Quantum oscillation of conductance and negative tunneling magnetoresistance in velocity-modulated graphene spin-valve device

Husnul Fuad Zein\(^1\), Wachiraporn Choopan\(^2\), Phitsini Suvarnaphaet\(^3\) and Watchara Liewrian\(^{1,*}\)

\(^1\) Theoretical and Computational Science Center (TaCS), Science Laboratory Building, Department of Physics, Faculty of Science, King Mongkut’s University of Technology Thonburi, Bangmod, Thungkru, Bangkok, Thailand 10140
\(^2\) General Education Section, Christian University of Thailand, Donyaihom District Nakhonpathom, Thailand 73000
\(^3\) Department of Physics, Faculty of Science, Mahidol University, Rama 6th Road, Bangkok 10400, Thailand

\(^*\)E-mail: watchara.liewrian@mail.kmutt.ac.th

Abstract. Mismatch effect of renormalized Fermi velocity of massive Dirac fermions on the spin transport properties and tunneling magnetoresistance in a gapped graphene-based ferromagnetic/velocity barrier/ferromagnetic (FG/VB/FG’) junction is investigated. The electrostatic potential created by the applied voltage on the VB region can generate spin-dependent collimation of Dirac fermions. The quantum beating pattern in the spin conductance oscillation are shown as a function of the Fermi energy at low velocity ratio (the Fermi velocity inside the barrier to that outside the barrier). The Fermi-velocity mismatch effect between graphene junction give rises to the oscillating behavior of negative tunneling magnetoresistance at the velocity ratio less than one.

Keywords: Graphene: Magnetic tunnel junction: Dirac equation: tunneling magnetoresistance: Velocity modulation: spin valve

1. Introduction

Graphene has two-dimensional atomic structure of carbon arranged on hexagonal lattice [2] where every unit cell is built from two sub-lattices. It is a basic concept to explain other carbon structures such as carbon nanotube, fullerene and graphite [1]. The linear dispersion relation makes graphene as the unique material with zero energy gap semiconductor [3]. The charge carries in graphene shows a behaviour like relativistic massless particle with Fermi velocity that replaces the speed of light, therefore many phenomena such us Klein tunnelling, anomalous quantum hall effect [2], etc. can be happened in graphene. This paper is interested in the magnetic junctions which consists of a FG/VB/FG (FG denotes a ferromagnetic gapped graphene; VB is normal gapped graphene with a metal gate potential place above it. The velocity dependence spin transport in this model is also considered, the Fermi velocity in the middle layer will be not the same from the other and the gap exists in all three layers, not just in the middle layer. We show Transmission probability, spin conductance, and tunnelling magnetoresistance (TMR).
2. Model and General Formulation
We assume that the ferromagnetic gapped graphene [3] was formed by depositing the ferromagnetic material [1] on top of the gapped graphene and the gate potential V induced barrier in the second region [2].

Figure 1. Gapped graphene-based magnetic tunnel junction model

For a gapped graphene-based magnetic tunnel junction as shown in Fig. 1, the relativistic-like carriers in the different regions will be governed by the Dirac equation

\[
\begin{bmatrix}
\frac{\mu + \Delta}{\hbar v_F(x)k_x + \hbar v_Fk_y} & \hbar v_F(x)k_x - \hbar v_Fk_y \\
\hbar v_F(x)k_x + \hbar v_Fk_y & \frac{\mu - \Delta}{\hbar v_F(x)k_x + \hbar v_Fk_y}
\end{bmatrix}\begin{bmatrix}
\psi_1 \\
\psi_2
\end{bmatrix} = E \begin{bmatrix}
\psi_1 \\
\psi_2
\end{bmatrix}
\]

(1)

where \( E_F \) is the Fermi energy in the graphene; \( \mu \), the chemical potential acting on a spin carrier in each region, \( v_F \) is the Fermi velocity and where \( \Delta \) is the energy band gap that opens up in the energy spectrum of the carriers. In our model, the graphene in regions \( x < 0 \) and \( x > L \) is in the ferromagnetic states having parallel (antiparallel) alignment of in-plane magnetic field. The solutions of the above Dirac equation in the three regions are

\[
\mu = \begin{cases} 
-E_F - \eta \hbar ; & x < 0 \\
-E_F + V ; & 0 < x < L \text{ and } v_F(x) = \begin{cases} 
v_1 ; & 0 < x < L \\
v_2 ; & x > L
\end{cases}
\end{cases}
\]

(2)

where \( \eta = 1(-1) \) denotes spin-up (down) of carrier in ferromagnetic regions, \( \sigma = 1(-1) \) denotes a parallel (antiparallel) alignment of in-plane magnetic field. The solutions of the above Dirac equation in the three regions can be determined in the usual manner.

\[
\Psi_{\sigma,\eta}(x < 0, y) = \left( \frac{1}{A_{\sigma,\eta}e^{i\theta_{\sigma,\eta}}} \right) e^{ik_{\sigma,\eta}\cos(\theta_{\sigma,\eta})x + r} \left[ \frac{1}{-A_{\sigma,\eta}e^{-i\theta_{\sigma,\eta}}} \right] e^{-ik_{\sigma,\eta}\cos(\theta_{\sigma,\eta})x} e^{ik_{\sigma,\eta}y}
\]

(3)

\[
\Psi(0 \leq x \leq L, y) = \left( a\left[1 \left[B_{\sigma,\eta}e^{i\phi}\right] e^{i\eta\cos(\phi)x} + b\left[1 - B_{\sigma,\eta}e^{-i\phi}\right] e^{-i\eta\cos(\phi)x} \right] e^{ik_{\sigma,\eta}y}
\]

(4)

and

\[
\Psi_{\sigma,\eta}(x > L, y) = \left( t\left[1 \left[A_{\sigma,\eta}e^{i\theta_{\sigma,\eta}}\right] e^{ik_{\sigma,\eta}\cos(\theta_{\sigma,\eta})x} \right] e^{ik_{\sigma,\eta}y}
\]

(5)

where

\[
k_{\sigma,\eta}(k_{\sigma,\eta}) = \frac{\sqrt{(E + E_F + \sigma)\eta h}}{h v_F}, q = \frac{\sqrt{(E + E_F - V)^2 - \Delta^2}}{\xi h v_F}, A_{\sigma,\eta}[A_{\sigma,\eta}'] = \frac{E + E_F + \sigma)\eta - \Delta}{h v_F}, \text{ and } B = \frac{E + E_F - V - \Delta}{h v_F}.
\]

The coefficients \( t \) is the amplitudes of transmitted Dirac spin carriers. The transmission probability is defined as

\[
T_{\sigma,\eta} = \frac{|I_{\text{out}}(\sigma,\eta)|}{|I_{\text{in}}(\sigma,\eta)|}.
\]

(6)

where \( I_{\text{in}} = v_F\Psi_{\text{in}}^*\sigma_{\text{x}}\Psi_{\text{in}}, I_{\text{out}} = v_F\Psi_{\text{out}}^*\sigma_{\text{x}}\Psi_{\text{out}}^* \) and \( \sigma_{\text{x}} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \). The transmission coefficient is obtained using the following boundary conditions

\[
\Psi_{\sigma,\eta}(x = 0^-, y) = \sqrt{\xi} \Psi (x = 0^+, y) \text{ and } \Psi (x = L^-, y) = \frac{1}{\sqrt{\xi}} \Psi_{\sigma,\eta}(x = L^+, y)
\]

(7)

where \( \xi = \frac{v_F}{v_1} \). Solving for \( t \), we get
\[
t(t_{\sigma,\eta}) = e^{2iLq(\sigma,\eta)(\theta_{\sigma,\eta}) - \Delta_0(1 + e^{2i\theta_{\sigma,\eta}})(1 + e^{2i\phi})},
\]

Transmission coefficient in equation (8) can be numerically evaluated for the different values of the incident angles by substituting into the equation (6) to obtain the numerical values of the transmission probability for the different angles of incidence. They can be substituted into the Landauer-Büttiker equation for the spin conductance

\[
G^\sigma_{\eta} = G_0 \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\theta_{\sigma,\eta} T_{\sigma,\eta}(\theta_{\sigma,\eta}) \cos \theta_{\sigma,\eta},
\]

where \(G_0 = \frac{e^2 m_e v_F W}{\hbar} N(E_F)\) with \(N(E_F) = \frac{\xi \sqrt{(E + E_F + \eta h)^2 - \Delta^2}}{\sqrt{(E + E_F)^2 - \Delta^2}}\).

The critical incident angle at which the wave vector in the graphene barrier becomes complex. It is given by

\[
\theta_{\sigma,\eta}^c = \sin^{-1} \left( \frac{1}{\xi} \sqrt{\frac{(E + E_F - V)^2 - \Delta^2}{(E + E_F + \eta h)^2 - \Delta^2}} \right).
\]

The charge conductance is defined as \(G_{\sigma} = \frac{1}{2} (G_{\eta=1}^\sigma + G_{\eta=-1}^\sigma)\) and the tunnel magnetoresistance (TMR) is

\[
TMR(\%) = \frac{G_{\sigma=1} - G_{\sigma=-1}}{G_{\sigma=1}} \times 100\%.
\]

3. Result and Discussion

We plot the transmission probability with the incident angles by varying Fermi velocity. Figure 2a and 2b show the numerical calculation of the spin-dependant transmission probability as a function of incident angles in parallel junction of FG/VB/FG’ with \(E_F = 50\ meV, \Delta = 20\ meV, h = 5\ meV, L = 100\ nm, V = 100\ meV\) and the velocity ratio \(\xi = 0.2, \xi = 0.5, \xi = 1.2\) and \(\xi = 1.5\). The transmission probability is zero after critical angles at \(\xi \geq 1\). They have different critical angle according to the eq. 10, the peak shows the maximum transmission probability. In the normal incident angle the transmission is not maximum due to the gapped graphene junction.

![Figure 2](image_url)

**Figure 2.** Transmission probability as the function of critical angle varying the velocity ration spin up (a) and spin down (b) in the parallel FG/VB/FG’ gapped graphene junction.
A quantum beats oscillation pattern is appeared in the conductance as the function of Fermi energy at the small velocity modulation because of the difference of resonant energy in asymmetry of two barriers and the presence of barrier voltage. The beat is not really clear at the small energy gap as shown in Fig. 3a but it will be clear when the energy gap increases as shown in Fig 3b. Moreover, using the different energy gap the beat will be clearer in Fig. 3c. The number of beats are proportional to the length of the barrier \( L \), it means that the different of resonant energy is much higher when the energy gap \( \Delta \) and the length of the barrier \( L \) increase.

The effect of velocity modulation in FG/VB/FG’ model is the oscillation of negative TMR at the velocity ratio less than one. The frequency of the oscillation decreases when the velocity ratio increases. Figure 4a, 4b, 4c and 4d show the TMR as the function of Fermi energy at \( \xi = 0.2 \), \( \xi = 0.4 \), \( \xi = 0.6 \), \( \xi = 0.8 \) respectively. The negative TMR is the signature of weak localization behaviour.

4. Conclusion
In the conclusion, we have investigated the effect of velocity modulation FG/VB/FG’ gapped graphene junction model in transmission probability, conductance and tunneling magnetoresistance. The transmission probability goes to zero after the critical angle. The quantum beats oscillation pattern is shown at the small velocity ratio. The negative oscillation of TMR is also shown at the velocity ration less than one and the frequency of the oscillation decreases with increasing the velocity ratio.

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