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Dirac electron in the various strained graphene stripes immersed into the magnetic barriers

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ABSTRACT

The transport properties of the three scenarios of the strained graphene magnetic barriers, where the first one is composed of the strained stripe in the positive magnetic field and the pristine stripe in the negative magnetic field on the left and right sides respectively, the second one is just the result of exchanging the stripes in the first one, and the last one contains the fully strained stripes on both sides, have been investigated. It is found that the first two configurations own the same evolution behavior both in transmission and conductance versus the strain, the joint contributions from the strains in the first two configurations lead to the enhancement both in transmission and conductance in the third one. The strain tends to devastate the regular shape of the energy bands within the scope of higher momentum/energy, where the more severe damage is observed in the superlattices with the fully strained periodic unit cell. The uniformity of the periodic unit between the left and right stripes in the third scenario makes the energy gaps of the superlattices diminish and even disappear in contrast to its first two counterparts, where the discrepancy between the strained stripe on the left side and pristine stripe on the right side increases the inhomogeneity, and thus the energy gaps.

1. Introduction

Graphene, the two dimensional monolayer prototypical materials, has been a subject of intensive research due to its salient mechanical, electronic and optical properties [1–5]. Owning the effective Fermi velocity of 1/300 light speed, the massless Dirac particle in graphene can be used to simulate relativistic phenomena in quantum electrodynamics (QED), originally impossible due to inaccessible high-energies however. In some sense, just as the analog between the solid state physics and cold atomic optical lattices [6], the graphene provides an opportunity to bridge the gaps between the condensed matter physics and high-energy physics. Besides providing an interface between the condensed matter and high-energy physics, the proximity of graphene to superconducting layers can lead to the unusual Andreev reflection [7,8], where intro-reflection as well as specular reflection can be observed during the process of electron-hole conversion. the high magnetic field can give rise to the anomalous quantum Hall effect [9–11], where the Hall plateaus appear at half-integer $4e^2/h$ instead of integer multiple of $4e^2/h$, etc.

The control of the motion of charge carriers in graphene poses a crucial problem due to the well-known Klein tunneling, where the normally incident Dirac particle can penetrate arbitrarily high electric potential barriers with the probability of unity [3–5]. Thus, as an alternative and effective tools of controlling the motion of the massless Dirac particles, the magnetic fields are introduced to confine the Dirac particles, which shows strikingly different behavior than the electric fields in controlling the Dirac particles in graphene quantum wells [12]. The strong dependence of the transmission and conductance on the total magnetic flux and wave-vector, provides a flexible way of confining charge carriers in graphene. Under the influence of the electric potential barriers, the transmission of the Dirac particle distributes symmetrically over the positive and negative angles of incidence [13–17], while the magnetic barriers [12,21,18–20] make the transmission of Dirac particle show remarkable anisotropic distribution over the positive and negative angles of incidence and disappearance of the Klein tunneling.

There are several ways to incorporate the strain [3,22] into the graphene, the usual way is to introduce a gauge transformation [3,23]. Substituting the changed nearest-neighbor distance vector between atoms A and B produced by the stress and expanding it around the so-called new Dirac point, is another way of taking the strain into account, resulting in the anisotropic massless Dirac equation [24–26], which is investigated not only in graphene [25], but in atoms within optical lattices [6] and light propagation in photonic crystals [27]. In this work, we focus on the effect of the strain on the tunneling properties of the three scenarios of

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strained/unstrained graphene stripes immersed into the alternating magnetic fields, forming the so-called magnetic barriers [12]: the first one is composed of the strained stripe within the positive magnetic field on the left hand side (LHS), and the pristine stripe in the negative magnetic field on the right hand side (RHS), the second one is just the opposite of the first one by exchanging the graphene stripes between the two sides, and the last one is the fully strained stripes on both sides being immersed into the alternating magnetic fields. The transmission, conductance and corresponding superlattices (SL) energy bands for the different configurations of magnetic barriers are investigated and interpreted. It is found that the strain is an effective tool to tune the transmission and conductance in multiple magnetic barriers, and remarkably change the energy bands of SL in the larger energy domain. In addition, there exists substantial difference between magnetic vector field and electric scalar field on both the transport in electric and magnetic barriers and energy bands of the respective SL. The work is organized as follows, the transport properties of the Dirac particle are studied for different structures of the magnetic barriers in Section 2; the electronic properties of the SL with the different magnetic periodic unit cells are given in Section 3; and Section 4 concludes our work.

2. The transmission through various magnetic barriers

In the framework of the tight-binding treatment, the motion of the Dirac particle can be described by $\widehat{\mathcal{H}} = \sum_{\mathbf{R},i}[t_i a^{\dagger}_{\mathbf{R}} b_{\mathbf{R}+\delta_i} + h.c.]$, where $a_{\mathbf{R}}, b_{\mathbf{R}+\delta_i}$ represent the annihilation operators of the Dirac particle at position $\mathbf{R}$ (atom A) and its three nearest neighbor atoms B locating at $\mathbf{R}+\boldsymbol{\delta}_i, (i=1,2,3)$ respectively. By introducing the Fourier transforms and a linear transformation, the Hamiltonian can be diagonalized as

$$\mathcal{H} = \sum_{\mathbf{k}} (c^{\dagger}_{\mathbf{k}} \;\; d^{\dagger}_{\mathbf{k}}) \begin{pmatrix} \sqrt{|\phi(\mathbf{k})|^2} & 0 \\ 0 & -\sqrt{|\phi(\mathbf{k})|^2} \end{pmatrix} \begin{pmatrix} c_{\mathbf{k}} \\ d_{\mathbf{k}} \end{pmatrix}, \tag{1}$$

where $\phi(\mathbf{k}) = \sum_i t_i e^{i\mathbf{k}\cdot\boldsymbol{\delta}_i}$ with the eigenenergy $E(k) = \pm\sqrt{|\phi(\mathbf{k})|^2}$. The strain takes effect through altering the parameters $\boldsymbol{\delta}_i$, which is defined by the following transformation rules:

$$\boldsymbol{\delta}'_i = (\mathbf{I}+\boldsymbol{\varepsilon})\boldsymbol{\delta}^0_i, \tag{2}$$

where $\boldsymbol{\delta}^0_i$ is the nearest-neighbor distance vector between atoms A and B in pristine graphene. The strain matrix $\boldsymbol{\varepsilon}$ can be obtained by using the following relation with the help of the symmetry consideration for the two-dimensional transversely isotropic materials:

$$\varepsilon'_{\underline{ij}} = \mathcal{S}_{\underline{ij},\underline{11}}\tau'_{\underline{11}} = R_{im}R_{jk}\varepsilon_{mk} \tag{3}$$

where R is the 2-D orthogonal rotation matrix with rotating angle θ, τ_{ij} is the stress, $\mathcal{S}_{ijk\ell}$ is the compliance coefficients with $T\mathcal{S}_{\underline{12}\,\underline{11}} = T\mathcal{S}_{\underline{21}\,\underline{11}} = 0$, $\mathbf{T} = T\mathbf{e}'_1$, and $\tau'_{\underline{k\ell}} = T\delta_{k,1}\delta_{\ell,1}$ in the transformed coordinate. Therefore the strain matrix $\boldsymbol{\varepsilon}$ can be obtained as [22]

$$[\varepsilon] = \mathcal{S}\begin{pmatrix} \cos^2\theta - \sigma\sin^2\theta & (1+\sigma)\sin\theta\cos\theta \\ (1+\sigma)\sin\theta\cos\theta & \sin^2\theta - \sigma\cos^2\theta \end{pmatrix} \tag{4}$$

where the Poisson ratio σ is defined by $\sigma \equiv -\mathcal{S}_{1111}/\mathcal{S}_{1211} \simeq 0.165$ and $\mathcal{S}$ represents the strain strength.

For armchair case, the distance vectors between the nearest-neighbor A, B carbon atoms are $\boldsymbol{\delta}'_1 = (\sqrt{3}/2(1-\sigma\mathcal{S})a, -1+\mathcal{S}/2a)$, $\boldsymbol{\delta}'_2 = (0,(1+\mathcal{S})a)$, $\boldsymbol{\delta}'_3 = -\boldsymbol{\delta}'_1$, while for zigzag case, they are $\boldsymbol{\delta}'_1 = (\sqrt{3}/2(1+\mathcal{S})a, -(1-\sigma\mathcal{S})/2a)$, $\boldsymbol{\delta}'_2 = (0,(1-\sigma\mathcal{S})a)$, $\boldsymbol{\delta}'_3 = -\boldsymbol{\delta}'_1$. The so-called Dirac point can be obtained by minimizing the altered eigen-energies $E'(\mathbf{k}) = \pm|\sum_i t'_i e^{i\mathbf{k}\cdot\boldsymbol{\delta}'_i}|$, where the hopping integral t'_i can be estimated by a empirical relation $t'_i = t_0\, e^{-3.37(|\boldsymbol{\delta}'_i|/a-1)}$ due to alteration of the distance vectors [22,26].

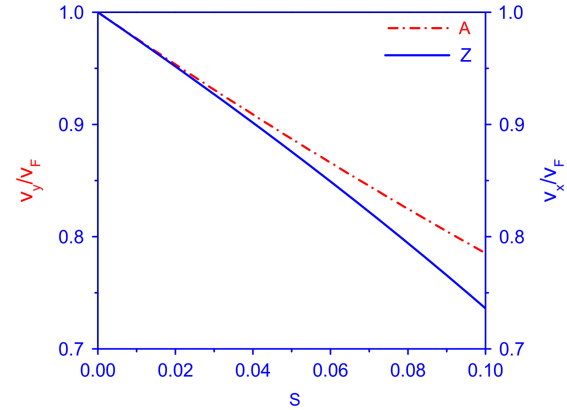

Fig. 1. The ratio of the effective velocities v_x, v_y to the Fermi velocity v_F versus the strain $\mathcal{S}$ exerted respectively along the armchair (red dashed-dot line) and zigzag (blue solid line) directions. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

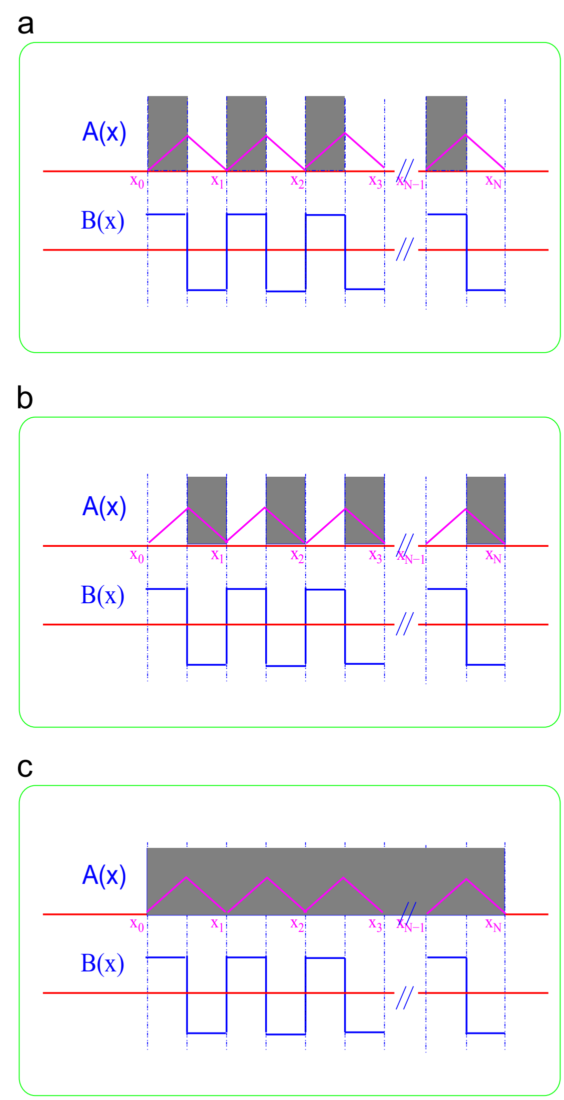

Fig. 2. The multiple strained graphene barriers, where the shaded regions represent the strained stripes, (a) the positive magnetic fields are exerted in the strained areas, (b) the negative magnetic fields are exerted in the strained areas, and (c) the whole central regions are fully strained with the alternating magnetic fields being applied. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)