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Disordered effect on a graphene-based spin–orbit interactions superlattice

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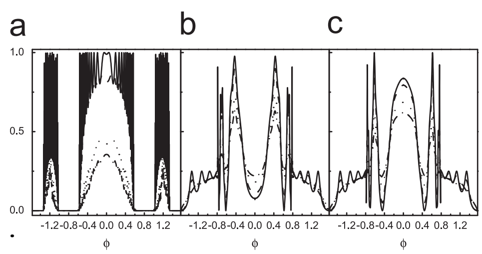
HIGHLIGHTS

- ► Angle-resolved transmission coefficients can be greatly modulated by disorder.
- ► Klein tunneling can be suppressed by disorder when only ISOI exists.
- ► Normal transmission channel would be selected by the system size when only ISOI exists.

GRAPHICAL ABSTRACT

It is notable that the transmission coefficient can be tuned by the disorder strength γ even at the normal incident angle



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ABSTRACT

The transmission character in the present superlattice under the influence of disorder is considered. It is shown that transmission coefficients are sensitive to the disorder strength and the system size. In particular, the Klein tunneling can be suppressed by disorder to a neglectable value only when the ISOI exists. In addition, the transmission channel through the system in the normal incidence case can be tuned by the system size only when the RSOI exists. The physical origination of those phenomena has also been analyzed.

1. Introduction

Graphene, a very special, slow-relativistic electronic membrane, is very interesting and promising for physical systems for present day since its discovery 8 years ago [1]. As time passes by, there has been an amazing series of spectacular properties revealed, such as the unconventional quantum Hall effect [2], strong electric-field effect [3], finite minimal conductivity [2–4], special Andreev reflection [5,6], and so on. Furthermore, another one closely related to the special Andreev reflection, Klein tunneling, which concerns processes at interfaces between regions of different dopings, has been intensively investigated theoretically [7] and experimentally in the last years [8]. Although the Klein tunneling is significant in the relativistic quantum theory from a theoretical perspective, it is a major and fundamental obstacle, seriously limiting in future nanoelectronic devices from an application perspective. The essential point is that, in contrast to the Schrodinger fermions, the Dirac fermions cannot effectively be confined by electrostatic potentials. To get rid of Klein tunneling [7], the transport behavior through the electrostatic potential barrier and superlattice [9], velocity barrier [10], and even magnetic barriers [11] has been addressed. Indeed, magnetic barriers seem to be a powerful route to circumvent the Klein paradox effect even at the normal incident case, but the main adverseness of such an approach is the necessary exploitation of the magnetic field. Besides, employing an angular modulate is a rather hard business in quantum electronics in contrast to optics. As a result, searching for an ordinary, effective way out of this dilemma is an urgent need for the design of various graphene-based devices.

Fortunately, by studying the effect of the spin–orbit interactions (SOI) in graphene-based microstructures [12], it is shown

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that the SOI can provide us with an alternative and feasible way to achieve the fascinating purpose. So SOI, one of the most interesting and fundamental electronic properties of graphene, is undergoing a rapid development in recent years [13–24]. Generally SOI in graphene has been proposed to include two different manifestations: an intrinsic (ISOI) and an extrinsic (RSOI) term. The former term can generate the spin-polarized edge states and result in a new phase of matter, the quantum spin Hall phase [13]. Although the strength of the ISOI estimated by many authors is very small, about $0.05-0.0011$ meV [14–16], it is also suggested that the ISOI can be increased by inducing a curvature of the graphene layer [15]. Except for ISOI, it is expected that a more prominent RSOI may exhibit in the material. Indeed, although it is predicted in the range of 1 meV in Refs. [14–16], a considerable (200 meV) RSOI splitting can be achieved in the graphene π bands through angle-resolved photoemission [17,18] or by using a first-principles method [19]. Also the impurity coverage was suggested by Castro Neto et al. to tuning the RSOI into a much higher value [20]. Thus, the important task, to yield large SOI strength in graphene layer under certain ambient environment, should be realized experimentally in graphene-based junctions in the future.

While theoretically and experimentally possible and potentially useful as a graphene-based device [21–25], the further unexpected transport properties of graphene-based samples may be brought about by disorder. Therefore, understanding the transport properties of disordered graphene system becomes an extremely necessary thing. To this end, in the study, the transport of charge in randomly layered graphene structures with the spatially-modulated strength of SOI is studied. Here, the key point is the effect of disorder on the angle-resolved transmission coefficients and the tunneling conductance. The rest of the paper is organized as follows: in Section 2, the theory and model will be given. In Section 3 we investigate in detail the angle-resolved scattering properties for various disorder parameters of the present system. It is shown that the angle-resolved transmission coefficients can be greatly modulated by disorder. Meanwhile the shape of transmission coefficients almost remains the same as that of the case without disorder. In particular, Klein tunneling, the transmission for graphene at normally incident, can be suppressed by the disorder when only ISOI exists. Besides, for the case where only RSOI exists, the transmission channel for the normal incidence quasiparticles would be selected by the system size. And a summary is given in Section 4.

2. Theory and model

The model we used for a SOI superlattice in graphene is shown schematically in Fig. 1. The growth direction is taken to be the x-axis. The system consists of two kinds of graphene flakes with different SOIs, the first being a graphene flake without SOI occuping the thickness d_N, while the second is a graphene flake with SOI occuping the thickness $d_S(\xi)$, standing alternately. The width (along the y direction) of the graphene strip, w, is supposed to be much larger than d_N and $d_S(\xi)$. So the details of the microscopic description of the strip edges become irrelevant in the study. The SOI of the graphene flake can be realized by either growing graphene on a Ni and SiC surface or adsorbing heavy atoms on a graphene flake [17–19]. The reports of those theoretical and experimental groups indicate that the spatially modulated strength of SOI in this study can be realized in experiments. The disorder effect is taken into account in this way: the value of $d_S(\xi)$ fluctuates around its mean value, given by $\langle d_S(\xi)\rangle = d_S$ and $d_S(\xi)=d_S(1+\gamma\kappa(\xi))$, where $\kappa(\xi)$ is a set of uncorrelated random variables $\kappa(\xi)\in[-1,1]$ and ξ is the index with regard to the SOI region. Here, γ is the disorder strength.

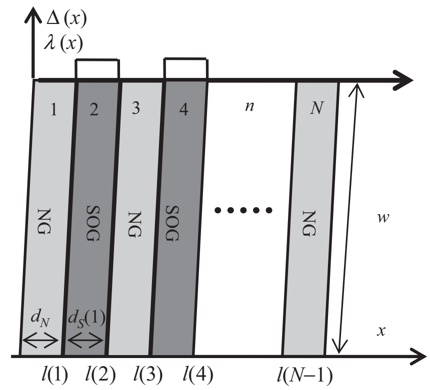

Fig. 1. Top: Sketch of the strength of SOI through the graphene-based spin–orbit interactions superlattice. Bottom: Sketch of the graphene-based spin–orbit interactions superlattice. d_s and d_n are the width of the graphene flake with and without SOI, respectively.

In the study we shall restrict ourselves to a single particle picture at zero temperature and neglect the electron–electron and electron–phonon interaction effects. The low energy massless Dirac-fermion propagation in the present structure can be described by the following continuum Hamiltonian model [12,13]:

$$\hat{H} = \hbar v_F \vec{p}\cdot\vec{\tau} + \left[\frac{\lambda}{2}(\vec{\tau}\times\vec{\sigma})\cdot\vec{e}_z + \Delta\tau_z\sigma_z\right]\vartheta(n) \tag{1}$$

where $v_F \approx 10^6\ \mathrm{ms}^{-1}$ is the Fermi velocity, the Pauli matrices $\vec{\tau}=(\tau_x,\tau_y)[\vec{\sigma}=\sigma_x,\sigma_y]$ describe the sublattice (spin) degrees of freedom, the parameters λ and Δ represent the strength of the RSOI and of the ISOI, respectively, and the function $\vartheta(n)$ is given by

$$\vartheta(n) = \begin{cases} 1, & n=2i, \quad i=1,2,\cdots \\ 0, & n=2i+1, \quad i=0,1,\cdots \end{cases}$$

In the following we set $\hbar = v_F = 1$. In the calculation, we assume that the incident electrons are (spin) unpolarized and we investigate only one of the spin state cases, for example, the spin-up one. If we assume that $\Psi^{\pm}_{Ns}$ and $\Psi^{\pm}_{\alpha}$ are the wave functions traveling along the $\pm x$ direction in the NG region and in the SOG region, respectively, those two wave functions are the general solutions to Eq. (1) and can be expressed by

$$\Psi^{\pm}_{N\uparrow(\downarrow)} = \left(1(0)), \pm e^{\pm i\phi}(0), 0(1), 0(\pm e^{\pm i\phi})\right)e^{i(\pm k_N x + qy)}/\sqrt{2\cos(\phi)}$$

$$\Psi^{\pm}_{\alpha} = (k_\alpha - iq, \varepsilon-\Delta-i\alpha(\varepsilon-\Delta)-i\alpha(k_\alpha+iq))e^{i(\pm k_\alpha x+qy)}/A_\alpha\phi$$
$$= \arcsin(q/\varepsilon)$$

$$A_\alpha = 1/\sqrt{2\left(|k_\alpha|^2 + q^2 + (\varepsilon-\Delta)^2\right)} \tag{2}$$

where $q=\varepsilon\sin(\phi)$ is the momentum along the y axis and $k_N=\varepsilon\cos(\phi)$ and $k_\alpha=\sqrt{(\varepsilon-\Delta)(\varepsilon+\Delta-\alpha\lambda)-q^2}$ are the momenta along the x-axis.

Let us now consider the case in which an electron is incident from the left NG electrode with energy ε, transverse momentum q, and spin s. The Dirac spinor wave functions in the left and right regions can be expressed as

$$\begin{cases} \Psi_L = \Psi^{+}_{Ns} + r_{ss}\Psi^{-}_{Ns} + r'_{s\bar{s}}\Psi^{-}_{N\bar{s}} & \text{in the NG region} \\ \Psi_R = t_{ss}\Psi^{+}_{Ns} + t'_{s\bar{s}}\Psi^{+}_{N\bar{s}} & \text{in the NG region} \end{cases} \tag{3}$$

where r_{ss} and $r'_{s\bar{s}}$ are the amplitudes of the normal and the spin–flip reflections in the left NG region, t_{ss} and $t'_{s\bar{s}}$ are the amplitudes of the normal and the spin–flip transmissions, respectively, in the right NG region. The wave functions in the middle regions can be