# Energy-Efficient Spintronic Devices for Memory and Computing by New Materials, New Physics and Voltage Control

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Spin-orbit torque (SOT) is a promising mechanism for next-generation magnetoresistive random-access memory (MRAM) and spin-based logic devices, offering advantages such as non-volatility and high endurance compared to traditional CMOS-based technologies. However, the limited energy efficiency of existing SOT materials and devices has posed a major barrier to widespread industrial adoption.

To address this challenge, we have proposed and experimentally demonstrated $Ni_4W$—for the first time—as a new, highly efficient unconventional SOT material [1]. Through symmetry analysis and material screening, we identified $Ni_4W$ as a unique low-symmetry alloy capable of generating spin polarizations along all X, Y, Z directions, as illustrated in the inset of Figure 1(a). To validate this, we fabricated epitaxial $Ni_4W$ thin films with high crystalline quality using industry-compatible magnetron sputtering. Harmonic Hall measurements revealed a large damping-like SOT efficiency of 0.73 for the Y-spin and a measurable Z-spin SOT efficiency of 0.02—both among the highest reported values for unconventional SOT materials to date. Moreover, we demonstrated efficient field-free magnetization switching of a perpendicular magnet using $Ni_4W$'s multi-directional spin components, as shown in Figure 1(b). The observed switching current density is 40% lower than that of Pt, a widely used benchmarking SOT material, highlighting $Ni_4W$'s significant advantage in power efficiency.

To further increase power efficiency, electric field effects such as voltage-controlled magnetic anisotropy (VCMA) and voltage-controlled exchange coupling (VCEC) have been systematically investigated. VCMA is a well-known solution for achieving low switching current by reducing the energy barrier of the ferromagnetic material through the application of an additional electric field. By applying electron depletion physics with a novel work-function-engineered underlayer, the VCMA coefficient can be further enhanced, as shown in Fig. 2(a) [2]. VCEC is a mechanism by which an applied voltage modulates both the direction and strength of interlayer magnetic exchange interactions. By integrating VCEC into a superparamagnetic magnetic tunnel junction (MTJ), we demonstrate device-level bipolar switching with an associated power consumption of only 40 nW, about two orders of magnitude lower than that of spin-transfer torque (STT) switching, as shown in Fig. 2(b) [3].

**References**

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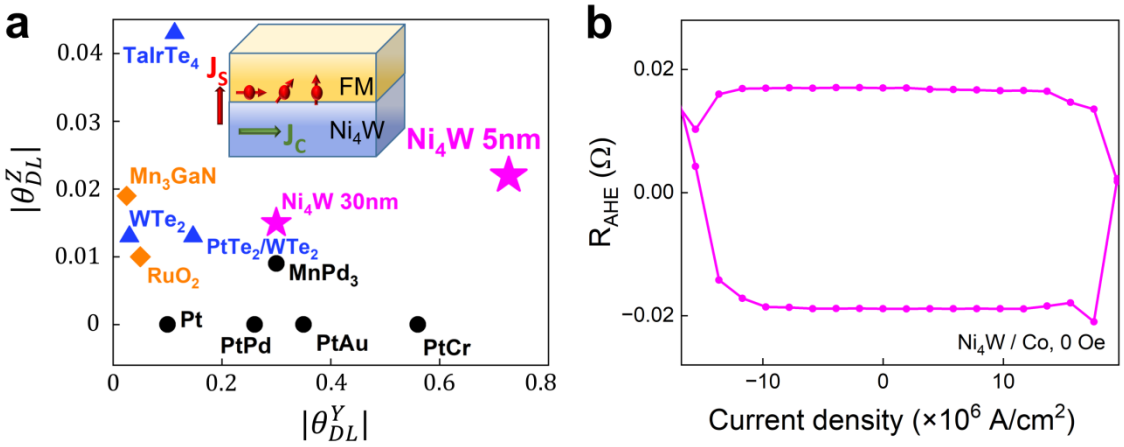


Figure 1. (a) Summary of conventional ($\theta_{DL}^{Y}$) and out-of-plane ($\theta_{DL}^{Z}$) SOT efficiencies of Ni4W and state-of-the-art SOT materials. (b) Field-free switching of Co single layer with perpendicular magnetic anisotropy at room temperature by the multi-directional spin components by Ni4W.

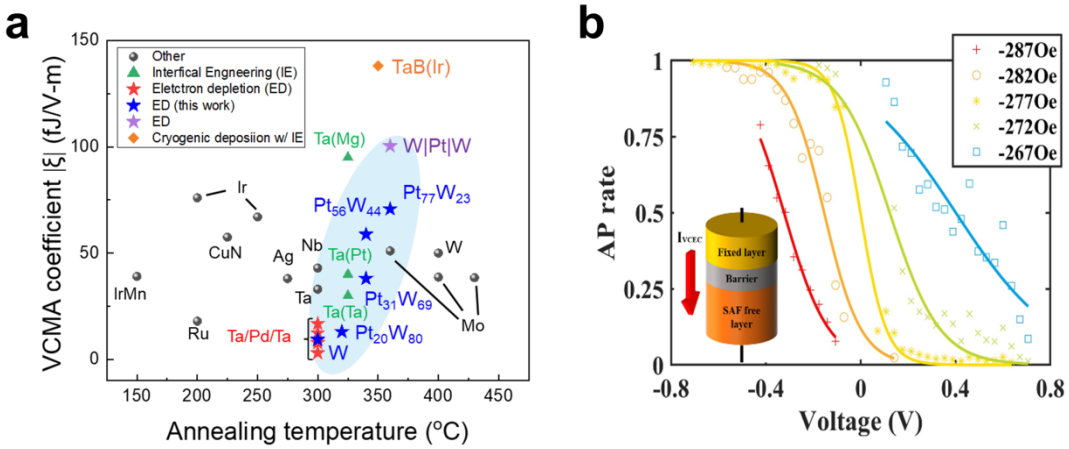


Figure 2. (a) Benchmarking of the VCMA coefficients in the PMA CoFeB/MgO system with various underlayer materials. (b) The antiparallel (AP) switching rate of the stochastic signal manipulated by VCEC. The inset illustrates the VCEC-integrated superparamagnetic MTJ (sMTJ) structure.