Rare-Metal Spintronics: Ni_4W to $TaIrTe_4$/$NbIrTe_4$ Low-Symmetry Platforms for Deterministic MRAM

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Abstract: Spintronics is a fascinating field, rich in physics, that moves beyond charge control to store data. It harnesses the electron's spin to develop high-endurance, low-energy, low-latency non-volatile memories (NVMs). Out of various generation of MRAM and switching mechanism [1] as shown in figure 1, there are two major classes of magnetic random-access memory (MRAM) adopted by industry: spin-transfer torque (STT) and spin–orbit torque (SOT). STT-MRAM has historically suffered from limited endurance and higher bit-error rates because it uses the same path for reading and writing. In contrast, SOT-MRAM mitigates these issues by separating the read and write paths. In SOT-MRAM there is a heavy metal channel to generate spin orbit coupling (SOC), rare metal enabled SOT devices promise ultra-low energy, field-free magnetic switching for next-generation NVM and probabilistic/AI hardware.

My current work focuses on different low-symmetry heavy metals like Ni_4W, PtW (alloy) and low symmetry rare wely semi-metal chalcogenides like $TaIrTe_4$ and $NbIrTe_4$. Their high SOC, large work functions, and rich interfacial chemistry, helps to achieve deterministic switching of SOT-MRAM.

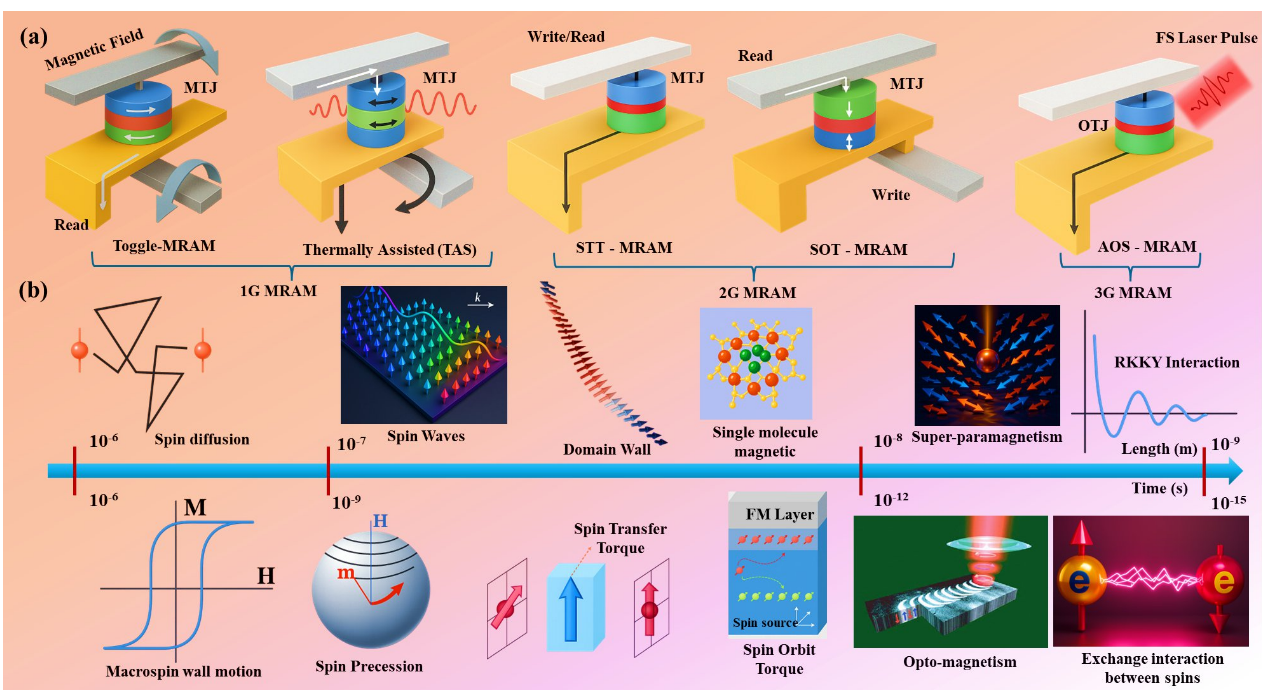


Figure 1: (a) Generational landscape of MRAM: toggle, STT, thermally assisted, SOT, and optically assisted architectures. (b) Corresponding dynamical regimes: fs–ps (ultrafast demagnetization, spin relaxation, coherent

precession), ps–ns (spin torques), ns–μs (domain-wall dynamics and STT), and beyond (thermal effects and magnetic retention) [1]. Disclaimer: This image is from one of my recent papers and you are allowed to use it in press releases.

Building on this, using industry compatible magnetron sputtering, we grew high-quality epitaxial Ni_4W thin films and reported high SOT efficiency of 0.73 this work recently being published by *Advanced Materials*. Extending this now we are targeting Fermi-level tuning in Ni_4W via tungsten stoichiometry control and cobalt doping in Ni4W to align the electronic states with peaks in spin Hall conductivity (SHC), thereby enhancing SOT efficiency and reducing critical current density. In parallel, I fabricate exfoliated $TaIrTe_4$ and $NbIrTe_4$ 2D flakes-based Hall-bar devices to exploit their intrinsic low symmetry for unconventional spin polarization and gate-controllable switching.

Article

Rare metals such as tungsten (W), tantalum (Ta), and niobium (Nb) highlight today's most promising spintronic based SOT-MRAM. When placed next to an ultrathin ferromagnet such as permalloy (Py) and CoFeB, these heavy elements convert charge current into transverse spin currents through strong SOC. The polarized injected spins can change the magnet's state; this is the fundamental of SOT memory. Compared with conventional CMOS based NVMs like NAND flash, SOT devices offer non-volatility, nanosecond-class writes, and ultralow energy per bit, making them attractive for cache-like MRAM, edge AI accelerators, and probabilistic in-memory computing.

Two main issues have limited wide deployment of SOT-MRAM: (1) the critical current density (J_c) required for fast switching, and (2) required external magnetic field to break symmetry in perpendicular magnetic anisotropy (PMA) devices. In this article, I will try to explain how Ni_4W and low symmetry weyl semimetals ($TaIrTe_4$ and $NbIrTe_4$), directly address aforementioned issues, and it outlines an experimental roadmap of several projects that I am currently working on. In the end, I will talk about how my research bridges and covers the entire spectrum of material science to device fabrication and its application in industry.

1) Ni_4W based SOT source with built-in symmetry breaking:

In our recent study as shown in figure 2 (featured on front page of *Advanced Materials Journal*) [2,3], we found that Ni_4W is a tungsten-rich intermetallic. Its low-symmetry crystal orientations support multi-directional spin accumulation, which enables field-free switching of perpendicular magnetic tunnel junctions (p-MTJs) when interfaced correctly. Practically, this means we can eliminate permanent magnets or external field coils, which is critical for area, reliability, and power.

Beyond symmetry, Ni_4W can deliver high SOT efficiency which is 0.73. The figure of merit, the effective spin Hall angle or damping-like torque efficiency, depends sensitively on the electronic states around the Fermi level (E_F). Peaks in the spin Berry curvature and "hot spots" in the band structure can amplify conversion from charge to spin.

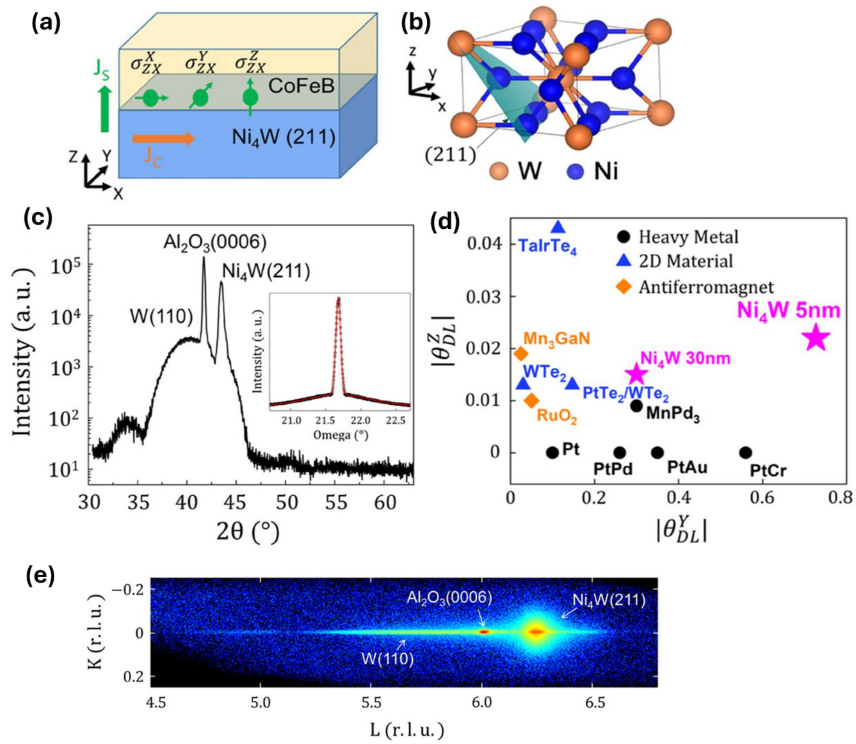


Figure 2: Schematic view of $Ni_4W(211)/CoFeB$, emphasizing spins oriented in several directions. (b) Structural representation of Ni_4W tetragonal crystal. (c) XRD θ–2θ scan for $Al_2O_3(0001)$/W (2 nm)/Ni4W (30 nm)/CoFeB (5 nm)/cap. *Inset:* rocking curve of the Ni4W(211) reflection (FWHM = 0.084°). (d) Comparison of Ni_4W conventional (in-plane) and out-of-plane spin Hall angles with leading SOT materials. (e) Reciprocal-space map of the same stack, plotted in sapphire coordinates [2]. Disclaimer: This image is from one of my recent papers and you are allowed to use it in press releases.

2) Fermi-level tuning with W stoichiometry and Co co-doping:

Currently, I am systematically tuning E_F in Ni_4W by hole doping adjusting the tungsten content and introducing light cobalt (Co) co-doping.

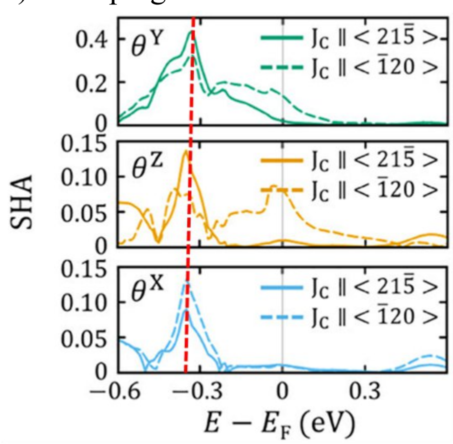


Figure 3: Spin Hall angles for $Ni_4W(211)$. Green, yellow, and blue trace θ_Y, θ_Z, and θ_X; solid vs dashed curves denote two orthogonal current directions. Here red dashed line shows to highest SHA that can be achieved for that specific fermi-level [2]. Disclaimer: This image is from one of my recent papers and you are allowed to use it in press releases.

As shown in figure 3, the goal is to align E_F with maximum in SHC (red dashed line), which should, (a) increase the damping-like torque efficiency (increasing the spin current delivered to the ferromagnet). (b) Lower J_c for nanosecond switching. (c) Preserve low resistivity and thermal stability needed for tight back-end-of-line (BEOL) integration. Like currently Globalfoundries has STT-MRAM on 22nm FDX and 28nm HKMG CMOS platform between M4-M5 metal line of BEOL.

3) My approach for Ni4W alloy and Co doped SOT study:

I deposit Ni_4W (211) on sapphire substrates using DC magnetron sputtering and target the orientations reported to maximize unconventional spin components. XRD/rocking-curve and reciprocal-space mapping ensure the desired texture, while AFM and TEM assess interface quality. Further, I perform UPS/XPS monitor work function and composition of Ni, W and Co in sputtered thin films. Then, I sputter a ferromagnetic layer like Py and CFB, for SOT measurement I do second-harmonic Hall and spin-torque FMR, I extract damping-like/field-like components. Further, using Hall bars and p-MTJs, I quantify switching probability vs pulse width, energy-delay scaling, and retention.

4) SOT study of low symmetry weyl semi-metals $TaIrTe_4$ and $NbIrTe_4$:

As shown in figure 4, rare metal Ta and Nb based alloy like $TaIrTe_4$ and $NbIrTe_4$, layered semimetals has intrinsically low crystalline symmetry. That low symmetry enables unconventional spin polarizations (including OOP z-spin) under in-plane current. This helps with field-free switching without additional symmetrical breaking layers.

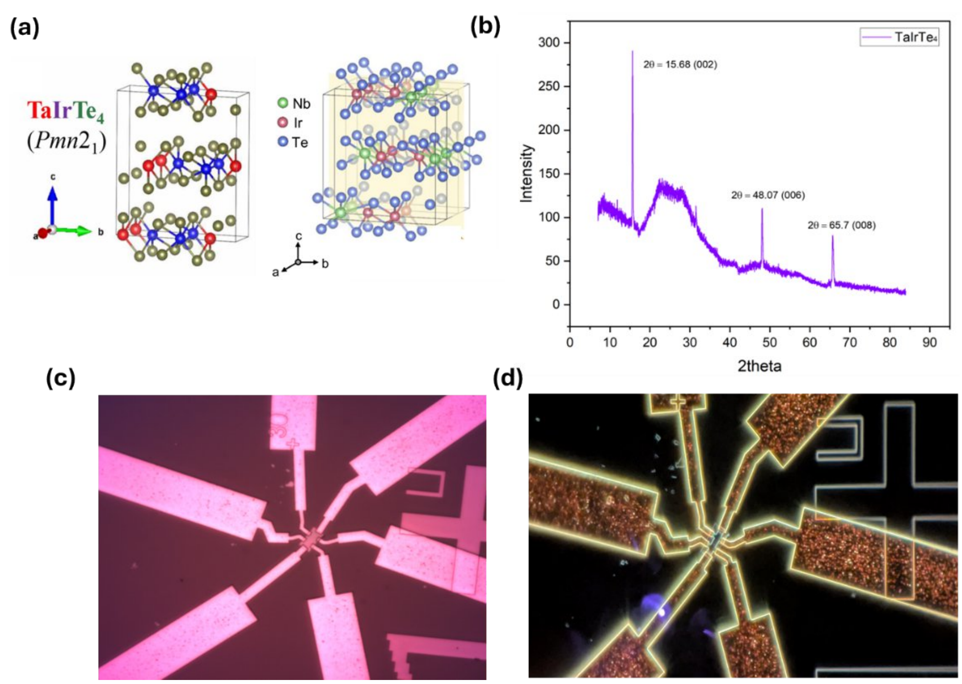


Figure 4: (a) Crystal structure of weyl semi-metals TaIrTe4 and NbIrTe4. (b) The XRD data of TaIrTe4 from Co based X-ray machine. (c), (d) Microscopic image of patterned hall bar device of TaIrTe4/Py/Ru stack before etching and after etching respectively.

I mechanically exfoliate $TaIrTe_4$ and $NbIrTe_4$ flakes from single crystals onto insulating pre-patterned Si/SiO_2 substrates, sputter Py or CoFeB ferromagnetic layer and patterned into Hall bars via e-beam lithography, complete process flow has been compiled in figure 5. With these hall bar devices, I perform second-harmonic Hall, measure unidirectional spin-magnetoresistance (USMR) signal, and explore electrostatic gating (HfO_2/Al_2O_3 dielectrics) to modulate volage control magnetic anisotropy and electric field effect.

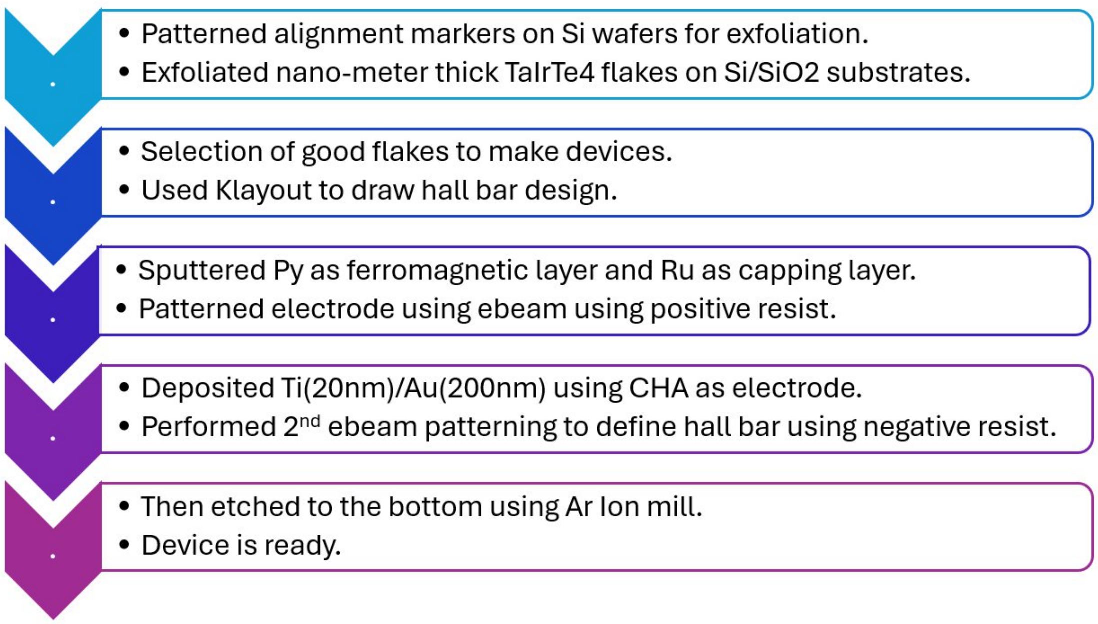


Figure 5: Process flow of hall bar fabrication of TaIrTe/Py/Ru stack devices for second harmonic and USMR measurements.

5) Integration of voltage control effects like Voltage Control Magnetic Anisotropy:

In our recent study [4], as shown in figure 6, we have shown that tuning the underlayer work function beneath CoFeB/MgO can markedly amplify VCMA. In $W/Pt_xW_{1-x}/CoFeB/MgO$ stacks, increasing Pt content raises the metal's work function and electron-depletes the CoFeB/MgO interface at equilibrium, which enhances the electric-field response of interfacial anisotropy. UPS and XPS confirm the work-function shift and interfacial charge transfer. By tuning Pt content, we achieved a VCMA coefficient up to ~ 8× larger than a pure W control, with the best performance at $Pt_{77}W_{23}$.

6) Applications and impact:

My projects on novel low-symmetric materials like Ni_4W, $TaIrTe_4$ and $NbIrTe_4$ will help industry to adapt SOT-MRAM for caches and embedded memory. Field-free stacks based on these rare metals remove external fields and simplify periphery circuits. With optimized doping and crystal symmetry the energy per bit can reach the femtojoule regime which directly helps in reducing data center power consumption.

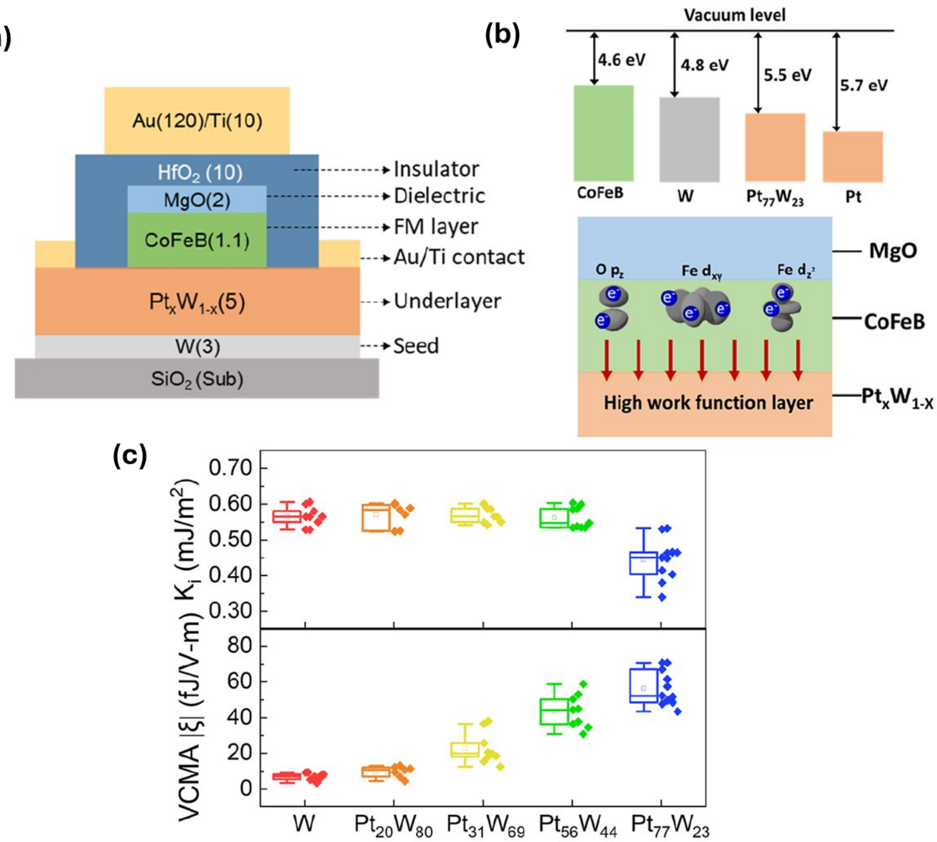


Figure 6: (a) Cross-sectional schematic of the gated Hall-bar device. (b) Energy-level alignment for CoFeB in the flat-band limit when paired with W, $Pt_{77}W_{23}$, or Pt and schematic of electron depletion from CoFeB/MgO into a high-work-function Pt_xW_{1-x} underlayer at thermal equilibrium. (c) Distribution plots (box plots) of K_i and VCMA for varying Pt_xW_{1-x} alloys used as underlayers [4]. Disclaimer: This image is from one of my recent papers and you are allowed to use it in press releases.

These novel SOT-MRAM devices can also be used in probabilistic and in-memory computing. By controlling switching probability via pulse width and gate voltage, these MRAM devices act as p-bits or weighted samplers which is further useful in optimization and generative AI accelerators.

CMOS based NVMs have issues with radiation in space exploration activities. SOT-MRAM provided a pathway to secure and radiation-hard electronics. Magnetic bits resist soft errors; rare-metal-based stacks are robust at temperature and under radiation, important for aerospace.

Through these research studies we can anticipate following outcomes such as: (i) a dopant/stoichiometry map for maximizing SOT in Ni_4W, (ii) field-free switching in exfoliated low-symmetry semimetals, and (iii) integration pathways for reliable, manufacturable SOT-MRAM and stochastic computing. More broadly, the project highlights how rare metals (W, Ta, Nb) can be engineered at the band-structure level to deliver sustainable, high-impact electronics, advancing both fundamental spintronics and practical memory technologies.

7) References:

[1] Dikshit, Surya Narain, Arshid Nisar, **Brahmdutta Dixit**, et.al. "Optically assisted ultrafast spintronics: A review." *Physics Reports* 1140 (2025): 1-46. **(IF: 29.5)**

[2] Yang, Yifei, Seungjun Lee, Yu-Chia Chen, Qi Jia, **Brahmdutta Dixit**, et al. "Large Spin-Orbit Torque with Multi-Directional Spin Components in Ni4W." *Advanced Materials* (2025): 2416763. **(IF: 26.8)**

[3] Yang, Yifei, Seungjun Lee, Yu-Chia Chen, Qi Jia, **Brahmdutta Dixit** et al. "Large Spin-Orbit Torque with Multi-Directional Spin Components in Ni4W (Adv. Mater. 32/2025)." *Advanced Materials* 37, no. 32 (2025): e70089. **(Cover Page)**

[4] Chen, Yu-Chia, Thomas Peterson, Qi Jia, Yifei Yang, Shuang Liang, Brandon R. Zink, Yu Han Huang, Deyuan Lyu, **Brahmdutta Dixit**, and Jian-Ping Wang. "Large and Tunable Electron-Depletion-Based Voltage-Controlled Magnetic Anisotropy in the CoFeB/MgO System via Work-Function-Engineered Pt x W1–x Underlayers." *ACS nano* 19, no. 16 (2025): 15953-15962. **(IF: 16.0)**

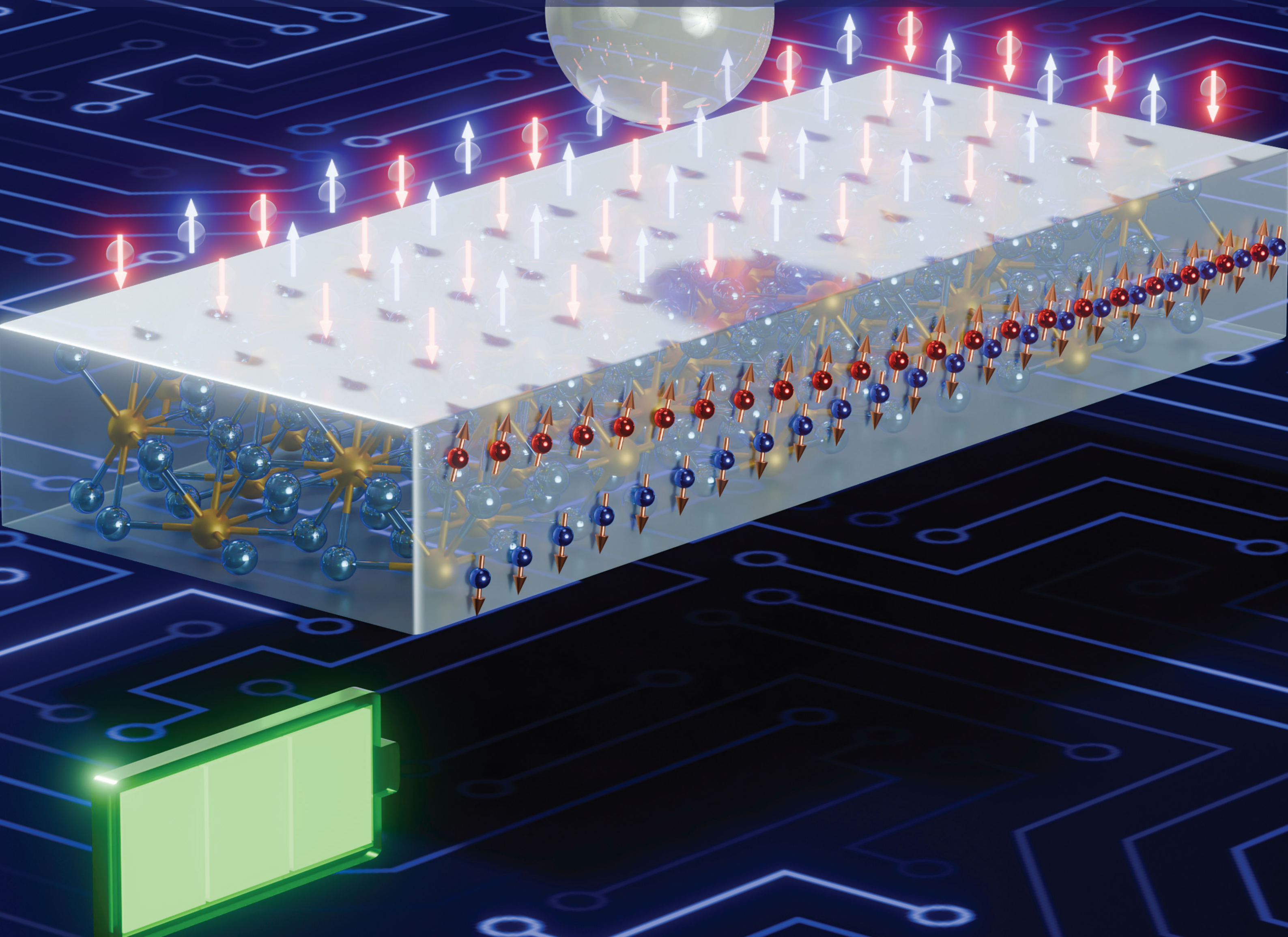
Biography

Brahmdutta Dixit is a 3rd year PhD graduate researcher in the Nano Magnetism & Quantum Spintronics Lab at the University of Minnesota Twin-Cities, Minnesota, USA. He has six years of combined industry and academic experience across device physics, materials science, and spintronics. His current work centers on rare-metal spintronics: epitaxial Ni_4W as a multi-directional SOT source; Fermi-level tuning via W stoichiometry and Co co-doping to enhance torque efficiency and reduce write current; and exfoliated $TaIrTe_4$/$NbIrTe_4$ Hall-bar devices for field-free switching. He integrates thin-film growth with XRD/UPS/XPS, ST-FMR, second-harmonic Hall, AHE/USMR, and co-designs SOT with Voltage Control Magnetic Anisotropy (VCMA) and Voltage Control Exchange Coupling (VCEC) toward few-fJ MRAM operations. Previously, he served as a Device/Integration Engineer at GlobalFoundries (yield and process improvements across 14nm FinFET, 28 nm HKMG and 40 nm NVM) and as an Advanced Technology Validation intern at Advanced Micro. Devices (AMD) (methodology and yield correlation on leading-edge nodes like 3nm and 5nm FinFET). Earlier at the University of Würzburg, Germany he worked on MBE-grown HgTe/CdHgTe/Py 3D topological-insulator stacks. A B.Tech gold medalist from Mizoram University, he has co-authored papers in Advanced Materials, Advanced Functional Materials, Physics Reports and ACS Nano.

ADVANCED MATERIALS

Large Spin-Orbit Torques from Multiple Spin Components

In article number 2416763 by Tony Low, Jian-Ping Wang, and co-workers, Ni_4W is proposed and experimentally demonstrated as an efficient unconventional spin-orbit torque material with tilted spin polarization. It enables field-free switching of perpendicular magnetic anisotropy magnets, offering significant potential for next-generation spintronic devices.



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