*This report features the work of Chung-Ling Wu, Cheng-Maw Cheng and their collaborators published in Adv. Mater. **37**, 2414442 (2025).*

TLS 21B1 Angle-resolved UPS

- Angle-resolved Photoemission Spectroscopy
- Materials Science, Condensed-matter Physics

Reference

1. S.-S. Wong, Z.-Y. Lin, S.-Z. Ho, C.-E. Hsu, P.-H. Li, C.-Y. Chen, Y.-F. Huang, K.-E. Chang, Y.-C. Hsieh, C.-H. Chen, M.-H. Lee, M.-W. Chu, K.-I Lin, T.-M. Chen, Y.-C. Chen, H.-C. Hsueh, C.-M. Cheng, C.-L. Wu, Adv. Mater. **37**, 2414442 (2025).

Peeling Ferroelectrics to Power the Next Electronics Revolution

Freestanding ferroelectric membranes unlock CMOS-ready, low-power two-dimensional transistors and enable scalable logic for next-generation three-dimensional electronics.

As silicon-based complementary metal–oxide–semiconductor (CMOS) technology approaches its physical scaling limits, further transistor miniaturization faces increasing challenges such as heat dissipation and carrier mobility degradation. Two-dimensional (2D) semiconductors, with their atomically thin bodies and excellent electrostatic control, offer a promising alternative channel material for next-generation electronics. A critical bottleneck, however, is the integration of high-quality, high-κ gate dielectrics into 2D materials. Conventional atomic layer deposition often produces amorphous oxides and defective interfaces on 2D surfaces, while buffer-layer approaches can degrade dielectric performance. Although van der Waals insulators such as hexagonal boron nitride improve interfaces, their integration with CMOS processes remains difficult.

To overcome the barrier of integration with CMOS-compatible high-κ dielectrics, Jan-Chi Yang (National Cheng Kung University), Yen-Fu Lin (National Chung Hsing University), and their teams establish a reliable route to fabricate high-quality freestanding ferroelectric $Hf_{0.5}Zr_{0.5}O_2$ (HZO) membranes and systematically investigate their structural and electronic properties prior to integration with two-dimensional semiconductors. The freestanding HZO membranes are produced by selectively etching a sacrificial $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) layer from epitaxial LSMO/HZO heterostructures grown on single-crystal $SrTiO_3$ substrates. They fabricated freestanding ferroelectric HfO_2-based oxides doped with zirconium (HZO) membranes using pulsed laser deposition and integrated with few-layer MoS_2 field-effect transistors (FETs). The membranes are produced by epitaxially growing an LSMO/HZO heterostructure on $SrTiO_3$, followed by selective chemical removal of the sacrificial LSMO layer. This approach yields mechanically intact membranes suitable for transfer without compromising crystallinity or ferroelectric functionality. Electrical characterization reveals that 20-nm-thick freestanding HZO membranes possess a high dielectric constant (~20.6), a large breakdown field (~2.2 MV cm^{-1}), and robust ferroelectric polarization.

High-resolution transmission electron microscopy reveals well-ordered atomic lattices in 20-nm-thick freestanding HZO membranes, dominated by the orthorhombic (o-) phase, which is responsible for ferroelectricity. Atomic force microscopy

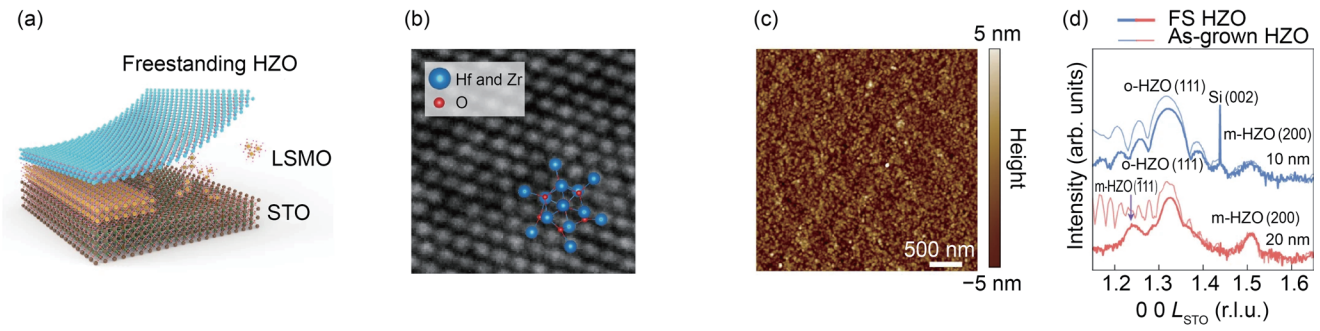

Fig. 1: Fabrication and characterization of ferroelectric freestanding HZO membranes. (a) Schematic of the fabrication process for freestanding HZO membranes. (b) Transmission electron microscopy image showing the o-phase (111) of freestanding HZO with the corresponding lattice model. (c) AFM image of a 20-nm freestanding HZO membrane, with an Ra value of 0.86 nm. (d) Comparison of XRD θ–2θ scans between as-grown and freestanding HZO membranes at thicknesses of 10 and 20 nm. [Reproduced from Ref. 1]

confirms smooth, crack-free surfaces, indicating that the release process preserves structural integrity. X-ray diffraction θ–2θ scans performed at **TPS 09A** and **TLS 13A1** comparing as-grown and freestanding HZO films (10–20 nm thick) show minimal changes in peak width and a slight high-angle shift, consistent with modest relaxation of in-plane compressive strain while maintaining high crystalline quality. Thickness-dependent X-ray diffraction (XRD) and off-normal measurements across films ranging from 5 to 40 nm further confirm excellent crystallinity and reveal a strong thickness dependence of phase composition. Notably, HZO films thinner than 20 nm exhibit an enhanced fraction of the ferroelectric o-phase, identifying them as optimal candidates for gate dielectrics.

To probe the connection between lattice symmetry and electronic structure, linear polarization-dependent X-ray absorption spectroscopy (XAS) was employed at **TPS 45A**. Oxygen K-edge spectra display clear linear dichroism arising from crystal-field-induced splitting of Hf (Zr) d states, enabled by the d^0 electronic configuration of Hf^{4+}/Zr^{4+}. Thick (~40 nm) HZO membranes show pronounced negative linear dichroism, characteristic of the centrosymmetric monoclinic phase. As membrane thickness decreases, the dichroism magnitude diminishes and reverses sign for sub-10-nm membranes, indicating a transition to a polar orthorhombic structure. This sign reversal provides direct spectroscopic evidence of polar lattice distortion and the emergence of ferroelectricity in ultrathin HZO membranes. Importantly, the linear dichroism trends of freestanding HZO closely match those of as-grown films, demonstrating that the freestanding process does not degrade structural or electronic quality. Together, these results confirm that ultrathin freestanding HZO membranes retain robust ferroelectricity and high crystallinity, providing a solid foundation for their integration as scalable, high-κ ferroelectric dielectrics in 2D electronic devices.

By transferring 20-nm-thick HZO membranes onto MoS_2, efficient top-gate control is achieved with a large capacitance of 0.44 μF cm^{-2}, corresponding to an equivalent oxide thickness of 4.5 nm. Analysis of the top- and bottom-gate coupling yields a dielectric constant of ~18.3, consistent with capacitance–voltage measurements. Crucially, carrier mobility remains comparable between SiO_2 bottom-gated and HZO top-gated devices, indicating that the freestanding membranes avoid charge doping and interface degradation typically associated with atomic layer deposition. Statistical measurements from 32 devices show excellent uniformity, with over 65% achieving on/off current ratios near 10^8 and an average subthreshold swing of 53 mV dec^{-1}. Moreover, the ferroelectric nature of HZO ensures efficient gate control and stable switching behavior. Using these devices, functional logic components such as inverters, logic gates, and a 1-bit full adder are demonstrated. In addition, short-channel MoS_2 transistors with channel lengths down to 13 nm maintain excellent performance, highlighting the scalability of this approach. The researchers' work establishes freestanding ferroelectric HZO membranes as a viable pathway for integrating high-κ dielectrics with 2D semiconductors for advanced, CMOS-compatible electronics.

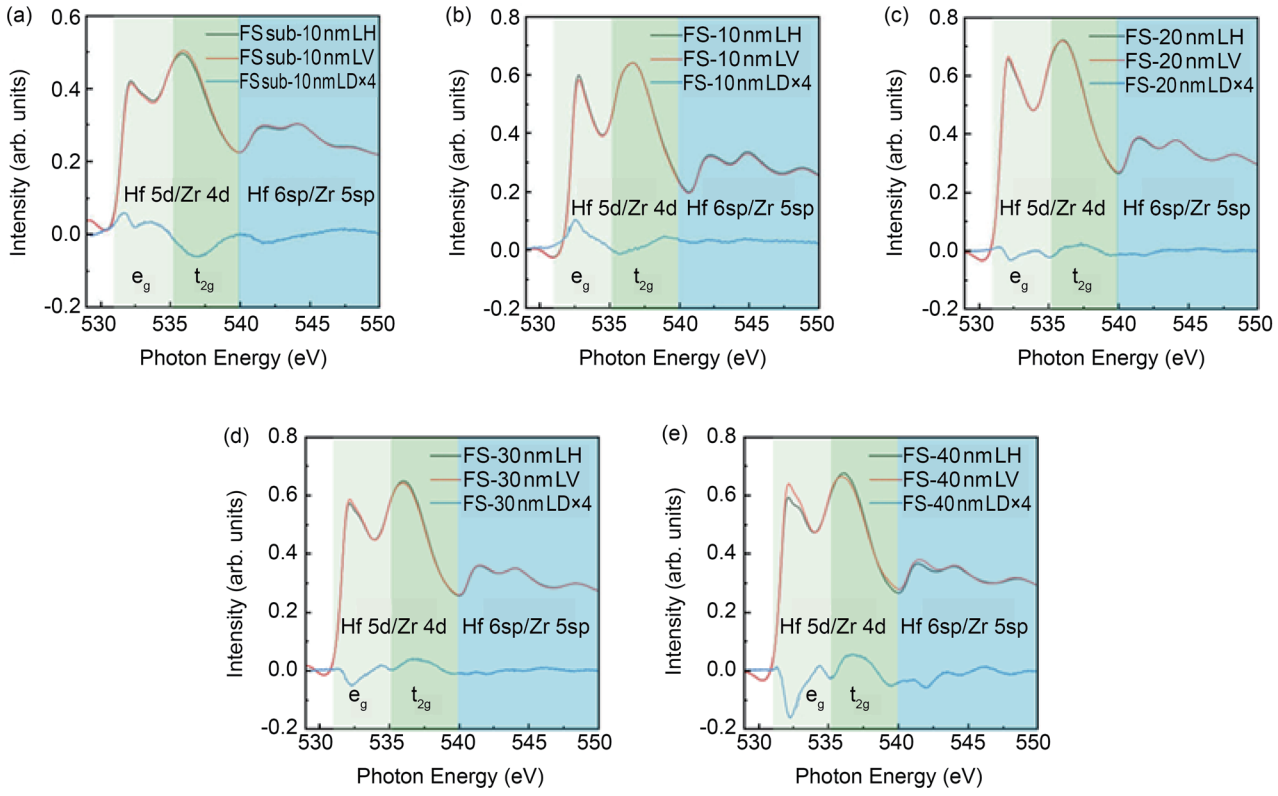

Fig. 2: Thickness-dependent XAS and XLS spectra of freestanding HZO membranes. [Reproduced from Ref. 1]

In summary, this work demonstrates freestanding high-κ ferroelectric HZO membranes grown by pulsed laser deposition and transferred onto 2D semiconductors to enable high-performance MoS_2 FETs. Owing to strong ferroelectricity, a dielectric constant of ~20.6, and an excellent interface quality (Dit ≈ 9×10^{10} cm^{-2} eV^{-1}), the devices achieve Ion/Ioff ≈ 10^9 and a minimum subthreshold swing of 53 mV dec^{-1}. Integrated logic circuits and scalable short-channel operation highlight HZO membranes as a CMOS-compatible dielectric platform for advanced 2D and 3D integrated electronics. (Reported by Cheng-Maw Cheng)

This report features the work of Jan-Chi Yang, Yen-Fu Lin and their collaborators published in Nat. Electron. ***8****, 560 (2025).*

TPS 09A Temporally Coherent X-ray Diffraction
TPS 45A Submicron Soft X-ray Spectroscopy
TLS 13A1 X-ray Scattering

- Soft-X-ray absorption spectroscopy, X-ray diffraction
- Materials Science, Condensed-matter Physics

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An "*s*-Electron" Donor Band Drives the Metallic Ferromagnetism in Co-Doped ZnO Films

Polarization-dependent, bulk-sensitive hard X-ray photoemission spectroscopy reveals that a metallic "s-electron" character donor band mediates ferromagnetism in Co-doped ZnO films and solves a long-standing problem in dilute magnetic materials.

Diluted magnetic semiconductors (DMSs) hold great potential for spintronic applications and continue to attract significant attention as room-temperature ferromagnetic (RTFM) materials. While doping transition metals (TMs) into oxide semiconductors is a common approach, the underlying physical mechanism remains poorly understood, particularly for the diluted magnetic oxide (DMO) Co-doped ZnO (Co:ZnO) films, which exhibit high Curie temperatures (T_C) exceeding 300 K. The most promising mechanism proposed for high-T_C ferromagnetism is the donor impurity band exchange model, in which donor electrons mediate the coupling between TM spins. However, the nature of the donor band electrons has not yet been identified experimentally. Based on a well-planned set of experiments, including material synthesis, magnetic measurements, X-ray absorption near-edge and extended X-ray absorption fine-structure spectroscopy (XANES, EXAFS), and polarization-dependent, bulk-sensitive hard X-ray photoemission spectroscopy (HAXPES), Jung-Chun-Andrew Huang (National Cheng Kung University) and his collaborators have now demonstrated that the donor band originates in $Zn^{1+}4s^1$ states in Co:ZnO epitaxial films.[1] The study provides new insight into the ferromagnetic mechanism in Co:ZnO, where $Zn^{1+}4s^1$ states mediate ferromagnetism, leading to Co^{2+} spin ordering and metallic-like transport. These results elucidate the complementary roles of dopant and host electronic states and open avenues for designing novel room-temperature DMSs.

It is well-known from the donor impurity band exchange mechanism proposed by Coey *et al.*[2] that hybridization between TM states and defects influences the magnetic and electrical properties of DMOs. In ZnO-based DMOs, impurity bands arising from defects or TM 3*d* states can behave as localized states at low density and retain semiconducting behavior, or they can broaden with increased defect density and exhibit metallic transport. Accordingly, the authors first developed fabrication methods that preserve structural defects in the films. Epitaxial Co-doped ZnO films were grown using radio-frequency magnetron sputtering (RF sputtering) on sapphire substrates, maintaining a low Co doping concentration (~5 at%) to avoid percolation effects. The films were carefully optimized to preserve structural defects, such as zinc interstitials and oxygen vacancies. For a comparative analysis, four sets of samples were prepared