Topological spin–valley filtering effects based on hybrid silicene-like nanoribbons

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Keywords: spin–valley filter, silicene, inner-edge, topological phase

Abstract

Topological edge states have crucial applications in nano spintronics and valleytronics devices, while topological inner-edge states have seldom been extensively researched in this field. Based on the inner-edge states of the hybridized zigzag silicene-like nanoribbons, we investigate their transport properties. We propose two types of spin–valley filters. The first type can generate two different spin–valley polarized currents in output leads, respectively. The second type outputs the specific spin–valley polarized current in only one of the output leads. All these inner-edge states have the spin–valley-momentum locking property. These types of filters can switch the output spin–valley polarizations by modulating the external fields. Besides, we also find that the device size plays a crucial role in designing these spin–valley filters. Moreover, the local current distributions are calculated to visualize the detailed transport process and understand the mechanism. The mechanism lies that the spin–valley polarized current can nearly freely pass through the system with the same momentum, spin and valley degrees of freedom. The small reflection of the current results from the inter-valley scattering. In particular, we also consider the realistic (disorder) effects on the performance of these filters to ensure the robustness of our systems. We believe these spin–valley current filtering effects have potential applications in the future spintronics and valleytronics device designs.

1. Introduction

After the discovery of graphene [1–3], some two-dimensional (2D) materials [4–6], such as silicene, germanene, stanene, and some other silicene-derived materials with honeycombed lattices, have attracted considerable interests in the field of condensed matter physics and materials. Different from the planar structure and weak spin–orbit interaction (SOC) of graphene, the silicene-like materials have a low-buckled honeycomb structure and a stronger intrinsic SOC. The buckled structure results in a tunable energy gap by applying a perpendicular electric field. The large SOC makes the silicene-like materials good candidates of the topological insulator [5, 7]. These silicene-like materials also have two inequivalent valleys (named K and K’) in the first Brillouin zone at the low-energy model [8]. Like the spin degree of freedom in spintronics devices [9–11], these inequivalent valleys or the valley degrees of freedom can also be used as information carriers to give birth to valleytronics [8, 12, 13]. Many unique transport phenomena can be realized by regulating these two degrees of freedom, such as fully spin-polarized current, the valley filter [14], and spin–valley filter [15–19].

Spin and valley properties often occur in topological-insulator materials. In them, the valley and spin–valley Chern number [20, 21] can be well defined in many topological phases under different external fields, such as electric field and antiferromagnetic field [22, 23]. These topological phases include quantum spin Hall effect, quantum anomalous Hall (QAH), quantum valley Hall (QVH), quantum spin–valley Hall (QSVH), and spin QAH insulators [24]. However, there is no topological valley edge state in silicene-like nanoribbons (SiNRs). In order to introduce the valley indicator to the edge states of the topological
insulator, Ezawa [25], Liu et al [17], Jin et al [21], and Sun et al [26] have done some studies. They hybridized SiNRs with different topological phases and found the topological valley edge states appeared at the interface between two different topological insulator phases. We have to mention that the valley edge states, also known as the kink states in graphene systems [27, 28] or photonic crystals [29, 30]. However, the definition of kink states are narrower than the inner-edge states. The kink states are only related to the valley Chern numbers, while the inner-edge states are related to the valley Chern number or spin–valley Chern number, which often occur in the silicene-like materials. The hybrid SiNRs generate the spin–valley polarized inner-edge state by adding the staggered electric field and the antiferromagnetic exchange field. However, to the best of our knowledge, there is seldom the quantum transport studies only based on these inner-edge states.

In this work, we study the transport properties of these topological inner-edge states. We design two types of spin–valley filters using the hybridized zigzag silicene-like nanoribbons (ZSiNRs), which can control specific spin–valley polarized current. In these systems, the current only flows along the inner edges. The first type can separate two different spin–valley polarized currents in the output leads. For the second type, the filter can output one spin–valley polarized current in the lead. The mechanism of these filters results from the topological band structures of the inner-edge states in the conductor and leads, and verified by the current distribution calculations. Based on this mechanism, many similar types of spin–valley filters are found.

This paper is organized as follows: in section 2, we present our model and methods used for the spin–valley filters. In section 3, we present the results for these spin–valley filters, including the transmission spectra, energy band, wavefunction distributions, local current distributions, as well as the disorder and size effects on the filters. The conclusion part is in section 4.

2. Model and methods

In this paper, the system consists of four parts: lead 1, lead 2, lead 3, and the conductor, which are hybrid ZSiNRs (figure 1). It should be noted that the conductor is the same as the part of lead 1, so they have the same energy band properties. As shown in figure 1, we use the Roman numeral to denote the regions of different topological phases. The currents are incident from lead 1 and finally are transmitted into lead 2 and lead 3.

With the tight-binding model, the Hamiltonian of the system is written as [21]:

\[
H_0 = -t \sum_{\langle ij \rangle, \sigma} c_{i \sigma}^\dagger c_{j \sigma} + i \frac{\lambda_{0}}{3\sqrt{3}} \sum_{\langle(ij)\rangle,\sigma \sigma'} \nu_{ij} c_{i \sigma}^\dagger \sigma_{\sigma'} c_{j \sigma'} - \ell E_z \sum_{\langle ij \rangle} u_{ij} c_{i \sigma}^\dagger c_{j \sigma} + M \sum_{i} u_{i} c_{i \uparrow}^\dagger c_{i \downarrow} + M \sum_{i} u_{i} c_{i \downarrow}^\dagger c_{i \uparrow}.
\]  

(1)

The first term is the tight-binding term with the hopping energy \( t \), where \( c_{i \sigma}^\dagger \) (\( c_{i \sigma} \)) creates (annihilates) an electron with the spin polarization \( \sigma = \uparrow, \downarrow \) at site \( i \). (\( i, j \)) denotes the nearest-neighbor atom pair. We here choose \( t = 1 \text{eV} \), which is close to the value of silicene and other silicene-like materials [25]. The second term denotes the intrinsic spin–orbit interaction with the strength \( \lambda_{0} \). The \( \sigma_{\sigma'} \) is the \( z \)-component of \( 2 \times 2 \) Pauli matrix with spin indices \( \sigma \) and \( \sigma' \), and the sum is taken over all the next-nearest neighbour (\( \langle(ij)\rangle \)) sites. \( \nu_{ij} = \langle 2/\sqrt{3} \rangle (\hat{d}_i \times \hat{d}_j) = \pm 1 \), where \( \hat{d}_i \) and \( \hat{d}_j \) are the unit vectors along the two bonds that the electron traverses going from site \( j \) to the next-nearest-neighbor site \( i \). \( \nu_{ij} = -1 \), when the hopping is clockwise to the positive \( z \)-axis [31], otherwise, \( \nu_{ij} = +1 \). The third term represents the electric field, where \( \ell \) is the buckling thickness of ZSiNRs, \( u_i = 1(-1) \) denotes the A(B) sublattice. The antiferromagnetic exchange field is described by the last term, with \( M \) being the magnetization energy. This term describes the anti-symmetric part of the exchange field induced by the absorbed magnetic atoms on the buckled A(B) sublattice atoms of SiNRs.

With the Bloch wave theory, equation (1) is rewritten in the k-space as the function of Bloch wavevector. Then near the K and K’ point, we approximate the Hamiltonian in the low-energy range as [22]

\[
H_1 = \hbar v_F(\eta \sigma_z k_x + \gamma \sigma_y k_y) + \eta \sigma_z s_z \lambda_{0} - \ell E_z \sigma_z + s_z M \sigma_z.
\]  

(2)

Here, \( \eta = \pm 1 \) indicates the K and K’ valleys; \( \sigma_z, \sigma_y \) and \( \sigma_z \) are the \( x, y, \) and \( z \) components of \( 2 \times 2 \) Pauli matrix, \( s_z = +1(-1) \) denotes spin up (down), \( \hbar \) is the reduced Planck constant, and \( v_F = \frac{\hbar^2}{2 m} \) is the Fermi velocity with a lattice constant \( a \). We note that with the first quantization, equation (2) becomes the Dirac equation of graphene or silicene materials [32, 33]. The corresponding Chern numbers of equation (2) are given in the following expression

\[
C_{\eta} = \frac{\eta}{2} \text{sgn} \left[ \eta \sigma_z \lambda_{0} + s_z M - \ell E_z \right],
\]  

(3)
Figure 1. Schematic diagram for the spin–valley filter. The device consists of four hybrid ZSiNRs (lead 1, conductor, lead 2, and lead 3). The dotted lines indicate the inner edges, which also separate the different topological phases (indicated by I and II). The real size parameters in our study (except section 3.4) are set as $N_{y1} = 220, N_{y2} = 108, N_{y3} = 108$, and $N_x = 16$.

where $S = s_z$, which indicates the spin degree of freedom; $\text{sgn}$ is the sign function: $\text{sgn}(x) = \pm 1$ for $x > 0$ or $x < 0$, respectively. For an adjacent hybrid nanoribbon with different external fields, the spin- and valley-dependent Chern numbers of inner-edge states between layer I and layer II can be deduced as $[21, 25, 34]$

$$\Delta C_{S\eta} = C_{S\eta}^{(I)} - C_{S\eta}^{(II)},$$

(4)

where $\Delta C_{S\eta}$ can only take one value in 0, 1, or $-1$ due to $C_{S\eta} = \pm \frac{1}{2}$. This set of the inner-edge Chern numbers gives the direction, spin, and valley properties of the inner-edge currents, which is in accordance with the energy band $[34]$.

The transmission coefficients ($T_{ij}$) from lead $i$ to lead $j$ is calculated by the non-equilibrium Green’s function (NEGF) formalism. In the spin-resolved case, it is expressed as

$$T_{\sigma}^{ij}(E) = \text{Tr} \left[ \Gamma_{\sigma}^{j}(E) G_{\sigma}^{\text{R}}(E) \Gamma_{\sigma}^{i}(E) G_{\sigma}^{\text{A}}(E) \right].$$

(5)

In equation (5), $G_{\sigma}^{\text{R}}(E)$ and $G_{\sigma}^{\text{A}}(E)$ are the retarded and advanced Green’s function with the spin $\sigma$; $\Gamma_{\sigma}^{i}(E)$ ($i = 1, 2, 3$) is the spin-resolved linewidth function of lead $i$, which describes the coupling between the conductor region and lead $i$. The retarded (advanced) Green’s function is calculated by the formula below $[35, 36]$.

$$G_{\sigma}^{\text{R(A)}}(E) = \left[ E + \eta - \Sigma_{\sigma}^{\text{R(A)}}(E) \right]^{-1}.$$

(6)

In equation (6), $E = E + i \eta = [E, \eta]^*$, where $E$ and $\eta$ are the incoming electron energy and an infinitesimal positive number, respectively; $I$ is the identity matrix; $\Sigma_{\sigma}^{\text{R(A)}}(E) = \text{H}_{\text{D}i} g_{\sigma}^{\text{R(A)}} \text{H}_{\text{D}j}$ is the retarded self-energy matrix with $\text{H}_{\text{D}j}$ and $\text{H}_{\text{D}j}$ being the coupling matrix between the conductor and the lead $i$; $g_{\sigma}^{\text{R}}$ is the retarded surface Green’s function of lead $i$, which can be calculated by using the routine of Lopez-Sancho’s iterative method $[37]$. The spin and valley polarization ratios can be expressed as

$$P_S = \frac{T^\uparrow_K - T^\downarrow_K + T^\uparrow_{K'} - T^\downarrow_{K'}}{T^\uparrow_K + T^\downarrow_K + T^\uparrow_{K'} + T^\downarrow_{K'}},$$

$$P_V = \frac{T^\uparrow_K + T^\downarrow_K - T^\uparrow_{K'} - T^\downarrow_{K'}}{T^\uparrow_K + T^\downarrow_K + T^\uparrow_{K'} + T^\downarrow_{K'}}.$$

(7)
respectively. One can obtain the spin and valley resolved polarizability from the transmission spectra and band structures of the system.

To study the electron transport details through such systems, we plot the local current in the conductor and lead regions. The energy-resolved bond current between the site $i$ and site $j$ is given by the formula below \cite{36, 38}

$$J_{ij}^{\sigma}(E) = H_{ij}^{\sigma} G_{ij}^{\sigma\sigma}(E) - G_{ij}^{\sigma\sigma}(E) H_{ij}^{\sigma}$$  \hspace{1cm} (8)

where $G^{\sigma\sigma}(E)$ is the lesser Green’s function in the energy domain, expressed as

$$G^{\sigma\sigma}(E) = -i G_{\sigma}^{\sigma}(E) \Gamma^\sigma(E) G_{\sigma}^{\sigma}(E),$$  \hspace{1cm} (9)

and $H_{ij}^{\sigma}$ is the relevant matrix element of the conductor’s Hamiltonian. It is noted that this formula is related to the local current from the incidence of lead $\alpha$.

### 3. Results and analysis

In this work, we propose some interesting spin–valley filters, which have different functions in controlling the behaviour of electrons. Based on the hybridization of ZSiNRs, these types of spin–valley filters are realized by modulating the topological phases and adjusting the device geometry shown in figure 1. In the following part, we will demonstrate these two types of spin–valley filters in detail. We default the fact that the intrinsic SOC exists in all regions.

#### 3.1. Double-output spin–valley filters

The double-output spin–valley filter is of the first type, where one of the spin–valley polarized currents propagates from lead 1 to lead 2, and the other propagates from lead 1 to lead 3. Figure 2(a) shows the cartoon picture of the system. Lead 1 and the conductor have the same hybridization structures with their respective topological phases. The upper and lower ZSiNRs are set the QSVH1 and QSVH2 topological phases by applying the antiferromagnetic exchange field: $M = 0.15t$ and $M = -0.15t$ \cite{21}, respectively. For lead 2, the upper and lower nanoribbons are set as the QSVH1 and QSVH2 phases by applying the antiferromagnetic exchange field $M = 0.15t$ and the staggered electric field $EL = -0.15t$, respectively. Lead 3 is similar to lead 2 but with different topological phases (QVH2 ($EL = -0.15t$)-QSVH2 ($M = -0.15t$)).

From equation (4) we obtain the Chern numbers set of the inner-edge state in lead 1 as $(\Delta C_{k_1}, \Delta C_{k_2}, \Delta C_{k_{15}}, \Delta C_{k_1}) = (+1, -1, -1, +1)$, and the Chern numbers set of the inner-edge state in lead 2 and lead 3 are $(+1, -1, 0, 0)$ and $(0, 0, -1, +1)$, respectively. Besides the spin and valley correspondence, the sign of Chern numbers also corresponds to the positive or negative directions of inner-edge current (or the slope of energy band) in the following discussions.

Figures 2(f)–2(h) show the band structures of these leads. For lead 1 (figure 2(f)), the spin-up and spin-down electrons both have two inner-edge channels with different directions in two valleys. For lead 2 (figure 2(g)), there is one spin-up (red) inner-edge channel with valley $K'$ in the positive $x$-direction and one spin-up (red) inner-edge channel with valley $K$ in the negative $x$-direction. These bands allow the spin-up current with the valley $K'$ and valley $K$ to move rightward and leftward near the Fermi level, respectively. The band structure of lead 3 (figure 2(h)) is similar to lead 2. The arrows (figure 2(a)) also demonstrate the allowed inner-edge states in this system. From figures 2(c)–(e), one can find that the spin-up and spin-down electrons are all localized near the interface of two nanoribbons and decays exponentially towards the outer regions, that indicate they are good inner-edge states.

Figure 2(b) shows the spin-resolved transmission spectra from lead 1 to lead 2 (magenta, cyan) and lead 1 to lead 3 (red, blue), respectively. The transmission ratio is about 80% and zero near the Fermi level ($E = 0$) for the spin-up (magenta) electron in $K'$ valley and spin-down (cyan) electron in $K$ valley from lead 1 to lead 2, respectively. For the transmission from lead 1 to lead 3, the results are the opposite. In other words, the transport calculations show that the spin-up current with the valley $K'$ can propagate from lead 1 to lead 2, while the spin-down current with the valley $K$ can propagate from lead 1 to lead 3. These results indicate that the filter can separate the two different spin–valley polarized currents in output leads. If we exchange the inner-edge channels of lead 2 and lead 3, we could obtain the opposite result, which is another form of the double-output spin–valley filter.

Based on the equation (7), we can calculate the spin and valley polarizability. For spin polarization, the values of $T_{K^1}'$, $T_{K^1}'$ and $T_{K^1}'$ are all zero from lead 1 to lead 2 near the Fermi level. Because there is only one spin-up (red) inner-edge channel in valley $K'$ with the positive momentum in $x$-direction in the lead 2, we see $T_{K^1}' > 0$. Therefore, the spin polarization ratio $P_S$ is 1.0 near the Fermi level. Similarly, from lead 1 to lead 3, the $T_{K^1}'$, $T_{K^1}'$ and $T_{K}'$ are all zero and $T_{K^1}$ is larger than zero near the Fermi energy. So $P_S = -1$ from lead 1 to lead 3. For the valley polarization ratio, $P_V = -1$ and 1.0 from lead 1 to lead 2 and lead 3 near the...
Fermi energy, respectively. These results indicate that carriers in the filter could achieve 100% spin and valley polarization without any backscattering.

To show the universality of this double-output filter for all silicene-like materials, we give the numerical results (transmission, inner-edge distributions, energy band) by using the parameters (hopping energy and SOC) of silicene ($t = 1.6$ eV, $t_{so} = 0.0039$ eV) and stanene ($t = 1.3$ eV, $t_{so} = 0.1$ eV) [24, 39]. Figures 3(a1)–(g1) show the results of silicene, which is similar to the results of figure 2(b)–(h). The transmission spectra and bandgap have some differences but no qualitative change to our conclusions. The results of stanene (figure 3(a2)–(g2)) also indicate that our conclusion is universal for all silicene-like materials. These are because of the same topological properties of these materials under proper external fields. With these external fields, all the SiNRs parts lie in the same topological phases as those in figure 2(a) [34]. So they have similar inner-edge states and transport properties.

To show the detailed transmission mechanism in the real space, we calculate the local current distributions based on equation (8). From figure 4, one can see that the spin-up and spin-down currents are localized near the interface of two ribbons and decaying exponentially towards outer regions in these leads. However, for lead 1 and conductor, the peak (maxima) positions of these two spin-polarized inner-edge currents have a small upward/downward shift, comparing to the eigenfunctions of a periodic system (figure 2(c)) that is due to the impact of two output leads in the right region. In the conductor region, there gradually appear two maximum peaks for each spin-polarized current, induced by the two separate inner-edge states in the lead 2 and lead 3. So near the boundary between the conductor and lead 2(3), the incident spin-up inner-edge current flows upward into the lead 2, while the spin-down inner-edge current flows downward into the lead 3, respectively. The electrons are also weakly reflected due to the short vertical distance between the interfaces in the conductor and lead 2 (or lead 3). Therefore, one can find there are some tiny red arrows in the blue inner-edge region and some tiny blue arrows in the red inner-edge region of lead 1. The hollow arrows in the figure briefly show these currents flow trends in this filter.

These results are consistent with the transmission in figure 2(b). The large transmission ratios suggest that the spin–valley current can nearly freely pass through the system when its direction, spin and valley degrees of freedom are the same between the conductor and leads. There still exists a small portion of reflection, as shown in figure 4. From the inner-edge state arrows and band structures in figure 2(a) and (f), we can conclude that the reflected electrons are in a switched valley (from K to K’ or from K’ to K). This is due to the valley- momentum locking properties of these inner-edge states in this type of hybridized...
ZSiNRs. So there occurs the inter-valley scattering across the conductor-lead boundary. Moreover, we can conclude that the electrons will be strongly reflected when increasing the vertical distance between the interfaces of conductor and leads. That is a basic issue for designing the size-determined single-output filter, and we will discuss the details in section 3.3.

There exist four forms of double-output filters. In the lead 1 (including the conductor), we may exchange the external fields in the upper and lower ribbons to obtain similar inner-edge bands with the opposite spin (or slope). Thus the input (rightward) current types become the spin-up with $K$ valley and the spin-down with $K'$ valley. We may also exchange the geometric positions of lead 2 and lead 3, so the output spin–valley currents can also be exchanged in the two terminals. This paper does not show the details.

To test the robustness of our system, we take the realistic effects (disorder) into account. In the following, we only compare the transmission spectra of figure 2(b) under different disorder effects.

Here, we consider the Anderson on-site energy disorder only in the conductor, with $W$ being the disorder strength randomly distributed in the range $[-W/2, W/2]$. The transmission spectra are calculated by taking an average of 100 times for different disorder configurations (figure 5). We find that the disorder...
intensity in the range of $[0, 0.1 \text{ eV}]$ has little influence on the transmission due to the topological protection of the inner-edge states against the disorders. However, the transmission gradually decreases with increasing disorder strength in the range of $[0.1, 1.5 \text{ eV}]$, which means that the strong disorder can reduce the filtration performance of the filter. In summary, the filtering properties of the system are stable to resist weak disorder.

### 3.2. Single-output spin–valley filters

This type of filter has eight forms, which are classified as four classes. Figure 6(a) shows the cartoon picture of one type of these filters, which is similar to the previous double-output filter. We here set the lead 3 as the ‘off’ state (QSVH2 ($M = -0.15t$)-QSVH2 ($M = -0.15t$)). So there is no current transmitting in the lead 3 due to the bandgap of lead 3 (see figure 6(c)). We discuss the case where the spin–valley current only propagate from lead 1 to lead 2. Figure 6(b) shows the transmission spectra between lead 1 to lead 2 (lead 3). Near the Fermi level ($E = 0$), the transmission ratio is about 80% and zero for the spin-up and spin-down electrons from lead 1 to lead 2, respectively. For the transmission from lead 1 to lead 3, the transmission ratios of spin-up and spin-down currents are both zero near the Fermi level due to the bandgap effect. Based on these analyses and the band structures of lead 1 and 2 (see figures 2(f) and (g)), we conclude that the spin-up inner-edge current with the valley $K'$ propagates from the lead 1 to the lead 2. These results indicate that this filter can separate the spin–valley polarized electrons to specific outlet lead. We could obtain the opposite result, which is another form of the single-output spin–valley filter when we exchange the inner-edge channels between lead 2 and lead 3.

As we know, there are four types of spin–valley polarization currents (spin-up or spin-down current with the valley $K$ or $K'$) and two different output leads (lead 2 and lead 3). These combinations lead to eight forms of the single-output filters. Besides the first types in figure 6(a) and the similar one with output lead 3 (not shown here), another six types of spin–valley filters are presented in the cartoon pictures in figure 7 below. In these filters, the spin, valley, and direction of the spin–valley current between the lead 1 and lead 2 (or lead 1 and lead 3) are all the same. Then the spin–valley currents pass through the system with a large transmission. We can modulate the topological phases in different regions of the leads to induce these types of the single-output spin–valley filter.

To better understand figures 6(a) and 7, we use a table below to underline the function of these single-output spin–valley filters, as well as the external fields to generate the corresponding topological inner-edge states (table 1).

### 3.3. The device-size effect

Finally, we take the size effect into account. In the following, we only compare the transmission spectra of figure 2(b) in different device sizes. Figures 8(a)–(c) show the transmission spectra of this double-output filter.
Figure 6. (a) Cartoon picture of the single-output spin–valley filter; (b) Transmission spectra from lead 1 to lead 2 and from lead 1 to lead 3; (c) Band structures of lead 3. In (c), red (blue) curves represent the spin-up (spin-down) bands. These two type of bands coincide due to the spin degeneracy. The fixed parameter are $N_{y1} = 220$, $N_{y2} = N_{y3} = 108$, $N_x = 16$, $t = 1$ eV, $\lambda_{so} = 0.05 t$.

Figure 7. Cartoon pictures of single-output spin–valley filter: (a1) and (a2) the second type; (b1) and (b2) the third type; (c1) and (c2) the fourth type. The arrows indicate the spin and valley of the inner-edge states, as shown in the legend of figure 2(a).

filter with different widths. In these width-change cases, the four atom space is fixed between lead 2 and lead 3 shown in figure 1. With increasing the width of the device symmetrically ($N_{y1}$, $N_{y2}$, $N_{y3}$), the transmission ratios decay slightly near the zero energy. The reason is that the vertical distance from the central interface of the lead 1 (including the conductor) to the interface of lead 2 or lead 3 is increased, which leads to the enhanced reflection of the current. Therefore, we find the smaller device size has the better current transmission property under the premise of a complete inner-edge state for these spin–valley filters.

Figures 8(d)–8(f) show the transmission spectra of the double-output filter (in figure 8(c)) with reducing the width of lead 3 and keeping the widths of lead 1 (including the conductor) and lead 2 unchanged. And lead 2 and lead 3 are spaced by 8, 20, and 64 atoms, respectively. One can find that near the Fermi level, the transmission of the spin-up current decreases slightly, and for the spin-down current, it quickly drops to zero comparing to figure 8(c). We believe that the spin-down current with the valley $K$ from lead 1 to lead 3 is reflected strongly due to the considerable vertical distance between the central line of the lead 1 (including the conductor) and the lead 3. Moreover, we find that the spin-up current with the valley $K'$ is also slightly decreased from lead 1 to lead 2. The reason lies that a decreased size of lead 3 causes the current of spin-up to diffuse more to lower half-ribbon. Thus, more spin-up electrons are reflected, resulting in less transmission of spin-up current from lead 1 to lead 2. In summary, these results indicate that we can obtain a single-output filter by just adjusting the device size.
Table 1. External fields and output functions of the single-out spin–valley filters.

| Numbers of the single output spin–valley filters | Lead 2 | Lead 3 |
|-----------------------------------------------|--------|--------|
| | Upper NRs | Lower NRs | Upper NRs | Lower NRs | Lead 2 | Lead 3 |
| | | | | | | |
| 2–1 (figure 6(a)) | 0.15t | 0.15t | 0.15t | 0.15t | K↑ |
| 2–2 (not shown in the paper) | 0.15t | 0.15t | 0.15t | 0.15t | K↑ |
| 2–3 (figure 7(a1)) | 0.15t | 0.15t | 0.15t | 0.15t | K↑ |
| 2–4 (figure 7(a2)) | 0.15t | 0.15t | 0.15t | 0.15t | K↓ |
| 2–5 (figure 7(b1)) | -0.15t | -0.15t | 0.15t | 0.15t | K↑ |
| 2–6 (figure 7(b2)) | -0.15t | -0.15t | 0.15t | 0.15t | K↓ |
| 2–7 (figure 7(c1)) | -0.15t | 0.15t | 0.15t | 0.15t | K↑ |
| 2–8 (figure 7(c2)) | -0.15t | -0.15t | -0.15t | 0.15t | K↑ |

Figure 8. (a)–(c) Transmission spectra of double-output filter in figure 2 with different widths of leads and conductor: (a) Ny1 = 268, Ny2 = Ny3 = 132; (b) Ny1 = 308, Ny2 = Ny3 = 152; (c) Ny1 = 340, Ny2 = Ny3 = 168; (d)–(f) Transmission spectra of double-output filter with the fixed widths of lead 1 and lead 2 (Ny1 = 340, Ny2 = 168) and different width of lead 3: (d) Ny3 = 164; (e) Ny3 = 152; (f) Ny3 = 108.

4. Conclusions

In this work, we investigate the spin–valley filter effects of the inner-edge states in the ZSiNRs system with different topological phases. By modulating the external fields, we obtain abundant topological phases, which can induce abundant inner-edge states. The mechanism of these filters lies that the spin–valley polarized currents can nearly freely pass through since they have the same direction, spin and valley degrees of freedom between the conductor and leads. These filters can be mutually switched by modulating the external fields in the leads and conductor. These systems are realistically robust against weak disorder. Local current distribution is employed to verify the detailed transmission mechanism for these spin–valley filters. Besides, we also find the device widths, or the vertical space between the two interfaces of leads play a crucial role in the transmission property. We believe that these intriguing results can extend the applications of topological-insulator-based 2D material devices in the future nano spintronics and valleytronics.

Acknowledgments

This work was supported by the starting foundation of Chongqing University (Grants No. 0233001104429) and NSFC (Grants No. 11847301).
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