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Spin-dependent dwell time through ferromagnetic graphene barrier

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ABSTRACT

We investigated the dwell time of electrons tunneling through a ferromagnetic (FM) graphene barrier. The results show that the spin polarization can be efficiently controlled by the barrier width, barrier height, and the incident electron energy. Furthermore, it is found that electrons with different spin orientations will spend different times through the barrier. The difference of the dwell time between spin-up and spin-down electrons arises from the exchange splitting, which is induced by the FM strip. Study results indicate that a ferromagnetic graphene barrier can cause a nature spin filter mechanism in the time domain.

1. Introduction

Graphene, a single layer of carbon atoms in a honeycomb lattice, was first synthesized by Novoselov et al. in 2004 [1]. In graphene, the energy dispersion relation is approximately linear near the Dirac points (often referred to as K and K') where the electron and hole bands touch. Such a peculiar band structure makes graphene different from the two dimensional electronic gases. It has many unique electronic and transport properties, such as the half-integer quantum hall effect [2], special Andreev reflection [3], Klein tunneling [4], and so on.

The ability to manipulate both the charges and the spin of the electrons has led to the development of a new field of application in spintronics. The generation of a spin-polarized current is a fundamental prerequisite for the construction of spintronic devices [5]. 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 defects [6], applying an external electric field [7], or depositing a ferromagnetic insulator on top of the graphene. In the latter case graphene is called "ferromagnetic graphene" [8,9]. This deposition induces an exchange splitting in graphene. 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 [9]. In the past few years, the spin-polarized transport of electrons in conventional ferromagnetic nanostructures [10], ferromagnetic monolayer graphene barrier [8,9,11], double ferromagnetic graphene barrier [12–14], magnetic barrier [15] and ferromagnetic monolayer graphene superlattice [16–20] has been investigated and many interesting results have been obtained.

The time aspect of quantum tunneling is another interesting problem, which can be expressed by Wigner delay or group delay time τ_g [21] and dwell time τ_d. The group delay time can be calculated by the method of stationary phase and given by the energy derivative of the transmission phase shift [22–26]. The group delay time τ_g characterizes the time delay between the appearances of the peak of wave packet at two boundaries of the barrier region. It can be calculated by the method of stationary phase and given by the energy derivative of the phase shift of the wave function tunneling [22–26], i.e, $\tau_g = \hbar d(\varphi_t)/dE$. Here, φ_t is the phase shift for the transmission packet peaks. It is necessary to mention that in the oblique incidence case the φ_t should be replaced by φ_t^T, where φ_t^T is the total phase shift [27]. The dwell time was first introduced by Smith, which was defined as the time spent by a particle in the barrier region $0 < x < L$ [28]. The relationship between the group delay and the dwell time for quantum tunneling is derived by Winful [22]. The group delay is equal to the dwell time plus a self-interference delay. The self-interference term named by Winful comes from the overlap of incident and reflected waves in front of the barrier. As the wave packet tunnels through the barrier, part of the incident packet interferes with a portion that has already been reflected. In graphene for normal incidence the self-interference delay disappears because the reflection vanishes due to the so-called Klein tunneling. In other words, only for normal incidence in graphene structure the group delay time equals the dwell time. Recently, some papers focused on the group delay and/or dwell time in graphene-based barrier nanostructures [19,27,29–36]. The relationship between the group delay and the dwell time is derived in Ref. [27] and the authors find that the group delay is equal to the dwell time plus a self-interference delay. The dwell time in graphene-based magnetic barrier nanostructures has been investigated in Ref. [29], and the authors found that the dwell time showed remarkable

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anisotropy varying in different magnetically modulated configurations. In Ref. [31] the group delay time for opaque barriers is found to be constant and independent of the barrier width, a phenomenon that is known as the Hartman effect [37].

In this work, we focus on the dwell time through a ferromagnetic graphene barrier. We show that the dwell time is strongly determined not only by the barrier width, barrier height, and the incident electron energy, but also by spin orientations. Our probes show that a ferromagnetic graphene barrier can cause a nature spin filter mechanism in the time domain. The rest of the paper is organized as follows. In Section 2 some details of the standard calculation of the electron spin-dependent transmission coefficients, the spin polarization, and the dwell time in a ferromagnetic graphene barrier are described. The results are discussed in Section 3. Finally, a brief summary and conclusion are given in Section 4.

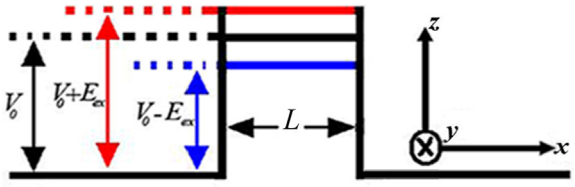

Fig. 1. Schematic of the ferromagnetic graphene barrier tunneling problem.

2. Model and method

In the present study we consider a ferromagnetic graphene barrier, which is obtained by putting a ferromagnetic (*FM*) insulator layer, such as *EUO*, with metallic gate on the top of a graphene sheet. This graphene sheet is located on a substrate such as SiO_2. A schematic of the structure is shown in Fig. 1. The growth 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 (w) is much larger than the width of barrier, namely L [38,39]. Potential profile of the system along the growth direction in the presence of the exchange field is given by

$$V(x)=\begin{cases} V_0 \pm E_{ex} & \text{for barrier} \\ 0 & \text{elsewhere} \end{cases} \quad (1)$$

Here V_0 is the electronic potential which is controlled by the metallic gate and E_{ex} is the exchange field. The $+$ and $-$ denotes the electrons with spin antiparallel or parallel to the exchange field, respectively. In the low energy limit, the charge carriers in a ferromagnetic graphene barrier are described by non-interacting Hamiltonian $\hat{H}=\hat{H}_0+V(x)\hat{I}$, where $\hat{H}_0=\hbar v_F\hat{\sigma}\cdot\vec{k}\,.\,\vec{k}$. represents wave vector of quasiparticles, $\hat{\sigma}$ is 2D Pauli matrix and $v_F\approx 10^6$ m s^{-1} is Fermi velocity. In order to study the transport problem, we shall solve the Dirac equation. To solve this equation, we suppose that incident electron from the left comes through the interface with incident angle ϕ along the *x*-axis. Therefore the Dirac spinor components, $\psi_{1\sigma}$ and $\psi_{2\sigma}$, which are the solutions to the Hamiltonian $\hat{H}=\hat{H}_0+V(x)\hat{I}$, can be written in the following form

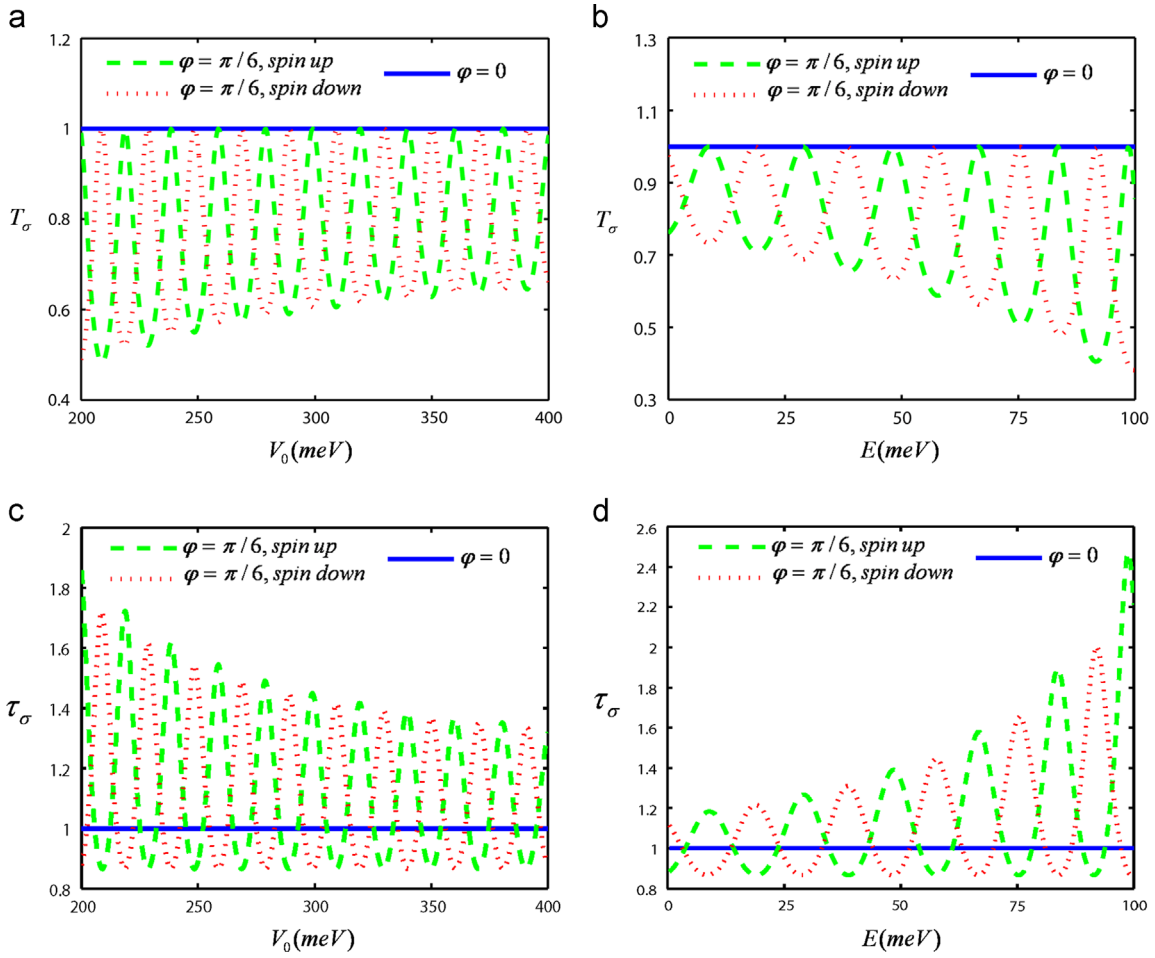

Fig. 2. Spin transmission probability [(a) and (b)] and the ratio of dwell time to the equal time τ_0 [(c) and (d)] as a function of the incident electron energy and barrier height.