Thermally Stable β-Tungsten for 64-kb SOT-MRAM: Structural Stability Revealed by Synchrotron Nanodiffraction

1-nanosecond magnetic memory breakthrough moves MRAM closer to mass production.

Modern computing systems rely heavily on charge-based memory subsystems, including static random-access memory (SRAM), dynamic random-access memory (DRAM), and flash memory.[1] However, as these technologies scale beyond the 10-nm node, they face significant physical challenges, specifically performance degradation, reliability concerns, and read/write disturbances. To overcome these challenges, emerging non-volatile memory technologies, such as spin–orbit torque magnetic random-access memory (SOT-MRAM), spin-transfer torque magnetic random-access memory (STT-MRAM), and phase-change memory (PCM), are being developed. These technologies provide low latency, reduced power consumption, and seamless integration with complementary metal-oxide-semiconductor (CMOS) technology. Among these options, SOT-MRAM is especially suitable to replace cache-level SRAM due to its rapid write speeds and high energy efficiency. By using materials with strong spin-orbit coupling (SOC), SOT-MRAM can switch the magnetization of magnetic tunnel junctions (MTJs) with high reliability. Additionally, its three-terminal architecture separates read and write paths, addressing the endurance limitations in STT-MRAM.

Tungsten (W) is a leading material for SOT applications because of its high SOC. Specifically, tungsten in its β-phase (A15 structure) exhibits a large spin-Hall angle of approximately -0.4 to -0.6, facilitating excellent switching efficiency. However, β-W is metastable and tends to transform into the thermodynamically stable α-phase, which has a negligible spin-Hall angle, when the film thickness exceeds 5 nm or during back-end-of-line (BEOL) annealing at 400°C.[2] This creates a significant integration conflict: although thick W layers are necessary to ensure a robust etching process and high yield, they also increase the risk of phase transformation.

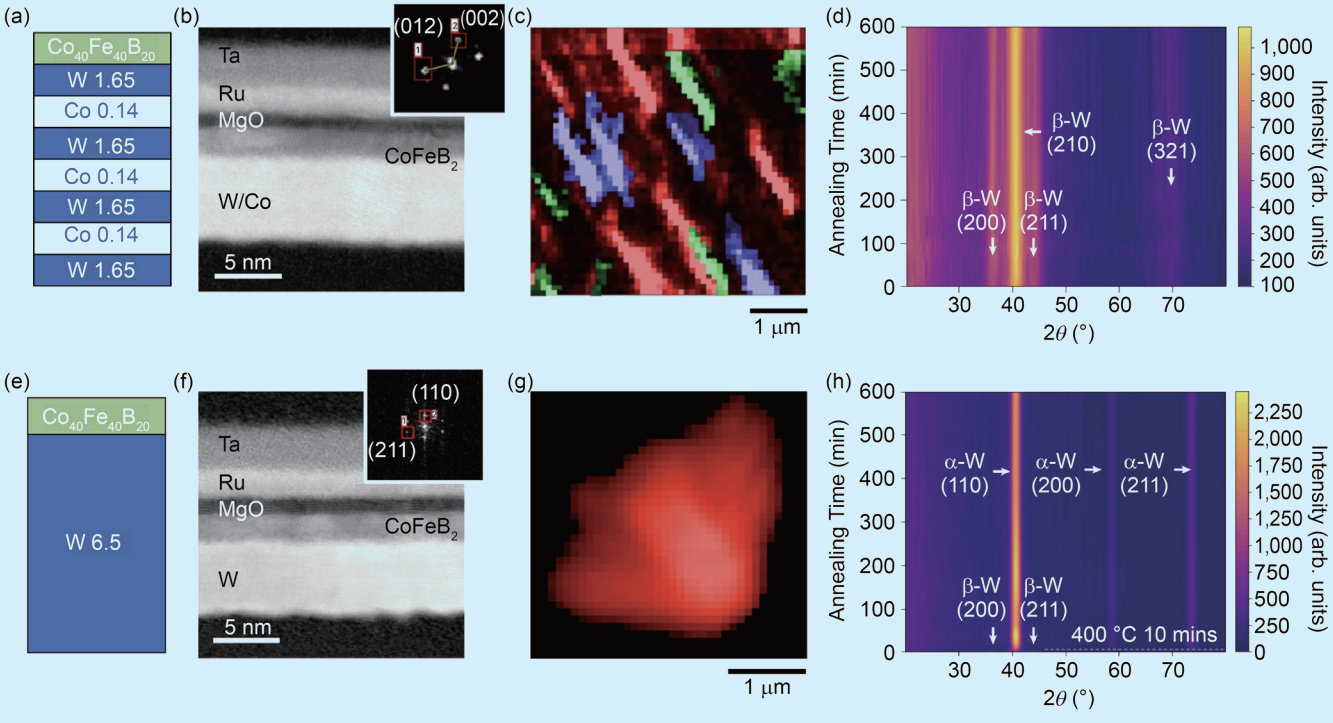

Fig. 1: Structural stability of composite-W. (a–d) The composite-W film incorporates Co insertion layers to maintain the β-W phase, as confirmed by transmission electron microscopy and grazing incidence X-ray diffraction. (c) Synchrotron nanodiffraction mapping (**TPS 21A**) reveals field-aligned β-W crystalline grains. (e–h) Single-layer W undergoes a full phase transformation to α-W under identical annealing conditions (400 °C). [Reproduced from Ref. 3]

In this study, Yen-Lin Huang's (National Yang Ming Chiao Tung University) team presents a cobalt (Co) insertion layer design that successfully stabilizes the β-W phase, which is revealed by the high-resolution X-ray nanodiffraction at **TPS 21A** at the NSRRC, even under stringent BEOL thermal constraints. This composite approach enables the creation of thick W layers that maintain high thermal stability and a record spin-Hall conductivity of approximately 4,500 $\Omega^{-1}cm^{-1}$.[3]

Synchrotron-Based Phase Characterization

To address this stability challenge, the team developed a composite-W structure incorporating thin cobalt insertion layers that serve as diffusion barriers. The critical evidence for the phase stability of this design was obtained through high-resolution X-ray nanodiffraction at **TPS 21A** at the NSRRC.

Using a monochromatic X-ray beam focused on a 90 × 90 nm^2 spot, the team performed spatial diffraction mapping to identify the distribution of W phases. As shown in **Fig. 1(c)**, the nanodiffraction maps revealed that the composite-W film maintains a robust, crystallized β-phase after annealing. Notably, we observed distinct stripy crystal features aligned with the direction of the annealing field, suggesting a symmetry-breaking effect potentially beneficial for field-free switching. In contrast, single-layer W films without Co insertion underwent complete transformation into the stable α-phase after only 10 minutes at 400 °C. These results demonstrate that our composite design can withstand 400 °C for up to 10 hours and even 700 °C for 30 minutes, meeting the most stringent BEOL thermal budgets.

64-kb SOT-MRAM Performance

Leveraging the stabilized β-W spin-current source, the team successfully integrated a 64-kilobit SOT-MRAM array using a standard CMOS process.

The device characterization presented in **Fig. 2** highlights the exceptional performance of the composite-W integration.

- High Read Margin: The magnetic tunnel junctions exhibit a tunneling magnetoresistance of approximately 146%, ensuring reliable data readout.
- Ultrafast Switching: The 64-kb chip demonstrates reliable SOT switching at speeds as fast as 1 ns.
- Long-Term Reliability: The team extracted a thermal stability factor (Δ) of approximately 116, corresponding to a data retention period exceeding 10 years.
- Field-Free Operation: The symmetry-breaking properties identified in the synchrotron maps enabled field-free switching, which is critical for simplifying high-density memory architectures.

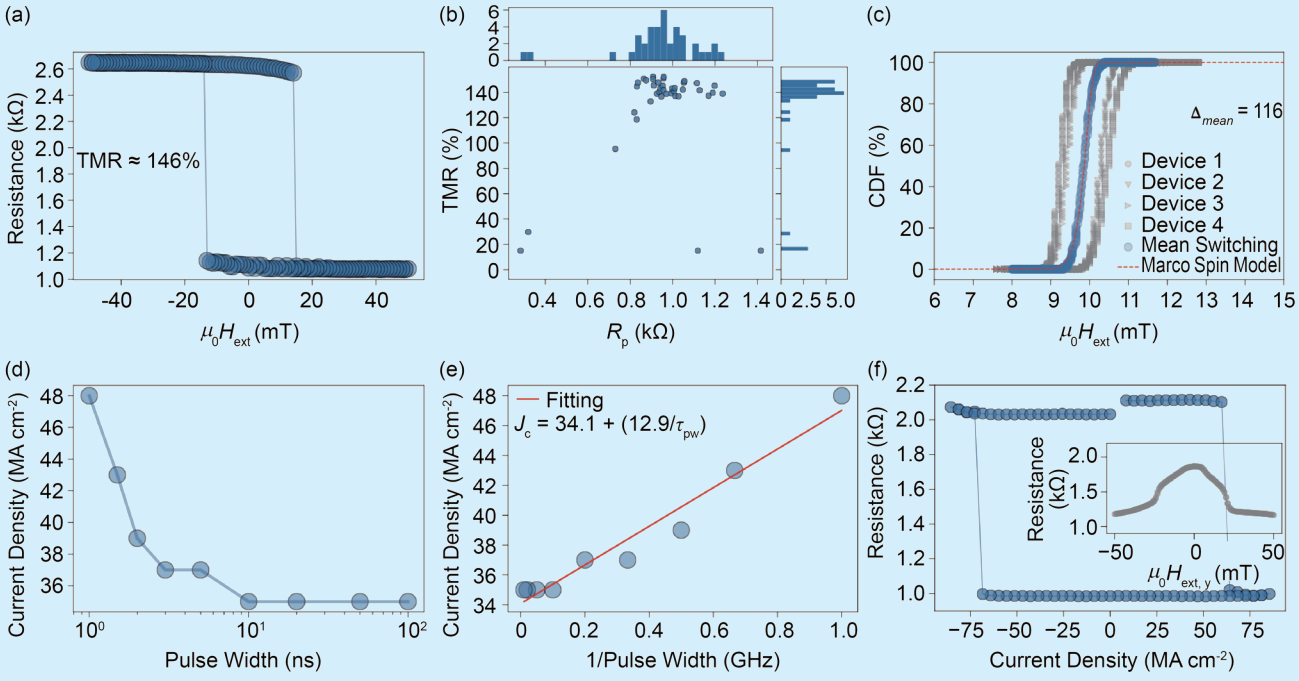

Fig. 2: 64-kb SOT-MRAM characterization. (a–b) The integrated MTJ exhibits a TMR of ~146%. (c–e) Statistical analysis of 8,000 devices shows a thermal stability (Δ) of 116 and successful 1 ns switching at high current densities. (f) Evidence of field-free switching due to the symmetry-breaking design of the composite W. [Reproduced from Ref. 3]

Conclusion

By combining innovative material engineering with advanced synchrotron analysis at the NSRRC, the team has demonstrated a BEOL-compatible SOT-MRAM solution that overcomes a major roadblock for commercial semiconductor integration. This work underscores the vital role of nanodiffraction techniques in characterizing next-generation spintronic materials. (Reported by Yen-Lin Huang, National Yang Ming Chiao Tung University)

This report features the work of Yen-Lin Huang and his collaborators published in Nat. Electron. ***8****, 794 (2025).*

TPS 21A X-ray Nanodiffraction

- n-XRD, ED-XND
- Materials Science, Electronic Device, Microstructural Domain Image

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Highly Crystalline Selenium-Substituted Acceptor-Donor-Acceptor-Type Acceptor Enabling High-Mobility N-Type Transistors

Selenium-substituted non-fullerene acceptor CB-2Se exhibits a single-crystal-like thin-film packing after thermal annealing, resulting in exceptional n-type organic field-effect transistor mobility of 1.18 $cm^2 V^{-1} s^{-1}$ with excellent air stability.

In 2019, the non-fullerene acceptor (NFA) material Y6 emerged as a groundbreaking development in organic solar cells, achieving a power conversion efficiency of 15.7%.[1] This milestone significantly advanced the development of organic photovoltaic (OPV) materials. Y6 features an A-$D_N A'_N$D-A-type molecular architecture with a characteristic C-shaped geometry, incorporating an electron-deficient thiodiazole (Tz, A′ unit) into the core. This structural motif effectively modulates intermolecular interactions and molecular packing. Recently, a structurally simplified A-$D_N B_N$D-A NFA, CB16, was developed, employing an unsubstituted *ortho*-benzodipyrrole (*o*-BDP) core derived from Y6 by removing the A′ moiety.[2] Both CB16 and Y6 derivatives share a key structural feature: the *o*-BDP core. This semi-circular, π-conjugated unit facilitates the formation of three-dimensional interpenetrated networks through self-assembly, promoting multidirectional charge transport pathways. As a result, inverted OPVs based on CB16 achieved efficiencies comparable to those of Y-series materials. Ongoing structural refinement of CB-based architectures is expected to drive the advancement of next-generation acceptor–donor–acceptor-type (A–D–A-type) NFAs.

Despite the rapid progress of OPV technologies, NFAs have yet to demonstrate high electron mobility in organic field-effect transistors (OFETs). To date, the development of n-type OFETs remains limited, particularly for solution-processable systems under ambient conditions. Key challenges include the suboptimal molecular ordering and stacking behavior of NFAs, which restrict their charge-transport capabilities. Reports of n-type OFETs with electron mobilities exceeding 1 $cm^2 V^{-1} s^{-1}$ remain scarce, and such performance is typically observed only in single-crystal devices—systems that are difficult to fabricate and scale, thus limiting their practical applicability. Therefore, there is an urgent need to design new NFAs that can self-assemble into highly crystalline, single-crystal-like domains in thin films *via* solution processing. However, rational design strategies for such materials remain underdeveloped. Notably, C-shaped NFAs based on the *o*-BDP core exhibit extensive π–π interactions in the solid state, enabling the formation of interpenetrating three-dimensional networks. These networks provide diverse charge transport pathways, underscoring their potential for single-component OFET applications.