Orbital-driven field-free switching in low-symmetry van der Waals heterostructures

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Abstract

The coupling between spin and orbital degrees of freedom enables electrical control of magnetism via orbital torques [1], offering a route to energy-efficient, field-free switching of perpendicular magnetic anisotropy (PMA). In conventional 2D spin–orbit torque (SOT) devices, deterministic PMA switching requires an external in-plane magnetic field, limiting scalability [2]. In contrast, low-symmetry quantum materials such as $1T_d$ transition-metal dichalcogenides and Weyl semimetals generate out-of-plane (OOP) spin and orbital densities, and unconventional OOP torques due to reduced mirror symmetries [3]. Both OOP field-like and damping-like torques have been observed experimentally, though their microscopic origin remains debated [4,5].

Here, we develop a microscopic model for orbital-driven, field-free magnetization switching in low-symmetry van der Waals heterostructures. Minimal tight-binding models of a $1T_d$ TMD–ferromagnet interface show that interfacial orbital hybridization transfers the TMD's reduced symmetry to the ferromagnet, generating OOP SOT components even when the ferromagnet is high-symmetry. The dominant mechanism is the orbital Rashba–Edelstein effect, where an in-plane electric field induces a nonequilibrium orbital polarization and effective torques. Theory and simulations predict field-free PMA reversal at current densities of ~5×10^7 A cm^{-2}, establishing an efficient orbital route for magnetization control.

References

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Figures

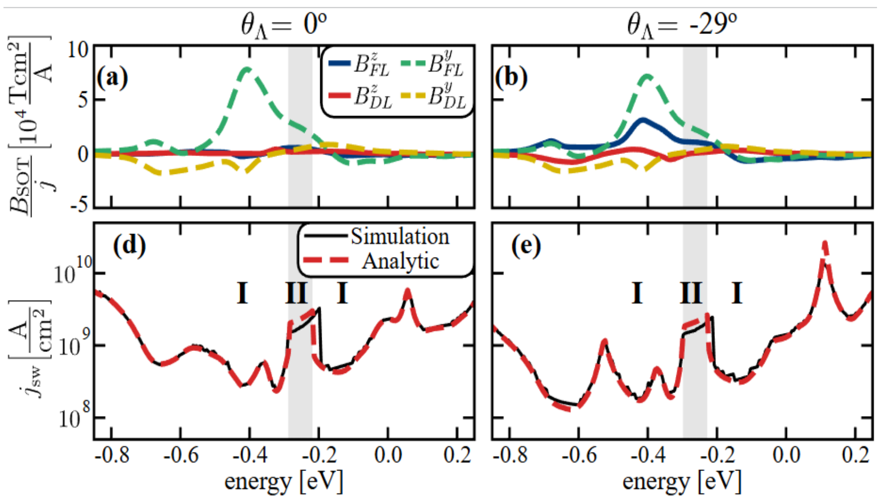

Figure 1: (a-b) SOT effective field linear response coefficients for the IP and OOP FL and DL torques, for the TMD SOC field angle. (d-e) Critical switching current computed by numerical simulation of the LLG equation (black solid curves) and by analytic calculations (dashed red curves), for their respective SOC field angles, respectively.