Manipulation of magnetization by electric-current-induced spin–orbit torque (SOT) is of great importance for spintronic applications because of its merits in energy-efficient and high-speed operation. An ideal material for SOT applications should possess high charge-spin conversion efficiency and high electrical conductivity. Recently, transition metal dichalcogenides (TMDs) emerge as intriguing platforms for SOT study because of their controllability in spin–orbit coupling, conductivity, and energy band topology. Although TMDs show great potentials in SOT applications, the present study is restricted to the mechanically exfoliated samples with small sizes and relatively low conductivities. Here, a manufacturable recipe is developed to fabricate large-area thin films of PtTe₂, a type-II Dirac semimetal, to study their capability of generating SOT. Large SOT efficiency together with high conductivity results in a giant spin Hall conductivity of PtTe₂ thin films, which is the largest value among the presently reported TMDs. It is further demonstrated that the SOT from PtTe₂ layer can switch a perpendicularly magnetized CoTb layer efficiently. This work paves the way for employing PtTe₂-like TMDs for wafer-scale spintronic device applications.

Spin–orbit torque (SOT) provides an ultrafast and energy-efficient means to switch magnetization, which is of fundamental and technical importance for spintronic devices.[1–5] A typical SOT device consists of heavy metal/ferromagnet (HM/FM) bilayer, where the HM (e.g., Pt, W, Ta, etc.) converts charge current into spin current mainly due to the spin Hall effect (SHE) and then exerts a torque on the adjacent FM enabling magnetization manipulation. To improve the energy efficiency of SOT-driven magnetization switching, considerable efforts have been made to enhance the charge-spin conversion efficiency of HM[6–9] and reduce the shunting current in the FM.[10,11] Engineering the bilayer structure[9,12] or replacing HM by novel materials with larger charge-spin conversion efficiency and higher conductivity[10,13,14] are possible avenues to realize higher SOT efficiency.
Among numerous new materials, transition metal dichalcogenides (TMDs) are appealing because of their tunable conductivity and spin–orbit coupling,\cite{15,16} non-trivial energy band topology,\cite{17} long spin-life time,\cite{18} and interplay between spin and pseudospin.\cite{19} Implementing TMDs for SOT devices has shown many advantages, such as controllable SOT by designing crystal symmetry\cite{20} and electric-field tunability.\cite{21} However, there are two crucial issues that need to be solved. First, the conductivity of most TMD materials is several orders of magnitude lower than that of HMs, resulting in most of current flowing in FM layer and hence less efficient magnetization switching. Second, the TMD-based SOT devices are usually fabricated by physical exfoliation method, which cannot be extended for practical applications. Thus, metallic TMD thin films with high spin Hall conductivity that can be manufactured on a large scale are demanded for spintronic application. This leaves PtTe₂ as a promising material candidate. PtTe₂ exhibits to date the highest room-temperature electrical conductivity (\(\approx 3.3 \times 10^6 \text{ S m}^{-1}\)) among metallic TMDs.\cite{22} In addition, PtTe₂ is categorized as a type-II Dirac semimetal,\cite{23,24} where the topological nontrivial \(Z_2\) invariant gives rise to topological surface states (TSSs) with spin-momentum locking (like the case of topological insulator\cite{25,26}). Although the bulk Dirac node of PtTe₂ and its corresponding TSSs are well below the Fermi level (\(\approx -1 \text{ eV}\)), another non-trivial conical dispersion located between \(\Gamma\) and \(M\) points were found slightly below the Fermi level in PtTe₂.\cite{24} Similar features in PdTe₂, another type-II Dirac semimetal, were identified as additional TSSs intersecting with Fermi level from angle-resolved photoemission spectroscopy.\cite{27} It is thus expected that the TSSs in PtTe₂ might manifest themselves at the Fermi level and be accessible in transport experiments (e.g., SOT measurement). Moreover, the helical spin textures at the Fermi level was observed in few-layer PtTe₂ and ascribed to the local Rashba effect.\cite{28} Motivated by these intriguing properties, the potential of PtTe₂ in SOT device applications calls for further investigation.

In this work, we developed a simple method to synthesize high-quality large-area PtTe₂ thin films which can be used for SOT devices. We found the SOT efficiency of PtTe₂-based devices (0.09–0.15 for 5 nm-thick PtTe₂ layer) is 1.5–2 times larger than that of a 4 nm-thick Pt-based control sample. The spin Hall conductivity of PtTe₂ (0.2–2 \(\times 10^5 \text{ } \hbar/2e (\Omega \text{ m})^{-1}\)) is the largest among the presently studied TMDs and comparable to that of Pt and topological insulator. Taking advantage of the large SOT of PtTe₂, we have further realized efficient switching of perpendicular magnetization in PtTe₂/Au/CoTb devices.

Large-area high-quality PtTe₂ films are obtained through a two-step process, which has been previously used for fabricating PtSe₂ and PtS₂ thin films.\cite{29–32} Large-area Pt thin films with nominal thicknesses of 0.5–4 nm were first prepared on Si/SiO₂ wafers by a magnetron sputtering system. We then transformed the Pt thin films into uniform and homogenous PtTe₂ thin films by annealing them in tellurium vapor at \(\approx 460 \text{ °C}\) (see Figure 1a,b, details can be found in experimental part). As a CdI₂-type trigonal (1T) crystal, PtTe₂ is composed of edge-shared PtTe₆ octahedra which form the basal a-b planes (see Figure S1a

Figure 1. Structure of PtTe₂ thin film. a) Schematic illusion of the CVD process that transforms large-scale Pt thin films into PtTe₂ thin films. b) Large-scale PtTe₂ thin films with thicknesses of \(\approx 5 \text{ nm} (\text{top})\) and \(\approx 10 \text{ nm} (\text{bottom})\). The rule is in a unit of centimeter. c) HRTEM image of a typical PtTe₂ thin film with thickness \(\approx 5 \text{ nm}\). In the middle, the overlaid Pt–Te atomic model shows the matching between ideal PtTe₂ (001) pattern with the real atoms. d) X-ray diffraction and e) Raman spectra for various PtTe₂ thin films (initial Pt thicknesses are labeled). Note that the green and red spheres in (a) and (c) present schematic Pt atoms and Te atoms, respectively.
Figure 2. Transport properties of PtTe2 thin films. a) Temperature dependence of conductivity in PtTe2 thin films (the numbers are the nominal thicknesses of the initial Pt thin films). b) MR of a PtTe2 thin film (~3 nm) at 2 K for magnetic field along with two different directions. The dashed line is parabolic fitting of MR under H//. c) Magnetoconductance of the PtTe2 thin film at low temperature under H⊥, where Δσxx = (L/W)Rxx, L, W, and t are length, width, and thickness of PtTe2 channel. d) Temperature dependence of phase decoherence length lφ and its fitting with lφ ∝ T1/2.

The conductivity of the PtTe2 thin films (3–20 nm) at room temperature is in the range of 0.2–3 × 106 S m⁻¹, as shown in Figure 2a, which is consistent with that of single-crystal PtTe2 flakes.[35] This again indicates the high quality of these thin films. The increase of conductivity upon decreasing temperature signifies their metallic behavior. Figure 2b,c shows the magnetoresistances (MR) and magnetoconductance of a 3 nm-thick PtTe2 thin film for magnetic field applied along the current (H//) and perpendicular (H⊥) to the film plane at 2 K. The remarkable difference in MR between H// (MR ≈ 8 when B < 2 T) and H⊥ is probably related to the confined vertical dimension of thin film or the chiral anomaly of Dirac fermions.[36] The MR under H⊥ obviously deviates from the parabolic behavior at low temperature for all the PtTe2 thin films, which is the typical signature of weak antilocalization (WAL). WAL is usually considered as an indication of strong spin–orbit coupling.[15,37] WAL persists up to ~30 K and the magnetoconductance curves can be fitted by the Hikami–Larkin–Nagaoka (HLN) model[38]

\[
\Delta \sigma(B) = \frac{\alpha e^2}{\pi h} \left[ \ln \left( \frac{B_{\|}}{B} \right) - \psi \left( \frac{1}{2} + \frac{B_{\|}}{B} \right) \right]
\]

(1)

Here, \(\alpha\) is the fitting constant, \(e\) is the electron charge, \(h\) is the Planck’s constant, \(\Psi\) is the digamma function, and \(B_{\|}\) is related to the phase decoherence length \(l_\phi = \sqrt{\hbar / 8\pi eB_{\|}}\). Fitting the conductance from 2–25 K (Figure 2c), the corresponding \(l_\phi\) are extracted to be ~60 nm at 2 K. The \(l_\phi\) decreases to ~20 nm when the temperature increases to 20 K, as shown in Figure 2d.
The temperature dependence of $I_\phi$ can be fitted as $I_\phi \propto T^{-\gamma}$ and $\gamma \approx 0.45$ was obtained which implies the electron dephasing in PtTe$_2$ thin film is dominated by electron-electron interactions ($\gamma = 0.5$) rather than the electron-phonon interaction ($\gamma = 1$). The range of $I_\phi$ and the electron scattering mechanism in our thin-film samples are consistent with the results of single-crystal PtTe$_2$.\[22\]

Next, we fabricate PtTe$_2$/FM hybrid structures and characterize the current-induced SOT. After preparation of the PtTe$_2$ films, we immediately transferred them into a sputtering system to minimize the contamination of the surface. Permalloy (Py) layers with various thicknesses were sputtered onto the PtTe$_2$ thin films followed by the capping layers of MgO(2)/Ta(1.5) (numbers in brackets are in nanometers throughout this paper). Figure 3c,d shows the high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images for the cross-section of the multilayer. A sharp interface is identified where the underneath PtTe$_2$ owns perfect layered structures with atomic steps. Most of the PtTe$_2$ at the interface remains intact due to its stability.\[39\] It is noted that some regions of the top layer are obscure, which might be related to air exposure during the transfer.

We characterize the SOT using the spin-torque ferromagnetic resonance (ST-FMR) technique.\[89\] Ground-Source-Ground (GSG) electrodes were deposited for radio-frequency (RF) signal injection and DC voltage signal detection (as illustrated in Figure 3a).

In the ST-FMR experiments, the oscillatory resistance due to SOT-induced magnetization precession together with RF current leads to a rectified mixing voltage ($V_{\text{mix}}$).\[40\] $V_{\text{mix}}$ is picked up by a lock-in amplifier and it can be decomposed as: $V_{\text{mix}} = V_S F_S + V_A F_A$, where the symmetric Lorentzian component is $F_S(H_{\text{ext}}) = \Delta H^2/[(H_{\text{ext}} - H_0)^2 + \Delta H^2]$ and the antisymmetric Lorentzian component is $F_A(H_{\text{ext}}) = \Delta H^2((H_{\text{ext}} - H_0)/[(H_{\text{ext}} - H_{\text{0}})^2 + \Delta H^2]$. Here, $\Delta H$ is the linewidth of $V_{\text{mix}}$ curve, $H_{\text{ext}}$ is the external magnetic field, and $H_0$ is the resonant field. $V_S$ and $V_A$ are the amplitudes of the symmetric and antisymmetric components which are proportional to the in-plane damping-like torque and out-of-plane torques, respectively (see Figure 3b).\[41\] Typical frequency-dependent ST-FMR spectra and $V_{\text{mix}}$ for sample PtTe$_2$ (S)/Py (t) are shown in Figure 4a–c. To exclude possible parasitic effects,\[25\] angular dependence of $V_{\text{mix}}$ is obtained by sweeping in-plane magnetic field along with different directions ($\phi$, relative to $+x$-axis). Normally, $V_{\text{mix}}(\phi) \propto V_S^0 \sin 2\phi \cos \phi$, where $V_S^0$ is the averaged amplitude for $V_S$ ($V_A$), the $\sin 2\phi$ and $\cos \phi$ parts are derived from angular magnetoresistance and the torque $\propto m \times \dot{y}$ respectively. For comparison, the angular dependence of $V_S$ and $V_A$ for the cases of $t = 2.5$ and 10 nm are shown in Figure 4e,f, respectively. Both $V_S$ and $V_A$ are well-fitted by above angular dependence, which excludes the contribution from spin Seebeck effect (in that case, $V_S \propto \sin \phi$)\[42\] and the possibility that the spin orientation deviates from $y$-axis.\[89\] Note that spin-pumping generates symmetric signals with the same angular dependence as.

Figure 3. Schematic illustration of PtTe$_2$/Py bilayer for studying SOT. a) Layout of ST-FMR device with GSG connection. The $I_{RF}$ flows along the longitudinal direction of the rectangular bars ($x$-axis). b) $I_{RF}$ flowing in PtTe$_2$ generates a SOT including $\tau_x$ and $\tau_y$ components and drives magnetization of Py into procession around the effective field direction. c) Cross-sectional HAADF-STEM image of a PtTe$_2$/Py stack, where the interface is indicated by the white dashed lines and d) the rectangular region is magnified, where the overlaid atomic model shows the Pt (green) and Te (red) atoms forming high-quality PtTe$_2$ lattices (with 1T structure) and the parallel red dashed lines mark the lattices of Py. The scale bars are 5 and 2 nm in (c) and (d), respectively.
the $V_A$ from damping-like torque in ST-FMR,\textsuperscript{[25]} but such contribution is negligible (see supporting material).\textsuperscript{[43,44]} The SOT efficiency $\xi_{\text{SOT}}$ can be expressed as

$$
\xi_{\text{SOT}} = \left( \frac{V^d}{V^A} \right) \left( \frac{\mu_0 M_{\text{eff}} h}{\hbar} \right) \left[ 1 + \left( 4 \pi M_{\text{eff}} / H_{\text{sat}} \right) \right]^{1/2}
$$

(2)

Here, $h$ is the reduced Planck's constant, $\mu_0$ is the permeability of free space, $M_{\text{sat}}$ is the saturation magnetization, $t$ is the thickness of FM, and $d$ is the thickness of nonmagnetic (NM) layer that generates SOT. $M_{\text{eff}}$ is the effective magnetization of FM/NM bilayer, which can be acquired from fitting frequency-dependent resonant field with Kittel's formula (see Figure 4d). $\xi_{\text{SOT}}$ is related to the spin Hall angle $\theta_{\text{SH}}$ by the relation of $\xi_{\text{SOT}} = T \theta_{\text{SH}}$, where $T$ is the interface spin transparency. On the other hand, $V_A$ signifies the out-of-plane torques which include field-like torque and the torque due to Oersted field. To extract the two contributions in $V_A$, thickness dependence of $\xi_{\text{SOT}}$ can be used as\textsuperscript{[40]}

$$
\frac{1}{\xi_{\text{SOT}}} = \frac{1}{\xi_{\text{DL}}} \left( 1 + \frac{h}{e \mu_0 M_{\text{eff}} d L} \right)
$$

(3)

Here, $\xi_{\text{DL}} = \mu_0 M_{\text{eff}} h / (2 e / c) = \hbar / (2 e) c$ is the SOT efficiency due to damping-like (field-like) torque. To plot $1/\xi_{\text{SOT}}$ as a function of $1/t$, a series of samples, PtTe$_2$ (5)/Py (t) with $t = 2.5$–10 nm, were fabricated at the same batch. The representative results are shown in Figures 4 and 5 (see the other results from the control samples in Figure S3 in the Supporting Information). The $\xi_{\text{DL}}$ are obtained to be: $\xi_{\text{DL}} \approx 0.09$ and $\xi_{\text{FL}} \approx -0.004$ by linearly fitting $1/\xi_{\text{SOT}}$ (Figure 5a). These values are comparable to that of Pt reported in the literature.\textsuperscript{[45,46]} Hence, PtTe$_2$ presents a larger SOT efficiency than Pt. The $\xi_{\text{SO}}$ of PtTe$_2$ can be further improved by minimizing the air exposure time and reducing the surface roughness as presented by the red circles in Figure 5a with $\xi_{\text{SO}} \approx 0.152$ and $\xi_{\text{FL}} \approx -0.004$ (samples prepared at a different batch). In conjunction with its conductivity (see $\sigma_{xx}$ in Figure S2c in the Supporting Information), the spin Hall conductivity ($\sigma_{\text{SH}} = \sigma_{xx} \theta_{\text{SH}}$) of PtTe$_2$ reaches up to $1.6 \times 10^5$ (h/2e) (\Omega m)$^{-1}$. As shown in Table 1, the obtained spin Hall conductivity in the studied PtTe$_2$ polycrystalline thin films is the largest one among TMDs reported so far. The value is even comparable to the values of Bi$_2$Se$_3$, a representative topological insulator. The large spin Hall conductivity is because the SOT efficiency and electrical conductivity of PtTe$_2$ are both large. This superior property is beneficial for low-dissipation applications.

To further explore the origin of the relatively large SOT in PtTe$_2$, we also characterized the SOT efficiency in various PtTe$_2$ (d)/Py (5) samples (d = 3–20 nm). As shown in Figure 5b, the...
On the other hand, the TSSs of PtTe₂ at the Fermi level might not reasonable to attribute our results to quantum confinement. samples are much larger than that "quantum size." It is thus Rashba–Edelstein effect. However, in that case, a significant T
SOT
momentum locking. The PtTe₂ thickness dependence of the SOT (with positive rates at 0.057
τ
SOT
≈
T
θ
SHE.

Note that for measuring SOT in WTe₂, the current direction was along a-axis of WTe₂ crystal in ref. [20], while it was along the b-axis in ref. [54].

In the Bi₂Se₃/Co₄₀Fe₄₀B₂₀ bilayer, the higher and lower ξ
SOT
in the thinner and thicker Bi₂Se₃ film were ascribed to the TSSs and SHE, respectively. The SOT comparison between PtTe₂ and Bi₂Se₃ may suggest that the TSSs of PtTe₂ contribute to the SOT in the studied sample. Further study is required to investigate more details about the origin of the large SOT in PtTe₂.

We subsequently implement the studied PtTe₂ thin films for efficiently switching magnetic moments. A robust bulk perpendicularly magnetized CoTb layer[49] was grown onto PtTe₂ thin films. A thin Au layer (~2.5 nm) was deposited before CoTb to avoid degrading its bottom surface due to the physically adsorbing oxygen and water molecules on the PtTe₂ surface. The patterned Hall-bar devices for measurement are depicted in Figure 6a. An in-plane magnetic field along x-axis (Hₓ) is required for a deterministic switching of perpendicular magnetization.[3] DC current pulses (width ~ 50 ms) are applied along x-axis which induces a SOT on the CoTb layer and switching its magnetic moments. This magnetization orientation is characterized by measuring the signals of anomalous Hall effect (AHE) after each current pulse (delay ~ 25 ms). The PtTe₂/ Au/CoTb stack exhibits a perpendicular magnetic anisotropy

![Figure 5. a) 1/ξ
SOT
versus 1/τ
SOT
for PtTe₂/Py (circles) and Pt/Py (squares) and the corresponding linear fitting. Note that there are two series of PtTe₂-based devices (in different colors) prepared at different batches. b) Thickness dependence of ξ
SOT
and spin Hall conductivity σ
SH.
](Image)

Table 1. A comparison of SOT in PtTe₂ with other TMD materials, topological insulator Bi₂Se₃, and heavy metal Pt.

| SOT Materials | Fabrication method | Conductivity [Ω m]⁻¹ | Spin Hall angle [θ
SH] | Spin Hall conductivity [(θ/2e)(Ω m)⁻¹] | Refs. |
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>TMDs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MoS₂</td>
<td>Exfoliation</td>
<td>1.4 × 10⁴</td>
<td>0.033</td>
<td>47</td>
<td>[53]</td>
</tr>
<tr>
<td>WTe₂ᵃ</td>
<td>Exfoliation</td>
<td>2.6 × 10⁴</td>
<td>0.029</td>
<td>8 × 10⁴</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4–1.7 × 10⁵</td>
<td>0.09–0.5</td>
<td>0.4–6 × 10⁴</td>
<td>[54]</td>
</tr>
<tr>
<td>NbSe₂</td>
<td>Exfoliation</td>
<td>6 × 10⁴</td>
<td>0.005–0.013</td>
<td>3–8 × 10⁴</td>
<td>[53]</td>
</tr>
<tr>
<td>MoTe₂</td>
<td>Exfoliation</td>
<td>1.8 × 10⁵</td>
<td>0.032</td>
<td>5.8 × 10⁴</td>
<td>[56]</td>
</tr>
<tr>
<td>PtTe₂</td>
<td>Two-step process</td>
<td>0.3–3 × 10⁶</td>
<td>0.05–0.15</td>
<td>0.2–1.6 × 10⁵</td>
<td>This work</td>
</tr>
<tr>
<td>Topological insulators and Pt:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi₂Se₃</td>
<td>Molecular beam epitaxy</td>
<td>=1 × 10⁴</td>
<td>0.16</td>
<td>1.6 × 10⁵</td>
<td>[49]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.7 × 10⁴</td>
<td>2–3.5</td>
<td>1–2 × 10⁵</td>
<td>[23]</td>
</tr>
<tr>
<td>Bi₂Se₃₋ₓ</td>
<td>Sputter</td>
<td>7.8 × 10⁴</td>
<td>18.62</td>
<td>1.45 × 10⁵</td>
<td>[14]</td>
</tr>
<tr>
<td>Pt</td>
<td>Sputter</td>
<td>2–5 × 10⁶</td>
<td>0.02–0.1</td>
<td>3.5 × 10⁵</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 × 10⁶</td>
<td>0.076</td>
<td>3.8 × 10⁵</td>
<td>[40]</td>
</tr>
</tbody>
</table>

—a Note that for measuring SOT in WTe₂, the current direction was along a-axis of WTe₂ crystal in ref. [20], while it was along the b-axis in ref. [54].
(PMA), as shown in Figure 6b. Switching behavior is observed when the DC current is larger than 20 mA ($j_c \approx 9.9 \times 10^6$ A cm$^{-2}$ in PtTe$_2$ under $H_x \approx 2$ kOe). The switching chirality is reversed after reversing the direction of $H_x$, which is consistent with the SOT switching behavior (Figure 6c). The maximum change of AHE by SOT-induced switching is $\approx 8$ m$\Omega$, indicating an uncompleted switching. We speculate that this uncompleted switching is related to broadening of current path (i.e., lower current density locally) at the cross section region of the Hall bar configuration.[50] With increasing $H_x$, a smaller switching current is required and the corresponding change of AHE becomes smaller (Figure 6c,d), which are typical features of SOT switching.[51] The control experiment reveals that there is no SOT switching in the Au (2.5)/CoTb (6) sample for DC current density of up to $\approx 1.2 \times 10^7$ A cm$^{-2}$, which is already $\approx 4$ times larger than the current density in PtTe$_2$ (10)/Au (2.5)/CoTb (6) ($\approx 3.1 \times 10^6$ A cm$^{-2}$) (see Figure S6 in the Supporting Information). The critical switching current density is in general proportional to the saturation magnetization and anisotropy energy.[3] From vibrating sample magnetometer and AHE measurements, it is found that Au (2.5)/CoTb (6) bilayer has a weaker PMA thus it should be easier to switch. However, even larger current density flowing in Au/CoTb cannot trigger the switching. The absence of current-driven switching in the control sample is reasonable because of the relatively small spin Hall angle in Au.[52] Therefore, the switching behavior in PtTe$_2$ (10)/Au (2.5)/CoTb (6) must be dominated by the current-induced SOT from PtTe$_2$. On the other hand, we also prepared Pt (4)/Au(2.5)/CoTb (6) stacks. A higher critical current density in Pt, $j_c \approx 3.7 \times 10^7$ A cm$^{-2}$, is required to switch the magnetization of CoTb (Figure S6f, Supporting Information). Considering the thicknesses, the critical current in Pt is roughly 1.5 times larger than that in PtTe$_2$. It implies that the 10 nm-thick PtTe$_2$ layer (transformed from 2 nm-thick Pt) is more efficient in charge-to-spin conversion than a 4 nm-thick Pt layer.

In conclusion, we demonstrated that homoogenous high-quality PtTe$_2$ thin films with high conductivity and strong spin-orbit coupling can be synthesized in a manufacturable manner. From ST-FMR measurements, substantial SOT dominated by the damping-like torque was established in the PtTe$_2$/Py bilayer, where the TSSs of PtTe$_2$ might play an important role. It suggests that PtTe$_2$ is a compelling material for low-power SOT devices and other applications related to charge-spin interconversion. In order to be compatible with modern spintronic technology,
transferring the as-grown PtTe₂ sample from CVD furnace into sputter system without air exposure is required, which can further enhance the device performance. This work presents a facile strategy to investigate potential TMD materials for spintronics.

Experimental Section

Sample Preparation and Characterization: PtTe₂ thin films were transformed from Pt thin films by annealing the sources in a CVD furnace. Si/SiO₂ wafers with sputtered Pt films and Te source were loaded into half-open quartz tube as shown in Figure 1a. The system was first evacuated (base pressure ≤ 1 Pa) and then protected by flowing a gas mixture, Ar/H₂ (19:1), with a rate of 100 standard cubic centimeters per minute. The reaction temperature was ≈ 460 °C and the typical reaction time was 5–10 min with a pressure ≈ 60 Pa. Py (Ni₈₀Fe₂₀) layers were directly sputtered onto PtTe₂ thin films (power = 120 W) after transferring the samples from CVD furnace into a magnetron sputtering chamber and protected by MgO/Ta. The 6 nm-thick CoTb layer was prepared by co-sputtering of Co and Tb, in which the atomic ratio of Co/Tb was ≈ 2.9, and capped with SiN₄/Ta. Raman analysis was carried out using a HORIBA Raman microscope with an excitation wavelength of 532 nm. As-grown samples were transferred onto TEM grids for STEM.[29] Cross-section samples of the multilayer devices were fabricated by using a focused ion-beam system. HAADF-STEM studies were performed in JEM-ARM200 spherical aberration-corrected transmission electron microscope.

Device Fabrication and Measurement: Two types of devices were made. For ST-FMR experiments, the stacks of PtTe₂/Pt/MgO/Ta were patterned into rectangular bars by photolithography and ion milling with the typical size of 20 × 60 μm². For conductivity and magnetotransport and magnetization switching, typical Hall-bar devices were made with 30 μm width by 35 μm length. After milling, the second step of photolithography and magnetron sputtering were employed to fabricate the Pt (5)/Au (70) electrical contact pads. Transport measurements were performed with a Keithley 2400 current source and a Keithley 2812 voltage meter in Quantum design PPMS system. In the ST-FMR measurements, the RF signals with frequencies from 3 to 12 GHz and a nominal max power of ≈14 dBm were applied along the longitudinal axis using a signal generator. The in-plane external magnetic field (H) was swept with an angle (θ) toward x axis. Because the highest signal/noise ratio was obtained at 3–4 GHz, 4 GHz was usually chosen for angular dependent measurements, which was important for recording the weak signals in the thinnest stacks, e.g. PtTe₂ (5)/Py (2.5).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

platina ditelluride, spin Hall conductivity, spin–orbit torque, thin film, type-II Dirac semimetal

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