Electrical control goes to topological antiferromagnets

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Received May 8, 2020; accepted June 1, 2020; published online July 24, 2020

Citation: C. Song, Electrical control goes to topological antiferromagnets, *Sci. China-Phys. Mech. Astron.* **63**, 117531 (2020), <https://doi.org/10.1007/s11433-020-1588-5>

Ferromagnets play an important role in our daily lives, in such common devices as: compasses, electric motors and hard disks. For a long time, the antiferromagnetic (AFM) materials have been ignored for the applications. Even the Nobel laureate L. Néel said that antiferromagnets are interesting, but useless¹⁾. This perception changed in the 1990s, when AFM alloy was used as an exchange-coupling layer to pin ferromagnetic electrodes in magnetic tunnel junctions, which are the main components of read head and nonvolatile magnetic random access memories. It should be noted that the antiferromagnet here is still a supporting material, with its spin structure remaining almost unchanged during device operation.

Compared with ferromagnets, antiferromagnets with zero net magnetic moment have huge potential for ultrahigh-density information storage because of their ultrafast spin dynamics, vanishingly small stray field, and strong anti-interference. In 2011, Park et al. [1] developed an AFM tunnel junction, in which the partial rotation of the AFM moments in IrMn is driven by the adjacent ferromagnetic layer. Later, this behavior was extended from around 100 K to room temperature [2]. Note that electrical control is at the heart of this device application. Initially, electric field was employed to modulate the AFM moments with low power consumption [3]; later, current-induced spin-orbit torque (SOT) switching was realized in crystals with sublattice symmetry breaking, such as CuMnAs and Mn₂Au, wherein

the current-induced field-like torque drives 90° rotation of the AFM moments [4]. In heavy metal/antiferromagnetic bilayers, the AFM moments can be switched by the anti-damping torque, to a direction parallel with the current [5]. Combined electrical methods using both electric fields and currents have also been used to switch AFM moments [6]. These methods have promising properties for information storage by antiferromagnets. However, one serious problem is that the readout signals of these devices, which are based on anisotropic magnetoresistance or spin Hall magnetoresistance are very small, generally lower than 1%. Thus there is a pressing need to develop different AFM materials and a novel switching scheme.

Very recently, the Nakatsuji's group [7] at the University of Tokyo reported electrical control of a topological AFM state in Mn₃Sn, which showed inverse triangular non-collinear 120° spin structures with Mn moments in a Kagome plane. An adjacent pair of the Kagome planes (a Kagome bilayer) is called magnetic octupole. The non-collinear antiferromagnet Mn₃Sn with a Néel temperature of ~420 K is a fascinating topological Weyl semimetal with a large anomalous Hall effect (AHE), anomalous Nernst effect, magneto-optical Kerr effect, and magnetic spin Hall effect [8]. These interesting phenomena are based on the orientation rotation of a magnetic octupole manipulated by the magnetic field (or its component) applied along the {2 $\bar{1}\bar{1}$ 0} axes within the Kagome plane. In heavy metal/Mn₃Sn (heavy metal=Pt, W)

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1) L. Néel, <https://www.nobelprize.org/prizes/physics/1970/neel/lecture/>

bilayers, it has been observed that a current density of 10^{10} - 10^{11} A m⁻² induces magnetic switching, e.g., the orientation rotation of the magnetic octupole, as shown in Figure 1. This was monitored by the zero-field AHE-related Hall voltage.

A combination of current direction, assistant magnetic field direction, and the spin Hall angle of the heavy metal determines the sign of the Hall voltage. There are several critical points for the deterministic SOT switching in Mn₃Sn: 1) The Kagome plane is both perpendicular to the film plane and the applied current direction (for which specific crystal grain configurations of the polycrystalline or (11 $\bar{2}$ 0)-oriented Mn₃Sn films are required [9]), in contrast to the absent or indeterminate SOT switching when the Kagome plane is located at other positions; 2) the assistant magnetic field is applied along the current direction; 3) the current first causes the magnetic octupole to rotate by $\pi/6$ to the state with an angle of $\varphi=0^\circ\pm\delta$, the sign of which is determined by the polarity of the assistant field. When the current is shut down, it further rotates another $\pi/6$, and the final state is determined by the directions of the assistant field and current. This generates a total of $\pi/3$ switching from easy axis to another $\{2\bar{1}\bar{1}0\}$ (Figure 1), accompanied by Hall voltage variation. Thus, SOT switching in Mn₃Sn offers a promising avenue for AFM spintronics with a robust readout signal.

Nakatsuji's other important contribution is relevant to the topological antiferromagnetic feature of Mn₃Sn-hosted magnetic Weyl fermions, in which the Weyl nodes act as

topologically protected, unit-strength monopoles of the underlying Berry curvature [10]. The SOT-induced AFM structure rotation is associated with control of the nodal direction, which connects a pair of Weyl points via magnetic octupole polarization [7]. This is the first work to show electrical switching of Weyl semimetals, both ferromagnetic and antiferromagnetic. Hence, this work builds a bridge between AFM spintronics and topological magnetism. The tuning of the electronic structure by AFM structure switching has great potential for enhancing the performance of AFM spintronics, and its marriage with topological system seems to have a promising future.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 51671110, and 51871130).

Figure 1 (Color online) Schematic of the current-induced rotation of an Mn₃Sn magnetic octupole in Pt/Mn₃Sn bilayers.

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