Electronic, Magnetic & Spintronic Devices

Magnetically Modulated Electrical Switching in an Antiferromagnetic MOSFET

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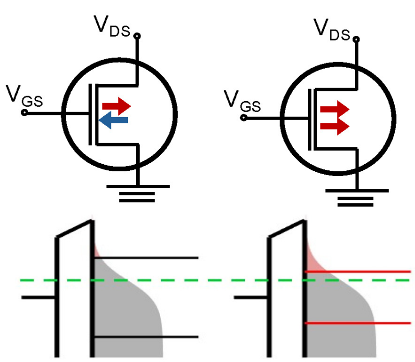
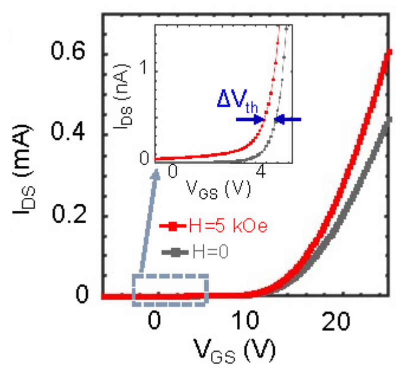
Sponsorship: SRC, Defense Advanced Research Projects Agency, NSF

The metal-oxide-semiconductor field-effect transistor (MOSFET) is a foundational component of modern electronics, relying on electric fields to control charge flow in a semiconductor. Spintronic devices, in contrast, leverage the electron's spin to enable new functionalities like non-volatile memory and logic. A long-standing goal in spintronics has been to integrate spin control into transistors, enabling spin-based switching to enhance performance and reduce energy consumption. While concepts like the Datta-Das spin transistor offer promising designs, practical realization has been hindered by challenges in spin injection, detection, and maintaining coherence—making high-performance, locally integrated spin transistors difficult to achieve.

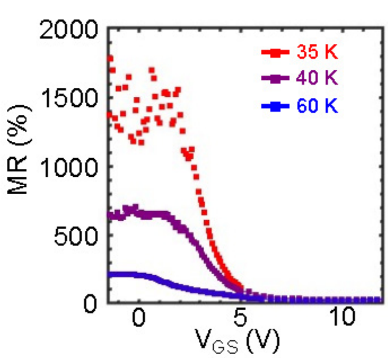
In this work, we study a magnetic MOSFET using CrSBr, a van der Waals (vdW) antiferro-magnetic semiconductor, as the channel material. Many two-dimensional vdW magnetic semiconductors exhibit moderate bandgaps and weak interlayer antiferromagnetic coupling, enabling magnetic transitions such as spin-flip and spin-flop under external stimuli. These transitions not only alter magnetic states but can also modify the electronic band structure via exchange interactions between local magnetic moments and conduction electrons. As adjacent layers switch from antiparallel to parallel alignment, interlayer spin-dependent hopping becomes allowed, significantly reducing the bandgap and altering carrier concentration. We show that both gate voltage and magnetic transitions modulate the channel current, achieving an ON/OFF ratio over 10^6 and magnetoresistance (MR) up to ~1500% at 35 K. Modeling reveals that spin-flip transitions drive significant carrier density changes, enabling strong magnetic tunability of channel conductance—beyond conventional MR mechanisms. Furthermore, by analyzing transport signatures alongside magnetic transitions, we demonstrate the potential of this magnetic MOSFET platform to distinguish interfacial magnetic switching from bulk effects.



▲Figure 1: Schematics of magnetic MOSFET in parallel (right) and antiparallel (left) magnetic states. Parallel state results in smaller band gap, thus increasing carrier density.



▲Figure 2: I_D vs. V_G curves of magnetic MOSFET in antiparallel (gray) and parallel (red) states. Clear shift of subthreshold voltage ΔV_{th} is observed.



◀Figure 3: MR of magnetic MOSFET vs. gate voltage and temperature. Gate-voltage-dependent MR with large MR plateau in subthreshold regime are consistent with theoretical calculations.

FURTHER READING

• C.-T. Chou, et al., "Magnetically Modulated Electrical Switching in an Antiferromagnetic Transistor," *arXiv preprint arXiv*: 2505.09019 (2025).

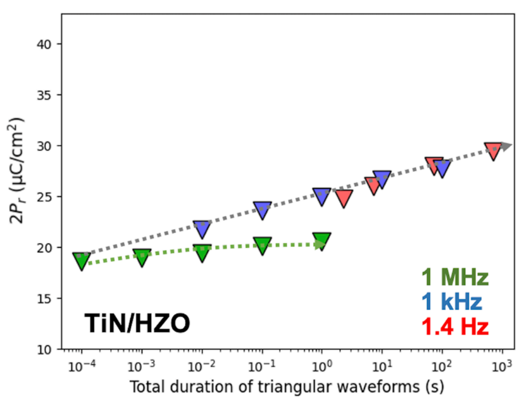
Frequency-dependent Wake-up in Ferroelectric $Hf_{0.5}Zr_{0.5}O_2$ Devices

T. E. Espedal, Y. Shao, J. C-C. Huang, E. R. Borujeny, D. A. Antoniadis, J. A. del Alamo
Sponsorship: MIT Undergraduate Research Opportunity Program, SRC, MIT AI Hardware Program

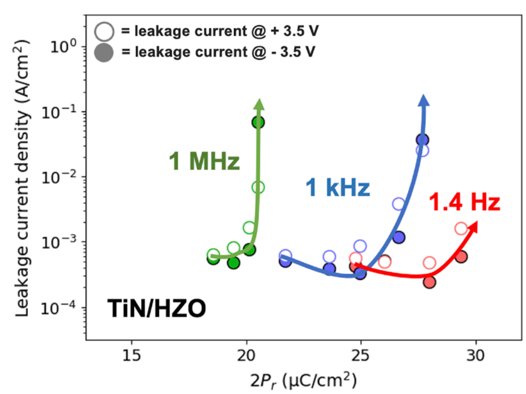
Among non-volatile memory technologies, ferroelectric (FE) memory based on com-plementary metal-oxide-semiconductor-compatible $Hf_{0.5}Zr_{0.5}O_2$ (HZO) has emerged as a promising one due to its potential for low-voltage, fast switching, long data retention, and high memory endurance. A drawback of this technology is the need for device "wake-up." Typically, >10^3 voltage cycles are required to sufficient wake-up metal-FE-metal (MFM) capacitors, while FE transistors usually wake up after a single direct current (DC) sweep, typically taking a few seconds. The frequency dependence of wake-up cycling is a poorly understood phenomenon, but it has great relevance for device performance and reliability.

In this work, we study the frequency-dependent wake-up behavior of 30x30µm TiN- and W-based FE-HZO capacitors. We apply repeated triangular voltage cycles at frequencies between 1.4 Hz and 1 MHz, monitoring polarization-voltage (P-V) and quasi-static DC current-voltage characteristics. We find a reproducible frequency depend-ence of P-V characteristics after some N wake-up cycles, a result which has not been reported thus far. We also find that high-frequency cycling leads to ineffective wake-up, likely due to domain pinning through high-voltage-induced defect generation.

Furthermore, we observe leakage current degradation upon repeated cycling that appears to be primarily determined by N rather than the total stress time. This contrasts with the wake-up behavior associated with increasing remanent polarization ($2P_r$) shown in Figure 1. This result evidences wake-up (increasing $2P_r$ early in device life) and device breakdown (observed in an upturn in leakage current, as shown in Figure 2) as distinct physical phenomena taking place within the HZO thin film.



▲Figure 1: Frequency-dependence of $2P_r$ over total duration of applied triangular waveforms, measured in capacitors with TiN elec-trodes.



▲Figure 2: Evolution of leakage current density and $2P_r$ with repeated cycling for TiN-electrode capacitors.

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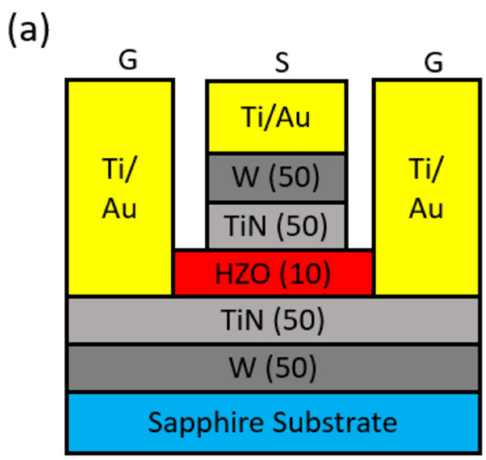
- Y. Shao, E. R. Borujeny, J. N. Fidalgo, J. C-C. Huang, T. E. Espedal, D. A. Antoniadis, and J. A. del Alamo. "Discrete Ferroelectric Polarization Switching in Nanoscale Oxide-Channel Ferroelectric Field-Effect Transistors," *Nano Letts.* 2025.
- T. E. Espedal, Y. Shao, J. C-C. Huang, E. R. Borujeny, D. A. Antoniadis, J. A. del Ala-mo, "Frequency-Dependent Wake-Up in Ferroelectric $Hf_{0.5}Zr_{0.5}O_2$ Devices," to be presented at *Devices Research Conference (DRC)*, Durham, NC, Jun. 2025.

Towards 65-GHz Capacitance-voltage Characterization of Ferroelectric $Hf_{0.5}Zr_{0.5}O_2$

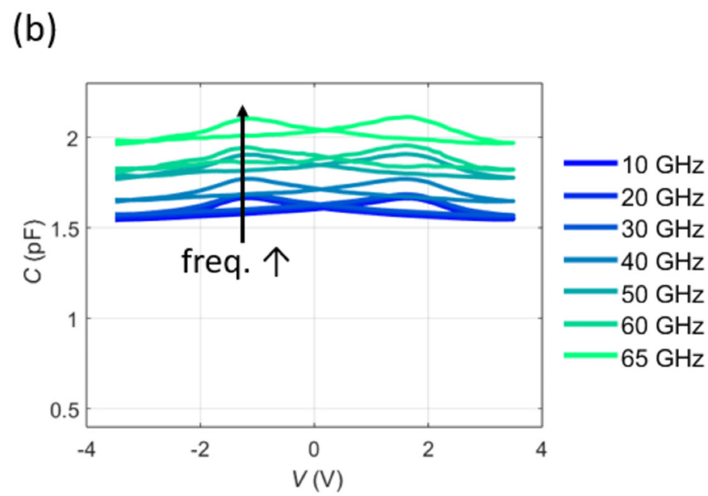
J. C.-C. Huang, Y. Shao, E. Borujeny, T. Espedal, H. Choi, J. Grajal, D. A. Antoniadis, J. A. del Alamo
Sponsorship: SRC

Doped hafnia has emerged as a popular family of materials in the field of microelectronics because of its surprising ferroelectric (FE) properties and compatibility with complementary metal-oxide semiconductor fabrication process. Among various hafnia, $Hf_{0.5}Zr_{0.5}O_2$ (HZO) stands out owing to its large remnant polarization and low coercive field, which is desirable for device applications. In such FE oxides, though the butterfly-like capacitance-voltage (CV) characteristic is a well-known phenomenon, its underlying physics has not been studied comprehensively. Our group has previously conducted CV characterization on HZO-based metal/FE/metal (MFM) capacitors across a broad frequency range up to 10 GHz, providing insights into the impact of defect dynamics in these devices.

In this study, we aim to extend the frequency range of CV characterization up to 65 GHz on HZO-based MFM structures built on impedance-matched coplanar waveguide structures. Our results highlight the significant influence of the intrinsic inductance of the coplanar waveguide on accurate capacitance extraction. Through the application of several de-embedding approaches, we demonstrate that the CV characteristics exhibit minimal frequency dependence across the GHz range, remaining stable up to approximately 40 GHz. More importantly, the butterfly-like feature of the CV curve persists even at 65 GHz. These findings shed light on the defect dynamics and FE switching behavior in HZO-based devices and promise to advance the understanding of undesired phenomena such as wake-up and fatigue, underscoring their potential relevance in high-speed memory and radio-frequency circuit applications.



▲Figure 1: Schematic diagram of a W/TiN/HZO/TiN/W coplanar waveguide device.



▲Figure 2: CV curves of W/TiN/HZO/TiN/W measured from 10 GHz to 65 GHz.

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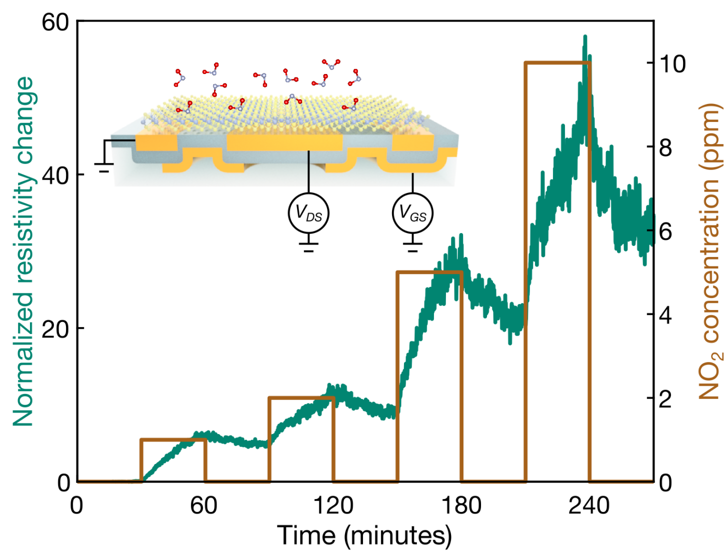
- J. Zhu, J.-H. Park, S. A. Vitale, W. Ge, G. S. Jung, J. Wang, M. Mohamed, T. Zhang, et al., "Low-thermal-budget Synthesis of Monolayer Molybdenum Disulfide for Silicon Back-end-of-line Integration on a 200 mm Platform," *Nature Nanotechnology*, vol. 18, pp. 456-463, 2023.

Direct van der Waals Integration of 2D Materials for High-performance Chemical Sensors

P. F. Satterthwaite, S. O. Spector, J. Song, F. Niroui
Sponsorship: MathWorks, NSF Division of Civil, Mechanical and Manufacturing Innovation, 2135846

Two-dimensional (2D) materials have the potential to serve as a platform for the fabrication of high-performance chemical sensors. Their atomically thin nature results in high surface area-to-volume ratios, allowing for high-sensitivity, low-power devices. Furthermore, the existing library of 2D materials includes diverse chemical and electronic properties, providing opportunities for selective sensing of different analytes. However, performance of current devices can often be limited by fabrication and design artifacts. Thus, platforms that overcome these limitations are desired.

Van der Waals (vdW) integration, where layers are physically contacted and held together by vdW forces, presents an alternative approach that enables the realization of diverse heterostructures with clean interfaces. Despite the clean interfaces, current vdW integration strategies typically result in encapsulated 2D materials where the top surface is not exposed for sensing applications. Using our newly developed adhesive matrix transfer platform, we have demonstrated direct integration of 2D materials into functional sensors. This allows for scalable, facile fabrication of 2D sensors with clean interfaces, in a design where the surface is fully exposed to maximize interaction with the analyte. The unique combination of these features enables high-performance chemical sensors, which we highlight by demonstrating a 50-fold enhancement in sensitivity of molybdenum disulfide-based sensors to nitrogen dioxide, a benchmark gas.



▲ Figure 1: Clean vdW integration for high-performance chemical sensors. Normalized change in resistance of an example device exposed to increasing concentrations of nitrogen dioxide. Inset shows schematic of fabricated device.

FURTHER READING:

- P. F. Satterthwaite, W. Zhu, P. Jastrezebska-Perfect, M. Tang, S. O. Spector, H. Gao, H. Kitadai, A.-Y. Lu, et al., “Van der Waals Device Integration Beyond the Limits of van der Waals Forces using Adhesive Matrix Transfer,” *Nature Electronics*, vol. 7, p. 17, 2024.

3D-integrated Circuits in GaN/Si CMOS/Glass for High-frequency, High-data-rate Applications

P. Yadav, J. Wang, D. Baig, X. Li, J. Pastrana, J. Niroula, M. Bakir, M. Swaminathan, R. Han, T. Palacios
Sponsorship: SRC Joint University Microelectronics Program 2.0 and National Defense and Science Graduate Fellowship

Gallium nitride (GaN) transistors are enabling the next generation of high-efficiency, high-power, and high-frequency integrated circuits. Furthermore, demonstrations of low-voltage GaN radio frequency (RF) switches for front-end modules (FEM) and low-noise figures in GaN low-noise amplifiers (LNAs), are broadening the applications of GaN into the mobile, artificial intelligence (AI), and quantum sectors. But this excellent performance comes with a high cost, due to limited wafer sizes and back-end-of-line (BEOL) metallization options. On the other hand, a Si complementary metal-oxide-semiconductor (CMOS) allows access to state-of-the-art 300-mm BEOL and digital circuit design.

Revolutionizing GaN chip design requires a holistic approach through integration with Si CMOS. This work, through these two approaches, makes three-dimensional (3D) GaN chips design more cost-effective while providing orders of magnitude improvement over convention 2D-circuits in Si or GaN-only front-end-of-line (FEOL). With the combination of Si CMOS digital, bias, and matching chips, high- frequency GaN dielets are integrated in a highly scaled manner through using direct Cu-Cu bonding for several 3D-amplifier first demonstrations. Such integration offers low RF losses as well as near- seamless-bonding interfaces. Similarly, glass offers a low-cost packaging option for multi-chiplet systems. Large substrate sizes and panel thickness down to 30 μm enable the next generation of packaging for nano-systems at scale, while also allowing for novel thermal cooling solutions such as microfluidic, two-phase vapor, etc. With the lamination of low-loss dielectric Ajinomoto build-up film (ABF) layers in glass, a highly capable package for 3D-RF stacking can be created. This work integrates GaN dielets directly in this glass package for the first time; it also studies and quantifies their properties.

Dipole-Engineered Contacts to Two-Dimensional Semiconductors

A. S. Gupta, J. Zhu, Y.-R. Peng, J. Kong, T. Palacios
Sponsorship: Army Research Office

Power transistors for fast-switching, high-voltage applications require wide bandgaps to enable large breakdown fields. Emerging ultrawide-bandgap (UWBG) two-dimensional (2D) semiconductors such as hexagonal boron nitride (hBN) and 2D gallium nitride (GaN) have bandgaps above 5 eV and are expected to provide better performance than current WBG semiconductors thanks to their higher critical fields and atomic thinness. However, forming low-resistance contacts to UWBG 2D materials is challenging due to their extreme energy band misalignment with conventional metal contacts and the Fermi level pinning effect, which both contribute to large Schottky barrier heights (SBHs).

Here, we propose using dipoles to reduce the SBH. Inserting a material with an appropriate built-in electric field at the contact interface will enhance carrier injection from the metal to the 2D channel. In this work, we study contacts to MoS_2 with MoSSe, a so-called "Janus" 2D material, which has vertical asymmetry and therefore an inherent dipole. We demonstrate higher current density in Janus 2D material contacts than in conventional MoS_2 contacts to bilayer MoS_2 transistors, confirming the positive impact of dipole-tuned contacts. Future work will focus on contact materials with stronger dipoles, as well as wider bandgap channel materials such as hBN and 2D GaN. Overall, this work is a step towards forming ohmic contacts with WBG and UWBG 2D materials, thus enabling the next generation of power electronic devices with higher operation voltage as well as future integrated circuits with increased functionalities.

Electrical-Controlled Magnetism in Rhombohedral Graphene

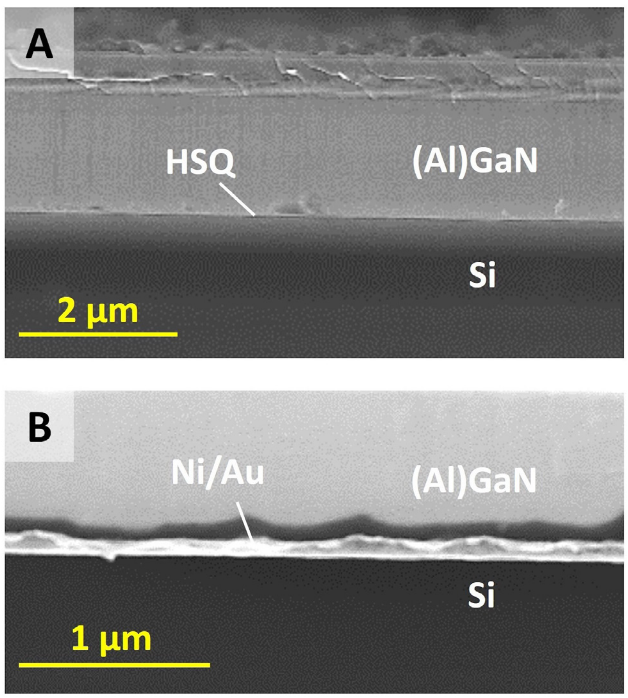
E. Aitken, T. Han, Z. Lu, J. Yang, J. Seo, S. Ye, Z. Wu, M. Zhou, L. Ju

Magnetism typically arises from the alignment of electron spin, which can only be indirectly influenced by an electric field. In contrast, orbital magnetism can be directly controlled by an electric field, enabling faster and more energy-efficient operation. Rhombohedral-stacked multilayer graphene, with its flat electronic bands and concentrated Berry curvature, facilitates the spontaneous ordering of electron orbital motion, resulting in a pure carbon-based orbital magnet. In this study, we investigate orbital magnetism in rhombohedral graphene by measuring the anomalous Hall effect, a Hall effect observed in the absence of an external magnetic field. By applying an out-of-plane magnetic field, we observe a hysteretic Hall resistance loop, providing clear evidence of magnetic ordering. Given graphene's negligible spin-orbit coupling, this anomalous Hall effect must arise from the ordering of electron orbital motion. Remarkably, an out-of-plane electric field can effectively modulate the magnitude of the anomalous Hall effect and magnetic hysteresis loop, demonstrating the electric-field control of magnetism. This control arises from the coupling of the electric field to the electron wave function, underscoring the potential for fast, low-energy magnetic memory and computation applications.

Materials Study of Flip-Processed Nitrogen-Polar GaN HEMTs

G. K. Micale, J. Niroula, P. Yadav, J. Hsia, H. Pal, Q. Xie, T. Palacios
Sponsorship: SRC Jump 2.0 SUPREME

GaN high electron mobility transistors (HEMTs) are the leading technology for high-power and high-frequency applications thanks to the high breakdown voltages and high electron saturation velocity of GaN. Utilizing wafer bonding, flip processing, and Si substrate removal, we demonstrate a technology for making N-polar devices from Ga-polar GaN-on-Si heteroepitaxy, which provides the flexibility to create innovative gate designs for greater electrostatic control. Here we present an in-depth study of this technology and the resulting N-polar AlGaN/GaN structure. Specifically, we investigate the adhesion between GaN and Si bonded with a hydrogen silsesquioxane (HSQ) interlayer and included back gate metal, looking at thermal compressive bonding variables and particle inclusions in the HSQ layer. Applying this technology for the fabrication of multichannel devices offers a path towards high current densities with superior gate control compared to previously demonstrated architectures.



▲ Figure 1: SEM cross-sections of (A) the bonding interface between the Ga-face GaN and the Si mechanical wafer, and (B) the bonding interface with the included Ni-Au gate metal.

High Temperature RF GaN Electronics

J. Niroula, M. Oh, M. Taylor, P. Yadav, Q. Xie, T. Palacios
Sponsorship: AFOSR (Grant No. FA9550-22-1-0367)

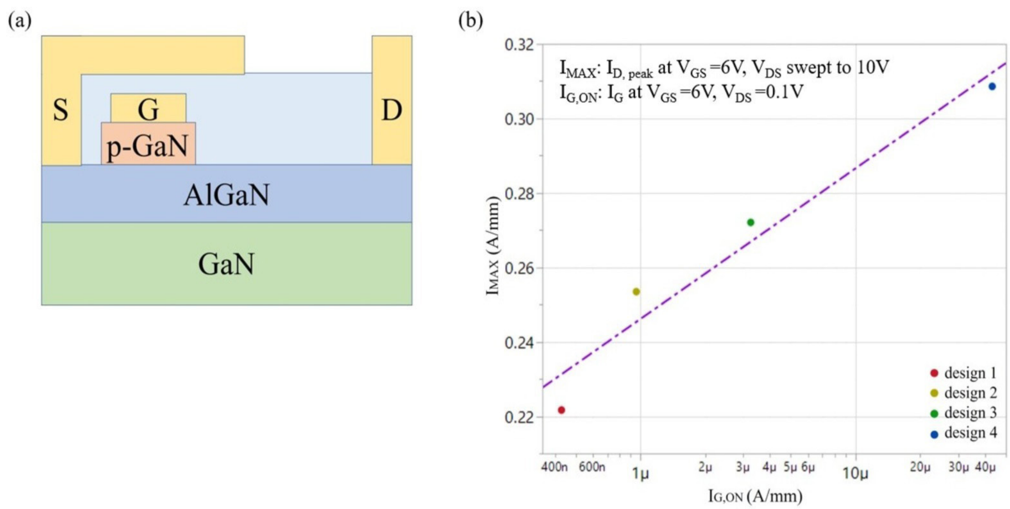
High temperature electronics has received much interest recently due to emerging applications in geothermal well exploration, hypersonic flight electronics, and space exploration. GaN based devices are an exciting contender for extremely high temperature environments due to their high mobility, high saturation velocity, especially beyond 250˚C, which is the limit of traditional silicon-based devices. In this project we aim to develop a high performing GaN based RF devices that operates at both room temperature as well as 500˚C, by developing highly scaled, high temperature refractory tungsten T-gates with AlN gate dielectric that has record current density at 500˚C. Such high temperature ready devices will allow high performing RF communication systems operating in the extreme conditions needed to enable the aforementioned applications.

Gate Stack Design of p-GaN Gate GaN High Electron Mobility Transistors

Y. Yu, J. A. del Alamo
Sponsorship: Texas Instruments

Gallium nitride (GaN) high electron mobility transistors (HEMTs) represent a breakthrough in semiconductor technology, offering superior high-frequency and high-power performance. However, reliability issues, particularly related to p-GaN gate designs, remain a challenge. This study investigates the impact of this design and fabrication on transistor performance, focusing on the trade-off between peak saturation drain current (I_{MAX}) and ON-state current ($I_{G,ON}$). Modest structural design and fabrication process changes have shown significant variations in I_{MAX} and $I_{G,ON}$, highlighting the need for strict process control.

In our work, we are carrying out extensive electrical characterization of prototype industrial transistors. In addition, we are performing Sentaurus TCAD simulations built to model such GaN HEMTs. By comparing experimental and simulated data, we aim to understand the dominant underlying physical mechanisms and refine predictive models for future GaN HEMT designs, ultimately improving device performance and reliability.



▲ Figure 1: (a) Cross-sectional view of p-GaN gate GaN HEMT (S is source, G is gate, D is drain), and (b) trade-off between I_{MAX} and $I_{G,ON}$ of prototype transistors from four differently-designed wafers.

Singlet Fission Sensitized Planar Silicon Solar Cells

J. Z. Wang, A. Li, K. Lee, N. Nagaya, M. A. Baldo
Sponsorship: DOE Materials Chemistry Program (DE-FG02-377 07ER46454), NSF Graduate Research Fellowship (112237)

Integrating singlet fission materials with silicon solar cells presents a pathway to surpassing the Shockley-Quiesser power conversion efficiency limit for single-junction solar cells. Singlet fission is a spin-allowed process in which one high energy singlet exciton is converted into two lower energy triplet excitons. These triplet excitons can transfer to silicon in a solar cell, enabling external quantum efficiencies over 100% and increasing the photocurrent output for the same incident light. Previous work in our group demonstrated enhanced external quantum efficiency in devices employing tetracene as the singlet fission material and zinc phthalocyanine as a charge transfer layer on silicon microwire cells, a geometry optimized to reduce reflection losses. In this work, we focus on a planar silicon system to further study and optimize the interface between singlet fission materials and silicon for efficient triplet exciton transfer. We examine new singlet fission materials such as rubrene, which introduces an uphill triplet exciton transfer to silicon, as well as more stable tetracene derivatives. Another key consideration is silicon surface passivation: the oxide layer must be thick enough to reduce surface recombination losses but also thin enough to allow efficient triplet transfer from the singlet fission material. This study contributes insights into the interface engineering required to leverage singlet fission in planar silicon solar cells towards the development of high-efficiency photovoltaic devices.

Photon-Assisted Quantum Tunneling in Two-Dimensional NiI2/hBN Heterostructures

J. Li, R. Comin
Sponsorship: NSF under Grant No. DMR-2405560

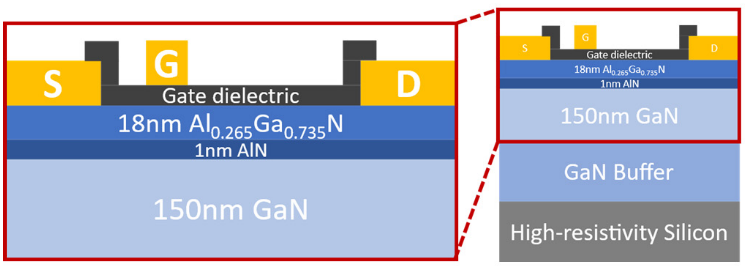
Quantum tunneling plays a fundamental role in modern physics and technology. Understanding the intricate relationships between quantum tunneling, light, and magnetic ordering expands the frontiers of quantum physics. Here, we demonstrate photon-assisted quantum tunneling in NiI_2/hBN heterostructures in the two-dimensional material NiI_2. Our measurements reveal a remarkable ten-fold enhancement in tunneling current through the junction at specific photon energies during the multiferroic phase (low-T) compared to the non-multiferroic phase (high-T).

This phenomenon suggests a complex interplay between photonic excitation, multiferroic ordering, and electron tunneling dynamics. Our findings open new possibilities for controlling quantum tunneling through light-matter interactions in multiferroic systems, and paving the way for integration of photonic, spintronic, and electronic quantum devices.

Systematic Study of Dielectric Materials for GaN MISHEMTs

K. Limanta, T. Palacios
Sponsorship: U. S. Army Research Office (ARO), AFOSR

Gallium nitride (GaN) heterojunction high-electron-mobility-transistors (HEMTs) are promising candidates for next-generation high-frequency and power electronics due to their superior performance characteristics. While Schottky-gate HEMTs are the current standard for lateral GaN transistors, metal-insulator-semiconductor HEMTs (MISHEMTs) are attractive due to their high on/off ratio and low gate leakage current. A comprehensive review of different insulators is necessary to identify the optimal gate dielectric material for GaN MISHEMTs. In this study, we cover a wide range of insulators, including conventional oxides (SiO_2, Al_2O_3), high-k dielectrics (HfO_2, ZrO_2), and nitrides (SiN_x, AlN), comparing their impact on device characteristics such as gate leakage, threshold voltage shift, and interface quality. By fabricating and measuring hundreds of MISHEMTs, we can systematically evaluate the feasibility of these dielectrics for GaN MISHEMTs.



Dielectric	Deposition technique	t_{ox} (nm)
AlN	PEALD	18
SiN_x	PECVD	18
Al_2O_3	Thermal ALD	15
Al_2O_3	PEALD	18
SiO_2	PECVD	18
HfO_2	PEALD	18
ZrO_2	PEALD	15

▲ Figure 1: Device diagram (enlarged on the left). Source and drain are alloyed metal contacts. Table: Deposition technique and thicknesses of gate dielectrics. PEALD – Plasma Enhanced Atomic Layer Deposition. PECVD – Plasma Enhanced Chemical Vapor Deposition.

High-performance Multi-channel MoS_2 Transistors for Front-end-of-line Integration Beyond 1 nm Node

A. Yao, J. Zhu, Y. Jiao, A. S. Gupta, J. Kong, T. Palacios
Sponsorship: SRC Jump 2.0 SUPREME Center

Front-end-of-line (FEOL) integration of transistors based on two-dimensional (2D) materials, e.g., molybdenum disulfide (MoS_2), provide exciting opportunities for device scaling by leveraging the unique material properties of 2D materials, e.g., atomic channel thickness, large band gap, to ensure excellent gate modulation and minimum leakage. The advancements of two-dimensional (2D) materials-based microelectronics have sparked notable efforts for both industry and academic research of novel 2D front-end-of-line (FEOL) device structures such as Gate-All-Around (GAA), stacked nanosheets, multi-channel transistors (MCT), and multi-fin transistors. However, functional multi-channel transistors (2 or more channels) have not been demonstrated, and sacrificial layers (SALs) or suspended structures are also required in previous fabrication flows, which could lead to potential damage and contaminations and more complexity in the fabrication.

Here, we demonstrated double-gate, single-channel MoS_2 transistors based on a novel reduced lithography step, low-temperature, high-quality MoS_2 synthesis. These devices demonstrate a high on-current (I_{ON}) of 386 μA/μm at V_{DS}=1 V, a subthreshold swing (SS) of 85 mV/dec and low drain-induced-barrier-lowering (DIBL) of 28 mV/V, showcasing record performance among 2D GAA transistors and MCTs. Additionally, we presented the first high-performance, functional 2-channel MoS_2 transistor, which achieves 673 μA/μm I_{ON} and 88 mV/dec SS at a channel length (L_{ch}) of 400 nm. Further with design-technology co-optimization (DTCO) analysis, our studies enable projections of 2D MCT scaling, addressing power and performance demands for the "1 nm" technology node and beyond.

AFM-Based Alignment of MATBG with hBN

D. Kumawat, S. Rao, T. Iwasaki, A. L. Sharpe, K. Watanabe, T. Taniguchi, P. Jarillo-Herrerro
Sponsorship: Department of Defense

In van der Waals heterostructures, two adjacent layers with similar lattice constants and a small angle alignment create a large length-scale moire pattern, changing periodically as the atoms modulate in and out of registry. When two moire patterns are overlaid, a larger supermoire can emerge. This supermoire pattern may be relevant in magic-angle twisted bilayer graphene (MATBG) aligned with hexagonal boron nitride (hBN), where it is possible to observe a quantum anomalous hall effect (QAHE) instead of the canonical superconducting phase [1, 2]. Recent theory papers suggest that quantization relies on the percolation of a well-defined non-zero Chern number throughout the sample, arising precisely when the two moire patterns are commensurate [3, 4]. However, crystal alignment between MATBG and hBN layers at precise angles close to zero degrees is challenging, requiring the identification of crystallographic edges as armchair- or zigzag-type cleavages. We use lateral force microscopy (LFM) techniques to determine the crystal orientation with high precision. We then use torsional force microscopy (TFM) to analyze the supermoire formed by the moire patterns. By constructing devices with well-characterized stacks, we aim to connect the supermoire length scale back to stable Chern insulators in MATBG. Partially filled Chern insulator bands in such moire systems have been suggested to host fractional quasiparticles, which are candidate platforms for topological quantum computation.

Non-Toxic Solvent System for Ubiquitous Coatings of Perovskite Solar Cells

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Sponsorship: Department of Energy Grant – ADDEPT Center

Perovskite Solar Cells (PSCs) have the potential to greatly disrupt the solar landscape due to their lightweight form factors as well as their simple manufacturing process. Bottom-up analysis performed on flexible PSC photovoltaics using Monte-Carlo simulation methods shows that, at scale, flexible perovskite modules cost $0.19/W, compared to $0.30/W/module for crystalline silicon. This reduction in cost also requires the lifetime of these modules to only be around 13 years to reach similar LCOE levels, which is in direct contrast with the 25 years required for silicon. From an industrial scalability perspective, the additional air handling costs required to keep toxic solvents under the governmental guidelines for permissible exposure levels increase exponentially with factory capacity. A recent internal study shows that the air handling costs for a DMF-based system, a commonly used solvent in perovskite manufacturing, would account for up to 12.3% of the overall module cost, whereas a less toxic alternative, THF, would only account for about 0.6% of the module cost. However, because the perovskite community has not settled on one particular architecture or deposition technique, it is advantageous to develop a perovskite ink which can be used ubiquitously across device designs. Therefore, in this project we developed a non-toxic solvent system for perovskite manufacturing which can be applied to both PIN and NIP architectures and two different thin film deposition techniques for the SnO_2 ETL in NIP. Thus far we have been able to demonstrate up to 15% power conversion efficiency (PCE) for the archetypical fully slot-die coated NIP stack and greater than 10% PCE for the slot-die coated PIN architecture and chemical bath deposited (CBD) SnO_2. These results demonstrate the first non-toxic ink able to be ubiquitously applied to three different solar cell stacks, and the first scalable demonstration of coating perovskite on an underlying layer grown by CBD.

Towards a Ferroelectric High Electron Mobility Transistor for Memory Applications

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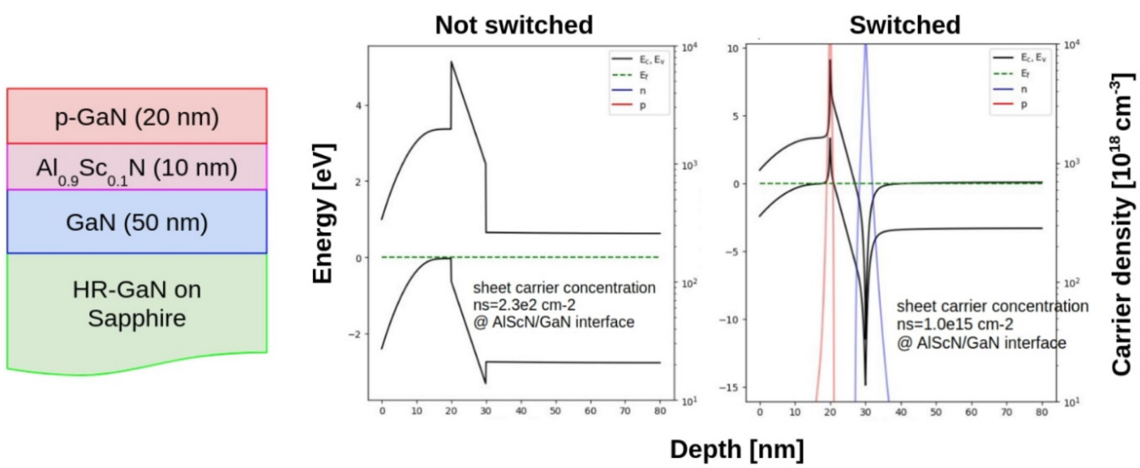
The development of ferroelectric high electron mobility transistors (FeHEMTs) presents a compelling pathway for memory applications. However, current demonstrated devices exhibit limited polarization switching capabilities, a critical feature for memory functionality. This challenge underscores the necessity for further advancements in FeHEMT design.

In this work, I used 1D Poisson simulation software to explore gate stack configurations suitable for a p-type FeHEMT (pFeHEMT) that depletes the two-dimensional electron gas (2DEG) at zero bias. This design strategy aims to achieve an enhancement-mode (E-mode) FeHEMT device controllable by polarization switching, supporting memory-like operation. Following simulation, I attempted device fabrication, but encountered significant challenges with achieving robust ohmic contacts to the 2DEG and demonstrating reliable polarization switching. These issues highlight critical areas for future research.



▲ Figure 1: (a) Gate stack design. (b) 1D Poisson band structure simulation showing E-mode behavior and switching capability.

Anomalous Hall Effect and Superconductivity in BN-aligned Magic-angle Twisted Bilayer Graphene

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Sponsorship: Department of Defense

Magic-angle twisted bilayer graphene (MATBG) hosts many exotic electronic states due to its combination of strong electron-electron correlations and band topology. Results published in 2019 reveal that MATBG, when tuned to a charge carrier density of 3 electrons per moiré cell (ν=+3), exhibits a quantum anomalous Hall effect, but not the canonical superconducting state typically observed near ν=+2]. These results are likely explained by the added moiré potential of an aligned BN which breaks inversion symmetry, gapping the otherwise protected Dirac cones of MATBG.

Using atomic force microscopy-based techniques, we verify BN alignment in a MATBG heterostructure prior to device fabrication. Subsequent transport measurements of a fabricated device reveal an anomalous Hall effect when filling 1 electron or hole per moiré cell (ν=±1). The anomalous Hall signal is comparable in both fillings, in contrast to earlier studies showing a strong particle-hole asymmetry. Additionally, we find hints of superconductivity near ν=2 despite the BN-induced inversion symmetry breaking, suggesting superconductivity and the quantum anomalous Hall effect might coexist in the same device. These findings contribute to a deeper understanding of stabilizing Chern bands in mesoscopic moiré systems, a critical step toward realizing novel fractional Chern insulator states that can serve as platforms for topological quantum computing.