Uniform magnetic structure revealed by X-ray magnetic circular dichroism and spin-torque diode effect in Mn_3Sn/W epitaxial bilayers

To advance beyond the modern electronics, there has been growing interest in spintronics, which leverages both the charge and spin degrees of freedom of electrons. Spintronics primarily focuses on ferromagnets, as they exhibit strong electrical responses to changes in magnetization direction. Recently, antiferromagnets systems have attracted significant attention due to their potential to operate at much faster frequencies than ferromagnets, although their weak electrical response poses substantial challenges for practical application.

Mn_3Sn is an antiferromagnet with an inverse triangular spin structure on the Mn Kagome lattice (Figs. 1(a) and 1(b)). This spin structure breaks macroscopic time-reversal symmetry and can be characterized by octupole polarization. Consequently, Mn_3Sn exhibits strong ferromagnet-like responses, such as the anomalous Hall effect [1] despite its negligible magnetization. Recent advancements in the epitaxial growth of W/Mn_3Sn bilayers have enabled electrical control of its spin structure [2] through spin-torque arising from the spin Hall effect of W. This development makes the material system a compelling building block for spintronics based on antiferromagnets. However, it remained unclear whether the observed spin-torque-induced phenomena are intrinsic to the W/Mn_3Sn interface or are influenced by the inclusion of ferromagnetic second phases.

To address this issue, we performed X-ray magnetic circular dichroism (XMCD) measurements. XMCD is a powerful method for studying ferromagnetic materials; however we recently demonstrated that XMCD can also probe the inverse triangular spin structure via the magnetic dipole term [3]. In this study [4], we utilized both surface-sensitive total electron yield (TEY) mode and bulk-sensitive partial fluorescence yield (PFY) mode to investigate the uniformity of the antiferromagnetic spin structure or octupole polarization in a W/Mn_3Sn/MgO multilayer, from the bottom to top interfaces.

We grew an epitaxial Mn_3Sn thin film using molecular beam epitaxy. The multilayer structure consists of an MgO(110) substrate/W (7 nm)/Mn_3Sn (30 nm)/MgO (3 nm). Figure 1(c) illustrates the experimental setup. The XMCD measurements were conducted at SPring-8 **BL25SU**. The measurement temperature was room temperature. We employed both TEY and PFY modes, which have probing depths of about a few nm and 100 nm, respectively. Thus, the TEY mode probes surface regions, while the PFY mode probes the entire 30-nm-thick Mn_3Sn layer.

Figure 2(a) shows the Mn L_3-edge XMCD spectra recorded using TEY and PFY modes at a magnetic field of 50 mT. Prior to applying 50 mT, a magnetic field of 1.9 T was applied to saturate the octupole polarization. Both spectra exhibit a distinct positive peak at 638.7 eV, characteristic of the inverse triangular spin structure [3]. Notably, the TEY and PFY spectra appear almost identical, indicating uniformity in both the electronic and magnetic structures from the bottom W/Mn_3Sn interface and top Mn_3Sn/MgO interface. Furthermore, the results confirm the absence of unwanted ferromagnetic secondary phases, such as ferromagnetic W-Mn-Sn intermetallic compounds, at the W/Mn_3Sn interface.

Figure 2(b) shows the TEY and PFY XMCD hysteresis loops measured at a photon energy of 638.7 eV, corresponding to the positive XMCD peak, as indicated by vertical line in Fig. 2(a). The coercive fields, approximately 150 mT, are consistent between the TEY and PFY hysteresis loops and align with values reported in a previous study [2]. The PFY XMCD signals exhibit a slight increase as the magnetic field approaches zero from higher values. This suggests that the octupole polarization changes its direction from the magnetic field direction to the surface normal direction, which is parallel to the X-ray incidence direction, due to the perpendicular magnetic anisotropy induced by tensile epitaxial strain [2].

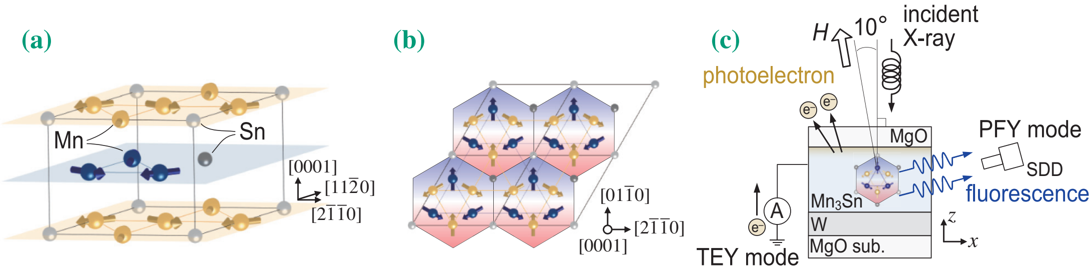

Fig. 1. **(a)** and **(b)** Crystal structure of $D0_{19}$-Mn_3Sn. **(c)** Experimental setup.

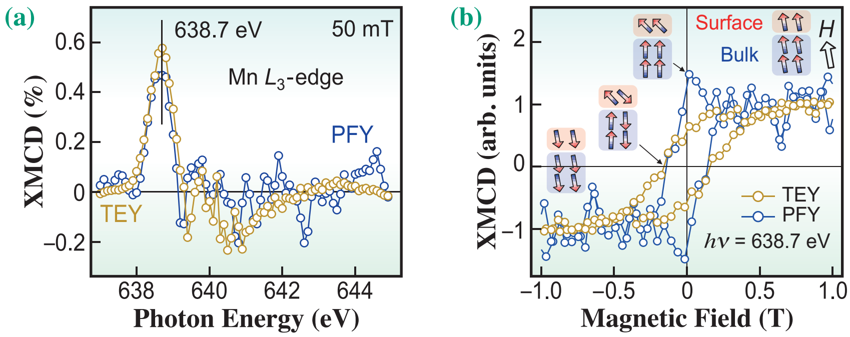

Fig. 2. **(a)** Mn L_3-edge TEY and PFY XMCD spectra. **(b)** TEY and PFY XMCD hysteresis loops. Schematic images along the hysteresis represent the inferred octupole polarization in the surface and bulk regions.

In contrast, the TEY hysteresis curve exhibits the opposite behavior, decreasing as the magnetic field approaches zero from higher values. Therefore, we infer that the perpendicular uniaxial magnetic anisotropy diminishes only near the MgO interface, possibly due to relaxed strain or the influence from the MgO interface, thereby tilting the octupole polarization away from the surface normal. The identical coercive fields observed in both the TEY and PFY hysteresis loops eliminate the possibility of other magnetic inclusions and suggest a finite magnetic coupling between the surface and bulk regions. The magnetization process described above is illustrated in the insets of Fig. 2(b).

The present findings suggest that the recently observed spin-torque-related phenomena [2], which occur at the W/Mn_3Sn interfaces, are intrinsic and arise from the interplay between the spin current and the octupole polarization. Having established this intrinsic nature, we investigated microwave spin-torque-induced phenomena in this W/Mn_3Sn bilayer system [5]. Figure 3(a) depicts the experimental setup, where both DC and microwave current were applied. DC and microwave currents inject DC and microwave spin currents into the Mn_3Sn layer via the spin Hall effect of W. Resultant DC Hall voltages were detected using a lock-in amplifier. Figure 3(b) shows observed DC Hall voltages measured with various DC bias currents and a microwave current of 5 GHz and 13 mW. Distinct peaks were observed when the DC current exceeded 30 mA, which is the threshold current to drive octupole dynamics.

Such conversion of a microwave current to a DC voltage via spin current is known as spin-torque diode effect in ferromagnets, which is considered promising for the development of sensitive microwave detectors. Our observation of the spin-torque diode effect in an antiferromagnet exploits antiferromagnetic exchange interaction and potentially expands the horizon of this effect to much higher frequencies and greater sensitivity [5].

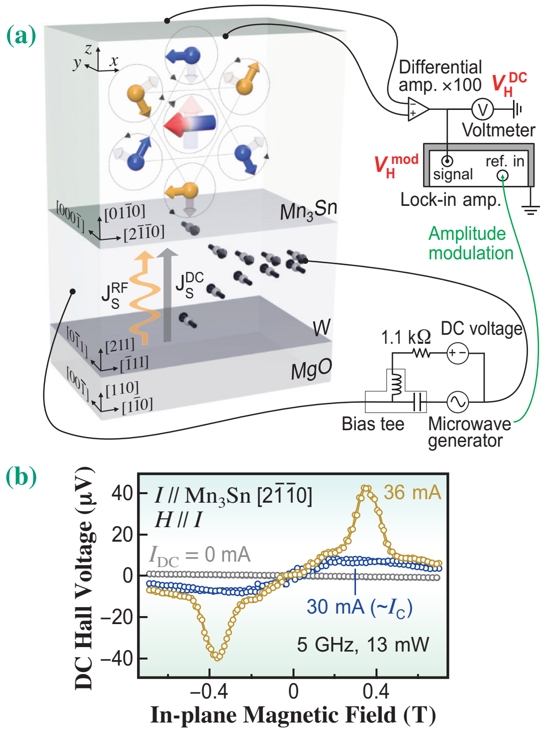

Fig. 3. **(a)** Experimental setup for spin-torque diode effect. **(b)** Observed diode signals.

Shoya Sakamoto*,† and Shinji Miwa

The Institute for Solid State Physics, The University of Tokyo

*Email: shoya.sakamoto.e1@tohoku.ac.jp

† Present address: Institute for Materials Research, Tohoku University

References

[1] S. Nakatsuji *et al.*: Nature **527** (2015) 212.
[2] T. Higo *et al.*: Nature **607** (2022) 474.
[3] S. Sakamoto *et al.*: Phys. Rev. B **104** (2021) 134431.
[4] *S. Sakamoto, T. Higo, Y. Kotani, H. Kosaki, T. Nakamura, S. Nakatsuji and S. Miwa: Phys. Rev. B **110** (2024) L060412. (Editors' suggestion)*
[5] S. Sakamoto *et al.*: Nat. Nanotechnol. **20** (2025) 216.