as:

$$\Gamma(E) = \sum_{n'=1}^{\infty} J_{n'}^2 \left(\frac{eV_{ac}}{n'\hbar\omega}\right).|t|^2 \quad (16)$$

The conductance, **G**, is obtained by the Landauer–Buttiker formula as [24, 56]:

$$G = \frac{e^2 k_F W}{2\pi h} \int_{E_F}^{E_F + n'\hbar\omega} dE. \int_{-\pi/2}^{\pi/2} \Gamma(E).\left(-\frac{\partial f_{FD}}{\partial E}\right)\cos(\theta).d\theta \quad (17)$$

where

$$\left(-\frac{\partial f_{FD}}{\partial E}\right) = \left(4k_B T\right)^{-1} \cosh^{-2}\left(\frac{E - E_F' + n'\hbar\omega}{2k_B T}\right) \quad (18)$$

represents the first derivative of Fermi-Dirac distribution, in which $k_B T$ is the thermal energy effect (k_B is Boltzmann constant and T is the temperature) , E_F' is the modulated Fermi energy by the potential of ferromagnetic insulator strips, ***W*** is the junction width along y-direction.

Now, the spin can be manipulated and detected by determination of giant magneto-resistance, GMR, and spin polarization, SP. These parameters are calculated in terms of conductance, G, with the different spin alignments through the following equations [25-27]:

$$GMR = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\uparrow}} \quad (19)$$

and,

$$SP = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\uparrow} + G_{\uparrow\downarrow}} \quad (20)$$

where, $G_{\uparrow\uparrow}$ represents conductance when alignments of spin are in the same direction and $G_{\uparrow\downarrow}$ represents the conductance when the alignments of spin are in opposite directions.

The Fano factor, F, is given by [44,45,57,58]:

$$F = \frac{\int_{E_F}^{E_F+n'\hbar\omega} dE \int_{-\pi/2}^{\pi/2} \Gamma(E)[1-\Gamma(E)]\left(f_{FD(L)} - f_{FD(R)}\right)^2 \cos\theta d\theta}{\int_{E_F}^{E_F+n'\hbar\omega} dE \int_{-\pi/2}^{\pi/2} \Gamma(E)\left(f_{FD(L)} - f_{FD(R)}\right)\cos\theta d\theta} \quad (21)$$

where $f_{FD(L)}$ *and* $f_{FD(R)}$ are the left and right Fermi-Dirac distribution functions:

$$f_{FD(L)} = \frac{1}{1 + \exp\left(\frac{E - E_F + n'\hbar\omega}{k_B T}\right)} \quad (22)$$

and

$$f_{FD(R)} = \frac{1}{1 + \exp\left(\frac{E - E_F + n'\hbar\omega + eV_{sd}}{k_B T}\right)} \quad (23)$$

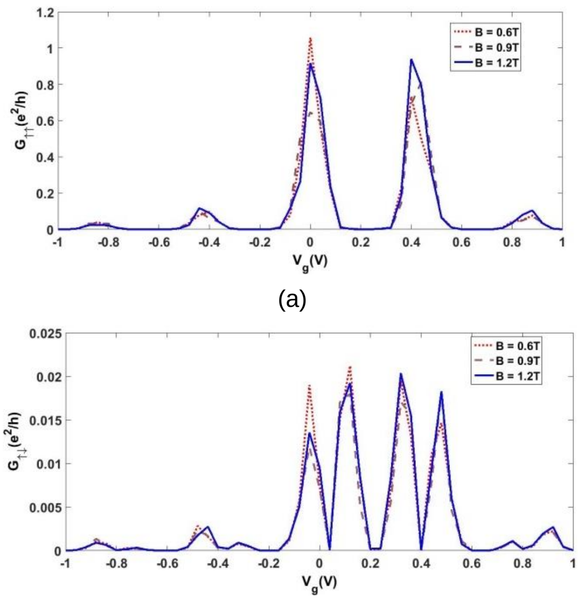
III. Numerical Calculations and Results

Numerical calculations are made for the present spin based nanstructure as: the conductance in the two different cases of spin alignments, G, (Eq.17), spin polarization, SP, (Eq.19), giant magneto-resistance, GMR, (Eq.20) and Fano factor, F, (Eq.21). The computations are made by taking N=1, (Eq.10). That is this nanostructure is normal graphene lead/ferromagnetic graphene/normal graphene/ ferromagnetic graphene/normal graphene lead. The values of the following parameters are [18, 19, 26, 29-31, 41-43,53, 59]: L=10 nm, W=100 nm, $v_F \approx 10^6$ m/s, barrier height, V_b, (Eq.3) equals 50 meV , Lande g-factor equals 4 and temperature, T= 50K. The modulated Fermi energy, E'_F , (Eq.18) is calculated in terms of the carrier density of quasiparticle Dirac fermions, n, through the following equation [60]:

$$E'_F = \sqrt{\pi}\,\hbar\,v_F\,\sqrt{n} \qquad (24)$$

Since the parameter n is tuned by proximity effect of the single layer ferromagnetic graphene [60,61]. Then, the parameter, n, is calculated using density function theory in order to get the optimum value of E'_F .

The IR range is expected to be the most suitable range to enhance both of the spin polarization, SP, and giant magnetresistance, GMR, of the present junction[54,55], as will be shown in the figures below, the value of the frequency of the IR ac-field was taken as an optimum value equals 100THz.



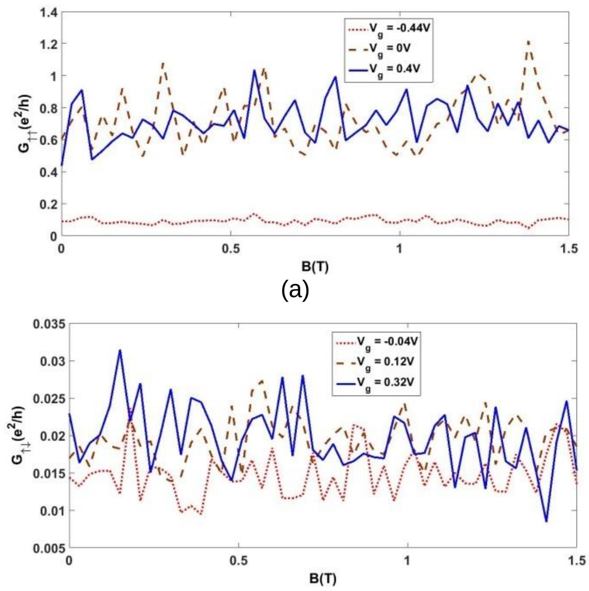
(a)

(b)

Fig.2. *The behavior of $G_{\uparrow\uparrow}$ (a) & $G_{\uparrow\downarrow}$ (b) with Vg, at various values of B in terms of (e^2/h) for Vg = [-1,1]V.*

-Figs.(2a, 2b) show the behavior of , G, with , V_g, in case of the two different spin alignments at various values of the applied magnetic field, B.

-Figs.(3a,b) show the behavior of the conductance in case of the two different spin alignments with magnetic field, B, at various values of gate voltage, V_g which is selected at peaks of the conductance in case of the two different spin alignments as shown from results in Fig.2.



(a)

(b)

Figs.3. *The behavior of the conductance (a) in case of parallel and (b) in case of anti-parallel spin alignments with magnetic field, B, at selected value of Vg at which the peaks occur.*

Figs.(2, 3) show oscillatory manner of conductance for the two different cases of spin alignments with different peak heights and also different periods.

Also it is noticed that from these figures that the magnitudes of conductance for the different cases of spin alignments are different. These results show that the two different spin alignments are predicted to play important role for encoding and manipulating digital quantum information processing. Also, these results show that the spin-dependent potential in high THz range (optimum value of frequency is 100THz) of the induced IR ac-field and certain range of the applied magnetic field is achieved by a set of strips made of ferromagnetic insulator material (eg. EuO) deposited above the top of graphene, and these strips will affect the spin states in graphene by splitting it because of the proximity effect. The structure of the proposed graphene superlattice nanostructure might serve as spin filters. These predicted results show that single layer graphene superlattice is a promising nanomaterial for spin filtering [28- 31].

-Fig.(4) shows the behavior of , SP, versus , V_g, at various values of magnetic field, B.

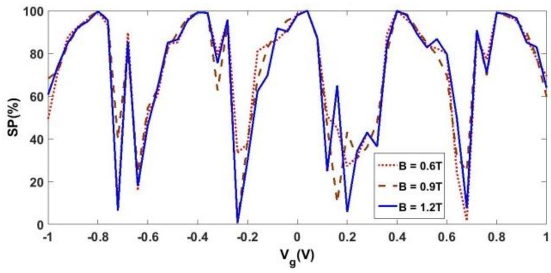


Fig.4. *The behavior of SP versus Vg, at various values of B.*

The spin polarization, SP, is found (see Fig.(4)) to exhibit oscillatory behavior and this trend depends on the values of magnetic field. The highest value of oscillating amplitude for SP% attains 100% under the conditions studied in the present paper. The above results means that design of the present spintronic nanostructure can be used to filter the spin states. Also, it is clear that the spin dependent parameters ($G_{\uparrow\uparrow}, G_{\uparrow\downarrow}$ & SP) have been enhanced because of the applied gate voltage, exchange field of ferromagnetic graphene superlattice, the applied magnetic field and applied IR ac-field. These present results for spin polarization are found in agreement with those in the literature [30, 31, 55, 62, 63].

-Fig.(5) shows the behavior of , GMR, versus , V_g, at various values of B.

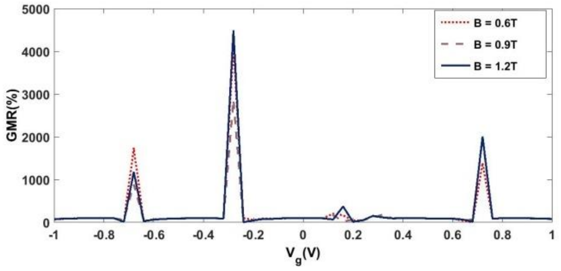
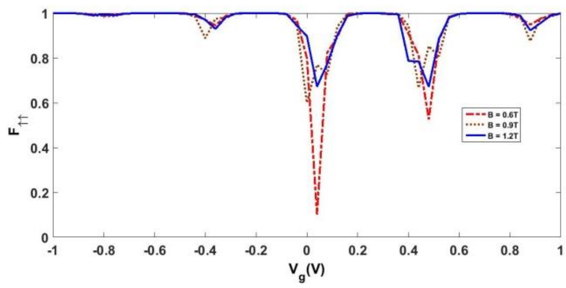


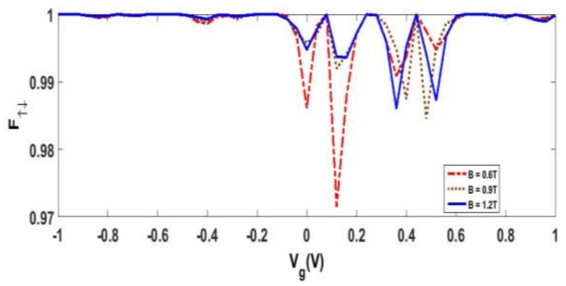
Fig.(5). *The behavior of GMR versus Vg, at various values of B.*

The giant magneto-resistance, GMR, exhibits certain peaks (see Fig.(5)) at certain values of gate voltages with certain values of the applied magnetic field. This result might be used for sensing magnetic fields [55, 59, 60] under the condition considered in our paper. It is noticed that the values of giant magneto-resistance, GMR, are very high, this might be to enhancements due to the parameters studied in the present paper [55, 63- 65].

-Figs.(6a, 6b) show the behavior of , F, with , V_g, in case of the two different spin alignments at various values of the applied magnetic field, B.



(a)



(b)

Fig.6. *The behavior of* $F_{\uparrow\uparrow}$ *(a) &* $F_{\uparrow\downarrow}$ *(b) with Vg, at various values of B.*

Fano factor for both spin alignments (Figs.6a,b) exhibits an oscillatory behavior. Also results show that the values of both $F_{\uparrow\uparrow} \& F_{\uparrow\downarrow}$ (Figs.6a,b) equal, approximately, to one which are corresponding to full Poissonian type and less than one for Sub-Poissonian type of transport [48-53]. The minimum in the Fano factor (Figs.6a,b) is associated with the maximum in the conductance (Figs2a,B) [48-53]. Also these results show that the value of Fano factor is a tool for distinguishing the behavior of transport that is why this kind of information cannot be extracted from the conductance [48-53].

IV. Conclusion

The spin-dependent transport property of single layer ferromagnetic graphene superlattice nanostructure is explored under influence of external magnetic field and induced IR ac-fields with certain optimum value of frequency.

Dirac equation is used to calculate conductance of the proposed nanostructure and tunneling probability through such nanostructure is deduced using transfer matrix method. Results show oscillatory manner for both the conductance and Fano factor with the two spin alignments and also oscillations trend of spin polarization. The highest value of spin polarization might be achieved and tuned by gate voltage and the two fields. These present results confirm that the spin transport property is coherent so as the weak spin-orbit coupling of electrons in single layer graphene nanostructure leads to an extraordinarily long spin-coherence length [66].This research is very important for ferromagnetic graphene superlattice based spin logic applications, quantum digital information processing and magnetic sensors in different electronic nanodevices. The proposed design of graphene superlattice nanostructure could be experimentally realizable in field of nanotechnology for spintronic nanodevices. These results motivate to explore spin transport properties of ferromagnetic graphene superlattice based nanostructure for the case of different sized superlattices and also for the effect of defects and applied strain to the graphene.

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