How Does Antiferromagnetism Drive the Magnetization of a Ferromagnet to Align Out of Plane?

This report features the work of Bo-Yao Wang, Minn-Tsong Lin, and their co-workers published in Phys. Rev. Lett. ***110****,117203 (2013).*

An antiferromagnet, which is a magnetic material with a compensated magnetic structure and an insensitivity to a magnetic field, was ignored for a long time in history. The revival of research interest began when it was placed next to a ferromagnet; the induced exchange bias field (i.e. a horizontal shift of the magnetic hysteresis loop) or coercivity enhancement became applicable to the design of a magneto-logic device, such as a spin valve, to pin the magnetization of a magnetic reference layer. In 2013, a research team of Minn-Tsong Lin from National Taiwan University Department of Physics, revealed a new aspect of antiferromagnetism. They report that the so-called "unpinned" moments of an antiferromagnet, located generally at an interface with a ferromagnet, can establish a perpendicular magnetization of an adjacent ferromagnetic (FM) layer.

According to their recent reports,[1-3] this team demonstrated that the magnetization direction of a FM layer (such as Fe or Permalloy) can be altered from its intrinsic in-plane direction to the out-of-plane direction via a coupling effect from an antiferromagnetic (AFM) fcc-Mn ultrathin film,[1] but the microscopic origin was unclear. To unmask the important physics behind this phenomenon, that team performed advanced research in applying element-specific techniques in NSRRC, including an X-ray photoemission electron microscope (X-PEEM) at **BL05B2** and X-ray magnetic circular dichroism (XMCD) at **BL11A1**. In their work, the conditions of samples were carefully controlled. The magnetic ultrathin films were prepared *in situ* in a NTU-NSRRC UHV chamber for preparation of nanomagnetism with base pressure 2 x 10^{-10} Torr. The ultrathin Fe/Mn films were deposited on a $Cu_3Au(001)$ single crystal near 23 °C; the rates of growth were monitored with electron diffraction at medium energy. The structure of the films was characterized with measurements of low-energy electron diffraction (LEED) and LEED I-V. To avoid contamination from the reactive gases in air, the research team performed measurements *in situ* of the X-PEEM and XMCD immediately after preparation of a sample, transferred directly either in vacuum or via a small mobile UHV chamber.

According to research of the past few years, magnetic moments of two types are known to be present in an antiferromagnet of a FM/AFM bilayer: one involves so-called "unpinned" moments of antiferromagnet, typically located at an interface with a ferromagnet and found to be correlated with the phenomenon of induced coercivity enhancement in a FM/AFM bilayer; the other type, namely the uncompensated "pinned" moments, might be present at a region deeper below the interface, and is found to be responsible for the phenomenon of an induced exchange bias field. According to the work of this research team, shown in Fig. 1, the induced perpendicular magnetization is likely to be correlated with the unpinned moments of an antiferromagnet rather than with uncompensated "pinned" moments, because the perpendicular magnetization can be established even without an exchange bias field.

As shown in Figs. 2(a) and 2(b), the unpinned moments of Mn element in Fe/Mn bilayer are detected with either X-PEEM or XMCD. As displayed in Fig. 2(b), the "unpinned" property of Mn moments is characterized by its magnetization that flips with an applied magnetic field. According to prior work, the perpendicular magnetization of a magnetic thin film is commonly given by the crystalline anisotropy originating from the symmetry breaking of the orbital moment. For a magnetic system with a strong perpendicular (uniaxial) crystalline anisotropy, the magnitude of the crystalline anisotropy is linked with the ratio of the orbital to spin moments, m_o/m_s, in the magnetic easy direction, and is roughly proportional to the enhanced value of the perpendicular coercivity. In the present work, a proportional relation between ratio m_o/m_s and the induced perpendicular coercivity thus became a fingerprint to clarify the origin of the perpendicular magnetization established in the FM/Mn bilayer.

Figures 3(a) and 3(b) show curves representing Mn and Fe $L_{3,2}$-edge XMCD of a 6 ML Fe/8 ML Mn bilayer measured at 141 and 199 K, respectively. Ratio m_o/m_s of the Mn unpinned moments at various temperatures is displayed in Fig. 3(c). A significant enhancement of that ratio with decreasing temperature indicates an establishment of a perpendicular crystalline anisotropy for the Mn unpinned moments. Within the same temperature range, the ratio for the Fe moments (Fig. 3(d)) remains, however, nearly constant. This effect indicates the nearly invariant perpendicular crystalline anisotropy for the Fe layer, although its perpendicular magnetization is established. This work of the research team yields clear experimental evidence that the perpendicular magnetization in a Fe/Mn bilayer originates from the unpinned moments of the Mn layer at the interface. This work not only renews our knowledge about antiferromagnetism, apart from the well investigated phenomena of induced coercivity enhancement

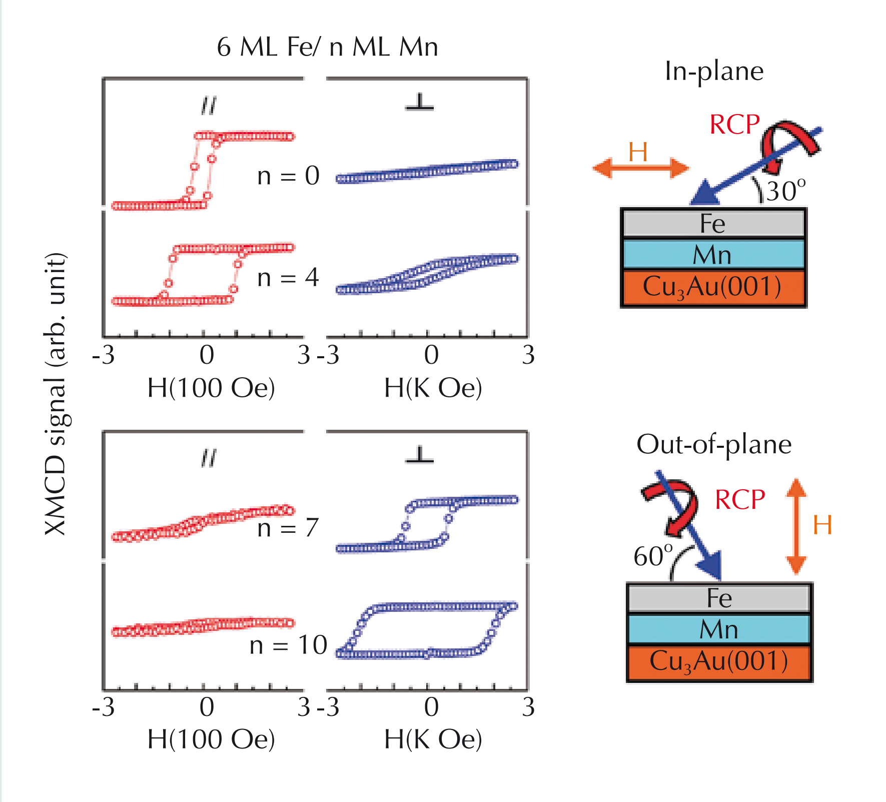

Fig. 1: Magnetic hysteresis loops of 6 ML Fe/n ML Mn measured by XMCD. (Reproduced from Ref. 4)

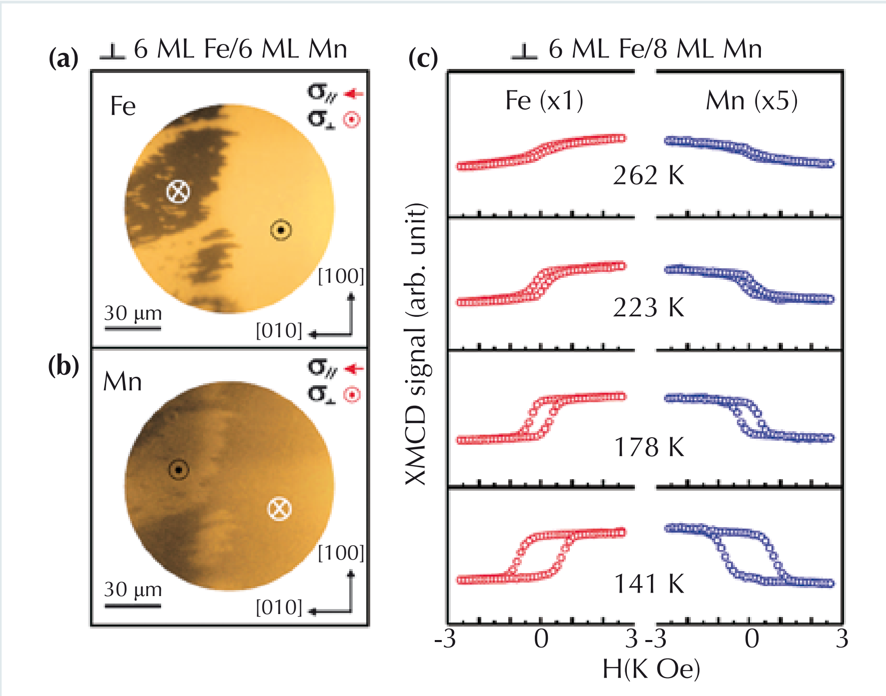

Fig. 2: (a) and (b): Magnetic domain images of Fe and Mn, respectively, measured with X-PEEM. (c): Fe and Mn magnetic hysteresis loops measured with XMCD at the indicated temperatures. (Reproduced from Ref. 4)

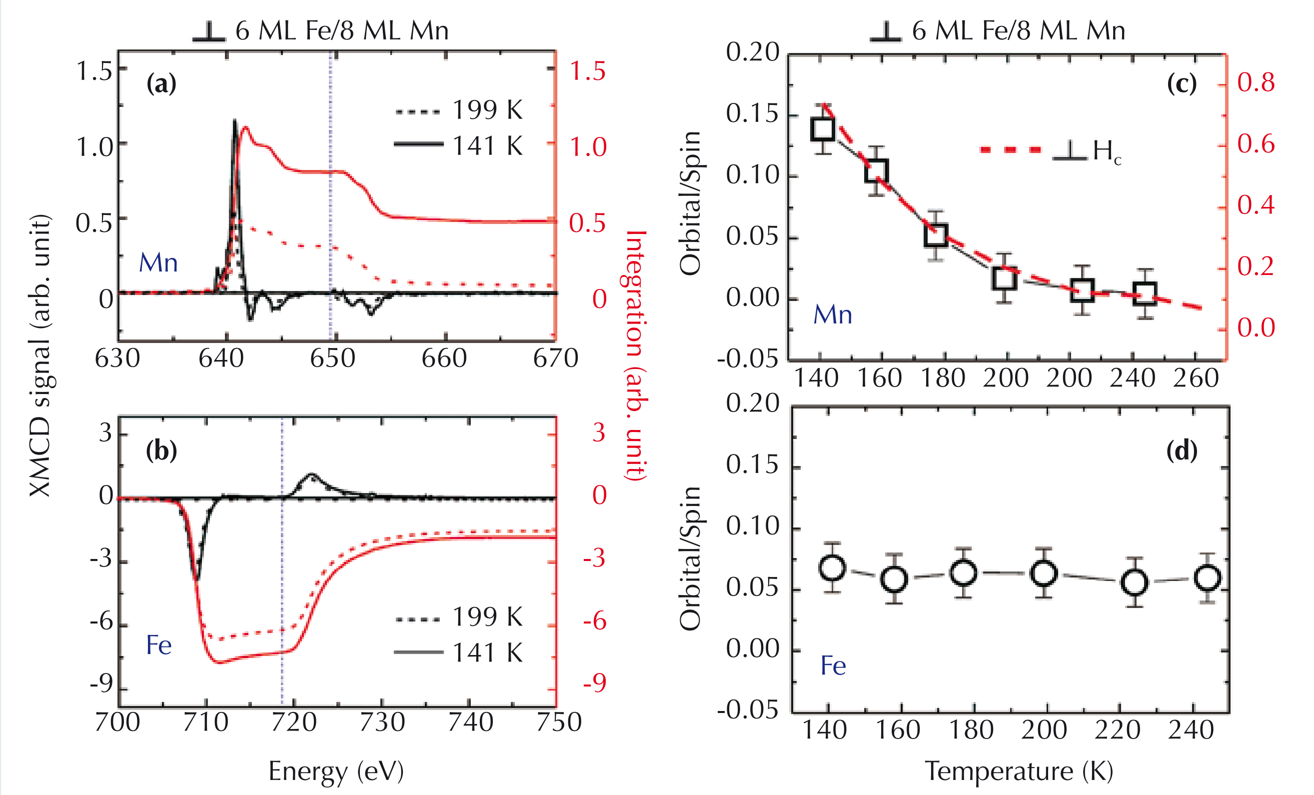

Fig. 3: (a) and (b): Curves represent Mn and Fe XMCD at 178 K and 199 K, respectively. (c) and (d): Ratio m_o/m_s of Mn and Fe moments, respectively, calculated from the XMCD curves; the red dashed line indicates H_c of a 6 ML Fe/8 ML Mn bilayer measured in the out-of-plane direction. (Reproduced from Ref. 4)

and exchange bias, but also indicates a new direction for the control of perpendicular magnetization in magnetic devices, which is the key to achieve a great recording density.

References

1. B.-Y. Wang, N.-Y. Jih, W.-C. Lin, C.-H. Chuang, P.-J. Hsu, C.-W. Peng, Y.-C. Yeh, Y.-L. Chan, W.-C. Chiang, D.-H. Wei, and M.-T. Lin, Phys. Rev. B **83**, 104417 (2011).
2. N.-Y. Jih, B.-Y. Wang, Y.-L. Chan, D.-H. Wei, and M.-T. Lin, Appl. Phys. Express **5**, 063008 (2012).
3. B.-Y. Wang, C.-C. Chiu, W.-C. Lin, and M.-T. Lin, Appl. Phys. Lett. **103**, 042407 (2013).
4. B.-Y. Wang, J.-Y. Hong, K.-H. Ou Yang, Y.-L. Chan, D.-H. Wei, H.-J. Lin, and M.-T. Lin, Phys. Rev. Lett. **110**, 117203 (2013).

Hydrogen Powers the Future

*This report features the work of Hao Ming Chen and his co-workers published in Small **9**, 2926 (2013).*

Hydrogen is regarded as a clean fuel because its only byproduct is water. The drawback is, however, that to generate hydrogen via water splitting requires the traditional fossil fuels. Splitting water in photoelectrochemical cells (PEC) with solar energy as fuel has therefore become an ultimate goal of sustainable energy. The impediment appears to be a lack of high-performance PEC electrodes. By recording X-ray absorption spectra at **BL01C1** of the TLS, researchers from National Taiwan University, Academia Sinica