Disorder is not always bad for charge-to-spin conversion in WTe<inf>2</inf>

Citation for the original published paper (version of record):
Guimarães, M., Dash, S. (2021). Disorder is not always bad for charge-to-spin conversion in WTe<inf>2</inf>. Matter, 4(5): 1440-1441. http://dx.doi.org/10.1016/j.matt.2021.04.009

CellPress
Matter

Previews

Disorder is not always bad for charge-to-spin conversion in WTe_2

Marcos H.D. Guimarães[1,*] and Saroj P. Dash[2]

The Wang group at Stanford University demonstrates disordered WTe_x films for efficient charge-to-spin conversion phenomena. The deposition of these films by sputtering and the charge-to-spin conversion resilience against disorder make them attractive for applications in new magnetic memory devices.

Materials that are capable of converting a charge current into an angular momentum current—or spin current—are at the heart of modern magnetic memory devices[1] (Figure 1). Potential materials for nonvolatile magnetic random-access memory (M-RAM) applications use an effect known as spin-orbit torque to manipulate the magnetization of an adjacent magnetic layer, working as information storage. Notably, proof-of-principle of spin-orbit torque M-RAM devices have been produced at the 300 mm wafer scale,[3] showing the potential of these memory devices to be adopted by industry. However, the charge-to-spin conversion efficiencies of materials fabricated using CMOS compatible processes—such as Pt, Ta and W—are still low, in the order of 10%–30%.[1] For this reason, researchers have turned to materials with nontrivial electronic properties, such as topological insulators[4] and Weyl semimetals,[5,6] which have the potential of showing very large conversion factors as well as different mechanisms for charge-to-spin current conversion.

The type 2 Weyl semimetal candidate WTe_2 is particularly interesting for spin-orbit torques. It has been shown to be capable of producing in-plane antidamping-like torques with efficiencies comparable or even higher than conventional heavy metals.[5] Even more interestingly, the low crystal symmetry of WTe_2 gives rise to an out-of-plane antidamping-like torque,[6] forbidden in high-symmetry materials and ideal for switching the magnetization of out-of-plane magnetized layers such as the ones used in modern high-density memory devices. Recently, both conventional and unconventional charge-spin conversion has also been observed in WTe_2 using spin transport experiments.[7] Nonetheless, the fabrication of high-quality materials at wafer-scales is still a bottle-neck for the industrial application of topological insulators and Weyl semimetals. Most of the works performed on WTe_2 have used the tedious and laborious mechanical exfoliation technique. While this technique gives high-quality single crystals, ideal for lab studies, it is impractical for industrial applications.

In this issue of *Matter*,[2] Li et al. demonstrate that disordered WTe_x films deposited by sputtering still maintain several of the appealing properties of its crystalline and stoichiometric cousin, WTe_2. Their films show similar behavior of conductivity as a function of temperature as well as weak antilocalization, indicating that their disordered and non-stoichiometric films still possess the signatures of a semimetal with high spin-orbit coupling. The latter is especially important for charge-to-spin conversion mechanisms. The fact that the films are fabricated using sputter deposition is another good news for future applications since this is the method of choice for many standard deposition processes of materials in the semiconductor industry.

Li et al. show the presence of large spin-orbit torques in WTe_x/ferromagnet (CoFeB) bilayers, with efficiencies on par with single crystal WTe_2/ferromagnet devices. Moreover, they observe a large unidirectional magneto-resistance, 5–20 times larger than standard devices. The large unidirectional magnetoresistance and current-to-spin-torque conversion are then put to use to switch and detect the magnetization direction of the ferromagnetic layer, using low switching currents.

This work brings good news and paves the way to the possible implementation of Weyl semimetals in future magnetic memory devices. Nevertheless, there are still many questions up in the air. Even though crystalline WTe_2 and disordered WTe_x show similar values for the spin-orbit torque efficiency, the mechanisms are not expected to be the same. In fact, the precise mechanisms for charge current-to-spin-orbit torque conversion in devices similar to these are a topic of heavy debate.[8] The enhancement of the spin-orbit torque efficiency found in WTe_x and in WTe_2 indicates the presence of a bulk-like effect, such as the spin Hall effect (Figure 1). However, the long-range disorder of WTe_x should enhance a side-jump mechanism for the spin Hall effect, while one would expect a major contribution of intrinsic charge-to-spin conversion phenomena for pristine WTe_2. The fact that the spin-orbit

[1]Zernike Institute for Advanced Materials, University of Groningen, Groningen, the Netherlands

[2]Department of Microtechnology and Nanoscience, Chalmers University of Technology, Göteborg, Sweden

*Correspondence: m.h.guimaraes@rug.nl

https://doi.org/10.1016/j.matt.2021.04.009

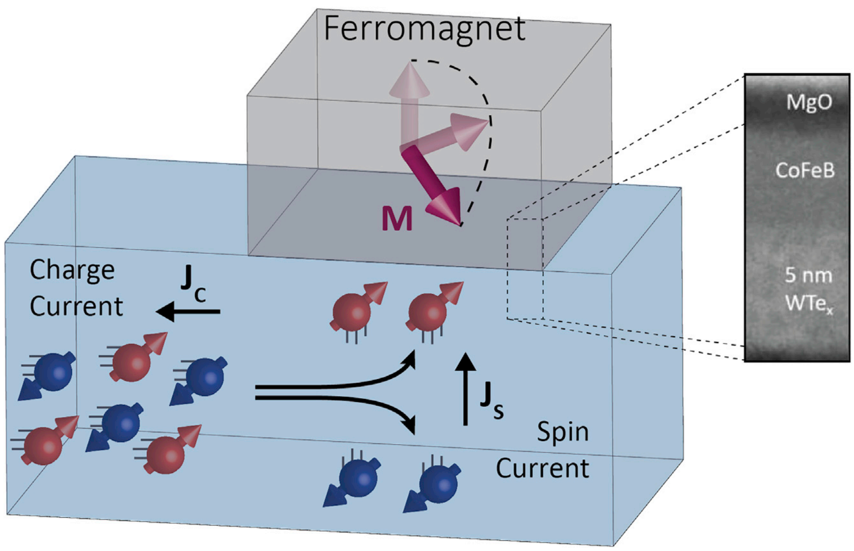

Figure 1. Charge-to-spin conversion for magnetization switching via spin-orbit torques
In the most common charge-to-spin conversion mechanism in bulk, the spin Hall effect, a charge current (J_C) consisting of electrons of opposite spins traveling in the same direction, is converted into a pure spin current (J_S) where opposite spins get deflected to opposite directions of the layer. The transfer of angular momentum from the spin current is used to manipulate the magnetization of an adjacent ferromagnetic layer. Inset: Cross-section scanning transmission electron microscopy image of WTe_x/CoFeB bilayer capped by MgO. Adapted from Li et al.[2]

torque efficiency and its thickness dependence is so similar between the two materials seems to be a coincidence, but could contain important information about the mechanisms at play. This serves as a motivation for future works which could focus on finding a connection between the level of disorder and stoichiometry with the spin-orbit torque efficiency.

The disorder in WTe_x seems to average out the desirable out-of-plane anti-damping torque observed in crystalline WTe_2. This can be explained by the lack of crystallinity of the films studied, which is a necessary condition for these special torques to appear. The optimization of the sputtering deposition procedure used here on different crystalline substrates could therefore lead to the discovery of methods to create wafer-scale WTe_x single-crystals, unleashing the full potential of this material for industrial applications. One could envision a demonstration of out-of-plane magnetization switching at very low current densities, potentially even more efficient than recently demonstrated in low-symmetry CuPt/CoPt bilayers.[9]

Finally, it is still an open question if the various properties[10] of WTe_2 could be used to tune or enhance the spin-orbit torque, and if they are present in the disordered WTe_x films studied by Li et al. These properties, such as ferroelectricity, conducting edge states, and superconductivity, could lead to different mechanisms for the generation of spin-torques. Furthermore, it will also be interesting to observe charge-to-spin conversion phenomena in WTe_2 by tuning the Fermi level close to its topological bands, where a significant effect is expected. These properties of WTe_2 should provide researchers a fertile ground for new discoveries, enriching the knowledge on spin-orbit torques even further.

1. Manchon, A., Miron, I.M., and Jungwirth, T. (2019). Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems. Rev. Mod. Phys. *91*, 035004.

2. Li, X., Li, P., Hou, V.D.-H., Mahendra, D.C., Nien, C.-H., Xue, F., Yi, D., Bi, C., Lee, C.-M., Lin, S.-J., et al. (2021). Large and Robust Spin-to-Charge Conversion in Sputtered Conductive WTex with Disorder. Matter *4*, this issue, 1639–1653.

3. Garello, K., Yasin, F., Hody, H., Couet, S., Souriau, L., Sharifi, S.H., Swerts, J., Carpenter, R., Rao, S., Kim, W., et al. (2019). Manufacturable 300mm platform solution for Field-Free Switching SOT-MRAM. In IEEE Symposium on VLSI Technology. https://doi.org/10.23919/VLSIT.2019.8776537.

4. Mellnik, A.R., Lee, J.S., Richardella, A., Grab, J.L., Mintun, P.J., Fischer, M.H., Vaezi, A., Manchon, A., Kim, E.A., Samarth, N., and Ralph, D.C. (2014). Spin-transfer torque generated by a topological insulator. Nature *511*, 449–451.

5. Shi, S., Liang, S., Zhu, Z., Cai, K., Pollard, S.D., Wang, Y., Wang, J., Wang, Q., He, P., Yu, J., et al. (2019). All-electric magnetization switching and Dzyaloshinskii-Moriya interaction in WTe_2/ferromagnet heterostructures. Nat. Nanotechnol. *14*, 945–949.

6. MacNeill, D., Stiehl, G.M., Guimarães, M.H.D., Buhrman, R.A., Park, J., and Ralph, D.C. (2017). Control of spin–orbit torques through crystal symmetry in WTe2/ferromagnet bilayers. Nat. Phys. *13*, 300–305.

7. Zhao, B., Karpiak, B., Khokhriakov, D., Johansson, A., Hoque, A.M., Xu, X., Jiang, Y., Mertig, I., and Dash, S.P. (2020). Unconventional Charge-Spin Conversion in Weyl-Semimetal WTe_2. Adv. Mater. *32*, e2000818.

8. Hidding, J., and Guimarães, M.H.D. (2020). Spin-Orbit Torques in Transition Metal Dichalcogenide/Ferromagnet Heterostructures. Front. Mater. *7*, 594771.

9. Liu, L., Zhou, C., Shu, X., Li, C., Zhao, T., Lin, W., Deng, J., Xie, Q., Chen, S., Zhou, J., et al. (2021). Symmetry-dependent field-free switching of perpendicular magnetization. Nat. Nanotechnol. *16*, 277–282.

10. Das, P.K., Di Sante, D., Cilento, F., Bigi, C., Kopic, D., Soranzio, D., Sterzi, A., Krieger, J., Vobornik, I., Fujii, J., et al. (2019). Electronic properties of candidate type-II Weyl semimetal WTe $_2$. A review perspective. Electron. Struct. *1*, 014003.