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Negative tunnel magnetoresistance and spin transport in ferromagnetic graphene junctions

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Abstract
We study the tunnel magnetoresistance (TMR) and spin transport in ferromagnetic graphene junctions composed of ferromagnetic graphene (FG) and normal graphene (NG) layers. It is found that the TMR in the FG/NG/FG junction oscillates from positive to negative values with respect to the chemical potential adjusted by the gate voltage in the barrier region when the Fermi level is low enough. Particularly, the conventionally defined TMR in the FG/FG/FG junction oscillates periodically from a positive to negative value with increasing the barrier height at any Fermi level. The spin polarization of the current through the FG/FG/FG junction also has an oscillating behavior with increasing barrier height, whose oscillating amplitude can be modulated by the exchange splitting in the ferromagnetic graphene.

(Some figures in this article are in colour only in the electronic version)

Since its successful isolation, graphene has drawn rapidly growing interest for its unique characteristics and potential applications [1]. Graphene, namely, a monolayer of graphite, is a two-dimensional honeycomb lattice of carbon atoms. It is a zero-gap semiconductor whose valence and conductance bands touch at two inequivalent Dirac points (often referred to as K and K') at the edges of the hexagonal Brillouin zone. The quasiparticles around the Fermi level in graphene are described by the massless relativistic Dirac equation, which results in the linear energy dispersion valid even for a Fermi level as high as 1 eV [2, 3]. Such peculiar electronic properties in graphene bring in many interesting phenomena, for instance, the half integer quantum Hall effect [4–6], minimum conductivity [4, 5] and Klein tunneling [7].

Graphene is clearly an excellent material for spintronics. The carrier density in graphene can be modulated continuously from hole-like to electron-like type across the Dirac points by the gate voltage. The long mean free path [8] and long spin relaxation length [9] make graphene a promising candidate for use in ballistic spin transport. Magnetism can be induced in graphene by doping and defects [10–12] or by applying an external transverse electric field [13]. Recently, it has been theoretically predicted [14] and experimentally realized [9, 15, 16] that the ferromagnetic correlation can be induced in graphene by the proximity effect. A rough estimation of the exchange splitting in graphene induced by the ferromagnetic insulator EuO could be 5 meV [14].

In this paper, we study the tunnel magnetoresistance (TMR) and spin filter effect in ferromagnetic graphene junctions which are composed of normal graphene (NG) and ferromagnetic graphene (FG) layers. In such a junction a local gate electrode is attached to the central region of the graphene to control its chemical potential. The graphene barrier can be normal or ferromagnetic. Note that the positive TMR oscillating with respect to the barrier height has been studied in the FG/NG/FG junction [17], while the spin polarization of current oscillating around the zero polarization with increasing barrier height has also been studied in the NG/FG/NG junction [18]. We combine these two effects in one model and investigate its properties. Based on analytical derivation and numerical calculations, we find that the TMR can oscillate from the positive to negative value without damping and the oscillating spin polarization of current can be modulated by the exchange splitting in the ferromagnetic graphene.

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Consider a two-dimensional FG/graphene/FG junction (see figure 1) in a graphene sheet, whose two interfaces are parallel to the y axis and located at $x = 0$ and L. The left and right FG electrodes are separated by a square barrier of length L and height U which is controlled by the local gate voltage. For simplicity, we assume that the two ferromagnetic graphene electrodes have the same exchange splitting h_0. The Hamiltonian of the system is

$$H = -\mathrm{i}\hbar v_F \boldsymbol{\sigma} \cdot \nabla + V(x) - \zeta h(x), \tag{1}$$

where $v_F \approx 10^6$ m s^{-1} is the Fermi velocity in graphene and $\boldsymbol{\sigma} = (\sigma_x, \sigma_y)$ is the two-dimensional vector of Pauli matrices. $V(x) = U\Theta(x)\Theta(L - x)$ is the potential profile of the barrier. $h(x) = h_0[\Theta(-x) \pm \Theta(x - L)]$ describes the exchange splitting in the two electrodes, where the signs $\pm$ correspond to the parallel (P) and antiparallel (AP) configurations of magnetization respectively, and $\Theta(x)$ is the Heaviside step function. $\zeta = 1$ ($\uparrow$) stands for up-spin and $\zeta = -1$ ($\downarrow$) stands for down-spin.

Due to the translational invariance in the transverse (y) direction, the momentum parallel to the y axis is conserved. We assume that a quasiparticle ballistically transports from the left FG electrode to the right at zero bias voltage. So the Hamiltonian (1) has the following plane wave solutions in regions I, II, and III, respectively [7]:

$$\psi_{\mathrm{I}} = \left[\begin{pmatrix} 1 \\ s_1 \mathrm{e}^{\mathrm{i}\theta_1} \end{pmatrix} \mathrm{e}^{\mathrm{i}k_{1x\zeta}x} + r \begin{pmatrix} 1 \\ -s_1 \mathrm{e}^{-\mathrm{i}\theta_1} \end{pmatrix} \mathrm{e}^{-\mathrm{i}k_{1x\zeta}x}\right] \times \mathrm{e}^{\mathrm{i}k_{y\zeta}y}, \tag{2}$$

$$\psi_{\mathrm{II}} = \left[a \begin{pmatrix} 1 \\ s_2 \mathrm{e}^{\mathrm{i}\theta_2} \end{pmatrix} \mathrm{e}^{\mathrm{i}k_{2x\zeta}x} + b \begin{pmatrix} 1 \\ -s_2 \mathrm{e}^{-\mathrm{i}\theta_2} \end{pmatrix} \mathrm{e}^{-\mathrm{i}k_{2x\zeta}x}\right] \times \mathrm{e}^{\mathrm{i}k_{y\zeta}y}, \tag{3}$$

$$\psi_{\mathrm{III}} = \delta_{s_1,s_3} t \begin{pmatrix} 1 \\ s_3 \mathrm{e}^{\mathrm{i}\theta_3} \end{pmatrix} \mathrm{e}^{\mathrm{i}k_{3x\zeta}x + \mathrm{i}k_{y\zeta}y} + \delta_{s_1,-s_3} t \begin{pmatrix} 1 \\ -s_3 \mathrm{e}^{-\mathrm{i}\theta_3} \end{pmatrix} \mathrm{e}^{-\mathrm{i}k_{3x\zeta}x + \mathrm{i}k_{y\zeta}y}, \tag{4}$$

where θ_i ($i = 1, 2, 3$) are the incident angles of the quasiparticle with the x-axis, the transverse wavevector in the y direction $k_{y\zeta} = |E + \zeta h_0| \sin\theta_1/\hbar v_F$, the longitudinal wavevectors in the x direction $k_{1x\zeta} = |E + \zeta h_0| \cos\theta_1/\hbar v_F$, $k_{2x\zeta} = \sqrt{(E - U)^2/(\hbar v_F)^2 - k_{y\zeta}^2}$ and $k_{3x\zeta} = |E \pm \zeta h_0| \cos\theta_3/\hbar v_F$, and the sign functions $s_1 = \mathrm{sgn}[E + \zeta h_0]$, $s_2 = \mathrm{sgn}[E - U]$, and $s_3 = \mathrm{sgn}[E \pm \zeta h_0]$, where $\pm$ corresponds to the P (AP) configuration. $\delta_{s_1,\pm s_3}$ are the Kronecker delta functions.

Note that there are two cases for the wavefunction in region III. If the incident quasiparticle in the left FG electrode does not change its charge type in the right FG electrode, i.e. $s_1 = s_3$, the wavefunction takes the first term on the right-hand side in equation (4). This case is the same as the result of [7]. On the contrary, if the charge type reverses, i.e. $s_1 = -s_3$, which happens when the Fermi energy $|E_F| < h_0$ for the AP configuration, the wavefunction takes the second term in equation (4). As we know, the latter case has been not studied so far in graphene-based ferromagnetic junctions. We will show below that these two cases result in quite different tunneling phenomena.

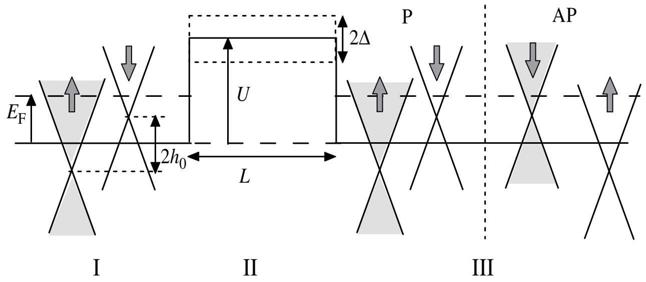

Figure 1. Schematic of a FG/graphene/FG junction for the P and AP configurations. The gray (white) subbands stand for the one (the other) spin channel.

By matching the wavefunctions at the interfaces ($\psi_{\mathrm{I}} = \psi_{\mathrm{II}}$ at $x = 0$ and $\psi_{\mathrm{II}} = \psi_{\mathrm{III}}$ at $x = L$), for $s_1 = s_3$ we obtain the transmission coefficient

$$t = \{(1 + \mathrm{e}^{2\mathrm{i}\theta_1})(1 + \mathrm{e}^{2\mathrm{i}\theta_2})\mathrm{e}^{\mathrm{i}k_{2x\zeta}L - \mathrm{i}k_{3x\zeta}L}\}\{(1 + s_1 s_2 \mathrm{e}^{\mathrm{i}(\theta_1+\theta_2)}) \times (1 + s_1 s_2 \mathrm{e}^{\mathrm{i}(\theta_2+\theta_3)}) + (\mathrm{e}^{\mathrm{i}\theta_2} - s_1 s_2 \mathrm{e}^{\mathrm{i}\theta_1})(\mathrm{e}^{\mathrm{i}\theta_2} - s_1 s_2 \mathrm{e}^{\mathrm{i}\theta_3}) \times \mathrm{e}^{2\mathrm{i}k_{2x\zeta}L}\}^{-1}. \tag{5}$$

Substituting θ_3 and $k_{3\zeta}$ by $-\theta_3$ and $-k_{3\zeta}$ respectively in equation (5), the transmission coefficient t in the case of $s_1 = -s_3$ is obtained. Then the transmission probability for a given transverse wavevector $k_{y\zeta}$ can written as $T_{\zeta\zeta'}(\theta_1) = |t|^2 \cos\theta_3/\cos\theta_1$, where $\zeta' = \zeta$ ($\bar{\zeta}$) for the P (AP) configuration. The conductance through the junction for each spin-independent channel at zero temperature is given by means of the Landuaer–Büttiker formalism,

$$G_{\zeta\zeta'} = \frac{g_v e^2}{h} \int_{-k_{F\zeta}}^{k_{F\zeta}} T_{\zeta\zeta'}(\theta_1) \frac{\mathrm{d}k_{y\zeta}}{2\pi/W} = \frac{g_v e^2}{h} \frac{W k_{F\zeta}}{\pi} g_{\zeta\zeta'}, \tag{6}$$

with the dimensionless conductance $g_{\zeta\zeta'}$ defined as

$$g_{\zeta\zeta'} = \int_0^{\theta_C} T_{\zeta\zeta'}(\theta_1) \cos\theta_1 \, \mathrm{d}\theta_1, \tag{7}$$

where $g_v = 2$ is the valley degeneracy, W is the width of the graphene sheet. θ_C is the critical incident angle of electrons or holes with ζ-spin in the left FG electrode. To guarantee that the longitudinal wavevector $k_{1(3)x\zeta}$ in the left (right) FG electrode is real, we find that $\theta_C = \pi/2$ for $k_{F\zeta} \leqslant k_{F\zeta'}$, and $\theta_C = \arcsin(k_{F\zeta'}/k_{F\zeta})$ for $k_{F\zeta} > k_{F\zeta'}$.

Note that the Fermi wavevector $k_{F\zeta}$ in ferromagnetic graphene is spin-dependent, i.e. $k_{F\zeta} = |E_F + \zeta h_0|/\hbar v_F$, so the conductance $G_{\zeta\zeta'}$ explicitly depends on the spin due to the factor $W k_{F\zeta}/\pi$ in equation (6). In fact it indicates the effect of the density of state for each spin in the FG electrodes at the Fermi level ($\rho_\zeta(E_F) = \frac{g_v|E_F+\zeta h_0|}{2\pi(\hbar v_F)^2}$) on the conductance. This is the extension of [14]. It is noted that some incorrect results were presented on this point in [17]. The total conductance G through the junction is the sum of the two spin-independent conductances. They are $G_P = G_{\uparrow\uparrow} + G_{\downarrow\downarrow}$ for the P configuration and $G_{AP} = G_{\uparrow\downarrow} + G_{\downarrow\uparrow}$ for the AP configuration. Then we obtain the tunnel magnetoresistance TMR $= (G_P - G_{AP})/G_P$.

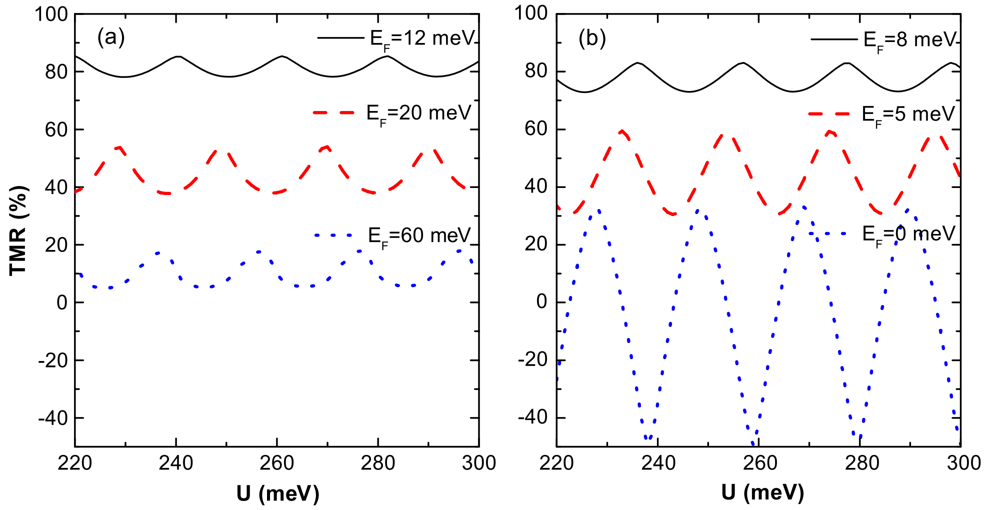

Figure 2. TMR as a function of the barrier height modulated by the local gate voltage for different Fermi energies. $E_F > h_0$ in (a) and $E_F < h_0$ in (b).

If the graphene barrier is spin-dependent, the electrons with ζ-spin in the left FG electrode see the barrier height $U_\zeta = U - \zeta\Delta$, as shown in figure 1. The positive (negative) Δ represents the exchange splitting in the graphene barrier with its magnetization parallel (antiparallel) to that of the left FG electrode. We can introduce the spin polarization of the current through the junction, $\eta_P = (G_{\uparrow\uparrow} - G_{\downarrow\downarrow})/(G_{\uparrow\uparrow} + G_{\downarrow\downarrow})$ for the P configuration and $\eta_{AP} = (G_{\uparrow\downarrow} - G_{\downarrow\uparrow})/(G_{\uparrow\downarrow} + G_{\downarrow\uparrow})$ for the AP configuration. If we fix the magnetization directions of the two FG electrodes parallel and switch the magnetization of the graphene barrier parallel (P′) or antiparallel (AP′) to that of the FG electrodes, we can study another kind of tunnel magnetoresistance $\mathrm{TMR}' = (G_{P'} - G_{AP'})/G_{P'}$, where $G_{P'} = G_{\uparrow\uparrow}(U - |\Delta|) + G_{\downarrow\downarrow}(U + |\Delta|)$ for the P′ configuration and $G_{AP'} = G_{\uparrow\uparrow}(U + |\Delta|) + G_{\downarrow\downarrow}(U - |\Delta|)$ for the AP′ configuration. The definition of TMR′ is the same as that of TMR in the conventional ferromagnetic metal/ferromagnetic insulator/ferromagnetic metal junction [19].

In the following, we would give some numerical results. Here, we choose the exchange splitting in the FG electrodes $h_0 = 10$ meV and the graphene barrier width $L = 100$ nm, which can be achieved by the present experimental technique [9, 15, 16]. We assume that $E_F \geqslant 0$ is always satisfied.

First, we consider the case of the spin-independent barrier. Figure 2 shows TMR versus the barrier potential U for different Fermi levels E_F. It is found that the TMR oscillates periodically with respect to U without damping, whose average is about the polarization ratio of the FG electrodes $\eta_0 = h_0/E_F$ for $E_F > h_0$ and $\eta_0 = E_F/h_0$ for $E_F < h_0$. So the more E_F approaches h_0 (the Dirac point of the spin-down subband), the larger TMR. Interestingly, the TMR can oscillate from a positive to negative value and the oscillating amplitude becomes larger, when the Fermi level is low enough (see figure 2(b)). This is one of our main results.

The origin of the oscillating TMR with signs changing can be understood in figure 3. We consider the situation of high barrier, i.e. $U \gg |E_F \pm h_0|$. We can see that the conductances $G_{\zeta\zeta}$ and $G_{\zeta\bar{\zeta}}$ oscillate synchronously with the increase of U for $E_F > h_0$ (see figure 3(a)), while for $E_F < h_0$ (see figure 3(b)) the phases of that are shifted by a half period. This phase shift arises from the fact that the charge types of quasiparticles tunneling through the graphene-based junction from one FG electrode to the other reverse their signs for the AP configuration in the case of $E_F < h_0$. So the TMR oscillates with increasing U according to $\mathrm{TMR} = 1 - G_{AP}/G_P$. Especially, for the case of $E_F < h_0$, the TMR can be negative when G_{AP} (G_P) corresponds to the resonant (anti-resonant) transmission at proper barrier heights. After some derivations in the high barrier limit, we find $\mathrm{TMR} = 1 - (1 - \eta_0)\frac{g_{\downarrow\uparrow}}{g_{\uparrow\uparrow}}$ for any Fermi energy. Because $g_{\downarrow\uparrow}/g_{\uparrow\uparrow}$ oscillates around about 1 with respect to U, the average of the oscillating TMR is the spin polarization of the FG electrodes h_0/E_F (E_F/h_0) for $E_F > h_0$ ($E_F < h_0$). The period of the oscillating TMR is ($\pi\hbar v_F/L \approx$) 20.7 meV, which is determined by the factor $e^{2ik_{2x\zeta}L}$ in the denominator of the transmission coefficient expression in equation (5).

Now we turn to the case of the spin-dependent barrier. figure 4 shows the effect of different barrier-splitting Δ on the TMR. It is found that for $E_F > h_0$ the oscillating amplitude of the TMR is rarely changed by the exchange splitting Δ (reduced a little in the high barrier limit), only with a shift of the curves along the U-axis (see figure 4(a)); while for $E_F < h_0$, the oscillating amplitude is remarkably suppressed compared with that of the case of the spin-independent barrier (see figure 4(b)).

Figures 5(a) and (b) exhibit the spin polarization of the current through the graphene-based junction as a function of the spin-dependent barrier height for the P and AP configurations respectively when the Fermi energy $E_F > h_0$. For the P configuration, the spin polarization η_P oscillates with respect to U, whose average is approximately the polarization of the FG electrodes η_0 and amplitude can be modulated by applying the different exchange splitting in the barrier. Actually the oscillating polarization happens even in the spin-independent barrier when U is not far larger than E_F. For the

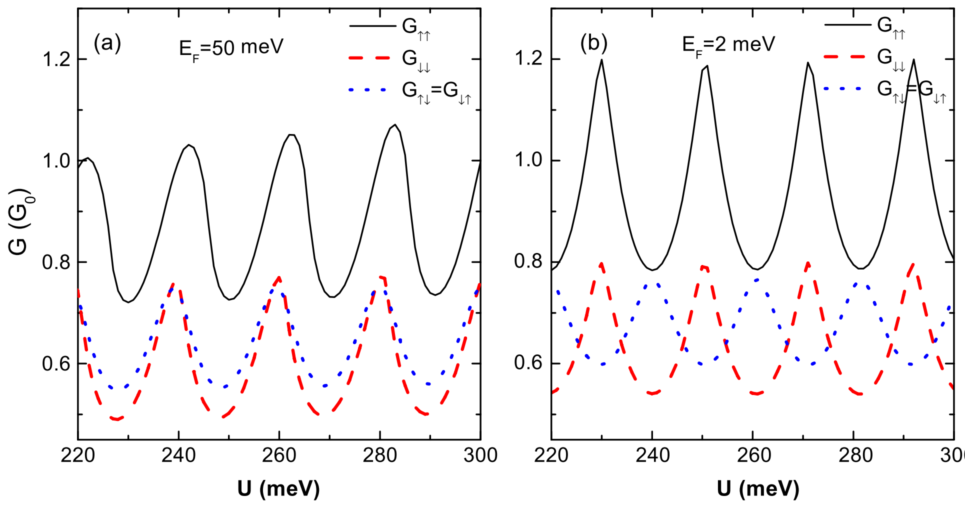

Figure 3. Conductance with different spin channels as a function of the spin-independent barrier height at (a) $E_F = 50$ meV and (b) $E_F = 2$ meV. Note that $G_{\uparrow\downarrow} = G_{\downarrow\uparrow}$ at zero bias voltage. $G_0 = \frac{2e^2}{h}\frac{WE_F}{\pi\hbar v_F}$ for $E_F > h_0$ and $G_0 = \frac{2e^2}{h}\frac{Wh_0}{\pi\hbar v_F}$ for $E_F < h_0$.

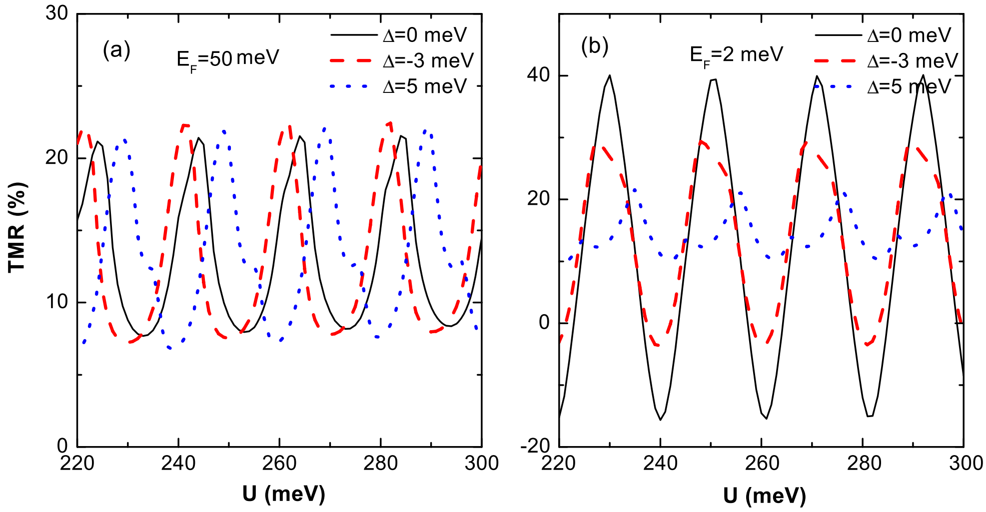

Figure 4. TMR as a function of the barrier height for different splitting in the graphene barrier at (a) $E_F = 50$ meV and (b) $E_F = 2$ meV.

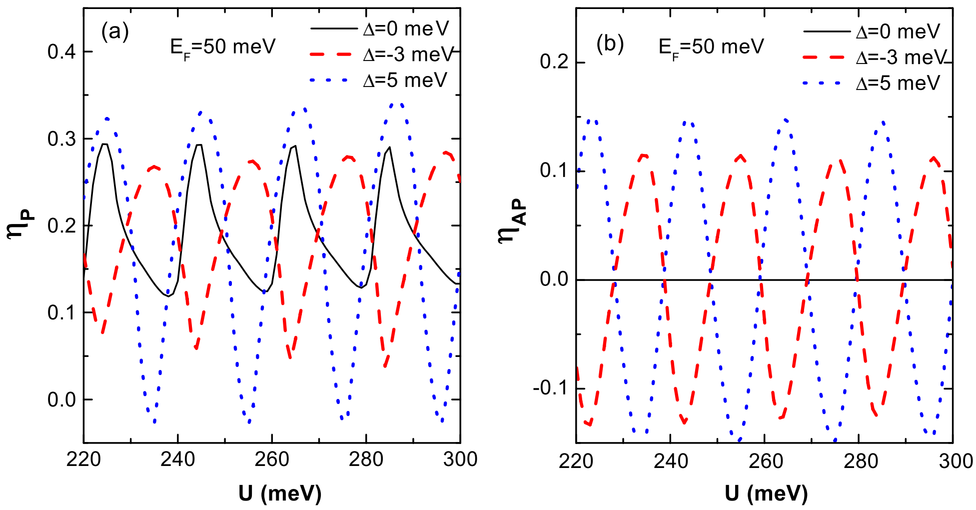

Figure 5. Spin polarization of current as a function of the barrier height for the P configuration (a) and for the AP configuration (b).

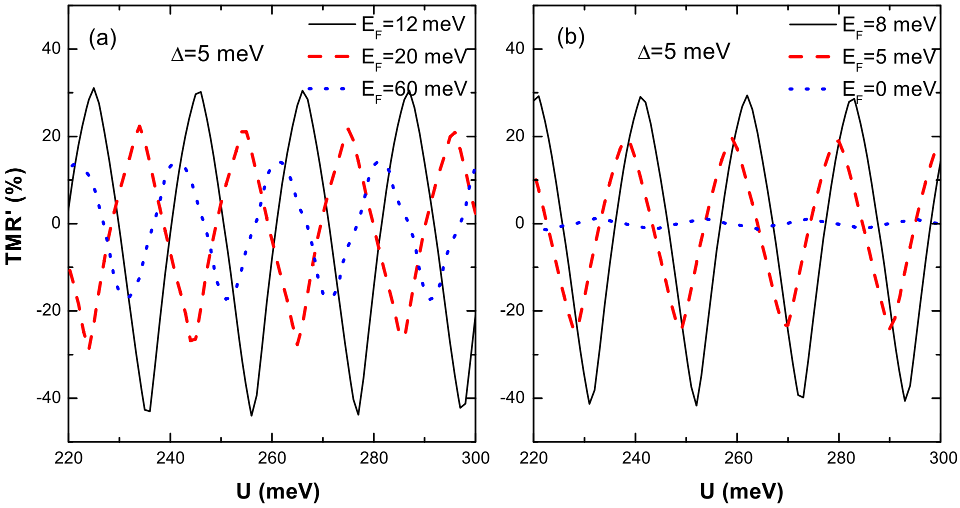

Figure 6. TMR′ as a function of the barrier height for different Fermi energies. $E_F > h_0$ in (a) and $E_F < h_0$ in (b).

AP configuration, only when the barrier is spin-dependent, the spin polarization η_{AP} oscillates with respect to U around the zero polarization, whose amplitude is also modulated by Δ. In fact, the spin polarizations η_P and η_{AP} have an oscillating behavior with respect to the barrier-splitting Δ for a given Fermi energy and gate voltage. Similar results can be obtained in the case of $E_F < h_0$.

The TMR in figure 4 and the spin polarization of current in figure 5 affected by the splitting barrier can also be explained by referring to figure 3. When the exchange splitting Δ is added into the barrier, $G_{\uparrow\uparrow}$ and $G_{\uparrow\downarrow}$ are shifted rightwards along the U-axis by Δ, while $G_{\downarrow\downarrow}$ and $G_{\downarrow\uparrow}$ are shifted leftwards by Δ. So the oscillating polarizations of current with respect to U for the two configurations emerge. The oscillating amplitude of TMR is hardly altered for $E_F > h_0$, while it is notably suppressed for $E_F < h_0$ due to the phase difference of each spin conductance.

Figure 6 shows the TMR′ in the graphene-based full ferromagnetic junction versus the barrier height for different Fermi levels at the barrier-splitting $\Delta = 5$ meV. It is found that the TMR′ oscillates periodically from the positive to negative value with respect to the barrier height but is never damped. The more E_F approaches h_0, i.e. the larger the spin polarization of the FG electrodes, the larger the oscillating amplitude of the TMR′. The amplitude is also modulated by the barrier splitting. This phenomenon can be understood from the formula of TMR′ at any Fermi energy in the high barrier limit, that is $\mathrm{TMR}' = \frac{2\eta_0[g_{\uparrow\uparrow}(U-|\Delta|)-g_{\uparrow\uparrow}(U+|\Delta|)]}{(1+\eta_0)g_{\uparrow\uparrow}(U-|\Delta|)+(1-\eta_0)g_{\uparrow\uparrow}(U+|\Delta|)}$. The factor $g_{\uparrow\uparrow}(U-|\Delta|) - g_{\uparrow\uparrow}(U+|\Delta|)$ results in the oscillating behavior of TMR′ from a positive to negative value with respect to the barrier height U. It is also modulated by the barrier-splitting Δ. The polarization of the FG electrodes η_0 determines the amplitude of the oscillating TMR′. This is another one of our main results.

In summary, we have studied the tunnel magnetoresistance and spin-polarized transport in a graphene-based full ferromagnetic junction. It has been found that, if the graphene barrier is spin-independent, in contrast to the TMR based on the conventional materials, the graphene-based TMR can oscillate from a positive to negative value with respect to the chemical potential adjusted by the local gate voltage in the barrier region but is never damped. If the graphene barrier is ferromagnetic, the former TMR is suppressed for the high barrier while the oscillating amplitude of the spin polarization of the current through the junction is enhanced for both P and AP configurations. In particular, the conventionally defined TMR in the full ferromagnetic junction largely oscillates without damping from the positive to negative value with respect to the barrier height. Our prediction, which is realizable within the present experimental technique, may contribute to the development of graphene-based devices.

Acknowledgments

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