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A scheme to realize the quantum spin-valley Hall effect in monolayer graphene

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ABSTRACT

Quantum spin Hall effect was first predicted in graphene. However, the weak spin orbit interaction in graphene meant that the search for quantum spin Hall effect in graphene never fructified. In this work we show how to generate the quantum spin-valley Hall effect in graphene via quantum pumping by adiabatically modulating a magnetic impurity and an electrostatic potential in a monolayer of strained graphene. We see that not only exclusive spin polarized currents can be pumped in the two valleys in exactly opposite directions but one can have pure spin currents flowing in opposite directions in the two valleys, we call this novel phenomena the quantum spin-valley Hall effect. This means that the twin effects of quantum valley Hall and quantum spin Hall can both be probed simultaneously in the proposed device. This work will significantly advance the field of graphene spintronics, hitherto hobbled by the lack of spin-orbit interaction. We obviate the need for any spin orbit interaction and show how graphene can be manipulated to posses features exclusive to topological insulators.

1. Introduction

Graphene is the material of the 21st century, what Silicon was to the 80's and 90's. It continues to be the most exciting material in condensed matter today, although challenged by topological insulators, for it's ability to show some striking unusual phenomena and it's potential applications in nanoelectronics [1]. Several remarkable features of graphene, which are in complete contrast to semiconductor heterostructures, are Klein tunneling [2] and room temperature quantum Hall effect [3]. It's electronic properties are governed by massless linear dispersion- Dirac behavior at low energy around two distinct valleys K and K' in it's Brillouin zone. These two valleys, connected by time reversal symmetry, can also act as an additional degree of freedom just like spin in spintronics [4]. Similar to spintronics, the valley degree of freedom can also be exploited as regards applications in quantum computation-referred as valleytronics [5–7]. In valleytronics proposals, via controlling the valley degree of freedom, valley based filter, valve and field effect transistor have been already reported [7–12]. There were also proposals of quantum spin valley Hall effect in multilayer graphene [13], spin-valley filter in graphene [14] and thermally driven spin and valley currents in Group-VI dichalcogenides [15].

An exciting aspect of graphene is that a mechanical strain provides an excellent way to control valley degree of freedom. Strain causes an opposite transverse velocity in the two valleys (K,K′) [16,17]. The separation in momentum space between two valleys, generated by the opposite velocity, causes the well known valley Hall effect [18,19]. The various Hall effects possible in graphene are mentioned in the Box. Apart from strain, there are several other proposed schemes to produce valley polarization-like triangular wrapping effects [7], edge effects in graphene nanoribbons [20] and a valley dependent gap generated by substrate [21–23], etc. Strained graphene can also show some electro-optic properties like: total internal reflection, valley dependent Brewster angle and Goos Hanchen effects [24].

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The possible Hall effects in monolayer graphene

Depending on the situation encountered one can have any or some of the following conditions satisfied in our proposed device:

- Ia. $I_c^K = I_c^{K'} = 0$ ($I_\uparrow = -I_\downarrow$)- The condition of pure spin current generation in each valley regardless of the angle of incidence of electron. Here, $I_c^{K/K'} = I^\uparrow_{K/K'} + I^\downarrow_{K/K'}$, the total charge current in *K/K'* valley,
- Ib. $I_c^K(\phi) = I_c^{K'}(\phi) = 0$- The condition of pure spin current generation in each valley at a particular angle of incidence ϕ.
- II. $I_c^K(\phi) = -I_c^{K'}(\phi)$, charge currents are same and opposite in each valley for a particular angle of incidence-quantum valley Hall effect (QVH).
- IIIa. $I_\uparrow^K(\phi) = -I_\downarrow^{K'}(\phi)$ with $I_\downarrow^K(\phi) = I_\uparrow^{K'}(\phi) = 0$ i.e; two valleys carrying opposite spin current with same magnitude but in opposite direction-quantum spin-valley Hall effect (QSVH) of 1st kind,
- IIIb. $I_\downarrow^K(\phi) = -I_\uparrow^{K'}(\phi)$ with $I_\uparrow^K(\phi) = I_\downarrow^{K'}(\phi) = 0$-QSVH of 1st kind.
- IV. $I_\uparrow^K(\phi) - I_\downarrow^K(\phi) = -[I_\uparrow^{K'}(\phi) - I_\downarrow^{K'}(\phi)]$, QVH with pure spin current in each valley. This can also be termed as QSVH of 2nd kind.

In the present work, we use the following symbols for different components of pumped currents: spin-up current: $I_\uparrow$, spindown current: $I_\downarrow$, spin current: $I_s = I_\uparrow - I_\downarrow$ and charge current: $I_c = I_\uparrow + I_\downarrow$. Quantum spin-valley Hall effect (QSVH) is defined as one valley carries a current of only spin up (spin down) and the other valley carries a current of spin down (spin up) with same magnitude but in exactly opposite direction. A variant of this, i.e., two valleys carry pure spin currents in exactly opposite direction with same magnitude is termed as QSVH of 2nd kind, see Fig. 1 for a pictorial on QVH and QSVH (first and second kinds). In this work, we aim to manipulate both degrees of freedom, i.e., spin and valley, for which we dope the graphene monolayer with a magnetic impurity and an electrostatic potential and also apply an in-plane strain to the graphene layer. We find that the condition (Ia) of pure spin current generation in each valley is satisfied in Fig. 7. The condition (Ib) of pure spin current generation at a particular angle of incidence and the QVH appear in Fig. 5(b) (upper panel). We get the condition (III) of QSVH of 1st kind in Fig. 4, while the condition (IV) of QSVH of 2nd kind is found in Fig. 5(b) (lower panel).

2. Theory

Graphene is a two dimensional carbon allotrope with hexagonal lattice structure [1] that can be split into two triangular sublattices *A* and *B*. We consider a mechanical strain to be applied to the graphene sheet which is lying in the *x*-*y* plane [16,17], in the region between magnetic impurity at $x = 0$ and electrostatic potential at $x = a$. The sketch of the considered system is shown in Fig. 2. Strain is included in the Dirac Hamiltonian as follows- In-plane mechanical strain affects the hopping amplitude between two nearest neighbors and can be described as a gauge vector which are opposite in two valleys. In the Landau gauge, the vector potential corresponding to the strain is $\mathbf{A} = (0, A_y)$. The system can be easily described by the Hamiltonian [24–26], as:

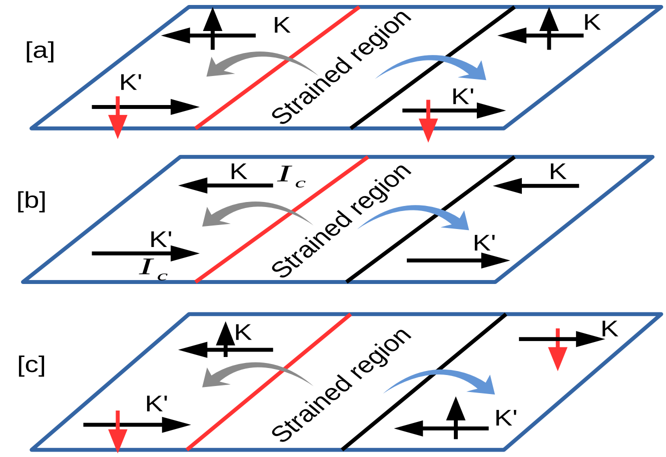

Fig. 1. A pictorial representation of different possible charge/spin pumped currents in each valley. The red and black solid lines are two scatterers (magnetic impurity and delta potential). In Fig. 1(a), K and K′ valley carry exclusively spin up and spin down currents in exactly opposite direction-quantum spin valley Hall effect (QSVH of 1st kind). Fig. 1(b) shows charge currents in each valley are same in magnitude and opposite in direction-quantum valley Hall effect (QVH). Fig. 1(c) shows pure spin currents in each valley are same and opposite in direction, we call it quantum valley Hall effect with pure spin current (QSVH of 2nd kind). (A color version of this figure can be viewed online.)

$$\mathscr{H}_{K/K'} = H_{K/K'} + J\mathbf{s}.\mathbf{S}\delta(x) + V\delta(x-a) \tag{1}$$

with $H_K = \hbar v_F \sigma.(\mathbf{k} - \mathbf{t})$ and $H_{K'} = \hbar v_F \sigma^*.(\mathbf{k} + \mathbf{t})$. Here, $t = \frac{A_y}{\hbar v_F}[\Theta(x) - \Theta(x-a)]$ is the strain with Θ being the step function, v_F is the Fermi velocity. The first term represents the kinetic energy for graphene with $\sigma = (\sigma_x, \sigma_y)$- the Pauli matrices that operate on the sublattices *A* or *B* and $\mathbf{k} = (k_x, k_y)$ the 2D wave vector. Second term is the exchange interaction between Dirac electron and magnetic impurity and final term is an electrostatic delta potential. In the second term *J* represents the strength of the exchange interaction which depends on the magnetization of the magnetic impurity and modulating it's magnetization one can effectively change *J*. The spin of Dirac electron is denoted by *s*, while *S* represents spin of the magnetic impurity. V is the strength of the potential, situated at

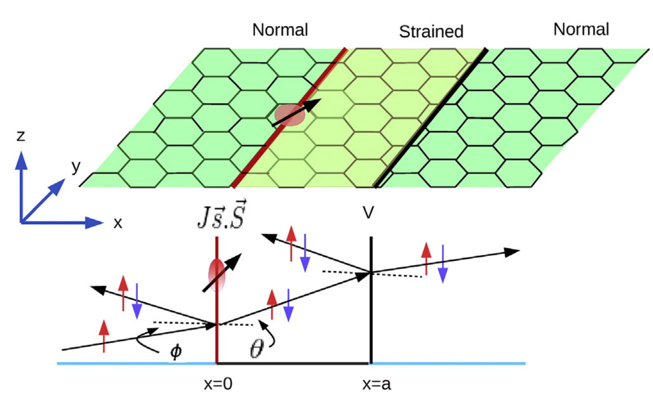

Fig. 2. Top: The graphene layer with the red solid line representing the magnetic impurity at $x = 0$, while black line is for electrostatic delta potential at $x = a$. The interveneing portion is the strained region. Valley and spin dependent currents are pumped out of the strained region by modulating magnetic impurity and electrostatic potential. The lower picture shows incident up electron (for K-valley) is reflected/transmitted with or without spin flip by magnetic impurity. The angle of incidence is ϕ, while the angle of refraction into the strained region is θ for a particular valley. Similar phenomena occurs at the other interface with electrostatic delta potential without spin flip. (A color version of this figure can be viewed online.)