Bipolar and unipolar valley filter effects in graphene-based P/N junction

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Abstract

We use the spin and valley degrees of freedom to design the bipolar and unipolar valley filter effects based on the graphene-based P/N junction. When the modified Haldane model and staggered potential are applied on the region P, while the off-resonant circularly polarized light and staggered ferromagnetic exchange field are applied on the region N, the unipolar valley filter effect emerges with the unidirectional spin–valley current. The direction and type of the unidirectional spin–valley current depend on the phase of the modified Haldane model and the direction of polarized light. Other types of the bipolar valley filter effects are also reported, such as the valley-mixed bipolar spin filter effect, valley-mixed bipolar filter effect, valley-locked bipolar spin filter effect and valley-locked bipolar filter effect. These bipolar filter effects have the similarity that the spin–valley currents flow bidirectionally. These types of the unipolar and bipolar valley filter effects can be also mutually switched by modulating the external fields. Moreover, these unipolar and bipolar valley filter effects are robust against a weak temperature. This work reveals that the graphene-based junction has the potential applications in designing the valley filter device and improving the reprogrammable spin logic.

1. Introduction

Graphene, a two dimensional honeycomb crystal of the carbon atoms, has many remarkable features, such as electric transport, optical and topological properties [1–4]. In analogy to the spin degree of freedom leading to the emergence of spintronics [5–7], the valley degree of freedom is utilized to the application of valleytronics [8, 9], where the bits of information is stored and manipulated. In the momentum space, the two degenerate and inequivalent valley indexes refer to the local maximum of the valence band and minimum of the conduction band in the first Brillouin zone [10–13]. The intervalley scattering is generally not considered due to the large separation between the two valleys [14–17]. In order to improve the functionalities in valleytronics, it has been realized in experiment that the electric, magnetic and optical approaches have been proposed to manipulate the valley degree of freedom [18–20]. Some theoretical models are also reported to manipulate the valley degree of freedom. For instance, an off-resonance circularly polarized light is applied on the epitaxial graphene to turn on or off a nonequilibrium valley current [21]. The strain-induced inhomogeneous pseudomagnetic fields acting oppositely on the two valleys are used to generate the valley polarized current [22, 23].

In recent years, the valley caloritronics driven by a temperature difference has attracted much attention due to the presence of the valley degree of freedom [16, 24–26]. It is found that a longitudinal spin Seebeck effect can be driven near room temperature [26]. A valley Seebeck effect is also found, where the currents flow in the opposite direction with different valleys [16]. Then the valley-locked spin-dependent Seebeck effect (VL-SSE), where the carriers from only one valley could be excited by a thermal gradient, is put forward with the help of Seebeck effects above. Based on these types of the Seebeck effects, the valley filter effects under the bias are naturally proposed in ferromagnetic/antiferromagnetic junction, such as the
Our proposed graphene-based P/N junction is plotted in figure 1(a), the regions P and N are covered by the bipolar-unipolar transition of the spin-diode effect [27] essentially regarded as a valley filter effect and a spin–valley filter effect [25].

The ideal of the valley filter effect has emerged [23, 25, 28–30]. But there is still a huge space to explore the bipolar and unipolar valley filter effects. For instance, how many types of the bipolar and unipolar valley filter effects exist? How many spin–valley current forms are there for each bipolar or unipolar valley filter effect? Do the bipolar and unipolar filter effects exist whether in graphene or not? What a surprise is that we find four types of the bipolar valley filter effects exist such as valley-mixed bipolar spin filter effect, valley-mixed bipolar filter effect, valley-locked bipolar spin filter effect and valley-locked bipolar filter effect. And each bipolar filter effect has abundant spin–valley current forms. We only find one type of the unipolar filter effect, but eight spin–valley current forms of this effect have been found. We here suggest four types of the bipolar valley filter effect and one type of the unipolar filter effect in a graphene-based P/N junction on the basic of filling a vacancy of the valley filter effects. These bipolar and unipolar valley filter effects have different spin–valley current forms, which depend on the direction and type of external fields. For instance, the unipolar valley filter effect has eight spin–valley current forms consisting of its directions and types, which depends on the direction of polarized light and the phase of the modified Haldane model [31, 32]. Therefore, our systematic and comprehensive findings of the valley filter effects have potential applications in improvement in future spintronics, valleytronics and reprogrammable spin logic.

2. Model and method

Our proposed graphene-based P/N junction is plotted in figure 1(a), the regions P and N are covered by the left and right charge batteries with different chemical potentials [33]. In the absence of the charge battery, the chemical potentials are both zeros. As we know, the chemical potential in the graphene without external field is zero. Actually, the external field proposed in our manuscript just modulate valence and conduction bands. And the electrochemical potential has the same effect on the spin-up and spin-down electrons [33]. With the modified Haldane model [31, 32], the low-energy effective Hamiltonian of graphene without polarized light is expressed as

\[
H_{\eta}' = \hbar \nu_F \left( \tau_x k_x + \eta \tau_y k_y \right) + \Delta \tau_z + \lambda_{\text{FM}} \tau_0 \sigma_z + \lambda_{\text{AF}} \tau_2 \sigma_z + \left( \eta t_2^e + \eta t_2^z \right) \tau_0 \sigma_0 + \eta \lambda_I \tau_0 \sigma_2. \tag{1}
\]

The first term denotes the massless Dirac fermion, and the Fermi velocity reads \( \nu_F = \sqrt{3} a t / 2 \hbar \), where \( a \) is the lattice constant and \( t \) is the nearest-neighbor hopping energy. For simplicity, we set \( \hbar = \nu_F = 1 \). \( \eta = \pm 1 \) stand for the valleys \( K \) and \( K' \), respectively. The second term is the staggered potential, which can be induced by an h-BN substrate [34, 35] in graphene-based P/N junction. The third and fourth term are the ferromagnetic and anti-ferromagnetic exchange interactions. The details of experimental realization are described in the appendix A. The Pauli matrices \( \tau_i \) and \( \sigma_i \), with the index \( i = x, y, z \), describe the sublattice pseudospin and electron spin, respectively. The fifth term is the modified Haldane model,

\[
t_2^e = -3\sqrt{3} t_2 \sin \phi \quad \text{and} \quad t_2^z = -3 t_2 \cos \phi.
\]

And the hopping \( t_2 \) is a next-nearest-neighbor interaction with a complex value \( t_2 \exp(-i e \phi) \) due to a periodic magnetic flux density, and a phase \( 2\pi (2\phi_0 + \phi_b) / \phi_0 \) where \( \phi_b \) is the flux in the region \( b \) and \( \phi_b \) is the flux in the region \( b \). In addition, \( \phi_0 = h / e \) is the flux quantum. The details of experimentally realizing the modified Haldane model are also presented in the appendix A. The last term is the staggered spin–orbit coupling [36–38]. And we assume the spin–orbit couplings between the nearest neighbors vanish following the reference [38].

When the monolayer graphene is exposed to a beam of off-resonant circularly polarized light of

\[
A(t) = A \left( \xi \sin (\omega t) e_x + \cos (\omega t) e_y \right), \tag{2}
\]

where the signs \( \xi = \pm 1 \) denote the right and left circularly polarized light, respectively, the Hamiltonian (1) can be rewritten as

\[
H_{\eta}' = \hbar \nu_F \left( \tau_x k_x + \eta \tau_y k_y \right) + \Delta \tau_z + \lambda_{\text{FM}} \tau_0 \sigma_z + \lambda_{\text{AF}} \tau_2 \sigma_z + \left( \eta t_2^e + \eta t_2^z \right) \tau_0 \sigma_0 + \eta \lambda_I \tau_0 \sigma_2 + \eta F \tau_2 \sigma_0, \tag{3}
\]

where \( F = (\xi e \nu_F)^2 / \hbar \omega \). The detailed derivation of the last term in Hamiltonian (3) is presented in the appendix B. The corresponding Dirac equation is expressed as

\[
H_{\text{eff}} \psi_{P/N} = E_{\text{eff}} \psi_{P/N}. \tag{4}
\]

By solving equation (4), the corresponding eigenvalues read

\[
E_{\text{eff}} = S \lambda_{\text{FM}} + \eta t_2^e + \eta t_2^z + S \eta \lambda_I \pm \sqrt{(\hbar \nu_F k)^2 + (S \lambda_{\text{AF}} + \Delta + \eta F)^2}, \tag{5}
\]
where the signs ± respectively denote the conduction and valence bands, and we define the variable \( S = 1 \) and \(-1\) denoting the spin-up and spin-down modes, respectively. The corresponding wave functions of the graphene-based P/N monolayer, utilized to calculate the transmission probability, are expressed as

\[
\psi_P = \left[ \left( \frac{1}{A e^{i\theta_\tau}} \right) e^{i k x} + t \left( \frac{1}{-A e^{-i\theta_\tau}} \right) e^{-i k x} \right],
\]

\[
\psi_N = t \left( \frac{1}{B e^{i\theta_\tau}} \right) e^{i q x},
\]

where

\[
A = \frac{E - M_P - M_{P1}}{\sqrt{(E - M_P)^2 - (M_{P1})^2}}
\]

\[
B = \frac{E - M_N - M_{N1}}{\sqrt{(E - M_N)^2 - (M_{N1})^2}}.
\]

The x-direction wavevectors are given as \( k_x = k \cos \theta_\tau \) and \( q_x = q \cos \theta_\tau \) in the regions P and N, respectively. \( k = \sqrt{(E - M_P)^2 - (M_{P1})^2} \) and \( q = \sqrt{(E - M_N)^2 - (M_{N1})^2} \) are the wavevectors, where the external fields \( M_P \) and \( M_{P1} \) applied on the region P are defined as \( M_P = E_{\text{FM}} + \eta \lambda \lambda_{\text{FM}} + \eta \lambda_{\text{AF}} \) and \( M_{P1} = S \lambda_{\text{FM}} + \eta \lambda_{\text{AF}} \) and \( M_{N1} = S \lambda_{\text{FM}} + \eta \lambda_{\text{AF}} + \eta F \). The conservation component in the \( y \) direction, the transmitted angle \( \theta_\tau \) can be obtained by \( k \sin (\theta_\tau) = q \sin (\theta_\tau) \), \( \theta_\tau = \text{arcsin} \left( \frac{k \sin (\theta_\tau)}{q} \right) \) if incident and transmitted states both from either the conduction or valence bands; and \( \theta_\tau = \pi - \text{arcsin} \left( \frac{k \sin (\theta_\tau)}{q} \right) \) if incident and transmitted states from different bands.

The coefficients \( t \) and \( r \) can be obtained by matching the wave function at the interface \( x = 0 \) of the graphene-based P/N junction. The angle-dependent transmission coefficient is expressed as

\[
t = \frac{2A \cos(\theta_\tau)}{B e^{i\theta_\tau} + A e^{-i\theta_\tau}}.
\]

But equation (8) is not our transmission probability, which should be consistent with the conservation of the probability current. The transmission probability is defined as \( T_{\mu \nu} = \frac{J_{\mu}}{I_{\mu}} \) [39], where the incident current density is defined as \( I_{\mu} = (\psi_P)^* \hat{J}_x (\psi_P) \) and the transmitted current density is defined as \( J_{\mu} = (\psi_N)^* \hat{J}_x (\psi_N) \). In addition, the current density operator in the \( x \) direction is defined as \( \hat{J}_x = v_{\text{F}} \tau_x \).

Then, one can get formula of the transmission probability as

\[
T_{\mu \nu} = \frac{\Re(B) \cos(\eta \theta_\tau) - \Im(B) \sin(\eta \theta_\tau)}{\Re(A) \cos(\eta \theta_\tau) - \Im(A) \sin(\eta \theta_\tau)} \exp(i \eta \theta_\tau) t^* t,
\]
in which the real and imaginary \( \theta_i \) cases are both considered. For the real \( \theta_i \) case, equation (6) can be
induced as

\[
T_{ij} = \frac{\text{Re}(B) \cos(\theta_i) - \text{Im}(B) \sin(\eta \theta_i)}{\text{Re}(A) \cos(\theta_i) - \text{Im}(A) \sin(\eta \theta_i)} I^e t.
\]  

(10)

According to the generalized Landauer–Büttiker transport approach, the spin–valley dependent currents read

\[
I_{\nu}^S = \frac{e}{h} \int_{-\infty}^{+\infty} dE \Delta f_{PN} N_0 \frac{k}{A} \int_{-\pi/2}^{\pi/2} d\theta T_{\nu} \cos(\theta_i),
\]

where \( N_0 = \frac{W}{\lambda} \) with the supposed spin–orbit coupling \( \lambda = 0.0039eV \) in order to make the factor \( \frac{k}{\lambda} \) dimensionless, \( W \) is the width of graphene monolayer. In addition, \( \Delta f_{PN} = f(E, \mu_L) - f(E, \mu_R) \) is the Fermi function difference. We here define a constant \( I_0 = \frac{\pi}{\lambda} N_0 \) utilized as the reduced value of \( I_{\nu}^S \).

3. Results and discussion

In the following, we present the bipolar and unipolar valley filter effects based on the graphene-based P/N junction shown in figure 1.

3.1. Valley-mixed bipolar spin filter effect

We consider a graphene-based P/N junction, where the ferromagnetic exchange field and staggered potential are presented in the region P, while the high-frequency circularly polarized light and antiferromagnetic exchange field are presented in the region N. The charge battery \( U [33] \) is used to modulate the chemical potential \( \mu_R \) in the region N depicted in figure 1. We find the valley-mixed bipolar spin filter effect (VMB-SFE) in the interval of \(-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV} \) depicted in figure 2(a), where only the spin-up valley current \( I_{K}^S \) moving from the left to the right for \( U < 0 \) and only spin-down valley current \( I_{K}^S \) moving from the right to the left for \( U > 0 \). Beyond the interval of \(-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV} \), four types of the spin–valley current simultaneously happen.

To better understand the reason why the VMB-SFE happens, we need to induce equation (11) as

\[
I_{\nu}^S = \frac{\pi}{4} \sum_E T_{\nu}^S(E) \Delta f \Delta E, \quad \text{where } T_{\nu}^S = N_0 \frac{k}{A} \int_{-\pi/2}^{\pi/2} d\theta T_{\nu} \cos(\theta_i)
\]

is the total transmission coefficient. For the region of \(-0.1 \text{ eV} \leq U < 0 \), the total transmission coefficient \( T_{K}^S \) satisfies the case of \( T_{K}^S \neq 0 \) under \( E < 0 \) due to the specific spin-matching tunneling shown in figures 2(c) and (d), and the case of \( \Delta f_{PN} = 0 \) under \( E \geq \mu_L \) or \( E \leq \mu_R \) and \( \Delta f > 0 \) under \( \mu_R < E < \mu_L \) is valid. Therefore, the spin–valley current \( I_{K}^S \) is positive for the region of \(-0.1 \text{ eV} \leq U < 0 \) shown in figure 2(a). Another spin–valley currents \( I_{K}^S, I_{K}^S \) and \( I_{K}^S \) in this region are zeros according to the same analysis above. For the region of \( 0 \leq U < 0.1 \text{ eV} \), the condition of \( T_{K}^S \neq 0 \) under \( E > 0 \) is valid, and the Fermi function difference satisfies the case of \( \Delta f = 0 \) under \( E \leq \mu_L \) and \( \Delta f < 0 \) under \( \mu_R < E \leq \mu_L \). Therefore, the spin–valley current \( I_{K}^S \) is negative in the region of \( 0 \leq U < 0.1 \text{ eV} \). Another spin–valley currents \( I_{K}^S, I_{K}^S \) and \( I_{K}^S \) are zeros in this region according to the same analysis above. In the region N, the band structure in figure 2(d) is transformed into the one shown in figure 2(c) as the direction of circularly polarized light is changed from the right to the left. The corresponding spin–valley currents are also shown in figure 2(b). These phenomena in figures 2(a) and (b) are both called the VMB-SFE, which have different forms of the spin–valley currents, summarized in table C1 in the appendix C.

We also investigate how the temperature effects the VMB-SFE, it is shown that the VMB-SFE is robust against a weak temperature, the detail of which is shown in figure D1 in the appendix D.

3.2. Valley-mixed bipolar filter effect

We consider staggered spin–orbit coupling and potential in the region P, while antiferromagnetic exchange field and staggered potential are applied on the region N. We find the valley-mixed bipolar filter effect (VMB-FE) in the interval of \(-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV} \), where the spin-down valley current \( I_{K}^S \) flowing from the left to the right for \( U < 0 \), and the spin-down valley current \( I_{K}^S \) flowing from the right to the left for \( U > 0 \) (figure 3(a)).

For the region of \(-0.1 \text{ eV} \leq U < 0 \), \( T_{K}^S \) satisfies the case of \( T_{K}^S \neq 0 \) under \( E < 0 \) due to the specific spin-matching tunneling shown in figures 3(c) and (d), and the case of \( \Delta f_{PN} = 0 \) under \( E \geq \mu_L \) or \( E \leq \mu_R \) and \( \Delta f > 0 \) under \( \mu_R < E < \mu_L \) is valid. Therefore, the spin–valley current \( I_{K}^S \) is positive for the region of \(-0.1 \text{ eV} \leq U < 0 \) shown in figure 3(a) according to the induced formula \( I_{\nu}^S = \frac{\pi}{4} \sum_E T_{\nu}^S(E) \Delta f \Delta E. \) In the same way, there exists a negative spin–down valley current \( I_{K}^S \) for \( 0 < U \leq 0.1 \text{ eV} \).
Figure 2. The parameters are set as $\lambda_{FM} = 0.05$ eV, $\Delta = 0.05$ eV in the region P and $\lambda_{AF} = 0.05$ eV, $F = 0.05$ eV in the region N. Spin–valley current with the right circularly polarized light (a) corresponds to (c) the band structure in the region P and (d) the band structure in the region N. Spin–valley current with the left circularly polarized light (b) corresponds to (c) and (d) the band structure in the region N. The red and blue lines denote the spin-up and spin-down modes, respectively. The red line crossing over (c)–(e) denotes the zero energy.

As we reverse the direction of the staggered potential in the region N, the band structure in figure 3(d) is switched into the band structure in figure 3(e). The corresponding spin–valley currents are depicted in figure 3(b), which is also called VMB-FE. These spin–valley current forms of the VMB-FE are summarized in table C2 of the appendix C. We also find that the VMB-FE is robust against a weak temperature not shown here, which is analogy to the VMB-SFE.

3.3. Valley-locked bipolar spin filter effect

The VMB-SFE shown in figure 2(a) will be switched into the valley-locked bipolar spin filter effect (VLB-SFE) as we apply the staggered potential instead of the antiferromagnetic exchanged field on the region N, where in the interval $-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV}$ only spin-up valley current $I^+_K$, moving from the left to the right for $U < 0$ and only spin-down valley current $I^-_K$, moving from the right to the left for $U > 0$. Beyond the interval of $-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV}$, four types of the spin–valley current simultaneously emerge. In the following, we also use the induced formula $I^\eta_s = \frac{e}{h} \sum E T^\eta_s(E) \Delta f \Delta E$ to explain the VLB-SFE shown in figure 4(a). In the same analyzation, it is obvious that the spin–valley current $I^+_K$ is positive in the region of $-0.1 \text{ eV} \leq U < 0$ and the spin–valley current $I^-_K$ is negative in the region of $0 < U \leq 0.1 \text{ eV}$ from the band structures in figures 4(c) and (d). The band structure in figure 4(d) will be transformed into the one in figure 4(e) as we modulate the direction of circularly polarized light from the right to the left, and the corresponding spin–valley currents shown in figure 4(b) are also called as the VLB-SFE. These spin–valley current forms of the VLB-SFE are summarized in table C3 of the appendix C. Moreover, the VLB-SFE is also robust against a weak temperature not shown here.

3.4. Valley-locked bipolar filter effect

The VLB-SFE shown in figure 4(a) will be switched into the valley-locked bipolar filter effect (VLB-FE) as we use the antiferromagnetic exchange field and circularly polarized light instead of the ferromagnetic exchange field and staggered potential in the region P, where in the interval $-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV}$ the same type of the spin–valley current $I^\eta_K$ moving from the left to the right for $U < 0$ and moving from the right to
the left for \( U > 0 \) (depicted in figure 5(a) and (b)). In figure 5(a), the spin–valley current \( I_{\uparrow}^K \) in the region of \(-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV}\) is analyzed by the induced formula \( I_{\uparrow}^K = \sum E T_{\uparrow}^K (E) \Delta f \Delta E \). We clearly find that the spin–valley current \( I_{\uparrow}^K \) is positive for the region of \(-0.1 \text{ eV} \leq U < 0\) and negative for the region of \(0 < U \leq 0.1 \text{ eV}\) from the band structures in figures 5(c) and (d). The band structure in figure (d) will be transformed into the one in figure 5(e) as we modulate the direction of the light applied on the region N from the right to left, and the corresponding spin–valley current \( I_{\uparrow}^K \) in the region of \(-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV}\) shown in figure 5(b) is also the VLB-FE. We also further modulate the direction of the light applied on the region P to change the spin–valley current forms, it is shown that the spin–valley currents \( I_{\downarrow}^K, I_{\downarrow}^{K'} \) in the region of \(-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV}\) shown in figure 5(b) is also the VLB-FE. These spin–valley current forms of the VLB-FE are summarized in table C4 of the appendix C. We also find that the VLB-FE is robust against a weak temperature not shown here.

3.5. Valley unipolar filter effect

The VMB-SFE shown in figure 2(a) will be switched into the valley unipolar filter effect (VU-FE) shown in figures 6(a) and (b) as we consider the modified Haldane mode instead of the ferromagnetic exchange field in the region P, where in the interval of \(-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV}\) the same type of the spin–valley current \( I_{\uparrow}^K \) moving from the left to right for \( U < 0 \) or moving from the right to the left for \( U > 0 \). In figure 6(a), only the spin–valley current \( I_{\uparrow}^K \) moving from the left to the right for \( U < 0 \) in the interval of \(-0.1 \text{ eV} \leq U \leq 0.1 \text{ eV}\). The induced formula \( I_{\uparrow}^K = \sum E T_{\uparrow}^K (E) \Delta f \Delta E \) is used to explain the VU-FE. For the region of \(-0.1 \text{ eV} \leq U \leq 0 \), the condition of \( T_{\uparrow}^K \neq 0 \) under \( E < 0 \) is valid due to the specific spin–matching tunneling shown in figures 6(c) and (e), and the condition of \( \Delta f = 0 \) under \( E \geq \mu_L \) or \( E \leq \mu_R \) and \( \Delta f > 0 \) under \( \mu_R < E < \mu_L \) is also valid. Therefore, the spin–valley current \( I_{\uparrow}^K \) is positive in the region of \(-0.1 \text{ eV} \leq U < 0 \) shown in figure 6(a). For the region of \(0 \leq U \leq 0.1 \text{ eV}\), the condition of \( T_{\uparrow}^K = 0 \) under \( 0 < E \leq 0.1 \text{ eV}\) due to the gap shown in figures 6(c) and (e) is valid, and the condition of \( \Delta f = 0 \) under \( E \leq \mu_L \) is also valid. Thus, the spin–valley current \( I_{\uparrow}^K \) is zero shown in figure 6(a). When we modulate the phase \( \phi = -\pi/6 \) instead of the phase \( \phi = 5\pi/6 \), the band structure in figure 6(c) will be
Figure 4. The parameters are set as $\lambda_{AF} = 0.05 \text{ eV}, \Delta = 0.05 \text{ eV}$ in the region P and $\Delta = 0.05 \text{ eV}, F = 0.05 \text{ eV}$ in the region N. Spin–valley current with the right circularly polarized light (a) corresponds to (c) the band structure in the region P and (d) the band structure in the region N. Spin–valley current with the left circularly polarized light (b) corresponds to (c) and (e) the band structure in the region N.

Figure 5. The parameters are set as $\lambda_{AF} = 0.05 \text{ eV}, F = 0.05 \text{ eV}$ in the region P and $\Delta = 0.05 \text{ eV}, F = 0.05 \text{ eV}$ in the region N. Spin–valley current with the right circularly polarized light in the regions P and N (a) corresponds to (c) the band structure in the region P and (d) the band structure in the region N. Spin–valley current with the left (right) circularly polarized light in the region N(P) (b) corresponds to (c) and (e) the band structure in the region N.
transformed into the one shown in figure 6(d), the direction of the corresponding spin–valley current $I_{K'}^\uparrow$ shown in figure 6(b) is changed compared to the one in figure 6(a). From figures 6(d) and (e), it is found that the condition of $T_{K'}^\uparrow = 0$ under $-0.2 \text{ eV} \leq E \leq 0$ is valid due to the gap. Moreover, the Fermi function difference satisfies the condition of $\Delta f = 0$ under $E \leq -0.2 \text{ eV}$, thus, the spin–valley current $I_{K'}^\uparrow$ is zero in the region of $0.1 \text{ eV} \leq U < 0$. For the region of $0 \leq U \leq 0.1 \text{ eV}$, the condition of $T_{K'}^\uparrow \neq 0$ under $E > 0$ and $\Delta f < 0$ under $\mu_L < E < \mu_R$ is valid, therefore, the spin–valley current $I_{K'}^\downarrow$ is negative in the region of $0 \leq U \leq 0.1 \text{ eV}$ according to the induced formula $I_{K'}^\downarrow = \frac{e}{2} \sum_{\eta} T_{\eta}^S (E) \Delta f \Delta E$. By modulating the direction of the light and the phase as $\pm \pi/6 \pm 5\pi/6$, eight spin–valley current forms of the VU-FE are thoroughly found, summarized in table C5 of the appendix C. The VU-FE is also robust against a weak temperature shown in figure D2 in the appendix D.

4. Conclusion

In summary, we systematically and comprehensively investigate four types of the bipolar valley filter effects in the graphene-based P/N junction using the Landauer’s formalism. Each type of the bipolar valley filter effect has abundant spin–valley current forms consisting of its direction and type, which depends on the direction of polarized light and another external fields. The unipolar valley filter effect having eight spin–valley current forms is also found in addition to the bipolar valley filter effects. These types of the bipolar and unipolar valley filter effects can also be mutually switched by changing the types of external fields. Moreover, the bipolar and unipolar valley filter effects are robust against a weak temperature. These results suggest that the graphene-based P/N junction is a perfect choice to design valley filter devices, where the four types of spin–valley current are independently separated. In addition, the switches between these types of the valley filter effects are also important for the improvement of reprogrammable spin logic based on the spin and valley degrees of freedom.
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Appendix A

A.1. Experimental realization of the exchange interactions

Here, we appropriately propose a way, which is not depending on the bulk or planar structure, to induce the exchange interaction. We consider that the graphene is put on the hexagonal BN planar deposited on ferromagnetic Co or Ni [40] or the hBN/(Co, Ni) [41]. Then, the exchange interaction and staggered potential emerge based on the ab initio calculations [42]. The induced staggered potential can be cancelled by the staggered potential mentioned above to obtain the pure exchange interaction. Hamiltonian for the exchange interaction is given by $H_{ex} = \frac{\lambda^A}{2} (\tau_z - \tau_0) \sigma_z + \frac{\lambda^B}{2} (\tau_z + \tau_0) \sigma_z$, where $\lambda^A_{ex}$ and $\lambda^B_{ex}$ are the exchange interaction corresponding to the sublattices A and B, respectively. In a special case of $\lambda^A_{ex} = \lambda^B_{ex} = \lambda_{AF}$, the fourth term denotes the antiferromagnetic (AF) exchange field which is obtained as $H_{ex} = \lambda_{AF} \tau_z \sigma_z$. In a special case of $\lambda^A_{ex} = -\lambda^B_{ex} = \lambda_{FM}$, the third term denotes the ferromagnetic (FM) exchange field which is obtained as $H_{ex} = \lambda_{FM} \tau_0 \sigma_z$. In addition, an antiferromagnetic substrate with a small lattice mismatching would induce antiferromagnetic exchange field with a spatial Moiré pattern [43].

A.2. Experimental realization of the modified Haldane model

The major experimental challenge for the realization of the Haldane model is to obtain the complex next-nearest-neighbor hopping $t_2 e^{i \psi_2}$ . Oka and Aoki [44] have proposed a rotating force to induce the required complex hopping in a honeycomb lattice. With a rotating force, Gregor Jotzu [45] has realized the Haldane model in experiment using ultracold fermions in an optical lattice. The same method could be used to realize the modified Haldane model [31]. The modified Haldane model might be realized in the transition metal dichalcogenides (TMD) monolayer [46] or ferromagnet/graphene/TMD junction [47].

Appendix B. Derivation of equation (3)

When the monolayer graphene is coupled to the irradiation of a time-dependent circularly polarized light, the vector potential modifies the Hamiltonian $H^S_{eff}$ by the minimal substitutions $k_x \rightarrow k_x + \frac{e \vec{A} \sin(\omega t)}{\hbar}$ and $k_y \rightarrow k_y + \frac{e \vec{A} \cos(\omega t)}{\hbar}$. Thus, the Hamiltonian is rewritten as

$$H^S_{eff} = \hbar v_F \left[ \tau_x \left( k_x + \frac{e \vec{A} \sin(\omega t)}{\hbar} \right) + \eta \tau_y \left( k_y + \frac{e \vec{A} \cos(\omega t)}{\hbar} \right) \right] + H_{ex}, \quad (A.1)$$

where $H_{ex} = \Delta \tau_z + \lambda_{FM} \tau_0 \sigma_z + \lambda_{AF} \tau_z \sigma_z + (\eta \tau_y^2 + \tau_z^2) \tau_0 \sigma_0 + \eta \lambda_1 \tau_0 \sigma_z$. In the high-frequency limit previously reported in references [21, 48, 49], the Hamiltonian (A1) is approximately equivalent to an effective Floquet Hamiltonian expressed as

$$H_{eff} = H_0 + \frac{[H_{-1}, H_0]}{\hbar \omega}, \quad (A.2)$$

where the second term arises owning to the circularly polarized light, and $H_m$ with $m = -1, 0, 1$ can be expressed as [50]

$$H_m = \frac{1}{T} \int_0^T dt e^{im\omega t} H^S_{eff}. \quad (A.3)$$

So we can get

$$H_{-1} = \hbar v_F \left( \tau_x \frac{e \vec{A} \xi}{2\hbar} + \eta \tau_y \frac{e \vec{A}}{2\hbar} \right)$$

$$H_0 = \hbar v_F \left( \tau_x k_x + \eta \tau_y k_y \right) + H_{ex} \quad (A.4)$$

$$H_1 = \hbar v_F \left( -\tau_x \frac{e \vec{A} \xi}{2\hbar} + \eta \tau_y \frac{e \vec{A}}{2\hbar} \right).$$

Substituting equation (4) into equation (2), we obtain the effective Floquet Hamiltonian as
Table C1. Corresponding parameters for the spin–valley currents of the valley-mixed bipolar spin filter effect.

| $\mu_R$ | Region P | Region N | Spin–valley current |
|--------|----------|----------|--------------------|
| $U$    | $\lambda_{FM}$ | $\Delta$ | $\lambda_{AF}$ | $\Delta$ | $I_k^\uparrow$ | $I_k^\downarrow$ | $I_{k'}^\uparrow$ | $I_{k'}^\downarrow$ |
| $[-0.1, 0]$ | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | + | 0 |
| $[0, 0.1]$ | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 |
| $[-0.1, 0]$ | 0.05 | 0.05 | 0.05 | $-0.05$ | + | 0 | 0 | 0 |
| $[0, 0.1]$ | 0.05 | 0.05 | 0.05 | $-0.05$ | 0 | 0 | 0 | $-$ |

Table C2. Corresponding parameters for the spin–valley currents of the valley-mixed bipolar filter effect.

| $\mu_R$ | Region P | Region N | Spin–valley current |
|--------|----------|----------|--------------------|
| $U$    | $\lambda_{AF}$ | $\Delta$ | $\lambda_{AF}$ | $\Delta$ | $I_k^\uparrow$ | $I_k^\downarrow$ | $I_{k'}^\uparrow$ | $I_{k'}^\downarrow$ |
| $[-0.1, 0]$ | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | + | 0 |
| $[0, 0.1]$ | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 |
| $[-0.1, 0]$ | 0.05 | 0.05 | 0.05 | $-0.05$ | + | 0 | 0 | 0 |
| $[0, 0.1]$ | 0.05 | 0.05 | 0.05 | $-0.05$ | 0 | 0 | 0 | $-$ |

Table C3. Corresponding parameters for the spin–valley currents of the valley-locked bipolar spin filter effect.

| $\mu_R$ | Region P | Region N | Spin–valley current |
|--------|----------|----------|--------------------|
| $U$    | $\lambda_{AF}$ | $\Delta$ | $\lambda_{AF}$ | $\Delta$ | $I_k^\uparrow$ | $I_k^\downarrow$ | $I_{k'}^\uparrow$ | $I_{k'}^\downarrow$ |
| $[-0.1, 0]$ | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | + | 0 |
| $[0, 0.1]$ | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 |
| $[-0.1, 0]$ | 0.05 | 0.05 | 0.05 | $-0.05$ | + | 0 | 0 | 0 |
| $[0, 0.1]$ | 0.05 | 0.05 | 0.05 | $-0.05$ | 0 | 0 | 0 | $-$ |

Table C4. Corresponding parameters for the spin–valley currents of the valley-locked bipolar filter effect.

| $\mu_R$ | Region P | Region N | Spin–valley current |
|--------|----------|----------|--------------------|
| $U$    | $\lambda_{AF}$ | $\Delta$ | $\lambda_{AF}$ | $\Delta$ | $I_k^\uparrow$ | $I_k^\downarrow$ | $I_{k'}^\uparrow$ | $I_{k'}^\downarrow$ |
| $[-0.1, 0]$ | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | + | 0 |
| $[0, 0.1]$ | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 |
| $[-0.1, 0]$ | 0.05 | 0.05 | 0.05 | $-0.05$ | + | 0 | 0 | 0 |
| $[0, 0.1]$ | 0.05 | 0.05 | 0.05 | $-0.05$ | 0 | 0 | 0 | $-$ |

$H_{\text{eff}} =$

\[
\left( \Delta + S\lambda_{FM} + S\lambda_{AF} + \eta F + \eta t_z^\uparrow + \eta t_z^\downarrow + S\eta \lambda_I \right) \frac{\hbar v_F}{h} \left( k_x - i\eta k_y \right) \left( \hbar v_F \left( k_x + i\eta k_y \right) \right) - \Delta + S\lambda_{FM} - S\lambda_{AF} - \eta F + \eta t_z^\uparrow + \eta t_z^\downarrow + S\eta \lambda_I \right) \hbar v_F \left( k_x - i\eta k_y \right). \tag{A.5} \]

where $F = \xi(eA\nu F)^2/h\omega$ is related to the amplitude of light field, which arises from the second term in equation (2).

Appendix C. Tables for different filter effect

In all the tables below, we consider the bias voltage region of $U \in [-0.1, 0.1]$. The units of all quantities except $\phi$ in the tables are set as eV. In the spin–valley current part, the sign $+$ denotes the current propagating from the left to the right while the sign $-$ denotes the current propagating from the right to the left; 0 denotes there is no corresponding current in the considered bias region.
Table C5. Corresponding parameters for the spin–valley currents of the valley unipolar filter effect.

| μ_R | Region P | Region N | Spin–valley current |
|-----|----------|----------|---------------------|
| U   | φ        | Δ        | λ_M         | U   | φ        | Δ        | λ_M         |
| [−0.1, 0] | 5π/6 0.1 | 0.05 | 0.05 | 0 0 | + | 0 0 |
| [0, 0.1]  | 5π/6 0.1 | 0.05 | 0.05 | 0 0 | 0 |
| [−0.1, 0] | 5π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |
| [0, 0.1]  | 5π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |
| [−0.1, 0] | −5π/6 0.1 | 0.05 | 0.05 | 0 0 | + |
| [0, 0.1]  | −5π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |
| [−0.1, 0] | −5π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |
| [0, 0.1]  | −5π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |
| [−0.1, 0] | π/6 0.1 | 0.05 | 0.05 | 0 0 | 0 |
| [0, 0.1]  | π/6 0.1 | 0.05 | 0.05 | 0 0 | 0 |
| [−0.1, 0] | π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |
| [0, 0.1]  | π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |
| [−0.1, 0] | −π/6 0.1 | 0.05 | 0.05 | 0 0 | 0 |
| [0, 0.1]  | −π/6 0.1 | 0.05 | 0.05 | 0 0 | 0 |
| [−0.1, 0] | −π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |
| [0, 0.1]  | −π/6 0.1 | 0.05 | −0.05 | 0 0 | 0 |

Figure D1. Spin–valley currents in figure 2(a) are affected by different temperatures.

Appendix D. Temperature on these valley effects

Here, we give two typical examples to discuss how the temperature affects the bipolar and unipolar valley filter effects. $T_L$ and $T_R$ are the temperature parameters in the regions P and N, respectively. In figures D1(a) and (b), the VMB-SFE is almost not broken in the region of $k_B T_L \leqslant 0.01 \text{eV}$, but when $k_B T_L > 0.01 \text{eV}$, this effect are obviously broken shown in figures D1(c) and (d). We also investigate the effect of the temperature on the VU-FE. In the region of $k_B T_L \leqslant 0.01 \text{eV}$, the unipolar filter effect is almost steady shown in
Figure D2. Spin–valley currents in figure 6(a) are affected by different temperatures. figures D2(a) and (b), but it will be broken in the region of $k_B T_L > 0.01eV$ shown in figures D2(c) and (d).

In summary, these filter effects almost keep steady for the region of $k_B T_L \leq 0.01eV$, while for the region of $k_B T_L > 0.01eV$ it will be obviously broken.

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