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Polarized-photon frequency filter in double-ferromagnetic barrier silicene junction

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ABSTRACT

We present an analytical study of effects from circularly polarized light illumination on controlling spin-valley currents in a dual ferromagnetic-gated silicene. Two different perpendicular electric fields are applied into the ferromagnetic (FM) gates and the photo-irradiated normal (NM) area between the gates. One parallel (P) and two anti-parallel (AP) configurations of exchange fields applied along with chemical potential to the gates are used in this investigation. Interestingly, the studied junction might give rise to polarized-photon frequency filter. Spin-valley filtering can be achieved at the off-resonant frequency region with appropriate direction of electric fields and the configuration of exchange fields (AP-1 or AP-2). Under the photo irradiation, this study found that tunneling magnetoresistance (TMR) is controllable to achieve giant magnetoresistance (GMR) by adjusting electric fields or chemical potentials. Our study suggests the potential of photo-sensing devices in spin-valleytronics realm.

1. Introduction

Silicene, two-dimensional silicon with out-of-plane bucklings, has recently attracted great attention after experimental discovery [1–3]. It is considered to be one of the candidates for the post-bulk-silicon era along with other artificial elemental 2D materials such as germanene (Ge) [4,5], phosphorene (P) [6], stanene (Sn) [7–9] and plumbene (Pb) [10] in electronics, spintronics, valleytronics and quantum computing applications. These novel 2D materials, especially stanene and plumbene, have large enough band gap opening and spin-orbital coupling (SOC) strong enough to maintain robust quantum spin Hall effect at high temperature. The abovementioned desirable characteristics are hard to achieve in graphene, the first elemental 2D material, due to the small ionic radius of carbon. The strong SOC also gives rise to the spin-valley coupling, which may lead to the integration of spintronics and valleytronics [11,12]. Among these 2D materials, silicene is currently considered to be the most promising candidate mainly due to the accumulation of silicon-related technology and knowhow in semiconductor industry [13,14]. Although in theory silicene has zero band gap, the buckled honeycomb lattice structure allows Dirac electron mass and its band structure to be manipulated easily by electric field [15,16].

The two-dimensional buckled honeycomb lattice structure in silicene causes tunable spin-valley coupled band structure giving rise to topological phase transition, an intriguing transport phenomenon [17]. Silicene has rich varieties of phases such as quantum spin Hall (QSH) state, quantum anomalous Hall (QAH) state, quantum Hall effect (QHE) state, fractional quantum Hall effect (FQHE) state, band insulator (BI), and valley-polarized metal (VPM). By controlling electric field and exchange field appropriately, it is possible to materialize these phases and achieve the topological phase transition [15,18]. There have been studies on ballistic transport, and the relationship between the transmission probability and valley conductance with electric field and exchange field in silicene junctions [19,20]. More recently, double ferromagnetic-gated silicene junction was proposed to control lattice-pseudospin current along with pure spin-valley current in silicene giving a possibility for pseudospintronics [21]. Another interesting development in making silicene devices is the self-doping phenomenon caused by strain [22].

Great attention in silicene has also led to more investigation and discovery in many other aspects such as hydrogenation effect, synthesis of multilayer silicene, and photoinduced effects. Fully hydrogenated silicene is called silicane, an interesting material for FET application, while half-hydrogenated silicene is a method to introduce magnetism and generate band gap in silicene [23,24]. In addition to synthesis of monolayer silicene on Ag, ZrB_2, and Ir(111) substrates, experimental groups have succeeded in synthesis of multilayer silicene using both epitaxial growth and non-epitaxial growth after theoretically proposal [25–27]. Another area that attracts attention recently is photo-induced

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effects, similarly to the study in graphene, where circularly polarized light is used to open a gap at the Dirac point [28]. By irradiation of circularly polarized light at fixed electric field, the topological class of silicene could be changed from quantum spin-Hall insulator (QSHI) to other phase [29,30].

Light irradiation on silicene has effects on the band structure. The photo-irradiation realizes a topological superconductor when s-wave superconductivity proximity coupling is applied [31]. It is reported that spin-valley polarization depends on the intensity of off-resonant circularly polarized light as well as electric field, and it can be inverted by reversing the direction of electric field or the circular polarization of the light [32]. Spin-valley polarizations and tunneling magnetoresistance in a ferromagnetic-normal-ferromagnetic (FNF) junction can be significantly enhanced by off-resonant circularly polarized light without electric field or magnetic field [33]. There is also a study in effective photo-induced band structure manipulation with intense terahertz irradiation beyond the off-resonant condition [34].

In this paper, we study the tight-binding model of silicene-based NM1/FM1/NM2/FM2/NM3 junction under the effects of electric fields, exchange fields, chemical potentials, and off-resonant circularly polarized light. Here, NMs stand for normal silicene and FMs stand for proximity-induced ferromagnetic silicene. Exchange field is applied to see the effects of parallel (P) and anti-parallel (AP) configurations. Then we study scattering process of the junction to obtain transmission probability. We particularly investigate the spin-valley conductance and tunneling magnetoresistance (TMR) of this junction. It is found that spin-valley filtering and TMR can be controlled by appropriate adjustment of the structure parameters and light frequency.

2. Model

We study ballistic transport of Dirac fermions in the double-barrier silicene-based structure shown in Fig. 1. The ferromagnetic barriers have length d, and are separated from each other by distance L. There were theoretical studies showing that exchange energy of 5 meV in graphene could be induced by ferromagnetic insulators EuO due to proximity-induced exchange splitting [35,36]. However, unlike the planar structure in graphene, silicene has buckling structure consisting of A-sublattice at the top and B-sublattice at the bottom (see Fig. 1). The two out-of-plane buckled sublattices may act like two separate atom layers of one silicene sheet. Therefore, it allows us to apply two different exchange fields into a silicene monolayer. One exchange field is induced by ferromagnetic gate at the top and another exchange field is induced by ferromagnetic gate at the bottom. The exchange energies induced at A- and B-sublattices, are designated as h_{1A} and h_{1B} at barrier FM1, while they are designated as h_{2A} and h_{2B} at barrier FM2.

Two controllable perpendicular electric fields, E_{z1} and E_{z2}, are applied to the ferromagnetic barriers FMs and NM2 region, respectively. Gate potential μ/e is applied from the top and the bottom of both ferromagnetic barriers, to induce chemical potential μ. Circularly polarized light $A(t) = A_0(\sin(\Omega t),\ \cos(\Omega t))$ is irradiated to the NM2 region, where Ω is frequency, A(t) is time-dependent vector potential of photon, and A_0 is magnitude. The off-resonant light frequency used in this study is the frequency region where the electronic band structures are changed by virtual photon absorption processes without direct electrons excitation. In π-band tight-binding model, this can be achieved when $\hbar|\Omega|\gg t_0$, where t_0 is nearest hopping energy. The lowest frequency Ω to satisfy this condition can be calculated from the bandwidth $3t_0$=4.8 eV=10^{15} Hz [29]. The perpendicular distance between A- and B-sublattices due to the buckling structure is represented with 2D=0.46 Å, where D=0.23 Å [37]. In this study, we investigate three junction types, one parallel junction (P) and two anti-parallel junctions (AP) as shown in Fig. 2. The parallel junction (P) is defined as the configuration in Fig. 2(a) where $h_{1A}=h_{1B}=h_{2A}=h_{2B}$=5 meV. As for anti-parallel junctions, AP-1 is the junction where $-h_{1A}=h_{1B}=-h_{2A}=h_{2B}$=5 meV, while AP-2 is the junction where $h_{1A}=-h_{1B}=h_{2A}=-h_{2B}$=5 meV as shown in Fig. 2(b) and (c), respectively.

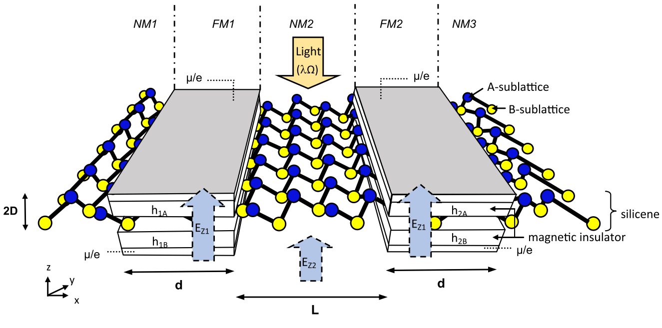

Fig. 1. Cross-sectional schematic model of double-barrier silicene-based NM1/FM1/NM2/FM2/NM3 structure.

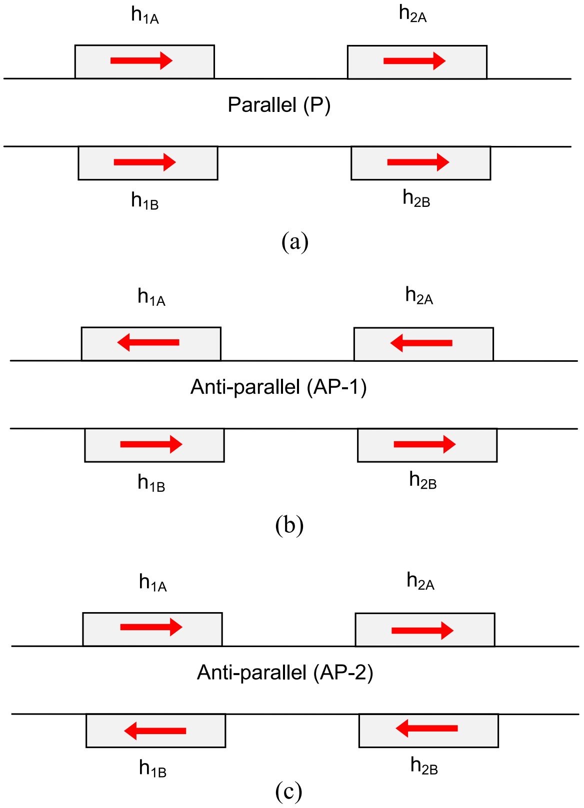

Fig. 2. Junction types used in this investigation, where→represents h, and ←represents −h. (a) Parallel junction (P), (b) anti-parallel junction type 1 (AP-1), (c) anti-parallel junction type 2 (AP-2).

The tight-binding Hamiltonians and low-energy effective Hamiltonians are used to describe the motion of electrons in A- and B-sublattices in our analysis [38–40]. Here, the effect of Rashba interaction is negligible comparing with the other terms at low energy, so the wave equation with excited energy E can be expressed with

$$\hat{H}_{\eta\sigma}\Psi_{\eta\sigma} = E\Psi_{\eta\sigma} \tag{1}$$

when k(k′) valley is represented by $\eta = 1(-1)$, and spin ↑(↓) is represented by $\sigma = 1(-1)$, respectively [39–41]. Here, $\psi_{\eta\sigma} = \begin{pmatrix} \varphi_{A,\eta\sigma} \\ \varphi_{B,\eta\sigma} \end{pmatrix}$ is spin-valley-dependent "lattice-pseudospinnor field", where $\varphi_{A,\eta\sigma}$ and $\varphi_{B,\eta\sigma}$ are wave functions at A- and B-sublattices, respectively.

In ferromagnetic regions FM1(2), the Hamiltonian is defined as

$$\hat{H}_{\eta\sigma} = \hat{H}_{F1(2)} = v_F(\hat{p}_x\tau^x - \eta\hat{p}_y\tau^y) - \Delta_{\eta\sigma1(2)}\tau^z - \mu_{\sigma1(2)}, \tag{2}$$