Contamination-free Ferromagnet/Two-dimensional Transition-metal Dichalcogenide Interface with Perpendicular Magnetic Anisotropy

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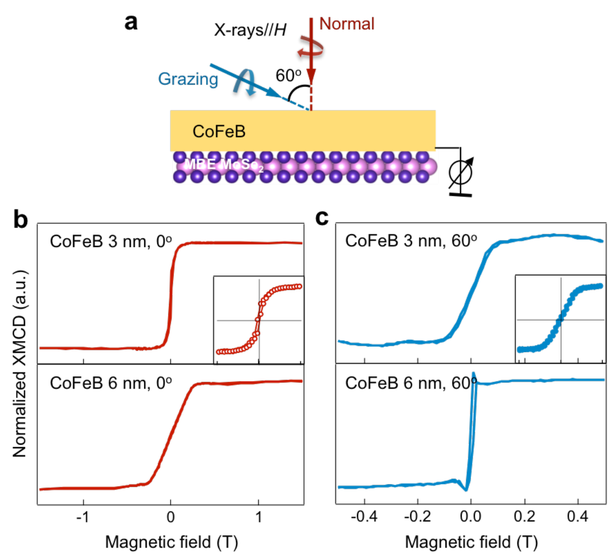
Ferromagnet/two-dimensional transition-metal dichalcogenide (FM/2D TMD) interfaces provide attractive opportunities to push magnetic information storage to the atomically thin limit. Existing work has focused on FMs contacted with mechanically exfoliated or chemically-vapor-deposition-grown TMDs, where clean interfaces cannot be guaranteed. Here, we report a reliable way to achieve contamination-free interfaces between ferromagnetic CoFeB and molecular-beam epitaxial $MoSe_2$. We show a spin re-orientation arising from the interface, leading to a perpendicular magnetic anisotropy (PMA), and reveal the CoFeB/2D $MoSe_2$ interface allowing for the PMA development in a broader CoFeB thickness-range than common systems such as CoFeB/MgO. Using X-ray magnetic circular dichroism analysis, we attribute generation of this perpendicular anisotropy to interfacial *d-d* hybridization, and deduce a general rule to enhance its magnitude. We also demonstrate favorable magnetic softness and considerable magnetic moment preserved at the interface, highlighting the CoFeB/2D $MoSe_2$ interface as an outstanding contender for harnessing spin-related effects in gigabit applications such as spin transfer torque magnetic random access memories.

Spin reorientation obtained in CoFeB(3 nm)/$MoSe_2$.

a, Schematic diagram of the experimental geometry for the XMCD measurements, with the applied magnetic field along the X-ray incidence direction.
b-c, Angle-dependent hysteresis loops taken at normal (γ = 0°, red) and grazing (γ = 60°, blue) incidences, respectively. The two insets display the loops in the same field scale of ±0.2 T, indicating an easy axis pointing along the direction of the surface normal, in contrast to CoFeB(3 nm)/$MoSe_2$ where the preferred magnetization is in the film plane.

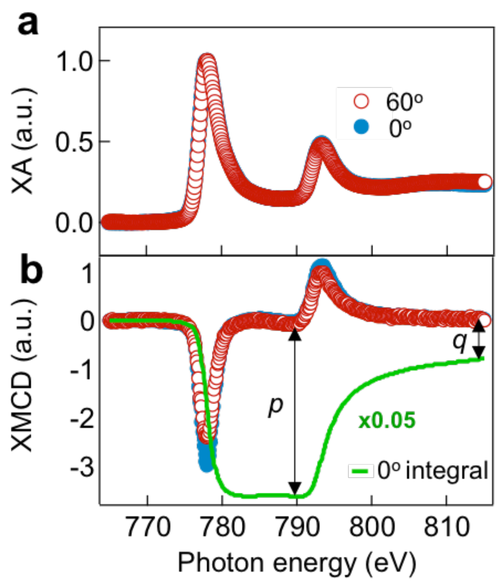


Comparable magnetic moment to those grown on metal or oxide buffer, topological insulator substrate, etc.

Total magnetic moments of Co and Fe extracted from Co and Fe $L_{2,3}$-edge XMCD show comparable magnetic moments to those grown on Ta, MgO or Bi_2Te_3, etc.[1].

CoFeB/2D-$MoSe_2$		CoFeeB(3 nm)	CoFeeB(6 nm)
$m_{L,Co} + m_{S,Co}$ (μ_B/hole)		0.39	0.61
$m_{L,Fe} + m_{S,Fe}$ (μ_B/hole)		0.45	0.71
References	CoFeB(1.7 nm) on Ta buffer	CoFeB(2 nm) on MgO buffer	CoFeB(5 nm) on Bi_2Te_3 buffer
$m_{L,Co} + m_{S,Co}$ (μ_B/hole)	~0.55	0.43	0.56
$m_{L,Fe} + m_{S,Fe}$ (μ_B/hole)	~0.57	0.60	0.51

[1] Ueno, T. *et al*. *Sci. Rep*. **2015**, *5*, 14858; Cui, B. *et al*. *J. Phys.: Condens. Matter* **2013**, *25*, 106003; Kaveev, A.K. *et al.* arXiv:1801.10061 [cond-mat.mtrl-sci].

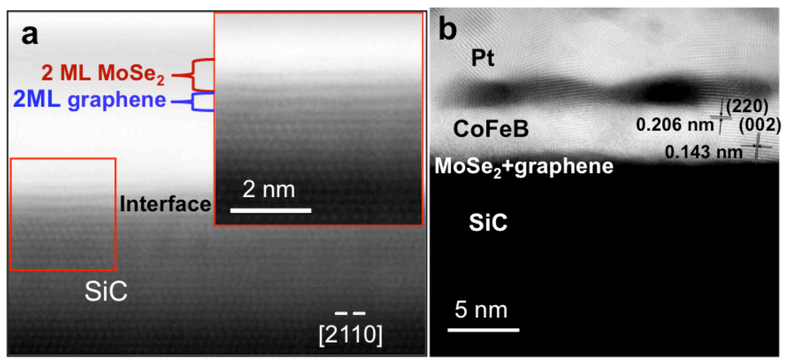


Spin reorientation caused by anisotropic orbital moment due to the orbital hybridization at the interface.

a, Clean XA and XMCD spectra taken at the Co $L_{2,3}$ edges, with no sign of multiplet structure, suggesting no intermixing or diffusion at the Pt/CoFeB or CoFeB/$MoSe_2$ interface.
b, The m_L/m_S ratios can be extracted from Co *L*-edge XMCD spectra. m_L/m_S = 1/(3-4.5p/q), where *p* and *q* are derived from the integrals of the dichroic signal, as marked by a green line. Obviously, the m_L/m_S ratio is larger in the normal geometry than in the grazing one, consistent with our observed magnetic anisotropy energy.

Epitaxial growth of $MoSe_2$ and clean interface of Pt/CoFeB/$MoSe_2$.

a, Cross-sectional high-resolution HAADF-STEM image of the $MoSe_2$/graphene interface taken along the [2-1-10] zone axis of SiC and a close up view of the interface (inset) showing the bilayer $MoSe_2$ and bilayer graphene at the interface.
b, Cross-sectional high-resolution HAADF-STEM image of the Pt/CoFeB/$MoSe_2$ interface showing *d*-spacing matching with (220) and (002) planes of bcc CoFeB.



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