Spin–Orbit Torque Switching in an All-Van der Waals Heterostructure

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DOI: 10.1002/adma.202101730

Current-induced control of magnetization in ferromagnets using spin–orbit torque (SOT) has drawn attention as a new mechanism for fast and energy efficient magnetic memory devices. Energy-efficient spintronic devices require a spin-current source with a large SOT efficiency ($\xi$) and electrical conductivity ($\sigma$), and an efficient spin injection across a transparent interface. Herein, single crystals of the van der Waals (vdW) topological semimetal WTe$_2$ and vdW ferromagnet Fe$_3$GeTe$_2$ are used to satisfy the requirements in their all-vdW-heterostructure with an atomically sharp interface. The results exhibit values of $\xi = 4.6$ and $\sigma = 2.25 \times 10^5 \Omega^{-1} \text{m}^{-1}$ for WTe$_2$. Moreover, the significantly reduced switching current density of $3.90 \times 10^6 \text{A cm}^{-2}$ at 150 K is obtained, which is an order of magnitude smaller than those of conventional heavy-metal/ferromagnet thin films. These findings highlight that engineering vdW-type topological materials and magnets offers a promising route to energy-efficient magnetization control in SOT-based spintronics.

Spintronics, a next-generation information technology, is based on effective spin-current generation and injection. Spin transfer torque (STT) induced by spin-polarized charge current injection across one ferromagnet (FM) layer into another has been successfully employed for the effective manipulation of magnetization, leading to the recent commercial STT-based magnetic memory solutions.[1] Spin–orbit torque (SOT), which uses out-of-plane spin current generated from in-plane charge current in high spin Hall effect (SHE) materials, can realize a more energy-efficient manipulation of magnetization and is reaching commercial maturity.[2–4] Thus far, various high spin–orbit coupling (SOC) materials, including heavy metals, topological insulators (TIs),[5–7] and recently, topological semimetals (TSMs),[8–11] have been studied to maximize their spin Hall angle, $\theta_{\text{SH}} = |J_s|/|J_c|$, a measure of their efficiency at converting charge current density $J_c$ to spin current density $J_s$. Also, the interface engineering between the layers of high-SHE and FM materials has been investigated to maximize the spin transparency, $T_{\text{int}}$, across the interface.[12–19] The key challenge for efficient SOT spintronic devices is to maximize the SOT efficiency, $\xi = \theta_{\text{SH}} \cdot T_{\text{int}}$.[20] Recent rapid developments in van der Waals (vdW) materials and their heterostructures provide new opportunities for

1. Introduction

Spintronics, a next-generation information technology, is based on effective spin-current generation and injection. Spin transfer torque (STT) induced by spin-polarized charge current injection across one ferromagnet (FM) layer into another...
improved spintronic functionalities. A large group of topological materials was identified in vdW structures with an atomically flat surface. Also recently, FM vdW materials have been discovered,[21,22] some of which exhibit a relatively high Curie temperature ($T_C$) and perpendicular magnetic anisotropy (PMA),[23] which is important for FM layers in spintronic devices. Thus far, topological and FM vdW materials have been used as one of the constituent layers, either for spin-current generation or as the FM layer, e.g., a vdW TI Bi$_2$Se$_3$ with a deposited FM CoFeB layer[7] or a vdW FM Fe$_3$GeTe$_2$ (FGT) with a deposited heavy-metal Pt layer.[24,25] While current-induced magnetization control was successfully demonstrated in both cases, SOT performance in all-vdW heterostructures has yet to be explored. Here, using a vdW heterostructure of the topological semimetal WTe$_2$ and ferromagnet Fe$_3$GeTe$_2$, we show efficient current-induced magnetization switching with a much smaller switching current and power dissipation, as compared to conventional SOT devices. These observations highlight that all-vdW heterostructure with vdW TSMs and ferromagnets provide a promising architecture for SOT-based spintronic devices.

2. Results and Discussion

Figure 1a schematically shows the spin Hall effect in WTe$_2$ producing a pure spin current, which is injected into the FGT layer, and exerts an SOT on the magnetization of FGT. In this study, we fabricated an all-vdW heterostructure consisting of WTe$_2$ (12.6 nm)/FGT (7.3 nm) using a dry transfer technique (Figure S1, Supporting Information). The exfoliation of WTe$_2$ and FGT crystals, and transfer processes were performed in an inert argon atmosphere glovebox. After capping the WTe$_2$/FGT stack with a 2.6 nm thick aluminium oxide layer without exposing it to air, we patterned the stack into a Hall bar shape; this was followed by electrode deposition, as shown in Figure 1b (device 1) (see Experimental Section and Figure S2, Supporting Information). The cross-sectional scanning transmission electron microscopic (STEM) image of a representative WTe$_2$/FGT stack clearly shows the atomic layers of WTe$_2$ and FGT with the atomically sharp interface between them. This confirms that vdW stacking produces a clean interface without any residue or intermixing (see Figures S3–S5 for detailed analysis on the interface, Supporting Information).

![Figure 1. Structure of WTe$_2$/Fe$_3$GeTe$_2$ (FGT) device and electric and magnetic properties of FGT. a) Device schematics of a WTe$_2$/FGT heterostructure. The charge current ($J_x$, yellow arrow) applied to WTe$_2$ generates a spin current that is injected into the FGT along the $-z$-direction. By conservation of angular momentum, this spin current exerts a torque on the magnetization ($M$) of the FGT. Ball symbols with arrows represent electrons with their spin, respectively. b) Cross-sectional annular bright field scanning transmission electron microscopy image of WTe$_2$/FGT heterostructure viewed from [120] directions of FGT (left panel) and optical image of the Hall bar device (right panel). The current is applied along the $x$-axis, and the Hall voltage is measured along the $y$-axis. c) Temperature dependence of symmetric part of Hall resistance at zero field $R_{xy}$ and longitudinal resistance $R_{xx}$ (inset) of the WTe$_2$/FGT Hall bar device. d) Anti-symmetrized Hall resistance $R_{xy}^A$ as a function of an in-plane magnetic field along the $x$-axis $H_x$ at different temperatures. e,f) Temperature dependence of e) anomalous Hall resistance $R_{AHE}$, f) easy-axis ($H_z^{coer}$) and hard-axis ($H_x^{coer}$) coercive field of the device. The critical temperature $T_c$ is $\approx$ 200 K.](image-url)
We first discuss the temperature and magnetic characteristics of the device. All the experimental data are measured in device 1, unless stated otherwise. Figure 1c shows the temperature dependence of the symmetrized Hall resistance ($R_{xy}^s$) and longitudinal resistance ($R_{xx}$) of the device, the former of which will be used later to estimate electronic temperature at a high bias current (see the temperature dependence of the WTe2 layer in Figure S6, Supporting Information). Figure 1d–f presents the electron temperature ($T_e$) during the current pulse is plotted as a function of $T$. The dashed lines represent the critical temperature $T_c$ ($\sim 200$ K of FGT and the corresponding $I_{\text{pulse}}$). The ratio of $R_{xy}^s$ to the anomalous Hall resistance $R_{\text{AHE}}$ measured with a sweeping $I_{\text{pulse}}$, under $\mu_0 H = 30$ mT and $-30$ mT at 150 K. The switching polarity is anticlockwise for (b) and clockwise for (c). Dots denote the initial magnetization states of FGT. The horizontal dashed lines represent the states of saturated magnetization of FGT.

![Figure 1](https://www.advmat.de)

**Figure 2.** Current-induced magnetization switching in WTe2/Fe3GeTe2 (FGT) heterostructure (device 1). a) Hall resistance $R_{xy}$ (red line) measured after applying 10 ms long current pulses of height $I_{\text{pulse}}$ in the presence of an in-plane magnetic field $\mu_0 H_x = 30$ mT parallel to the charge current at 150 K. $\mu_0$ is a vacuum permeability. The initial state of FGT is saturated by the up-state ($M$ || z-axis), which is denoted by a dot. Arrows indicate the $I_{\text{pulse}}$-sweep direction, and the switching polarity is anticlockwise. The electron temperature $T_e$ (blue line) during the current pulse is plotted as a function of $I_{\text{pulse}}$. The dashed lines represent the critical temperature $T_c$ = 200 K of FGT and the corresponding $I_{\text{pulse}}$. b) The ratio of $R_{xy}^s$ to the anomalous Hall resistance $R_{\text{AHE}}$ measured with a sweeping $I_{\text{pulse}}$, under $\mu_0 H = 30$ mT and $-30$ mT at 150 K. The switching polarity is anticlockwise for (b) and clockwise for (c). Dots denote the initial magnetization states of FGT. The horizontal dashed lines represent the states of saturated magnetization of FGT.

a)

![Image](https://www.advmat.de)

b)

![Image](https://www.advmat.de)

c)

![Image](https://www.advmat.de)
The initial state of Fe$_3$GeTe$_2$ (FGT) is denoted by circles. For each case, the maximum electronic temperature that the device cannot return to its original state (see the case for device 2 in Figure S10, Supporting Information). We suspect that when $T_{e,max}$ exceeds $T_c$ of FGT the significant thermal fluctuations induced by large bias current randomizes the magnetic domain of FGT and makes switching behavior unstable. This also emphasizes that the Joule heating issue is important to consider when using vdW FMs with a low $T_c$.\cite{21,22}

The temperature dependence of current-induced switching is shown in Figure 3b,c. The maximum $I_{pulse}$ was limited so that $T_{e,max}$ did not exceed $T_c = 200$ K for FGT. The difference in the $R_{xy}$ value at opposite magnetizations decreases with a decrease in $T$, which is attributed to changes in the current distribution between WTe$_2$ and FGT. At lower $T$, the resistivity of WTe$_2$ decreases significantly, while that of FGT remains almost constant; therefore, less current flowing through FGT results in a smaller Hall voltage. Figure 3d summarizes the temperature dependence of the switching current (Figures S12–16, Supporting Information). The reduction of the switching current with increasing $T$ is due to the simultaneous decrease in the magnetization of FGT and the easy-axis coercive field.

Generally, the charge-to-spin conversion efficiency is quantified by the SOT efficiency $\xi = \frac{4e}{\pi\hbar} \frac{M_{FGT} H_{z,coer}}{J_{sw}}$,\cite{30,35} where $e$ is the electron charge, $\hbar$ is the reduced Plank constant, $M_{FGT}$ is the saturation magnetization of FGT, $H_{z,coer}$ is the thickness of FGT, $H_{z,coer}$ is the easy-axis coercive field (Figure 1f), and $J_{sw}$ is the switching current density of the device. From the parallel resistor model for WTe$_2$/FGT, we estimated that 60% of the total current flows through WTe$_2$ at $T_c \sim 160$ K ($T = 150$ K), which results in $J_{sw} = 3.90 \times 10^6$ A cm$^{-2}$. If taking $M_{FGT} = 240$ emu cm$^{-3}$ and $H_{z,coer} = 522$ G at $T_c \sim 160$ K, we obtain $\xi = 4.6$. Here, $M_{FGT}$ is measured in a bulk crystal of FGT with $T_c \sim 200$ K, which is similar to that of the SOT device discussed thus far (Figure S17, Supporting Information). Another device (device 2) consisting of 9.1 nm WTe$_2$ and 5.8 nm FGT reproduced current-induced magnetization switching with similar $\xi = 2.2$ (see Figures S18 and S19, Supporting Information).

We now discuss the SOT performance of our WTe$_2$/FGT device in comparison with previous SOT devices. First, we compare our WTe$_2$/FGT device to Pt/FGT devices that use the same FM material, FGT, but sputtered spin-current generation material, Pt. The switching current density $J_{sw}$ of Pt/FGT devices is 1.2 $\times$ 10$^7$ A cm$^{-2}$ at 120 K\cite{24} and 2.5 $\times$ 10$^7$ A cm$^{-2}$ at 180 K.\cite{25} Second, we compare our WTe$_2$/FGT device to three consecutive sweeps show a relatively consistent current-induced switching. However, as the maximum $I_{pulse}$ increases to 2.9 mA, $T_{e,max}$ becomes comparable to, or exceeds, $T_c$, and the current-induced switching behavior becomes more inconsistent for consecutive sweeps. For these cases, the magnetization of the device cannot return to its original state (see the case for device 2 in Figure S10, Supporting Information). We suspect that when $T_{e,max}$ exceeds $T_c$ of FGT the significant thermal fluctuations induced by large bias current randomizes the magnetic domain of FGT and makes switching behavior unstable. This also emphasizes that the Joule heating issue is important to consider when using vdW FMs with a low $T_c$.\cite{21,22}

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We now discuss the SOT performance of our WTe$_2$/FGT device in comparison with previous SOT devices. First, we compare our WTe$_2$/FGT device to Pt/FGT devices that use the same FM material, FGT, but sputtered spin-current generation material, Pt. The switching current density $J_{sw}$ of our WTe$_2$/FGT (3.90 $\times$ 10$^6$ A cm$^{-2}$) is an order of magnitude smaller than that of Pt/FGT devices. At a similar $T/T_c = 0.8$, the $J_{sw}$ of Pt/FGT devices is 1.2 $\times$ 10$^7$ A cm$^{-2}$ at 120 K\cite{24} and 2.5 $\times$ 10$^7$ A cm$^{-2}$ at 180 K.\cite{25} Second, we compare our WTe$_2$/FGT device to Pt/FGT devices that use the same FM material, FGT, but sputtered spin-current generation material, Pt. The switching current density $J_{sw}$ of our WTe$_2$/FGT (3.90 $\times$ 10$^6$ A cm$^{-2}$) is an order of magnitude smaller than that of Pt/FGT devices. At a similar $T/T_c = 0.8$, the $J_{sw}$ of Pt/FGT devices is 1.2 $\times$ 10$^7$ A cm$^{-2}$ at 120 K\cite{24} and 2.5 $\times$ 10$^7$ A cm$^{-2}$ at 180 K.\cite{25} Second, we compare our WTe$_2$/FGT device to
WTe2/Py that uses the same spin-current generation material, WTe2, but with sputtered FM, Py. WTe2/Py device had a SOT efficiency $\xi = 0.09–0.51$ estimated with spin-torque ferromagnetic resonance measurement,[38] which is an order of magnitude smaller than our results ($\xi = 4.6$). These comparisons suggest that using WTe2 as a spin-current generation material combined with FM layers through vdW stacking enhanced SOT performance, which can be attributed due to better spin transparency across the atomically sharp vdW interface. Here, we discuss two factors that can affect interfacial spin transparency: one is the roughness of the interface, and another is the electric potential gradient at the interface. Rough ferromagnetic interface has been suggested to create inhomogeneous local magnetic field, which causes inhomogeneity of the spin precession and reduction of spin accumulation.[43] In this regards, atomically flat interface of all-vdW heterostructure is expected to be beneficial for better spin injection efficiency. On the contrary, several researches on transition metal ferromagnets and nonmagnetic materials argue that the rough interface or the intermixing of atoms near the interface may suppress the abrupt potential gradient and reduce the interface spin loss, leading to better spin transparency.[44,45]

In our WTe2/FGT heterostructure, the terminated atoms in FGT, i.e., tellurium (Te), are the same as those in WTe2, which can be strongly coupled through the 5p orbital.[46] According to the STEM and the energy dispersive X-ray spectroscopy analysis (see Figures S3–5, Supporting Information), there is a Te-rich interfacial layer of single atomic thickness ($\approx 0.3$ nm), which was presumably formed by Te atoms escaped from FGT and/or WTe2 crystals. The coupling between Te termination atoms of WTe2 and Te termination layer of FGT via single atomic-layer thick Te-rich interfacial layer may have been beneficial for minimizing electron scattering and spin loss across WTe2 and FGT layers. However, further experimental and theoretical investigation on the spin transparency of vdW interfaces is needed. Lastly, WTe2 is a TSM with a large conductivity ($2.25 \times 10^5 \, \Omega^{-1} \, \text{m}^{-1}$), which is an order of magnitude larger than that of Bi2Te3–TIs (1.4–9.4 $\times 10^4 \, \Omega^{-1} \, \text{m}^{-1}$)[5,7,41,47] or similar to that of narrow-gap TI Bi2.6Sb0.4 (2.5 $\times 10^5 \, \Omega^{-1} \, \text{m}^{-1}$).[41] In addition, the conductivity of FGT (2.69 $\times 10^5 \, \Omega^{-1} \, \text{m}^{-1}$) is $\approx$2–20 times smaller than that of conventional FMs, such as Co, Py, CoPt, and CoFeB (0.5–4.2 $\times 10^6 \, \Omega^{-1} \, \text{m}^{-1}$).[5,7,36,47] Therefore, a larger portion of current flows through the spin-current generation layer, and the dissipation power density of the whole device at magnetization switching ($P_{sw}$) is lowered as summarized in Figure 4, hence exhibiting improved energy efficiency.

### Figure 4.
Comparison of spin–orbit torque (SOT) efficiency and dissipation power density for magnetization switching. Spin–orbit torque efficiency $\xi$ estimated from the current-induced magnetization switching and dissipation power density of the whole device at magnetization switching ($P_{sw}$) for devices based on heavy metals (green symbols) [2,3,25,36–40] and topological materials (blue symbols)[5–7,41,42] at room temperature unless noted otherwise. Results from this work (devices 1 and 2) are denoted by star symbols. The vertical length of the bar represents the range of the parameter. "WTe2" represents sputtered disordered WTe2.

better performance for spintronic applications with a large spin Hall angle.[48] Also, a theoretical study[49] and a related experiment[50] suggest that owing to the lowered geometrical symmetries in the single FGT layer, the current flow in FGT layer may induce SOT, which can contribute to magnetization switching. Moreover, WTe2 has exhibited out-of-plane antidamping torque, which was induced by a current bias along the low-symmetry axis.[8,9,51] This is owing to its broken screw-axis and glide plane symmetries at the surfaces, which is not allowed for conventional HMs. Such unconventional SOT can enable current-induced magnetization switching without an external magnetic field, which is highly desirable for practical applications and also demonstrated recently.[52] Further optimization with novel topological materials, together with interface engineering, can lead to highly energy-efficient all-vdW spintronics devices.

### 4. Experimental Section
A WTe2 (FGT) single crystal was mechanically exfoliated to provide WTe2 (FGT) thin flakes with a thickness of 10–15 nm (<10 nm) on GelFilm PF-30/17-X4 from Delphon Industries (silicon oxide wafer). The WTe2 flakes were transferred onto the FGT flake to make WTe2/FGT vdW heterostructures. All the exfoliation and transfer processes were performed in an inert argon atmosphere glovebox to minimize the degradation of the materials and interfaces. To protect a stack of WTe2/FGT during the fabrication process, aluminum oxide with a thickness of 2.6 nm was deposited via electron beam (e-beam) evaporation, without exposing the WTe2/FGT stack to the air. The thickness of the WTe2 and FGT flakes was confirmed using atomic force microscopy before the fabrication process. Electrodes were patterned using e-beam lithography, and in situ argon ion milling was used to eliminate the aluminum oxide of the WTe2/FGT stack, followed by Cr (5 nm)/Au (35 nm) electrode
deposition. Last, the WTe2/FGT stack was shaped into Hall bar geometry using in situ argon ion milling, followed by aluminium oxide (50 nm) deposition to protect etched sides of the WTe2/FGT stack from air exposure. Current direction of the WTe2/FGT device was 23° off from α-axis of WTe2 crystal.

Supporting Information

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

Acknowledgements

I.S. and W.J.C. contributed equally to this work. This work was supported by Samsung Advanced Institute of Technology (SAIT). M.N.A. acknowledges support from the Alexander von Humboldt Foundation Sofia Kovalevskaja Award, the German Federal Ministry of Education and Research’s MINERVA ARChES Award, and the Max Planck Society. S.-Y.C. acknowledges the support of the Global Frontier Hybrid Interface Materials of the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (2013M3A6B1078872), and Korea Basic Science Institute (National Research Facilities and Equipment Center) grant funded by the Ministry of Education (2020RIAC6C101A202). H.-W.L. acknowledges support from National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (no. 2020R1A2C2013484). J.S.K. was supported by the Institute for Basic Science (IBS) through the Center for Artificial Low Dimensional Electronic Systems (no. IBS-R014-D1) and by the National Research Foundation of Korea (grant nos. 2016R1A5A6075964, 2016K1A4A4A01922028). H.-W.L. was supported by National Research Foundation of Korea (NRF) of the Government (grant no. 2016R1A5A1008184, 2020R1C1C1013241, 2020M3H3A1008391), Samsung Science and Technology Foundation (project no. SSTF-BAT1702-05), and Samsung Electronics Co., Ltd. (I0201207-07801-01).

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

current-induced magnetization switching, energy-efficient SOT device, interface engineering, spin–orbit torque, van der Waals materials

Received: March 3, 2021
Revised: December 9, 2021
Published online: January 18, 2022

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