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Electron tunneling of graphene modulated by realistic magnetic barriers

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ABSTRACT

Transport property of graphene electron in two kinds of realistic magnetic barriers is studied. For symmetric magnetic barriers with perpendicular magnetization, transmission is symmetric in (E, k_y) space. There exists a $(2n-1)$-fold resonance splitting rule for n-barrier structure due to the splitting of energy levels. For antisymmetric magnetic barriers with parallel magnetization, transmission is asymmetric in (E, k_y) space, and the Fabry–Pérot resonance is observed. The smoothness of magnetic barrier weakens the resonant behavior of transmission. The conductance resonance can be controlled by the thickness of strips, the distance between strips and graphene, and the smooth electric barrier.

1. Introduction

Electron motion in a conventional semiconductor two-dimensional electron gas subjected to an inhomogeneous magnetic field has caused tremendous interest, due to the advance in the microfabrication technique and its potential applications to electronic devices [1–10]. Such systems can be experimentally realized by the deposition of a heterostructure in an inhomogeneous magnetic field [1–3]. Theoretical studies on electron tunneling showed that magnetic barriers possess wave-vector filtering property and the energy spectrum of magnetic superlattice consists of magnetic minibands [2]. The oscillatory magnetoresistance resulting from a commensurability effect between the classical cyclotron diameter and the period of magnetic modulation has also been observed [3]. On the aspect of spin-dependent transmission, various schemes have been proposed for spin polarization and spin filtering in the magnetic modulated nanostructures [7,8].

Recently, the inhomogeneous magnetic fields have been suggested to confine massless Dirac electrons [11–28], providing an efficient tool to manipulate electrons in graphene. Graphene exhibits fascinating characteristics and various potential applications, due to its honeycomb lattice structure. The electrons in graphene are described as massless and chiral relativistic fermions, governed by an effective Dirac equation with linear energy dispersion. Experimentally, it is believed that the same technologies for semiconductor can be used to create similar magnetic structures in graphene [11]. Theoretically, the transport, band structure, and magnetic edge states of Dirac electrons were researched in various magnetic structures involving single barrier [11–14], several barriers [15–21], and quantum dots [22–24]. It is found that the Fermi velocity at Dirac points is isotropically renormalized in magnetic superlattices with rectangular barriers [15]. The direction-dependent tunneling and quantum bound states have been discussed in graphene-based δ-function magnetic barriers [16]. The low-energy electronic structure of graphene under an inhomogeneous magnetic field could be mapped into that of graphene under an electric field or vice versa [29]. The results manifest that the effect of magnetic field on Dirac electrons in graphene is different from that on conventional electrons, especially for the Klein tunneling.

In these theoretical studies, one often uses a δ-function barrier or a rectangular barrier to model the spatial dependence of a magnetic field for simplicity. However, it is obvious that in actual realizations, some form of smoothness of the magnetic field will be present inevitably. Due to the intricate relationship between the magnetic field and electronic properties, it is relevant to investigate the effect of smoothness of the magnetic field. It has been demonstrated that the smoothness of potential barrier makes it difficult to open a band gap in graphene [30]. Since the magnetic field can suppress Klein tunneling and control the trans-

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mission effectively in graphene, one may wonder. How about the transmission through a realistic magnetic field? Will the smoothness of magnetic barrier weaken the control? In this work, we focus our attention on the transport properties through two realistic magnetic structures with smooth edges created by depositing ferromagnetic metallic strips on the top of graphene. The results show that for magnetic barriers with different symmetries, the transmission spectra and resonant behaviors have completely different characteristics, which are related to resonant states in the vector potential barriers or wells. In the presence or absence of a smooth electric barrier, the effect of structural parameters on the transmission probability and conductance is discussed in detail, and compared with that for idealistic magnetic barriers.

The paper is organized as follows. In Section 2, we introduce the proposed realistic magnetic barriers, the smooth electric barrier, and the transfer-matrix method. In Section 3, we show the numerical results and discussions for two kinds of magnetic barriers with different magnetization orientations. Finally, we draw conclusions in Section 4.

2. Model and method

We shall consider two kinds of realistic magnetic barriers (see Figs. 1(b) and (c)), which can be produced by the deposition of a local ferromagnetic metallic strip on the top of graphene sheet with perpendicular or parallel magnetization (see Fig. 1(a)). The profiles of magnetic barriers can be expressed by $\mathbf{B} = B(x, z_0)\hat{z}$ with

$$B = B_0[K(x + d/2, z_0) - K(x - d/2, z_0)], \tag{1}$$

where $B_0 = M_0 h/d$ [2]. M_0, h, and d are the magnetization, height, and thickness of strips, respectively, and z_0 is the distance between the strips and the graphene sheet. It has been assumed that $h \ll d$ and $h \ll z_0$. For magnetization perpendicular to graphene sheet, $K(x, z_0) = 2xd/(x^2 + z_0^2)$. For magnetization parallel to graphene sheet, $K(x, z_0) = z_0 d/(x^2 + z_0^2)$. In the Landau gauge, the corresponding magnetic vector potential has the form $\mathbf{A}(x, z_0) = [0, A(x, z_0), 0]$, in which

$$A(x, z_0) = B_0 d \ln \frac{(x + d/2)^2 + z_0^2}{(x - d/2)^2 + z_0^2}, \tag{2}$$

and

$$A(x, z_0) = B_0 d[\tan^{-1}(\frac{x + d/2}{z_0}) - \tan^{-1}(\frac{x - d/2}{z_0})], \tag{3}$$

for perpendicular and parallel magnetizations, respectively, as depicted in Figs. 1(b) and (c). One can see that the magnetic barrier in Fig. 1(b) is symmetric, $B(-x, z_0) = B(x, z_0)$, while its vector potential is antisymmetric, $A(-x, z_0) = -A(x, z_0)$. However, the magnetic barrier in Fig. 1(c) is antisymmetric, $B(-x, z_0) = -B(x, z_0)$, while its vector potential is symmetric, $A(-x, z_0) = A(x, z_0)$. The symmetry of vector potential plays a key role to the transport properties of graphene (as discussed in Section 3). The local top gate of Fig. 1(a) produces an electric barrier and defines a shift of the Dirac points. In order to model a more realistic electric barrier and study its effect on transmission, we use an analytical expression for the potential distribution, which is read as

$$V(x) = \frac{V_0}{2}[erf(\frac{2(d/2 + x)}{b} - 2) + erf(\frac{2(d/2 - x)}{b} - 2)], \tag{4}$$

as shown in Fig. 1(d). Here, $erf(x)$ is the error function, and b determines the width of the crossover region [12]. It should be noted that, for the electric barrier, we are mainly interested in the transport behavior as the edge of potential region becomes smooth, even though Eq. (4) is not exact enough for a realistic barrier. The specific structures of realistic electric barriers produced by gate voltage or by adsorbing adatoms are different and complicated [31–33], however, they should be smooth inevitably.

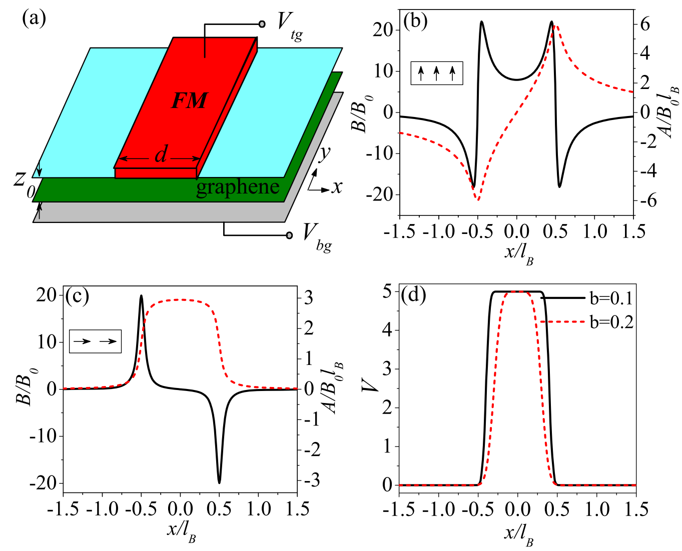

Fig. 1. (a) Schematic diagram of the magnetic–electric structure created by a local ferromagnetic metallic (FM) strip, a local top gate, and a global back gate. Here, the FM strip with the top gate is deposited on the top of graphene sheet separated by a thin oxide layer, and the graphene is sat on SiO_2 substrate with an applied back gate. (b) Profiles of the magnetic barrier (the solid curve) and its corresponding vector potential (the dashed curve) produced by the FM strip for perpendicular magnetization, where $d = 1.0$ and $z_0 = 0.05$. (c) The same as that in (b) but for parallel magnetization. (d) Profile of the electric potential $V(x)$ produced by the local top gate and modelled by an error function, where $V_0 = 5.0$.

At low energy, the electron in graphene could be described by a massless Dirac equation with a linear energy dispersion. In the presence of an inhomogeneous magnetic–electric field perpendicular to the plane, the equation reads as

$$[v_f \sigma \cdot (\mathbf{p} + e\mathbf{A}(x)) + V(x)I]\Psi = E\Psi, \tag{5}$$

where $v_f \approx 0.86 \times 10^6$ m/s, the pseudospin matrix $\sigma = (\sigma_x, \sigma_y)$ is Pauli matrix, $\mathbf{p} = (p_x, p_y)$ is the momentum operator, I is the 2×2 unit matrix. The dimensionless units are introduced: $l_B = \sqrt{\hbar/eB_0}$, $E_0 = \hbar v_f/l_B$, $B(x) \to B_0 B(x)$, $A(x) \to B_0 l_B A(x)$, $\vec{r} \to l_B \vec{r}$, $k \to k/l_B$, and $E \to E_0 E$. For $B_0 = 0.1$ T, one has $l_B = 81$ nm and $E_0 = 7$ meV. For an arbitrary vector potential or electric potential in the region $-d/2 \le x \le d/2$, it could be divided into N segments, each of which has the width d/N. The vector potential or electric potential in jth segment can be approximately viewed as constant A_j or V_j. We consider a short and wide magnetic–electric structure, i.e., its length in the x direction is much smaller than its width in the y direction, in which the edge effect along the y direction could be neglected and the transverse wave vector k_y is conserved [27]. Thus, the wavefunction can be assumed as $\Psi(x, y) = \psi(x)e^{ik_y y}$. Substituting $\Psi(x, y)$ into Eq. (5), we can obtain

$$[\frac{d^2}{dx^2} + (E - V)^2 - (k_y + A)^2]\psi(x) = 0. \tag{6}$$

If we define $\epsilon = (E - V)^2$ and $U_{eff} = (k_y + A)^2$, Eq. (6) will reduce to a Schrödinger equation for a conventional electron, which is helpful for analyzing the resonant tunneling of Dirac electron. The effective potential U_{eff} depends not only on the vector potential A but also on the transverse wave vector k_y. For given incident