Spin-valley filter effect and Seebeck effect in a silicene based antiferromagnetic/ferromagnetic junction

Zhi Ping Niu
College of Science, Nanjing University of Aeronautics and Astronautics, Jiangsu 210016, People’s Republic of China
E-mail: zpniu@nuua.edu.cn

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Abstract
The presence of the coupled spin and valley degrees of freedom makes silicene an important material for spintronics and valleytronics. Here we report a spin–valley filter effect in a silicene based antiferromagnetic/ferromagnetic junction. It is found that at zero Fermi level a valley locked bipolar spin filter effect is observed, where in a broad gate voltage range in one valley one spin (the other spin) electrons contribute to the current under the positive (negative) bias, but in the other valley the transport is forbidden. At the finite Fermi level a valley locked fully spin-polarized current can exist under both the positive and negative biases. Furthermore, at the high Fermi level by reversing the bias direction, the spin filter effect can switch to the valley filter effect. In addition, by changing the sign of the Fermi level, the spin polarization direction of the current can be reversed. If a temperature bias is applied, the spin-dependent Seebeck effect (SSE) always exists. With increasing the temperature bias, the system undergoes three regions: valley locked SSE, normal SSE and valley Seebeck effect. Moreover, by tuning the interlayer electric field, three phases: thermally induced valley locked spin filter effect, valley Seebeck effect and valley mixed Seebeck effect are observed.

1. Introduction
Silicene, the counterpart of graphene for silicon, has been successfully synthesized in the laboratory recently [1–3]. Similar to the graphene, conduction and valence bands in silicene form two inequivalent valleys K and K’ at the corner of the Brillouin zone [4]. The valley degree of freedom is similar to the spin one and provides another means to control electrons, leading to the so-called valleytronics [5–13]. Unlike graphene, silicene has an observable intrinsic spin–orbit interaction [14, 15]. The band structure of silicene is spin and valley coupled, making silicene an important material for valleytronics and spintronics [2, 3, 15–19]. The buckled structure allows us to control the bulk band gap of the Dirac electrons by applying external fields such as electric field [20], ferromagnetic/antiferromagnetic exchange field [15, 18, 19]. Although the spin-valley polarized current in silicene has been studied recently, most studies were focused on the conductance at zero bias, and very little attention [21] has been paid to the effect of the electric bias on the spin-valley resolved currents.

On the other hand, due to its novel physics as well as its potential applications in environmental protection and energy conversion, spin caloritronics has attracted much recent interest [22–39]. Besides the spin Seebeck effect using magnons as carries, the spin-dependent Seebeck effect (SSE) using fermions as carries has also attracted much recent attention in two dimensional graphenelike materials, such as graphene [30–32] and silicene [33–39]. In these works thermally induced spin-polarized current [30, 31], thermoelectric spin voltage [32], and spin–Seebeck diode [33] have been reported. Due to the presence of the valley degree of the freedom, similar to SSE, valley Seebeck effect is also put forward, where the pure or valley polarized current can be induced by the temperature gradient [34–38]. For instance, in our previous work [34] we pointed out that due to the coupling between the valley and spin degrees of freedom thermally induced pure valley and spin currents can be demonstrated in a normal/ferromagnetic/normal silicene junction. The valley Seebeck effect is also reported in [35–41]. Very recently, Zhai et al [39] proposed that a valley-mediated giant Seebeck magneto-resistance effect,
triggered and controlled by an interlayer electric field, can be engineered near room temperature in a ferromagnetic/antiferromagnetic junction based on heavy group-IV monolayers. But they focused on the Seebeck magnetoresistance effect and did not discuss the spin-valley polarized currents in detail. Thus the detailed studies of the thermally spin-valley polarized currents in a silicene based ferromagnetic/antiferromagnetic junction are still lacking.

Motivated by the works mentioned above, we study the spin-valley resolved currents in a silicene based antiferromagnetic/ferromagnetic (AF/F) junction under the electric bias and temperature bias, respectively. We first consider the current driven by the electric bias. It is found the behavior of the current is sensitive to the Fermi level. A valley locked (bipolar) filter effect can be seen at the low Fermi level. Furthermore, at the high Fermi level a valley filter effect can be demonstrated. Then the current induced by the temperature bias is discussed. With increasing the temperature bias, the system undergoes three regions: valley locked SSE, normal SSE and valley Seebeck effect. Moreover, by tuning the interlayer electric field, three phases: thermally induced valley locked spin filter effect, valley Seebeck effect and valley mixed Seebeck effect are observed.

The manuscript is organized as follows. We first introduce the system Hamiltonian and obtain the expression of the spin-valley resolved currents in section 2. Next we show the results of the spin-valley resolved currents under the electric bias and discuss the spin-valley filter effect in the AF/F junction in section 3. The spin-valley Seebeck effect is investigated in section 4. Finally, in section 5, we present a conclusion.

2. Model and formulation

We consider a silicene-based two dimensional AF/F junction with the interface located at \( x = 0 \) under the electric bias \( V_E \) or temperature bias \( \Delta T = T_L - T_R \), where \( T_L \) (\( T_R \)) is the temperature in the left (right) lead. The silicene is parallel to the \( x \)-\( y \) plane. The low energy effective Hamiltonian of such a structure can be expressed as

\[
H = H_0 - \lambda_\nu \tau_z + (\sigma \lambda_{AF} \tau_z + eV_g)\Theta(-x) - (\sigma h + eV_g)\Theta(x).
\]

Here the first term \( H_0 = -i/\hbar v_F(\partial_x \tau_x - \eta \partial_y \tau_y) + \eta \sigma \lambda_\nu \tau_z \) is the Hamiltonian without external fields, where \( \lambda_\nu \) is the spin–orbit coupling strength. \( \eta = \pm \) represents the \( K \) \( (K') \) valley, \( \sigma = \pm \) denotes the spin indices and \( v_F \) is the velocity of electrons. In the second term \( \lambda_\nu = I_F \) with half of the interlayer distance \( f \) is the on-site potential difference between A and B sublattices, which can be efficiently tuned by the interlayer electric field \( E_z \). \( \Theta(x) \) is the Heaviside function. The third term corresponds to the AF exchange field with strength \( \lambda_{AF} \). The fourth term denotes the gate voltage \( V_g \) in the AF lead. \( h \) in the fifth term stands for the ferromagnetic exchange field strength. The F and AF exchange fields can be induced by putting EuO, EuS or YIG on the top or bottom of a silicene sheet [18, 42]. The last term indicates the longitudinal electric bias with strength \( V_g \). We set \( h = 1 \), \( v_F = 1 \) and \( e = 1 \) for the brevity of notation. The eigenvalues of the Hamiltonian (1) are given by

\[
E_{\nu \sigma} = \alpha \sqrt{k^2 + (\eta \sigma \lambda_\nu - \lambda_\nu + \sigma \lambda_{AF} \Theta(-x))^2} - (\sigma h + eV_g)\Theta(x) + V_g \Theta(-x),
\]

with \( k = \sqrt{k_x^2 + k_y^2} \) and \( \alpha = \mp \) corresponding to the conduction (valence) band. It is noted that there exists a spin-valley dependent band gap \( E_{g\nu}^{\sigma} = 2|\eta \sigma \lambda_\nu - \lambda_\nu + \sigma \lambda_{AF} \Theta(-x)| \), which can be tuned by the parameters \( \lambda_\nu \) and \( \lambda_{AF} \). In order to generate a finite current, the propagating modes in the leads should be generated, which requires that the energy \( E \) of the incident carriers should be satisfy \( |E - V_g| > E_{g\nu}^{\sigma}/2 \).

Consider an electron with the energy \( E \) incident from the AF lead on the AF/F interface at an angle \( \theta \) to the interface normal. With general solutions of equation (1), the wave functions in the AF and F leads are given by

\[
\Psi_{AF} = \phi_\nu e^{i k_{\nu x}} + r_\nu e^{-i k_{\nu x}} \quad \text{and} \quad \Psi_{F} = t_\nu e^{i k_{\nu x}},
\]

where \( \phi_\nu = (\hbar v_F k_{\nu x}, E_{\nu \sigma}) \) and \( \phi^T_\nu = (\hbar v_F k_{\nu x}, E_{\nu \sigma}) \), which the superscript \(^T\) denotes transposition, \( k_{\nu x} = (\pm s k_{Lx} + \eta k_y) \) and \( k_{\nu x} = (s' k_{Rx} + i k_y) \) with \( s \) = sign(\( E - V_g \)) and \( s' \) = sign(\( E + \sigma h + V_g \)). Here the wave vectors are

\[
k_{Lx} = (E - V_g)^2 - (\eta \sigma \lambda_\nu - \lambda_\nu + \sigma \lambda_{AF})^2 \cos \theta, \quad k_{Rx} = (E - V_g)^2 - (\eta \sigma \lambda_\nu - \lambda_\nu + \sigma \lambda_{AF})^2 \sin \theta \quad \text{and} \quad k_{Rx} = (E - \sigma h + V_g)^2 - (\eta \sigma \lambda_\nu - \lambda_\nu)^2.
\]

With \( E_L = E - V_g - (\eta \sigma \lambda_\nu - \lambda_\nu + \sigma \lambda_{AF}) \) and \( E_R = E + \sigma h + V_g - (\eta \sigma \lambda_\nu - \lambda_\nu) \). From the wave function continuity at the interface \( \Psi_{AF|\xi = 0} = \Psi_{F|\xi = 0} \), we can obtain the transmission coefficient \( t \). Then by using \( t \) the transmission probability for spin \( \sigma \) and valley \( \eta \) carriers is given

\[
T_{\nu \sigma} = \frac{4k_{\nu x} k_{Lx} |E_L E_R|}{(|E_L| k_{Rx} + |E_R| k_{Lx})^2 + (E_L - E_R)^2 k_y^2}.
\]

Once the transmission probability \( T_{\nu \sigma} \) is obtained, the current can be written as [34, 35]

\[
I_{\nu \sigma} = \int dE \int d\theta \cos \theta T_{\nu \sigma} \left( f_L - f_R \right).
\]
where \( N(E) = \sqrt{(E - \mathcal{K}_0)^2 - (\sigma \lambda_{so} - \mathcal{K}_f)^2} \) \( W \) with \( W \) the width of the silicene sheet is the carrier density of states. \( f_{cL} = 1/[1 + \exp(E - \mathcal{K}_f)/k_B T] \) and \( f_{cR} = 1/[1 + \exp((E - \mathcal{K}_f + \frac{1}{2})/k_B T)] \) with the Fermi level \( E_F \) stand for the Fermi distribution function in the AF and F electrodes.

### 3. Spin-valley filter effect

The gate voltage dependence of spin-valley resolved currents under zero Fermi level is plotted in figure 1(a). For the low \( V_g \) there exists a valley locked bipolar spin filter effect, where \( I_{Kf} \) is finite under the positive bias and \( I_{Kl} \) is nonzero under the reversed bias, while the transport in the K valley is forbidden. When \( V_g \) is further enhanced, \( I_{Kl} \) and \( I_{Kf} \) appear. The currents under the positive bias come from spin up electrons, while those under the negative bias originate from spin down electrons. To understand this valley locked bipolar spin filter effect, we need to analyze the band structures of this junction plotted in figures 2(a) and (b). For the parameters taken here, in the AF the spin degree of freedom is degenerate, but the valley degeneracy is broken. For the \( K' \) valley it is a gapless band structure with linear conduction and valence bands touched at the Dirac point, while for the K valley there exists a band gap. In the right F valley the degree of freedom is degenerate, but the spin degeneracy is broken. The combination of AF and F exchange fields in this junction makes the band-matching tunneling mechanism specific spin-valley dependent. As indicated by the shaded regions in figures 2(a) and (b), under the positive (negative) bias only spin up (spin down) electrons in the K' valley contribute to the current, resulting in a finite \( I_{Kf} \) \( I_{Kl} \) under a positive (negative) bias. For the large \( V_g \) electrons in the K valley begin to contribute to the currents, thus \( I_{Kl} \) and \( I_{Kf} \) become finite too. It should be pointed out if the sign of \( \lambda_{so} \) is reversed, the band structures of the K and \( K' \) valleys can interchange, so a valley locked bipolar spin filter effect with finite current in the K valley but zero current in the \( K' \) valley can also be observed.

Next, spin-valley resolved currents versus \( V_g \) at finite \( E_F = \lambda_{so} \) is given in figure 1(b). Unlike figure 1(a), the valley locked bipolar spin filter effect is destroyed. Here only spin up currents are allowed to transport. For the positive (negative) bias in the range of \(-1.0 < V_g/\lambda_{so} < 2.5 \) \(-0.5 < V_g/\lambda_{so} < 3.0 \) \( I_{Kf} \) \( I_{Kl} \) is nonzero, leading to a valley locked spin filter effect. The behavior of this effect can be understood from the band structures of this AF/F junction depicted in figure 2(c). In the AF the spin degree of freedom is degenerate, but the valley degeneracy is broken. The band structure of the \( K' \) valley is gapless, while a band gap exists for the K valley. In the F for the low \( V_g \) only spin up channel is open (see shaded region in figure 2(c)). Because of the specific spin-valley band-matching tunneling mechanism, a finite \( I_{Kf} \) presents. For high \( V_g \) the electrons in the K valley begin to contribute to \( I_{Kl} \).

In figure 1(c) we further study the spin-valley resolved currents at \( E_F = 2\lambda_{so} \). Similar to the low Fermi level case \( (E_F = 0 \) or \( \lambda_{so} \)), under the negative bias only spin up currents flow, thus the spin filter effect still holds. However, unlike the valley locked (bipolar) spin filter effect at \( (E_F = 0 \) \( E_F = \lambda_{so} \) under the positive bias there exhibits a valley filter effect instead of spin filter effect, where at the positive \( V_g \) the currents in the K valley are allowed to flow but the transport in the \( K' \) valley is blocked. In this case by reversing the bias direction the spin filter effect can switch to the valley filter effect. We can explain these phenomena as follows. Under the negative bias only the spin up channel in the F is open, leading to the spin filter effect. Different from the negative bias case, under the positive bias both spin up and spin down electrons contribute to the current, which destroys the spin filter effect. When \( V_g \) is positive, the region responsible for the electron transport lies in the band gap of the K valley, thus a valley filter effect is seen. However, for the negative \( V_g \) the region responsible for the electron transport lies in the conduction band of the K and \( K' \) valleys, therefore the currents in both valleys are finite.

Since the spin-valley resolved currents are sensitive to the Fermi level, it is necessary to investigate the dependence of the currents on the Fermi level. As shown in figure 3, for low Fermi level at \( V_g = 0 \) a valley locked spin filter effect is found, where for the positive Fermi level \( I_{Kl} \) is finite, while by reversing the sign of the Fermi level \( I_{Kf} \) converts into \( I_{Kl} \). For high Fermi level, the currents in the K valley appear. Therefore we can obtain a valley locked fully spin polarized current with its spin direction depending on the sign of the Fermi level. It is noted that this valley locked spin filter effect can be also found in the system under the negative bias (not shown here). For the low \( V_g \) we can see the valley locked spin filter effect too.

### 4. Spin-valley Seebeck effect

Now we turn our attention to the effect of the temperature bias \( \Delta T = T_L - T_R \) on the spin-valley resolved currents. As shown in figure 4(a), in the normal/F junction with \( \lambda_{AF} = 0 \) \( I_{n} \) flows from left to right and \( I_{af} \) flows in opposite direction. Due to the band structure symmetry \( E_{so} = -E_{k0} \), the relationship of \( I_{so} = -I_{k0} \) holds, leading to a pure spin (valley) current. This is different from the system under the electric bias, where the valley (spin) current accompanying with a finite charge current is generated. Next, in figure 4(b) thermally
induced spin and valley currents through the AF/F junction are given. Here \( \lambda_v \) in the left AF is fixed at \( \lambda_vL = 0 \), while that in the right F is set to be \( \lambda_vR = 0.5 \lambda_v \). It is found that \( I^\uparrow \) and \( I^\downarrow \) flow in opposite direction, so SSE always exists. With increasing \( \Delta T \), three regions: I, valley locked SSE, where \( I_{K^\uparrow} \) and \( I_{K^\downarrow} \) counterpropagate along the temperature bias direction (see the inset of figure 4(c)), while no carriers from the K valley are excited; II, normal SSE, where \( I^\uparrow \) and \( I^\downarrow \) propagate in opposite direction but both \( I_{K^\uparrow} \) and \( I_{K^\downarrow} \) flow in the same direction; III,
valley Seebeck effect, where $I_{K}$ and $I_{K'}$ transport in opposite direction. We can explain the behavior of spin and valley currents by studying $I_{\text{t}}$ plotted in the inset of figure 4(c). As seen from figure 4(d), in the AF the band structure for the $K'$ valley is gapless, while that for the $K$ valley has a band gap. Because of the fast variation of the Fermi distribution function $f_{L(R)}$ with energy, only the electronic states above and below the Fermi level about $kT_{10}$ ($kT_{L(R)}$) are active and can effectively contribute to the current. Due to the incident energy located at the band gap of the $K$ valley at low $\Delta T$ $I_{K'}$ (solid line) and $I_{K}$ (dashed line) are zero. When $\Delta T$ increases, more transport channels are open and the carriers in the conduction and valence bands begin to contribute to $I_{K'}$ and $I_{K}$, which

![Figure 2](https://example.com/image2.png)

**Figure 2.** The band structures of the AF/F junction at $E_F = 0$ under the positive (a) or negative (b) bias. (c) The band structures of the AF/F junction at $E_F = \lambda_{\text{so}}$ is plotted. In the AF the black (blue) lines correspond to the $K$ ($K'$) valley, while in the F the red (dark cyan) lines correspond to the spin up (spin down) channel.
valley polarization, the spin polarization decreases with negative $\Delta T$. At the boundary of the II and III regions, a 100% valley polarization is found. Unlike the tunneling mechanism in the left AF, which can be tuned by the interlayer electric field $E_\parallel$, in the right AF, which is under the positive electric field, the spin up and spin down valence bands of $E_{K\uparrow}$ ($E_{K\downarrow}$) are close to the Fermi level, while the valence (conduction) band of $E_{K\downarrow}$ ($E_{K\uparrow}$) in the F is near the Fermi level (see figure 4(d)), so it is due to specific spin-valley band-matching tunneling mechanism a finite $I_{K\uparrow}$ ($\lambda_{dL} < 0$) is found. While in the F the spin up valence band is close to the Fermi level, therefore for $\Delta T$ considered here $I_{K\uparrow}$ mainly comes from the electrons, $I_{K\uparrow}$ increases faster than $I_{K\downarrow}$ and becomes larger than $I_{K\downarrow}$ at high $\Delta T$. This case the sign of $I_{K\uparrow}$ can change with $\Delta T$. We also study the valley and spin polarization in figure 4(c). The valley polarization (dotted line) increases with $\Delta T$, and then begins to decrease. At the boundary of the II and III regions, a 100% valley polarization is found. Unlike the valley and spin polarization, the spin polarization decreases with $\Delta T$.

Next, in figure 5 we discuss thermally driven spin-valley resolved currents versus $\lambda_{dL}$. Here $\lambda_{dL}$ is set to be $\lambda_{dL}$. In the left AF, which can be tuned by the interlayer electric field $E_\parallel$, in the right AF, the system undergoes three phases: I, valley locked spin filter effect, where only $I_{K\uparrow}$ ($\lambda_{dL} > 0$) or $I_{K\downarrow}$ ($\lambda_{dL} < 0$) is finite and a 100% spin (valley) polarization is obtained in this region; II, valley Seebeck effect, where the currents in different valleys flow in opposite direction; III, valley mixed Seebeck effect, where the currents in both valleys can transport in the same direction. We can understand this behavior from the band structures of the junction. From equation (2), one find for the spin $\sigma$ band structure of the $y$ valley, there exists a band gap

$$E_{K\parallel}^{\sigma} = 2|\sigma\lambda_0 - \lambda_{dL} + \lambda_{AF}|.$$

For large negative (positive) $\lambda_0$, the conduction and valence bands of $E_{K\downarrow}$ ($E_{K\uparrow}$) in the AF are close to the Fermi level, while the valence (conduction) band of $E_{K\uparrow}$ ($E_{K\downarrow}$) in the F is near the Fermi level (see figure 4(d)), so it is due to specific spin-valley band-matching tunneling mechanism a finite $I_{K\uparrow}$ ($\lambda_{dL} < 0$) or $I_{K\downarrow}$ ($\lambda_{dL} > 0$) is seen, leading to a valley locked spin filter effect. When $|\lambda_{dL}|$ decreases, the band gap

$$E_{K\parallel}^{\sigma} = 2|\lambda_{dL}|$$

reduces and the currents from the $K'$ valley appear, one can observe the currents in different valleys counterpropagate. By further reducing $|\lambda_{dL}|$, more transport channels are open, so the currents in both valleys can flow in the same direction, which results in a valley mixed Seebeck effect.

Last, it is necessary to discuss the robustness of this spin-valley filter effect and valley Seebeck effect on some realistic situations. First, we consider the bias $V_\parallel$ changes abruptly across the interface. In fact because our results depend on the band structures of the AF and F leads, we can obtain the same results in the AF/barrier/F junction, where the bias voltage drop linearly in the middle normal barrier region [44, 45]. Second, a real silicene sample inevitably contains atomic defects in the bulk. As discussed in [36–39] the features reported here can be held when the defect ratio is less than 7.5%. Third, due to the weak Rashba spin–orbit interaction, we neglect its influence on the carriers transport. Last, although silicene is considered here, the results can be observed in other heavy group-IV monolayers, such as germanene and stanene. In germanene and stanene based junction a large ferromagnetic exchange field and higher bias are required.

5. Summary

In summary, we study the spin-valley resolved currents under the electric bias and the temperature bias, respectively. For zero Fermi level in a broad gate voltage range due to specific spin-valley band-matching tunneling mechanism $I_{K\uparrow}$ ($I_{K\downarrow}$) flows under the positive (negative) bias, but in the $K$ valley the transport is
forbidden, so a valley locked bipolar spin filter effect is demonstrated. By reversing the sign of $\lambda_{AF}$ we can observe
the bipolar spin filter effect in the $K$ valley with zero current in the $K'$ valley. For a finite Fermi level a valley locked
fully spin-polarized current can exist under both the positive and negative biases. At the high Fermi level by
reversing the bias direction, the spin filter effect can switch to the valley filter effect. Furthermore, by changing

Figure 4. (a) $I_{hp}$ under $\lambda_{AF} = 0$ versus $\Delta T$. (b) $I_{hk}$, $I_{k'}$, $I_{l}$, and $I_{k}$ as functions of $\Delta T$. (c) spin (solid line) or valley polarization (dashed line) as a function of $\Delta T$ with spin–valley currents versus $\Delta T$ in its inset. (d) the band structures of the AF/F junction. In figure 4(d) in the AF the black (blue) lines correspond to the $K$ ($K'$) valley, while in the F the red (blue) lines correspond to the spin up (spin down) channel. The other parameters are $\lambda_{L} = 0$, $\lambda_{AF} = \lambda_{W}$, $\lambda_{R} = 0$, $h = 0.5\lambda_{V}$, and $T_{R} = 5$ K.
the sign of the Fermi level, the spin polarization direction of the current can be reversed. When the system is under a temperature bias, SSE always exists. With increasing the temperature bias, the system undergoes three regions: valley locked SSE, normal SSE and valley Seebeck effect. In addition, by increasing $\lambda_v$, three phases: thermally induced valley locked spin filter effect, valley Seebeck effect and valley mixed Seebeck effect are shown. Although the silicene-based AF/F junction is investigated here, the results can be observed in other heavy group-IV monolayers, such as germanene and stanene. Our results open opportunities for fabricating valleytronics and spin caloritronics devices based on silicene.

Note added. After we finish our manuscript, we became aware of a related work by Zhai et al [46]. In their work they found a valley-mediated and electrically switched bipolar-unipolar transition of the spin-diode effect in Heavy Group-IV Monolayers. But they did not consider the effect of the gate voltage and the Fermi level on the valley locked spin filter effect and the spin-valley Seebeck effect, which is focused on in our present work.

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ORCID iDs

Zhi Ping Niu https://orcid.org/0000-0003-3943-4335

References

[1] Vogt P, De Padova P, Quaresima C, Avila J, Frantzeskakis E, Asensio M C, Resta A, Ealet B and Le Lay G 2012 Phys. Rev. Lett. 108 155501
[2] Tao L, Cinquanta E, Chiappe D, Grazianetti C, Franciulli M, Dubey M, Molle A and Akinwande D 2015 Nat. Nanotechnol. 10 227
[3] Zhao J et al 2016 Prog. Mater. Sci. 83 24
[4] Liu C-C, Feng W and Yao Y 2011 Phys. Rev. Lett. 107 076802
[5] Liu C C, Jiang H and Yao Y G 2011 Phys. Rev. B 84 195430
[6] Rycerz A, Tworzydlo J and Beenakker C W J 2007 Nat. Phys. 3 172
[7] Akhmerov A R, Bardarson J H, Rycerz A and Beenakker C W J 2008 Phys. Rev. B 77 205416
[8] Xiao D, Yao W and Niu Q 2007 Phys. Rev. Lett. 99 236809
[9] Isberg J, Gabrysch M, Hammersberg J, Majdi S, Kovi K K and Twitchen D J 2013 Nat. Mater. 12 760
[10] Pereira V M and Castro Neto A H 2009 Phys. Rev. Lett. 103 046801
[11] Pereira V M, Castro Neto A H and Peres N M R 2009 Phys. Rev. B 80 045401
[12] Fujita T, Jalil M B A and Tan SG 2010 Appl. Phys. Lett. 97 043508
[13] Zhai F and Yang L 2011 Appl. Phys. Lett. 98 062101
[14] Niu Z 2012 J. Appl. Phys. 111 103712
[15] Wu Z et al 2019 Nat. Commun. 10 611
[16] Ni Z, Liu Q, Tang K, Zheng J, Zhou J, Qin R, Gao Z, Yu D and Lu J 2012 Nano Lett. 12 113
[17] Ezawa M 2012 Phys. Rev. Lett. 109 055502

Figure 5. $I_{\sigma}$ as a function of $\lambda_v$ (in units of $\lambda_m$) under $\Delta T = 50$ K and $T_R = 20$ K. Here VL-SFE, VSE and VMSE correspond to valley locked spin filter effect, valley Seebeck effect and valley mixed Seebeck effect, respectively. The other parameters as same those in figure 2.
[16] Tsai W-F, Huang C-Y, Chang T-R, Lin H, Jeng H-T and Bansil A 2013 Nat. Commun. 4 1500
[17] Ezawa M 2013 Phys. Rev. B 87 155415
[18] Yokoyama T 2013 Phys. Rev. B 87 241409(R)
[19] Ezawa M 2015 Phys. Rev. Lett. 114 056403
[20] Ezawa M 2012 New J. Phys. 14 033003
[21] Zhai X, Zhang S, Zhao Y, Zhang X and Yang Z 2016 Appl. Phys. Lett. 109 122404
[22] Uchida K, Takahashi S, Harri K, Ieda J, Koshiba W, Ando K, Maekawa S and Saitoh E 2008 Nature 455 778
[23] Bauer G E W, Saitoh E and van Wees B J 2012 Nat. Mater. 11 391
Bauer G E W, MacDonald A H and Maekawa S 2010 Solid State Commun. 150 459
[24] Boona S R, Myers R C and Heremans J P 2014 Energy Environ. Sci. 7 885
[25] Dubi Y and Di Ventra M 2011 Rev. Mod. Phys. 83 131
[26] Adachi H, Uchida K, Saitoh E and Maekawa S 2013 Rep. Prog. Phys. 76 036501
[27] Gu L, Fu H-H and Wu R 2016 Phys. Rev. B 94 115422
[28] Wu D-D, Fu H-H, Liu Q-B, Du G-F and Wu R 2018 Phys. Rev. B 99 115422
[29] Fu H-H, Wu D-D, Liu Q-B and Wu R 2019 Phys. Rev. B 100 085407
[30] Niu Z P 2013 Europhys. Lett. 101 37008
Niu Z P 2014 Phys. Lett. A 378 73
[31] Zeng M, Feng Y and Liang G 2011 Nano Lett. 11 1369
[32] Sierra J F, Neumann I, Cuppens J, Raes B, Costache M V and Valenzuela S O 2018 Nat. Nanotechnol. 13 107
[33] Fu H-H, Wu D-D, Gu L, Wu M and Wu R 2015 Phys. Rev. B 92 045418
[34] Niu Z P and Dong S 2014 Appl. Phys. Lett. 104 202401
[35] Niu Z P, Zhang Y M and Dong S 2015 New J. Phys. 17 073026
[36] Zhai X, Gao W, Cai X, Fan D, Yang Z and Meng L 2016 Phys. Rev. B 94 245405
[37] Zhai X, Wang S and Zhang Y 2017 New J. Phys. 19 063007
[38] Zhai X, Wang Y, Wen R, Wang S, Tian Y, Zhou X, Chen W and Yang Z 2018 Phys. Rev. B 97 085410
[39] Zhai X, Gu J, Wen B, Liu R-W, Zhu M, Zhou X, Gong L-Y and Li X 2019 Phys. Rev. B 99 085421
[40] Chen X, Zhang L and Guo H 2015 Phys. Rev. B 92 155427
[41] Yu Z, Xu F and Wang J 2016 Carbon 99 451
[42] Haugen H, Hernando D H and Brataas A 2008 Phys. Rev. B 77 115406
Wei P et al 2016 Nat. Mater. 15 711
Leutenantsmeyer J C, Kaverzin A A, Wojtaszek M and van Wees B J 2016 2D Mater. 4 014001
Singh S, Katoch J, Zhu T, Meng K-Y, Liu T, Brangham J T, Yang F, Flatté M E and Kawakami R K 2017 Phys. Rev. Lett. 118 187201
Zhong D et al 2017 Sci. Adv. 3 e1603113
Jiang S, Shan J and Mak K F 2018 Nat. Mater. 17 406
[43] Niu Z P, Li F X, Wang B G, Sheng L and Xing D Y 2008 Eur. Phys. J. B 66 245
Li H 2016 Phys. Rev. B 94 075428
[44] Wang Y, Liu Y and Wang B 2014 Appl. Phys. Lett. 105 052409
[45] Song Y, Wu H-C and Guo Y 2013 Appl. Phys. Lett. 102 093118
[46] Zhai X, Wen R, Zhou X, Chen W, Yan W, Gong L-Y, Pu Y and Li X 2019 Phys. Rev. Appl. 11 064047