Spin transport in ferromagnetic bilayer graphene superlattice

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Abstract

Using the transfer-matrix method, Spin transport in ferromagnetic bilayer graphene superlattice, which can be realized by putting a series of ferromagnetic insulator layers on top of a bilayer graphene is studied. The ferromagnetic layers with exchange energy $E_{ex}$ are in contact with gate of potential energy $V_g$. It is considered that the magnetization of the two ferromagnetic layers are aligned parallel (P) and antiparallel (AP) to each other. The spin transmissions probability (T$_P$ and T$_A$) and the spin conductance ($G_P$ and $G_A$) are studied. The spin polarization is calculated through the spin conductance. The total conductance ($G^P_T$ and $G^AP_T$) is also considered. It is found that perfect reflection can occur at normal incident, i.e., $T_P = T_A = 0$. The spin conductance and the spin polarization are found to exhibit oscillatory depending on the barrier height. The highest value of oscillating amplitude for SP% can rich 100% or (-100%) under special condition.

PACs: 73.22.Pr; 72.80.Vp; 68.65.Pq; 61.48.Gh

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1. Introduction

Graphene is a monolayer of carbon atoms densely packed in a honeycomb lattice that consists of two non equivalent sublattice A and B with two atoms per unit cell [1]. The effective carrier of graphene behave like the massless relativistic particle [1-3]. One of the interesting aspects of graphene is that the low energy electron states near the edges of Brillouin zone can be described by the conical energy spectrum. As a result, Fermi velocity of electron in graphene is constant ($v_F \approx 10^6$ m/s) and we can describe the charge carriers (electrons and holes) by the Dirac equation near to the Dirac point $K$ and $K'$ [2,3]. It exhibits many novel electronic and transport properties for example, the observer of half-integer quantum hall effect [2], ultrahigh carrier mobility [3] optical effect [4,5], finite minimal electrical conductivity [2,6,7], special Andreev reflection [8] and so on.

The charge carriers in bilayer graphene have parabolic energy spectrum, which means they are massive quasiparticles, similar to the conventional nonrelativistic electrons. In addition, due to symmetry in four sublattice in honeycomb lattice these quasiparticles are chiral. A bilayer graphene due to the arrangement of layers is divided to two types of AA and AB. In AA arrangement, the two graphene layers are stacked directly on top of each other that is metastable [9], while in AB configuration, the two layers are stacked alternatively providing a more stable structure.

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In the past few years, the spin polarized transport of electrons in conventional ferromagnetic nanostructures [10], ferromagnetic monolayer graphene barrier [11,12], a double ferromagnetic monolayer graphene barrier [13], and ferromagnetic monolayer graphene superlattice [14] have been investigated which contribute to interesting results. It would, therefore, be worth to investigate the spintronic property in ferromagnetic bilayer graphene superlattice. Graphene is not ferromagnetic naturally. However, researchers have recently shown that ferromagnetism state can be induced in graphene layer by different methods such as doping and defect [15], applying an external electric field [16], or deposit a ferromagnetic insulator on top of the graphene - called “ferromagnetic graphene” [12]. The deposit of a ferromagnetic insulator on top of the graphene sample to induces an exchange splitting in graphene. A narrow gate on top of the insulator allows to control the Fermi level in the same region. For instance, a ferromagnetic state with exchange energy of $E_{ex} \sim 5$ meV can be induced by depositing the ferromagnetic insulator EUO (Europium oxide) on top of graphene [12]. The electronic transport in a ferromagnetic structure is spin dependent. The ability to manipulate both the charges on and the spins of the electrons has lead to the development of a new field of application, spintronics.

In this paper spin transport in ferromagnetic bilayer graphene superlattice is investigated by using the transfer-matrix method. The ferromagnetic bilayer graphene superlattice can be realized by putting a series of ferromagnetic insulator layers on top of a bilayer graphene, and its local magnetization is induced by magnetic proximity effect. We have evaluated the spin dependent transmission probability, the spin
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conductance, and spin polarization for the system. In addition, we consider the total conductance for parallel (P) and antiparallel (AP) configuration.

The paper is organized as follows; our method and theory are described in the next section. In Section 3, we discuss our results, and finally, we end the paper with a brief summary.

2. Model and theory

To study spin dependent transport, we consider a ferromagnetic graphene superlattice with rectangular potential barrier which is obtained by putting a series of magnetic insulator layers, such as EUO, with metallic gate on the top of bilayer graphene sheet. This bilayer graphene sheet is located on a substrate such as \( SiO_2 \). The grown direction is supposed to be the x axis. In order to neglect the strip edges, we focus on the case where the width of the graphene strip is much larger than the width of barriers in graphene superlattice [17,18]. The schematic of potential profiles for the ferromagnetic graphene superlattice is shown in Fig.1.

Charge carriers in bilayer graphene are described by an off-diagonal Hamiltonian [19,20]:

\[
\hat{H}_0 = -\frac{\hbar^2}{2m^*}(k_x - ik_y)^2,
\]

which yields a gapless semiconductor with chiral electrons and holes with finite mass \( m^* \). \( m^* \) is taken as 0.035 \( m_e \) which \( m_e \) is the bare electron mass. Therefore, we can describe the Hamiltonian of charge carriers in the bilayer ferromagnetic graphene superlattice as:

\[
\begin{bmatrix}
0 & (k_x - ik_y)^2 \\
0 & 0
\end{bmatrix}
\]

(1)

where

\[
\begin{align*}
V(x) &= \begin{cases} V_0 + E_{ex} & \text{for the barrier areas,} \\ 0 & \text{for the well areas.} \end{cases} \\
\psi_1(x,y) &= (a e^{i k_x x} + h e^{-i k_x x} + c e^{i k_x x} + d e^{-i k_x x}) e^{i k_y y} \\
\psi_2(x,y) &= (a e^{i k_x x} + h e^{-i k_x x}) e^{i k_y y}.
\end{align*}
\]

(3)

Fig. 1. Schematic view of the ferromagnetic graphene superlattice (a), the electronic energy profile (b), and \( N \) ferromagnetic barriers of thickness \( D \) separated by wells of thickness \( L \) (c).
Here $E$ is the energy of the incident electron and $\sigma$ denotes its spin state. An important difference in wave function between the monolayer and the bilayer graphene is that in the latter case there are four possible solutions as shown in Eq. (3). By applying the continuity of wave function and their derivatives at the boundaries for system which consist of $N$ barriers and using the transfer-matrix method, we can obtain the angular dependent spin transmission probability as:

$$ T_{\sigma}(\varphi) = \frac{1}{2} \alpha_{\sigma} \alpha_{\sigma^*} $$

(6)

The spin-dimensionless conductance of the system can be calculated by means of Butiker formula [22]:

$$ G_{11} = G_0 \int_{-\pi/2}^{\pi/2} G_{11}(\varphi) \cos(\varphi) d\varphi, $$

(7)

where $G_0 = e^2 v_F \omega / h^2$ in which $\omega$ is the width of the graphene strip along the $y$ direction and the total conductance can be read as:

$$ G_{q} = G_{1} + G_{\uparrow}. $$

(8)

In order to investigate the spin filtering and spin polarization in a simple way, we introduce the spin polarization of conductance in the parallel magnetization configuration as:

$$ SP\% = \left( \frac{G_1 - G_{\downarrow}}{G_1 + G_{\downarrow}} \right) \times 100. $$

(9)

### 3. Numerical result and discussion

In this section we present our numerical study based on the method described in the previous section. In all calculations, the Fermi energy $E$ and the exchange energy $E_{exx}$ are equal to 17 $meV$ and 5 $meV$ in orderly. Firstly, we calculate the spin transmission probabilities for the charge carriers through the ferromagnetic bilayer graphene superlattice with four barriers and three wells. The spin transmission probabilities as a function of incident angle $\varphi$, at various barrier height $V_0$ are shown in Fig. 2. Figs. 2(a) and 2(b) represent $T_{\uparrow}(\varphi)$ and $T_{\downarrow}(\varphi)$ in the parallel configuration, respectively. Figs. 2(c) and 2(d) represent $T_{\uparrow}(\varphi)$ and $T_{\downarrow}(\varphi)$ in the antiparallel configuration, respectively.

The barrier thickness $D$ and well thickness $L$ are taken as 20 $nm$ and 15 $nm$, respectively. The angular dependence of spin transmission probability also depends on...
the number of barriers or wells. Fig. 3(a) and 3(b) show such a spin transmission probability for the ferromagnetic bilayer graphene superlattice with ten barriers in the parallel magnetization configuration. Figs. 3(c) and 3(d) represent the corresponding results for the antiparallel magnetization configuration. In these figures the barrier thickness $D$ and the well thickness $L$ are taken as 7 nm and 3 nm, respectively. Compare them with the case of double barriers (Fig. 2), we find that more peaks appear with the increase of barrier number. This indicates that the number of barriers play an important role in transmission for the ferromagnetic bilayer graphene superlattice. According to Figs. 2 and 3 when $V_0 > E$ perfect reflection $T_{11}(0) = 0$ is observed at normal incidence. This is completely different from the ferromagnetic monolayer graphene superlattice, in which the spin transmission probability of normally incident electrons always equals to 1 [5]. The latter is the feature unique to massless Dirac fermions and is directly related to Klein paradox [21]. The perfect reflection due to the fermions in monolayer and bilayer graphene exhibit chiralities that resemble those associated with spin 1/2 and 1, respectively [22]. Another explanation for this phenomenon can be thought as in bilayer graphene barrier, when $V_0 > E$ the electron wave vector in the barriers is imaginary, which corresponds to evanescent wave inside the barrier. In addition, Figs. 2(c), 2(d), 3(c) and 3(d) show that in the antiparallel magnetization configuration $T_{11}(0) = T_{1}(0)$ which is due to the symmetry of the structure for the electrons with spin up and spin down. Also as it can be seen clearly, all spin transmission probability at various barrier height exhibits different behavior which relate to the oscillating behavior of the $T_{11}(0)$ with respect to $V_0$. Fig. 4(a) shows the spin and total conductivities as function of barrier height $V_0$ for the parallel magnetization configuration and Fig. 4(b) represents the same plots for the antiparallel magnetization configuration. Fig. 4(c) displays spin polarization as a function of $V_0$. In these figures the number of the barriers is taken as four. Figs. 5(a-c) represent the corresponding results for the ferromagnetic bilayer graphene superlattice with ten barriers. In Figs. 4(a), 4(b), 5(a) and 5(b) the barrier and the well thicknesses $D$, $L$ are taken as 6 nm and 4 nm, respectively. In Fig. 4(c) the aforementioned parameters are both taken 6 nm, while 5 nm in Fig. 5(c). According to Fig. 4 and 5 the conductivities and the spin polarization are an oscillating function of $V_0$. This oscillatory behavior is as a result of the angular dependences of spin transmis-

![Fig. 3. Transmission probability as a function of incident angle $\varphi$ for spin up and spin down in the parallel magnetization configuration [(a) and (b)], and in the antiparallel magnetization configuration [(c) and (d)] for ten barriers structures.](image-url)
sion probability for the ferromagnetic bilayer graphene superlattice which is an oscillating function of $\sigma$ and $\tau$ and is determined by $\lambda$. This lead to that $\lambda$. Conductivities and spin polarization are oscillating function of $\lambda$. In Figs. 4(c) and 5(c) we see the highest value of oscillatory amplitude for SP% can reach 100% or (-100%) under special condition. when SP% = 100% or SP% = -100% the system transports only the electrons with spin up or spin down respectively. Because the barrier height is easy to be changed by controlling the gate voltage, this means that we can filter the electrons with spin up or spin down by this system.

The antiparallel magnetization configuration causes identical angular-dependent transmission probability for both spin up and down, which is clear in Figs. 4(b) and 5(b).
4. Summary

Based on transfer-matrix method, we have investigated spin transport in a ferromagnetic bilayer graphene superlattice, which is made of a series of ferromagnetic insulator layers with gate voltages on top of a bilayer graphene. It is found that when $V_o > E$ perfect reflection $T_{e}(O) = 0$ is observed at normal incidence. We have calculated the conductivity and spin polarization of the system and showed that conductivity and spin polarization exhibit oscillatory behavior with the barrier height. In addition we have found that in the antiparallel magnetization configuration $T_{f}(\phi) = T_{g}(\phi)$ and $G_1 = G_2$. We have also found an interesting result, the highest value of oscillating amplitude for SP% can reach 100% or (-100%) under suitable condition which means we can filter spin up and spin down and graphene has a great potential for application in nano-material spintronic devices.

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Reference