Energy-Efficient Spin-Orbit-Torque Devices for Memory and Computing by New Materials, New Physics and Voltage Control

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Energy-efficiency has long been the bottleneck for the implementation of spin-orbit torque (SOT)-based memory and computing devices. To address this, we have proposed and demonstrated Ni_4W as a novel and energy efficient SOT material. Epitaxial Ni_4W thin films were successfully grown using magnetron sputtering, yielding a high damping-like SOT efficiency of 0.73 and a Z-spin SOT efficiency of 0.02. Efficient field-free switching was demonstrated using the multi-directional spins [1]. To enhance the voltage-controlled magnetic anisotropy (VCMA), we have also proposed and demonstrated a tri-layer SOT stack structure through a working function engineering, inducing electron depletion in the PMA CoFeB/MgO system with a VCMA coefficient of -100.8 fJ/V-m [2]-[3]. Field-free switching with optimized performance was demonstrated. We have also demonstrated that voltage-controlled exchange coupling (VCEC) induces a directional exchange field that persists under nanosecond voltage pulses in a perpendicular magnetic tunnel junction (pMTJ). We will report a latest result that VCEC assisted by VCMA enables magnetization switching within 87.5 ps with 50% switching probability and 100 ps with 94% switching probability, respectively [4]. These advancements pave the way for next-generation spintronic applications.

Index Terms—**Magnetoresistive RAM, Spintronics, Spin-orbit torque, Voltage-controlled device**

I. Introduction

Spin-orbit torque (SOT) is a promising mechanism for the efficient manipulation of magnetization, offering lower power consumption, higher endurance, and faster switching speeds compared to the traditional spin-transfer torque (STT). However, challenges such as the high write current requirement and the need for field-free switching of magnets with perpendicular magnetic anisotropy (PMA) remain key limitations to broader adoption.

To address these challenges, several approaches have been proposed. Unconventional SOT materials have been discovered that intrinsically break symmetry and enable field-free switching [5]. These materials also exhibit significantly higher energy efficiency for switching PMA magnets compared to conventional sources such as heavy metals and topological insulators, owing to the generation of Z-polarized spin currents.

The electron-depletion voltage-controlled magnetic anisotropy (VCMA) effect presents another promising strategy to reduce energy consumption during SOT-induced switching. By integrating VCMA with field-free SOT mechanisms, highly efficient switching can be achieved. To further minimize power requirements, voltage-controlled exchange coupling (VCEC) is combined with VCMA, enabling ultrafast magnetization switching. In this study, we demonstrate switching within 87.5 ps with a 50% probability, highlighting the potential of this voltage-driven approach for energy-efficient spintronic applications.

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II. Unconventional SOT in Ni_4W

Although unconventional SOT materials present promising results for the spin source, the SOT efficiency of these materials is not ideal, typically below 0.1. Through a thorough search of the material database with over thousands of materials, we have first identified Ni_4W (211) as an unconventional SOT material that allows unconventional spins, as shown in the inset of Fig. 1. Symmetry analysis and density-functional theory were used to confirm the existence of X-, Y-, Z-spins, providing the theoretical support to our proposal. To experimentally demonstrate the properties, we have grown epitaxial thin films of Ni_4W (211), with outstanding crystalline quality. The full width at half maximum was below 0.1° for Ni_4W films with thicknesses ranging from 5 nm to 30 nm.

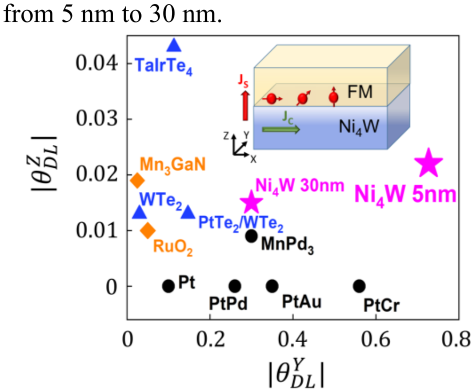

Fig. 1. Summary of SOT efficiencies of Ni_4W and other state-of-the-art materials. The inset shows the generation of spins along all X, Y, Z directions [1].

Second harmonic Hall measurements were used to characterize the SOT efficiency of Ni_4W. A large conventional

SOT efficiency (θ_{DL}^{Y}) of 0.3 was observed at room temperature in the bulk Ni_4W. Notably, a larger θ_{DL}^{Y} of 0.73 was found in W / Ni_4W(5 nm), which is attributed to additional interfacial or extrinsic effects. The unconventional Z-spin efficiency (θ_{DL}^{Z}) of 0.02 was also observed. The SOT efficiencies Ni_4W are among the largest compared to state-of-the-art materials, as summarized in Fig. 1. Field-free switching of a PMA magnet was demonstrated using the multi-directional spins of Ni_4W, and the switching current density is almost 40% less than Pt, which is a commonly used SOT material.

III. Electron-depletion-based VCMA enhancement

The limited efficiency of the VCMA coefficient remains a key challenge for practical implementation of the VCMA strategy in real-world applications. To overcome this limitation, first-principles calculations have predicted the intrinsic distribution of magnetic anisotropy energy (MAE) as a function of excess electron number [6]. An enhanced VCMA coefficient was observed with decreasing excess electron concentration at the Fe/MgO interface. Our previous study utilizing Ta/Pd/Ta underlayers indicated that a significantly higher underlayer work function is required due to the insufficient VCMA enhancement [7].

To experimentally reduce the excess electron density, high work function PtW and W/Pt/W underlayers were investigated in the PMA CoFeB/MgO system. As illustrated in Fig. 1(a), Pt has a work function of 5.7 eV, which is considerably higher than that of CoFeB (~4.6 eV). Under thermal equilibrium, electrons in CoFeB are more likely to transfer into the higher work function underlayers, as shown in Fig. 1(b). The anomalous Hall effect was employed to extract the VCMA coefficients under various gate bias conditions. As shown in Fig. 1(c), the VCMA coefficients for PtW and W/Pt/W samples are –70.7 and –100.8 fJ/(V·m), respectively. In addition, field-free spin–orbit torque (SOT) switching was demonstrated in the W/Pt/W trilayer structure, which features opposite spin Hall angles in its constituent layers.

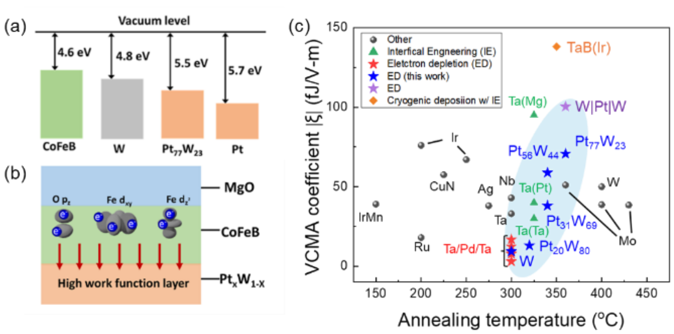

Fig.2.(a) Energy band diagrams of CoFeB with W, $Pt_{77}W_{23}$, and Pt underlayers under flat-band conditions. (b) Eectron depletion at the CoFeB/MgO interface in thermal equilibrium with high work function underlayers. (c) VCMA coefficients in CoFeB/MgO structures vs underlayers. [2,3]

IV. Combination of VCEC and VCMA

VCEC theoretically serves as a mechanism capable of achieving bipolar deterministic switching of a magnetically coupled layer [8]. This is realized by modulating spin scattering at the FM/NM/FM (ferromagnetic material / nonmagnetic material / ferromagnetic material) interface by introducing a boundary barrier [9]. The concept was subsequently integrated into MTJ structures, manifesting as a voltage-controlled analog of the traditional STT effect [9]. Notably, the associated critical current density is one to two orders of magnitude lower than that of conventional STT mechanisms [4],[9].

We examined the influence of voltage pulse width on the switching probability under a constant magnetic field. A pulse generator with a fixed 5 V output (~10 V across the MTJ) and sub-100 ps pulse capability was employed. After each pulse, the resistance was measured to confirm the switching event. This configuration achieved 50% switching probability within 87.5 ps (Fig. 3), accompanied by a 40 ps rise time, highlighting an exceptionally short incubation period [10].

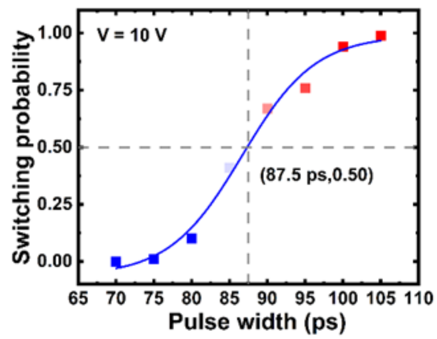

Fig. 3. The switching probability as a function of pulse width, measured under a constant 10 V pulse applied by a high-speed pulse generator capable of delivering sub-100 ps pulses, with each data point averaged over 100 trials [10].

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