Study of Spin-Orbit Torques in Transition Metal Dichalcogenide / Ferromagnet Heterostructures

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Primary CNF Tools Used: AFM Veeco Icon, Zeiss Supra SEM and Nabity, SC4500 even hour evaporator, Oxford 81 etcher, AJA sputter deposition

Abstract:

Two-dimensional (2D) transition metal dichalcogenides (TMDs) present a unique platform for spintronics because of their strong spin-orbit (S-O) couplings and atomically flat surfaces which can be readily interfaced with other materials. Our focus is the study of TMDs coupled to ferromagnets, which can lead to the generation of novel spin-orbit torques. Fabrication of these heterostructures requires special techniques to ensure that their interface remains clean and well-ordered throughout. We discuss the methods for fabricating TMD/ferromagnet devices and present electrical measurements that measure the spin-orbit torques produced.

Summary of Research:

Recent experiments have demonstrated that integrating a ferromagnetic material with a low symmetry crystalline material that possesses strong spin-orbit (S-O) coupling can generate new forms of S-O torques, which can be used to efficiently manipulate magnetic devices with perpendicular magnetic anisotropy [1,2]. Single-crystal transition metal dichalcogenides (TMDs) are a family of layered materials with strong S-O coupling that have a wide variety of crystal symmetries [3]. This makes them ideal candidate spin source materials for the generation of novel S-O torques. Here, we discuss methods to assemble heterostructures of exfoliatable TMDs (like WTe_2, $TaTe_2$, $MoTe_2$, $NbSe_2$) and thin metallic ferromagnets for making quantitative measurements of the various torques generated.

The layers in a TMD crystal are bonded by weak van der Waal interactions and can be easily isolated by mechanical cleaving. We fabricate our samples by exfoliating the TMD from a bulk crystal using the scotch tape method, onto a high resistivity silicon wafer. The final step of the exfoliation process is carried out under high vacuum (< 10^{-6} torr). This prevents degradation of the atomically flat TMD surface through absorption of water vapor and/or oxygen.

The TMD is interfaced with 6 nm of permalloy (Py = $Ni_{81}Fe_{19}$), which is deposited by grazing-angle DC magnetron sputtering (with a rate < 0.2 Å/s) to minimize mechanical damage to the TMD surface. To prevent oxidation of the ferromagnet, the sample is further capped with 2 nm of aluminum. A combination of optical microscopy and atomic force microscopy (CNF AFM Veeco Icon) are used to identify thin (< 15 nm) and homogenous (surface roughness < 300 pm) regions on TMD flakes (Figure 1).

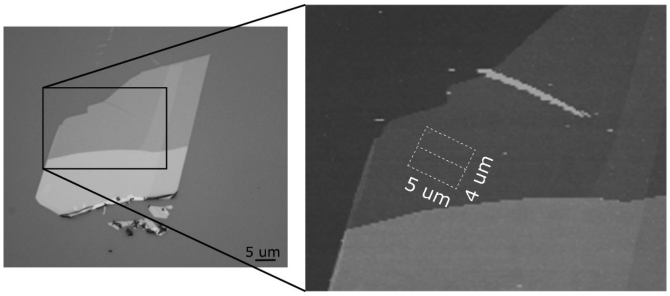

Figure 1: (left) Optical image of TMD/Py sample on a Si substrate before device patterning. The different color intensities indicate different thicknesses. (right) AFM image of the boxed region. White dashed lines indicate the active region used to make the device, with surface roughness < 300 pm and thickness 2.2 nm.

E-beam lithography (CNF Zeiss Supra SEM, Nabity) is used to pattern the selected flakes into bar geometries of ~ 4 × 5 μm in size, needed to perform spin-torque

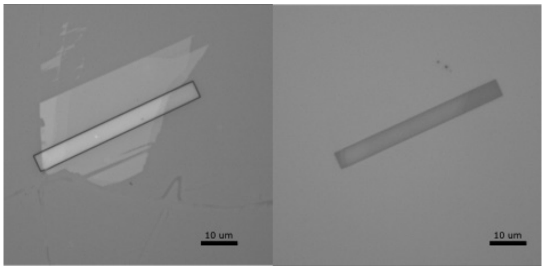

Figure 2: Optical Images of (left) Bar geometry patterned onto a TMD flake. (right) The flake around the bar is etched away using Ar ion milling. The region under the bar is protected by a hard SiO_2 mask.

ferromagnetic resonance (ST-FMR) measurements [4,5] or second harmonic Hall measurements [6,7]. A hard mask of SiO_2 is used (CNF SC4500 even hour evaporator) to protect the active region of the device while the rest is etched out using Ar ion milling (Figure 2).

To protect the edges of the TMD/Py bilayer after ion milling, the sample is re-clamped by sputtering a thin conformal coating of SiO_2 (CNF AJA sputter deposition). A final round of e-beam lithography (CNF Zeiss Supra SEM, Nabity) is performed to make electrical contact with the defined bars. The SiO_2 mask in the contact region is removed using reactive-ion etching (RIE) with a CHF_3/Ar mixture (CNF Oxford 81 etcher). Finally, Ti/Pt (CNF AJA sputter deposition) contacts are sputter deposited through a lift-off process.

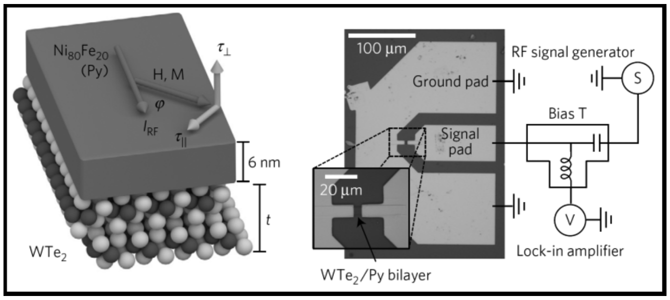

Figure 3: (left) Schematic of the heterostructure geometry [1] (right) Optical image of final device and schematic of the circuit used for ST-FMR measurements [1].

We use ST-FMR to measure the torques produced at room temperature [4,5]. As depicted in Figure 3, an RF current (8-12 GHz) is applied to the sample along with an in-plane magnetic field to tune the ferromagnet through resonance. The precessing magnetization gives rise to a changing anisotropic magnetoresistance (AMR), which mixes with the current leading to a DC signal V_{mix} that is measured (Figure 4). By analyzing the symmetric and antisymmetric components of the V_{mix} lineshape as a function of applied field, the various torque contributions can be computed [1].

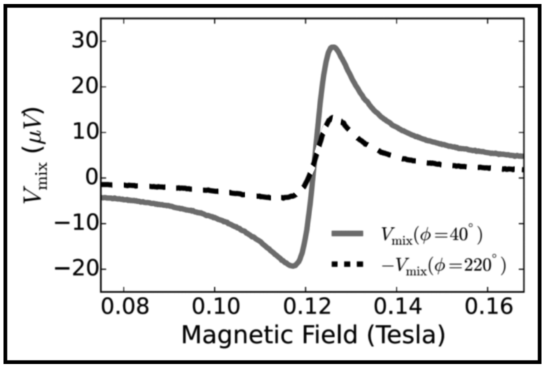

Figure 4: ST-FMR resonances for a TMD/Py sample with magnetization oriented at 40° and 220° relative to the current direction [1].

In conclusion we have provided a detailed discussion of the techniques employed in fabricating TMD/ferromagnet heterostructure devices and have presented spin-torque ferromagnetic resonance data that measures the S-O torques generated. TMDs allow for a systematic study of these torques as a function of various crystal symmetries and thicknesses [2]. These investigations provide important clues towards identifying the role of broken symmetries and bulk- vs. interface-driven mechanisms in the generation of spin-orbit torques.

References:

[1] MacNeill, D. et al., "Control of spin–orbit torques through crystal symmetry in WTe_2/ferromagnet bilayers," Nature Physics 13, 300 (2017).

[2] MacNeill, David, et al., "Thickness dependence of spin-orbit torques generated by WTe_2," Physical Review B 96, 054450 (2017).

[3] Wilson, J. A., and A. D. Yoffe, "The transition metal dichalcogenides discussion and interpretation of the observed optical, electrical and structural properties," Advances in Physics 18, 193 (1969).

[4] Liu, Luqiao, et al., "Spin-torque ferromagnetic resonance induced by the spin Hall effect," Physical Review Letters 106, 036601 (2011).

[5] Liu, Luqiao, et al., "Spin-torque switching with the giant spin Hall effect of tantalum," Science 336, 555 (2012).

[6] Hayashi, Masamitsu, et al., "Quantitative characterization of the spin-orbit torque using harmonic Hall voltage measurements," Physical Review B 89, 144425 (2014).

[7] Garello, Kevin, et al., "Symmetry and magnitude of spin–orbit torques in ferromagnetic heterostructures," Nature Nanotechnology 8, 587 (2013).