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Controllable photo-induced spin and valley filtering in silicene

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ABSTRACT

We investigate theoretically the spin- and valley-dependent ballistic transport in silicene, which is assumed to be modulated by local application of a gate voltage and off-resonant circularly polarized light. We show that, due to the coupling between valley and spin degrees of freedom in silicene, the current through it is spin and valley polarized. The spin (valley) polarization can be enhanced by tuning the light intensity and the value of the perpendicular electric field, leading to perfect spin (valley) filtering for certain of their values. It is also found that the spin (valley) polarization can be inverted by reversing the perpendicular electric field (by reversing the perpendicular electric field or reversing the circular polarization of the light irradiation).

1. Introduction

Silicene, a monolayer of silicon atoms arranged in a honeycomb lattice structure, has been synthesized recently [1–4]. Due to the large ionic radius of the silicon atoms, the honeycomb lattice structure is puckered such that the A and B sublattices are shifted vertically with respect to each other and sit in two parallel planes with a separation of 0.46 *nm*[5,6]. Due to the puckered structure, which results in a large spin-orbit interaction [7], the low energy dynamic near the Dirac points in the hexagonal Brillouin zone of silicene is dominated by a massive Dirac Hamiltonian [7], with a mass which could also be tuned via an electric filed applied perpendicular to the silicene plane [5,8]. These novel features donate many attractive properties to silicene [5,8–15].

In silicene, the valley and spin degrees of freedom have been coupled via a spin-orbit interaction [7] which is large compared with that in graphene [16]. This can lead to a detectable spin- or/and valley-polarized transport in silicene, if the spin or/and valley degeneracies of its band structure are lifted [14,17]. Furthermore, silicon has long spin-coherence length [18] and spin-diffusion time [19,20]. Motivated by these facts, recently several groups have investigated ballistic transport of Dirac fermions in the different configurations of the ferromagnetic silicene systems [21–26]. They studied the influence of electric and exchange fields on ballistic transport across single [21–24], double [22] and arrays of ferromagnetic (FM) barriers [25]. They reported novel results such as perfect spin and/or valley polarization and tunable transport gap which are electrically controllable.

In this letter, we propose a scheme to employ off-resonant circularly polarized light to achieve electrically/optically controllable nearly perfect spin- and valley-filtering in silicene. Our motivation to propose this scheme is the development of

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new experimental probes [27,28] which makes it possible to access non-equilibrium effects arising from the off-resonant light irradiation. In our proposed scheme, a strip in a silicene plane is subjected to off-resonant circularly polarized light. Hence, the band structure inside the strip is modified through virtual photon absorption/emission processes. This leads to a new energy band which, due to the spin-valley coupling in silicene, is spin-polarized. If a perpendicular electric field is applied, the band structure becomes valley-polarized too. Such a light-irradiated strip can act as a spin- and/or valley-dependent barrier, leading to nearly perfect spin or/and valley filtering for certain values of the light intensity and the perpendicular electric field.

2. Model Hamiltonian

We study ballistic transport of Dirac fermions across a strip in a silicene plane, when the strip is subjected to off-resonant circularly polarized light and a perpendicular electric filed. Let us take x-axis perpendicular to the edges of the strip (the interfaces) and y-axis along them (see Fig. 1). The interfaces are located at $x = 0$ and $x = L$. We also assume the translational invariance along y-axis satisfied in the limit of large W (W is the width of the silicene plane). We restrict our consideration to $W/L \gg 1$ limit, in which the effects of the microscopic details of the upper and lower edges of the silicene plane on the electron transport become insignificant [29].

The low energy excitations in silicene, which occur in the vicinity of the Dirac points ($\mathbf{K}$ and $\mathbf{K}'$), are dominated [7] by a 2×2 Hamiltonian matrix as

$$H^{\eta,s_z} = \hbar v_F\left(k_x\tau_x - \eta k_y\tau_y\right) - \eta s_z\Delta_{so}\tau_z, \tag{1}$$

acting in the sublattice pseudospin space. The first part of the Hamiltonian is the Dirac Hamiltonian arising from the nearest neighbor transfer energy with $\eta = +$ ($\eta = -$) for $\mathbf{K}$ ($\mathbf{K}'$). In this term $v_F = \sqrt{3}ta/2\hbar$ is the Fermi velocity with $t = 1.6\ eV$ and $a = 0.386\ nm$ being the nearest-neighbor transfer energy and the lattice constant of silicene respectively. τ_i ($i = x,y,z$) are the Pauli matrixes and $\mathbf{k} = (k_x,k_y)$ is the two dimensional momentum measured from the Dirac points. The second term is the Kane-Mele term [30] for the intrinsic spin-orbit coupling, in which $\Delta_{so} = 3.9meV$[7] is the spin-orbit coupling and s_z index refers to two spin degrees of freedom with $s_z = +1$ and $s_z = -1$ for the spin up and spin down electrons respectively.

As mentioned above, the strip is subjected to a perpendicular electric filed and off-resonant circularly polarized light. Due to the buckled structure of silicene, applying the perpendicular electric filed, E_z, causes a staggered sublattice potential as [8] $\Delta_z\tau_z$ where $\Delta_z = e\ell E_z$ with $\ell = 0.023\ nm$ being the perpendicular distance between the inequivalent sublattices. The circularly polarized light is described by an electromagnetic potential as

$$\mathbf{A}(t) = (\pm A\sin\Omega t, A\cos\Omega t), \tag{2}$$

where Ω is the frequency of light and the plus (minus) sign corresponds to the right (left) circulation. The gauge potential is periodic in time, $A(t+T) = A(t)$, with the time periodicity $T = 2\pi/\Omega$. The light intensity can be characterized by a dimensionless parameter as $\mathscr{A} = eaA/\hbar$, where e is the electron charge. To capture the effects of the light irradiation, one can apply the minimal substitution, $\hbar k_i \rightarrow P_i \equiv \hbar k_i + e\mathbf{A}_i$, and use Floquet theory [31–33]. In this paper, we focuss on the off-resonant frequency regime satisfied when $\hbar\Omega \gg t$ in our calculation. In this regime light does not directly excite the electrons, and instead effectively modifies the electron band structure through virtual photon absorption/emission processes. In the off-resonant frequency regime and in the limit of small light intensity, $\mathscr{A} \ll 1$, the influence of the off-resonant light irradiation on the electron band structure is well described by a static effective Hamiltonian [10,31] as

$$\Delta H^{\eta,s_z} = -\frac{\left[H_{+1}^{\eta,s_z}, H_{-1}^{\eta,s_z}\right]}{\hbar\Omega} + \mathscr{O}\left(\mathscr{A}^4\right), \tag{3}$$

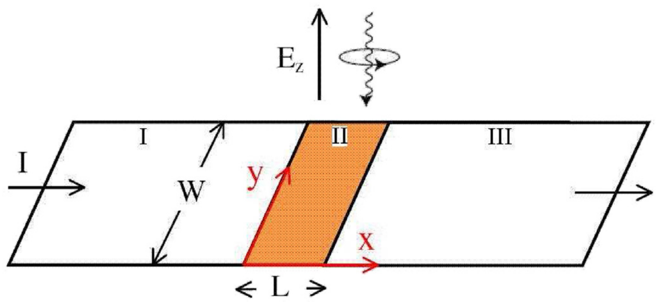

Fig. 1. Schematic of a silicene plane in which a strip (the orange region), is subjected to a perpendicular electric field and off-resonant circularly polarized light. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)