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Switching magnetization with a Weyl semimetal

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can be extracted with a resolution better than 7 nm.

This ultra-high speed, high spatial resolution approach is then applied to the study of surface-deposited silica nanospheres coated with a 15-nm shell of silver that was in turn homogeneously coated with dithionitrobenzoic acid. The recorded intensity fluctuations from the particles reveal prominent dynamic processes of the metal adatoms and clusters at the surface of the shells. An analogous large, but spatially sparse, signal enhancement has been observed in transient picometre-size cavities⁵. The origin of a large TERS signal has been assigned to the extreme localization of the electromagnetic field generated in the proximity of a small cluster of metal atoms located at the extremity of an AFM tip^{6,7}.

Lindquist et al. analyse the SERS intensity fluctuations over a full particle by dynamic evaluation of the average SERS activity. The characteristic 'ON' time, where the SERS signal is intense, has a typical duration of 70 μ s, but occurs for only 2% of the total recorded time; a hot spot with average intensity has a short phase of activity followed by long dark periods. Interestingly, fluctuations recorded at different wavelengths within the plasmon resonance do not always show temporal correlation but have similar

on and off statistics. This highlights the inhomogeneous response of the hot spots, which are not driven by a specific plasmon resonance but rather by the corrugated surface of the particles. Moreover, the rate of fluctuations is increased under higher irradiances, indicating a thermally driven mechanism of constant rearrangement of the surface structure at the atomic level. Altogether, the plastic nature of the hot spots, combined with a low molecular coverage, favours a mechanism where SERS activity is drastically enhanced because of the dynamic nature of the hot spot due to constant rearrangement of metal adatoms at surfaces. It is indeed the hot spots that find the analyte, rather than the molecular species that diffuse into the static hot spots.

A temporal gain of three orders of magnitude, as demonstrated by Lindquist et al., is a major step towards revealing intimate mechanisms that could not be visualized otherwise. Limitations in terms of spectral resolution could be improved in the future using high-resolution spectrographs, rather than bandpass filter-based spectral selection. This trick would enable better discrimination of the background fluctuations from the Raman signal. Application of the proposed approach to plasmon-mediated chemistry and

surface reactivity could reveal elemental chemical steps in hot-electron driven chemical surface reactions and nanoscale photopolymerization reactions at the surface of metallic structures^{8,9}. It will also help to better understand, and possibly exploit, temperature-dependent fluctuations to access single atom geometries in SERS and TERS experiments under ambient conditions¹⁰. □

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SPINTRONICS

Switching magnetization with a Weyl semimetal

Energy-efficient magnetization manipulation is a prerequisite for competitive spintronic devices. The Weyl semimetal WTe₂ can act as a spin current source that enables magnetization switching of an adjacent ferromagnet at low power consumption and additionally induces chiral magnetism.

Marcos H. D. Guimarães

Efficient control of magnetization using electrical currents is one of the key goals for the development of novel magnetic devices for memory and computation. One promising direction that could provide fast and non-volatile magnetic memory devices is the use of spin–orbit interaction to produce the magnetic torques necessary to manipulate magnetic bits. For this we require materials that can generate a large spin current J_s for a given charge current J_c (Fig. 1). Writing

in *Nature Nanotechnology*, Shuyuan Shi and colleagues now show that devices based on the layered van der Waals material WTe₂ coupled with a ferromagnetic layer (permalloy, Py) can show low threshold currents for magnetization switching, indicating a large J_s/J_c ratio in their devices¹.

WTe₂ is a material with very peculiar properties, showing superconductivity², ferroelectricity³ and strong indications of being a type-II Weyl semimetal⁴. One of the reasons that make WTe₂ interesting for

spintronics is its large spin–orbit interaction combined with a non-trivial band structure. This leads to a strong coupling between the electron's momentum and its spin. Moreover, its layered structure provides an atomically flat surface and an excellent interface to the ferromagnet. Shi et al. use these properties to their advantage and demonstrate current-driven magnetization switching of an in-plane ferromagnet using very low current densities, around 2×10^5 A cm⁻². For comparison, the widely-used

Fig. 1 | Charge-to-spin current conversion for spin-orbit torques. An electric current (J_c) induces a spin current (J_s) in a direction perpendicular to both J_c and the spin direction. The spin current can then be used to apply a torque on the magnetization of an interfaced ferromagnet.

heavy metal/ferromagnet bilayer Pt/Py shows switching at current densities in the order of 10^7 A cm^{-2} .

But what is the mechanism behind such large spin torques in WTe_2/Py devices? The authors performed a thickness-dependence study of the critical current densities and high-frequency measurements to obtain the J_s/J_c ratio in their samples. With an increase in WTe_2 thickness they observe an increase in the J_s/J_c ratio and a reduction of the current densities necessary for magnetization switching. This indicates a bulk origin of the torque. One likely mechanism is the spin Hall effect, where electrons get deflected towards a direction orthogonal to both the charge current and the electron's spin (Fig. 1). Devices based on Pt/Py show spin Hall efficiencies around 10%, that is, $J_s/J_c \sim 0.1$, while the WTe_2/Py devices used in this study seem to show efficiencies above 20%. The authors also show that the magnetization switching is even more efficient if the charge current flows along a specific crystallographic

direction. This generates an unusual type of spin-orbit torque made possible by the low symmetry of the WTe_2 crystal⁵.

One question that remains is the exact value for the spin Hall efficiencies in thick WTe_2/Py devices. The values estimated by the magnetization switching experiments are very sensitive to the mechanism of the switching itself. Moreover, the values extracted using the high-frequency measurements were strongly dependent on the frequency used. This is likely caused by a skin effect of the RF currents, where most of the high-frequency current flows close to the surface of the WTe_2 crystal. This ambiguity calls for further experiments that measure the spin torques directly using, for example, low frequency currents and the magneto-optical Kerr effect to read the magnetization direction. Another open question is how efficient WTe_2 would be for switching of ferromagnets that are aligned in the out-of-plane direction. This is the geometry used in present magnetic devices because bits can be densely packed together as compared to in-plane magnetized bits. Efficient out-of-plane switching would make WTe_2 significantly more attractive for real-world applications.

In addition to the very efficient manipulation of magnetization, the WTe_2/Py devices also host chiral magnetic domain walls. These structures arise because of a strong Dzyaloshinskii–Moriya interaction (DMI) at the WTe_2/Py interface. They could be further explored in the field of topological magnetism, for example, for the stabilization of magnetic skyrmions⁶. The DMI strength of around -1.8 mJ m^{-2} determined by Shi and coworkers is in the range of the ones determined for more conventional Pt/Py devices.

While the strong DMI still asks for confirmation in other devices, future research should also look for skyrmions in bilayers of WTe_2 and ferromagnets. New concepts of magnetic memory, such as race-track memory, build on topological magnetic structures like domain walls or skyrmions⁶. These require high quality devices with strong DMI. The large spin-orbit coupling of WTe_2 seems to provide an ideal platform for hosting these structures. Its smooth surface should further allow for the growth of ferromagnets with a low number of pinning

sites, which is another requirement for fast movement of skyrmions and domain walls.

And this work could also add a new flavour to van der Waals heterostructures and their application in devices. The combination of materials with a plethora of properties and atomically flat, crystalline and clean interfaces make layered materials a wonderful playground for spintronics. Yet, it is still an open question how the various properties of WTe_2 such as superconductivity and ferroelectricity could be explored for spintronic devices with hybrid functionality or if larger or gate-controlled spin-orbit torque efficiencies can be achieved. The recently discovered atomically-thin ferromagnets⁷ give further boost to this field. In future, they will allow for the fabrication of more complex spintronic devices composed solely of two-dimensional materials with high interface quality and likely very efficient spin torques. And there is one unique degree of freedom in van der Waals heterostructures; the rotation angle between different layers can be precisely controlled during the fabrication process. The manipulation of this twist angle has allowed for the observation of interlayer excitons in two-dimensional semiconductors⁸ and superconductivity in twisted graphene layers⁹. It should provide an extra tuning knob for spintronic devices, for example, to stabilize skyrmions lattices through a Moiré pattern induced by a twist angle between two van der Waals layers¹⁰. □

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