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Gate-tunable valley-filter based on suspended graphene with double magnetic barrier structures

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ABSTRACT

We theoretically investigate the effects of strain-induced pseudomagnetic fields on the transmission probability and the ballistic conductance for Dirac fermion transport in suspended graphene. We show that resonant tunneling through double magnetic barriers can be tuned by strain in the suspended region. The valley-resolved transmission peaks are apparently distinguishable owing to the sharpness of the resonant tunneling. With the specific strain, the resonant tunneling is completely suppressed for Dirac fermions occupying the one valley, but the resonant tunneling exists for the other valley. The valley-filtering effect is expected to be measurable by strain engineering. The proposed system can be used to fabricate a graphene valley filter with the large valley polarization almost 100%.

1. Introduction

Graphene, a two-dimensional honeycomb crystal consisting of only carbon atoms, has received a lot of attention from researchers during the last several years. The electronic structure of graphene can be described by linear energy dispersions at six corners of the Brillouin zone, which are called Dirac points [1]. Charge carriers (electrons and holes) near the Dirac points are characterized by two degenerate valleys in addition to the spin degree of freedom, leading to the four-fold degeneracy. The existence of the valley degeneracy makes graphene a potential candidate as a new class of nanoelectronic devices, “valleytronics”.

There have been considerable efforts in the design and realization of manipulation of the valley index of graphene through diverse theoretical schemes [2–10]. One might use the fact that valley polarization is produced by nonequilibrium population of different valleys in a nanoconstriction with zigzag edges [2,3]. A graphene valley filter was suggested by using line defects [4,5]. It is difficult to realize these valley filters because the atomic-scaled precision of the edges and defects is required to control the valley transport for practical studies. On the other hand, some works have focussed on the effects of substrate-induced strain in graphene in order to construct a feasible valley filter [6–10]. The pseudomagnetic field indeed plays a role of creating valley-dependent tunneling with high valley polarization. Despite of the high valley polarization, one practical issue has remained for the strain-induced valley filter: controlling the substrate-induced strain of graphene is not easy. Thus, it is natural to ask whether the tunable valley-dependent transport through graphene is possible. In this paper, we take notice a gate-tunable strain of suspended graphene as a way of realizing the tunable valley-filter in graphene.

Research on suspended graphene was originally motivated by the fact that the advantage of using suspended graphene lies in its ability to avoid the substrate-induced effects which deteriorate the electrical properties of graphene [11–16]. It has been demonstrated that suspended graphene sheets show extremely high mobility due to reduced interactions between graphene sheets and substrates [17,18]. The other significance of suspended graphene is a potential ability to study the effects of strain on Dirac fermion transport in graphene. Since graphene has an advantage of being able to stand elastic deformation up to 20% [19,20], the physics of interplay between strain and electronic properties of graphene becomes a very promising field in recent condensed matter research. For suspended graphene, the magnitude of strain in a suspended region can be tuned by controlling the back gate voltage owing to the Coulomb interaction between a two-dimensional Dirac fermion gas

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and a back gate [21]. The tunable strain of suspended graphene may offer the opportunity to study how one can control the transport of Dirac fermions by mechanical strain.

In this paper, we present a strategy to realize a tunable valley transport by controlling strain for suspended graphene. We investigate the valley dependence of the transmission probability and ballistic conductance because of the existence of pseudomagnetic fields. Compared to substrate-induced strain, the strain in suspended graphene can be very easily controlled by field effects, based on typical gated structures. We find that suspended graphene with a double magnetic barrier (DMB) structure can be a efficient valley filter, and the considerable valley polarization can be achieved by applying strain to the suspended region. The DMB structure is produced by two ferromagnetic (FM) top gates placed at both sides of the suspended region over a trench, as illustrated in Fig. 1. The system comprises of two distinct components, i.e., pseudo- and external magnetic fields induced by the strain and the FM gates, respectively. We further show that the valley-filtering effect is also observed in the ballistic conductance as a measurable quantity for practical investigations. The results may provide a way of manipulating the valley degree of freedom for future valleytronics.

2. Theoretical background and model

We begin with the Hamiltonian of a two-dimensional Dirac fermion gas. The Dirac Hamiltonian with the formation of mechanical strain in the presence of external electric and magnetic fields is given by.

$$H_{K,K'} = v_F \vec{\sigma}\cdot\left(\vec{p} + e\vec{A}_{ex} + \xi e\vec{A}_s\right) + U_{ex} + \xi U_s, \qquad (1)$$

where $\vec{\sigma} = (\sigma_1, \sigma_2)$ are Pauli matrices, and $\xi = \pm 1$ for different valleys K or K'. In this study, we assume that the external electric potential is constant as zero for simplicity. Both the in- and out-of-plane stresses induce effective vector and scalar potentials as below:

$$\begin{pmatrix} A_{s,x} \\ A_{s,y} \end{pmatrix} = \frac{\hbar\beta}{ea_0}\begin{pmatrix} \cos 3\Omega & \sin 3\Omega \\ -\sin 3\Omega & \cos 3\Omega \end{pmatrix}\begin{pmatrix} u_{xx} - u_{yy} \\ -2u_{xy} \end{pmatrix}, \qquad (2)$$
$$U_s = U_0(u_{xx} + u_{yy}),$$

where $a_0 \approx 1.4$ Å is the carbon–carbon bond length, $\beta = -C(\partial \log t)/(\partial \log a_0) \approx 2$ with $\mathscr{O}(C) \sim 1$, and $U_0 = 10$ eV. Note that we set $\Omega = 0$ or $\pi/2$ when the strain is applied along the armchair or zigzag directions. The strain tensor u_{ij} is derived as follows:

$$u_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial r_j} + \frac{\partial u_j}{\partial r_i}\right) + \frac{1}{2}\frac{\partial h}{\partial r_i}\frac{\partial h}{\partial r_j}, \qquad (3)$$

where $\vec{u}(\vec{r})$ and $h(\vec{r})$ are in- and out-of-plane displacements, respectively.

It has been shown that the homogeneous effective gauge field is generated in the suspended region when the profile of vertical deformation of suspended graphene sheet is parabolic [21]. Throughout this paper, we assume that the suspended region of graphene sheet undergoes the parabolic vertical deformation, allowing convenience of the theoretical framework. In this case, we have the following profile of vertical deformation:

$$h(x) = \frac{4h_0}{L^2}\left(x^2 - \frac{L^2}{4}\right), \qquad (4)$$

where the maximum deformation h_0 is given by Ref. [21]

$$h_0 = \left(\frac{3\pi}{64}\frac{e^2}{\varepsilon E}n^2 L^4\right)^{\frac{1}{3}}, \qquad (5)$$

where $E = 22$ eV Å^{-2} is Young's modulus of graphene, ε is the electric permittivity, and L is the length of the suspended region. The in-plane stress, on the other hand, is:

$$u_x(x) = \frac{8h_0^2}{3L^2}x - \frac{32h_0^2}{3L^4}x^3, \qquad (6)$$

satisfying boundary conditions, $u_x(\pm L/2) = 0$. We put $u_y = 0$ since the in-plane strain is applied along the x-direction. When we have the strain lay along the zigzag direction, i.e., $\Omega = \pi/2$, the effective vector potential induced by the strain is given by

$$\vec{A}_s = \xi\frac{\hbar\beta}{ea_0}\frac{8h_0^2}{3L^2}\left[\theta\left(x + \frac{L}{2}\right) - \theta\left(x - \frac{L}{2}\right)\right]\hat{y}. \qquad (7)$$

Note that, in case of $\Omega = 0$, the x-component of the effective vector potential becomes constant, and its y-component vanishes. The corresponding pseudomagnetic field $\vec{B}_s = \nabla \times \vec{A}_s$ is given by a set of delta-function spikes at the edges of the suspended region. Now, let us focus on the effects of pseudomagnetic field with the

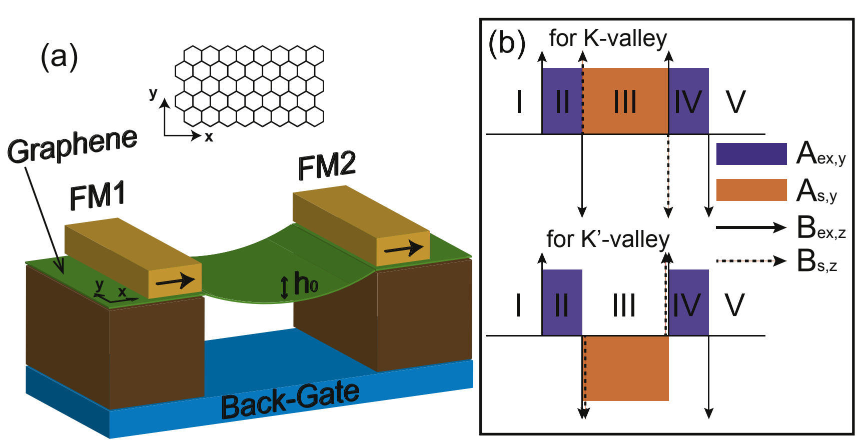

Fig. 1. (a) Schematics of the model considered in this study. A graphene sheet is suspended between two clamps, and strain in the suspended region is induced by an electrostatic pressure via a back gate. Two FM top gates deposited on unsuspended regions of the graphene sheet produce a double magnetic barrier structure. The suspended graphene is placed as its zigzag direction is along the x-axis of the reference frame in this study. (b) Profiles two kinds of magnetic fields and vector potentials ($B_{s,z}$and $B_{ex,z}$; $A_{s,y}$ and $A_{ex,y}$) for Dirac fermions in different valleys. As notations, the subscripts 's' and 'ex' indicate 'strain-induced' and 'external' magnetic fields (vector potentials), respectively.