

Electronic, Magnetic, Superconducting, and Spintronic Devices

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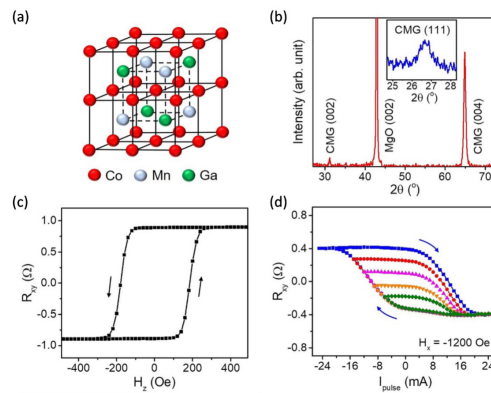
Current-induced Switching of a Ferromagnetic Weyl Semimetal Co₂MnGa

J. Han, B. C. McGoldrick, C.-T. Chou, T. S. Safi, J. T. Hou, L. Liu
Sponsorship: NSF, Semiconductor Research Corporation Program

The introduction of magnetic moments to topological materials provides rich opportunities for studying the interplay among magnetism, electron correlation, and topological orders, which can give rise to exotic magnetoelectric effects and allow one to manipulate the topologically nontrivial band structure via spintronic approaches. Weyl semimetal is a type of novel topological material that exhibits exotic magnetoelectric effects enabled by the Berry curvature around the Weyl nodes of the topological band structure. The valley conservation of Weyl node also provides a potential source of robust tunneling magnetoresistance, which can be utilized to develop energy efficient memory devices.

In this work, current-induced spin orbit torque switching of ferromagnetic Weyl semimetal Co₂MnGa perpendicular magnetic anisotropy (PMA) is demonstrated. X-ray diffraction results confirm that the Co₂MnGa is epitaxially grown and in L2₁ phase of

the $Fm\bar{3}m$ space group, which has been theoretically predicted and experimentally shown to own topological Weyl states. The strong anomalous Hall effect associated with Weyl states is also observed. The thickness of Co₂MnGa is tuned to have PMA, and current-induced switching of PMA Co₂MnGa is achieved by an adjacent Pt layer through spin-orbit torque. The reversal of the large anomalous Hall signal indicates an effective electrical control of the Berry curvatures and therefore the associated magnetoelectric effects. The efficiency of the spin-orbit torque switching is calibrated to be comparable to that in conventional ferromagnets. Given the compatibility of Co₂MnGa films with various spintronic devices and techniques, our work represents an essential step towards incorporating topological ferromagnetic materials in memory and computing



▲ Figure 1: (a) Crystal structure of Co₂MnGa (CMG), (b) XRD θ - 2θ scan of a 70-nm Co₂MnGa film grown on (001) MgO substrate, (c) Hall resistance as a function of the out-of-plane field H_z , (d) current-induced switching with different minimum writing currents.

devices.

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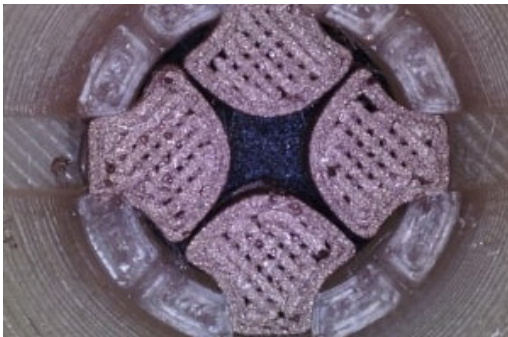
3-D Printed Quadrupole Mass Filters for CubeSat Mass Spectrometry

A. Diaz, L. F. Velásquez-García
Sponsorship: MIT Portugal

Mass spectrometry is the gold standard for quantitative chemical analysis. Mass spectrometers employ mass filters that generate electromagnetic fields to sort out in vacuum the ionized constituents of a sample based on their mass-to-charge ratio, making it possible to determine the chemical composition of the sample. However, mass spectrometers are typically large, heavy, and power hungry, restricting their deployability into in-situ, portable, and hand-held scenarios, e.g., CubeSats. Miniaturization of electronics and mass spectrometry hardware has made possible the implementation of compact instruments. Nonetheless, instrument miniaturization has been attained at the expense of great loss in performance, caused in part by fabricating unideal electrode shapes and losing assembly resolution

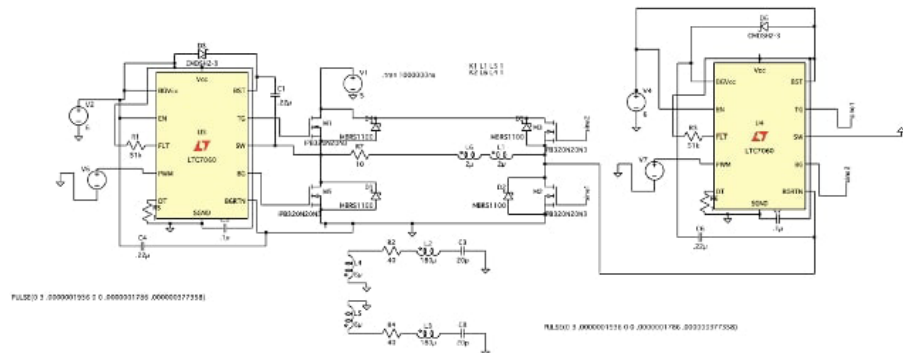
via post-assembly. Via additive manufacturing, it is possible to create monolithically and more precisely electrode shapes, avoiding some or most of the key assembly steps in a traditional mass filter, potentially resulting in hardware that performs better.

In this project we are developing compact, monolithically 3D-printed RF quadrupole mass filters that operate in the MHz range. Figure 1 shows an early-stage prototype of this filter. Moreover, the work includes developing compact, precision electronics for running the quadrupole and reading the current transmitted by the mass filter (Figure 2). We will also explore ideas for improving the performance of the mass filter, e.g., operating the devices in the second stability region.



◀ Figure 1: 3-D printed prototype of a quadrupole with conductive electrodes and non-conductive supporting structure.

▶ Figure 2: Full bridge class D amplifier setup to maximize power efficiency with a 2.65-MHz driving frequency.



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Compact, Monolithic, Additively Manufactured Quadrupole Mass Filters

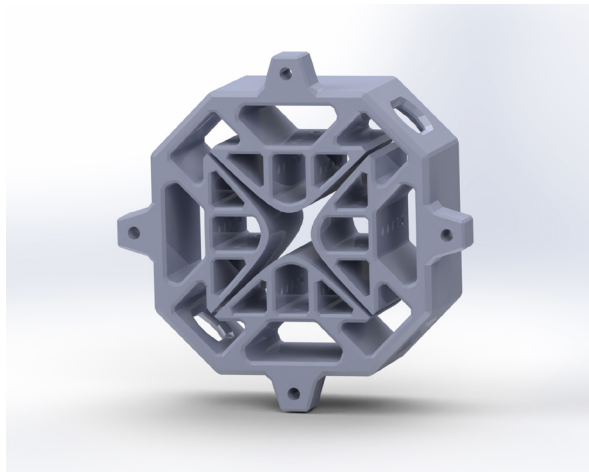
C. Eckhoff, L. F. Velásquez-García
Sponsorship: Empiriko Corporation

Mass spectrometry (MS) is the gold standard for identifying matter. Whether quantitative precision is needed to study absolute amounts of target molecules or qualitative resolving power is needed to discriminate isotopes down to a single neutron of difference, MS is often the tool of choice in the biotech and medical fields. However, the emergent focus of medical device industries on point-of-care (POC) testing has not brought with it a POC MS device satisfying the requirements of physicians and clinical regulatory agencies.

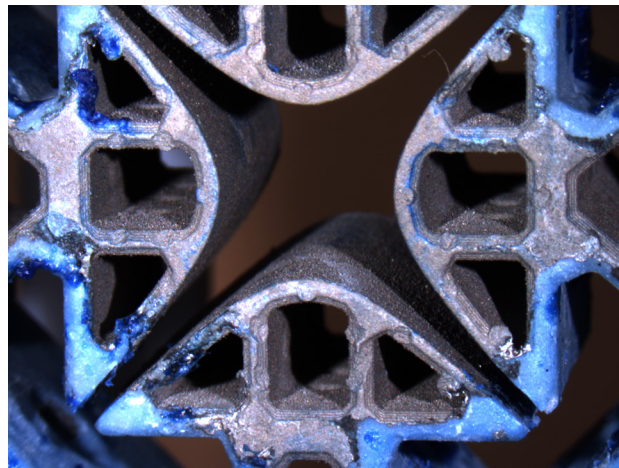
Our group seeks to improve POC MS systems by creating novel micro-electromechanical system (MEMS) mass filters, using design techniques permitted exclusively by additive manufacturing. This includes arbitrary electrode shapes, precision electrode alignment, and the efficient use of device space. Our manufacturing approach is to use a digital light processing of glass-ceramic resin to produce monolithically fabricated, pre-aligned hyperbolic electrodes (Figure 1). By integrating parts that are usually separate, monolithic designs reduce the need

for fastening, alignment, and mounting hardware. This not only reduces costs but increases assembly precision, improving quadrupole resolution. Furthermore, the hyperbolic geometry of the quadrupole electrode rods eliminates field harmonics that are present on common, commercial circular rods. Plating is used to metallize the electrodes (Figure 2), resulting in thermally stable, electrically conductive electrodes.

Additive manufacturing, mass filter design, and post-print metallization all pose challenges of their own; when these processes are combined, even greater challenges exist. Our research currently focuses on optimizing each of these processes while considering the needs and effects of the other processes. For instance, we have designed a working quadrupole filter that prints well in ceramic while also being easy to metallize. Proof-of-concept data is being collected for the early prototypes, which will guide future refinement and miniaturization of the quadrupole design.



▲ Figure 1: CAD model of singular, monolithic quadrupole mass filter.



▲ Figure 2: Close-up photo of metallized, 3D-printed electrodes.

FURTHER READING

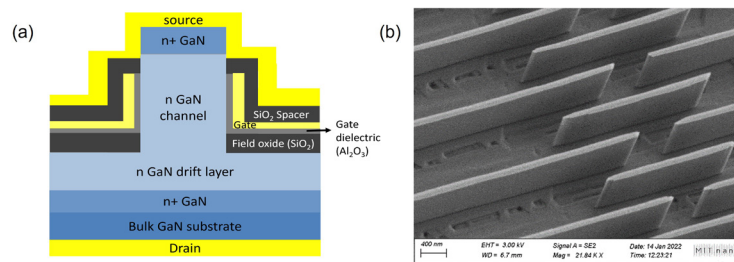
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Robust and Scalable Vertical GaN Transistor Technology

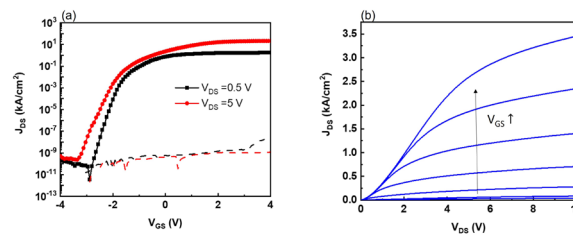
J.-H. Hsia, J. Perozek, A. Zubair, R. Molnar, J. Niroula, O. Aktas, V. Odnoblyudov, T. Palacios
Sponsorship: Advanced Research Projects Agency-Energy

Vertical GaN fin field-effect transistors (FinFETs) have attracted significant research interest due to their potential in overcoming the limitations of traditional lateral devices. The unique vertical structure provides area-independent, large breakdown voltages, improved thermal management, and reduced susceptibility to surface states, which make GaN FinFETs excellent candidates for high performance, highly scaled power and radio frequency (RF) devices. However, one of the biggest challenges in this field is the complex, low yield fabrication of these devices. Over last few years, our group has developed a robust process flow for vertical

GaN FinFETs, whose basic structure is shown in Figure 1a. One of the key fabrication technologies we use is anisotropic wet etch based on heated tetramethylammonium hydroxide, which smoothens the fin sidewalls and improves channel properties (Figure 1b). The use of this technology produced devices with high yields for both RF and power applications. Furthermore, we have obtained excellent device characteristics for our fully vertical bulk GaN devices (Figure 2). We are currently extending our fabrication technology to build more advanced vertical GaN structures, such as vertical super junction devices.



▲ Figure 1: (a) Basic device structure of vertical GaN FinFET. (b) Scanning electron microscope image of GaN fin channels with smooth sidewall.



▲ Figure 2: (a) Transfer and (b) Output characteristics of our fully vertical bulk GaN device.

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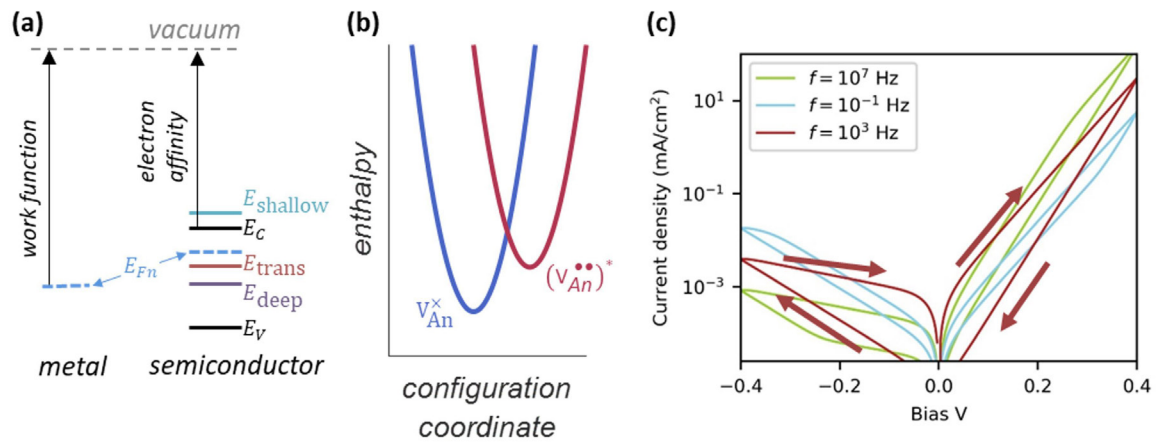
Modeling Defect-level Switching for Highly-Nonlinear and Hysteretic Electronic Devices

J. Dong, R. Jaramillo

Sponsorship: Office of Naval Research MURI (N00014-17-1-2661)

Many semiconductors feature defects with charge state transition levels that can switch due to structure changes following defect ionization: we call this defect-level switching (DLS). For example, DX centers in III-V compounds can switch between deep and shallow donor configurations. This effect is known to produce persistent photoconductivity. We recently demonstrated highly-nonlinear, hysteretic, two-terminal electronic devices using DLS in CdS. DLS devices operate in the opposite sense to most resistive switches: they are in

a high-conductivity state at equilibrium. Although DLS uses the crystal defects that are responsible for photoconductivity, DLS devices operate without light and can be orders-of-magnitude faster. In this work we use theory and numerical simulation to explore the design space of DLS devices, emphasizing the tradeoff between switching speed and on/off ratio. Our results establish a platform for future numerical optimization of circuits using DLS-based resistive switches.



▲ Figure 1: (a) Metal-semiconductor DLS heterojunction device schematic. (b) System enthalpy vs. atomic configuration around the DLS-active defect. (c) Current-voltage characteristics of a DLS device for various drive frequencies.

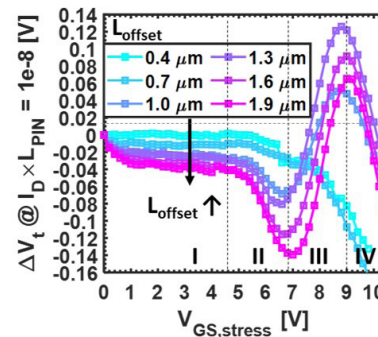
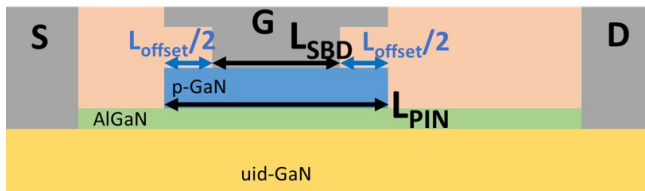
Impact of Gate Geometry on Threshold Voltage Instability of p-GaN-Gate High-electron-mobility Transistors

E. S. Lee, J. A. del Alamo
Sponsorship: Texas Instruments

Enhancement-mode GaN high-electron-mobility transistors (HEMTs) that incorporate a p-doped GaN layer in the gate stack are attractive for power electronics due to a positive threshold voltage, low resistance, and high voltage capabilities. However, the p-GaN layer brings concerns on instability of the threshold voltage. Experimental studies in this type of devices have revealed the occurrence of threshold voltage shifts, both recoverable and permanent. Furthermore, the p-GaN sidewall has been found responsible for poor reliability and excessive gate leakage. This realization suggests a gate design in which the p-GaN is longer than the Schottky gate contact, resulting in a p-GaN offset, as sketched in Figure 1. Among other considerations, it is

important to understand the reliability implications of transistor designs where the p-GaN layer is longer than the metal Schottky barrier.

We have experimentally studied the reliability of industrial pre-competitive p-GaN HEMTs with different gate dimensions. In particular, we have studied the impact of prolonged positive gate bias stress on the electrical characteristics of the devices. Our study reveals a new permanent threshold voltage degradation mechanism that uniquely takes place in the offset region of the gate. This is a concern as it might compromise long-term reliability. Our research thus reveals the existence of a constraint on how long the offset region of p-GaN HEMTs can be.



▲ Figure 1: (Left) simplified schematic of p-GaN HEMT. $L_{SBD} = 0.7\mu\text{m}$ is the metal-gate/p-GaN interface length, L_{PIN} is the p-GaN/AlGaIn/GaN heterostructure length, and $L_{offset} = L_{PIN} - L_{SBD}$. (Right) changes to V_t as a function of increasing V_{GS} step stress for devices with different L_{offset} . Regime III, associated with a prominent positive V_t shift disappears as L_{offset} is reduced below $0.7\mu\text{m}$.

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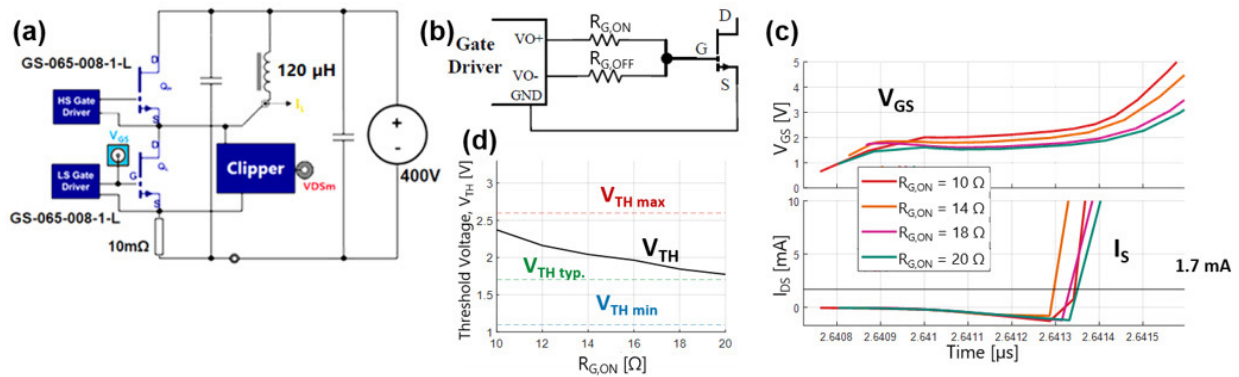
In-situ Monitoring of Dynamic Threshold Voltage in GaN Transistors Under Multi-pulse Hard-switching Conditions

A. Massuda, J. A. del Alamo
Sponsorship: Analog Devices

Recently, GaN HEMT technology entered a new generation of development and production. With the prospect of power management applications, a successful technology must meet strict reliability requirements. Since power management applications involve operating the transistors under repeated switching, reliability and robustness under pulsed operation is a concern. In this mode, parameters such as dynamic on-resistance, $R_{DS(ON)}$, and threshold voltage, V_{TH} , are subject to the influence of various trapping effects as well as permanent degradation. Since GaN HEMT has relatively low turn-on V_{TH} , it is more susceptible to high di/dt and dv/dt during the dynamic operation.

$R_{DS(ON)}$ has been the major focus in switching

reliability studies of GaN power transistors. In contrast, the impact of a shift in V_{TH} as an indicator to detect device degradation remains much less studied. This work explores a test system for in-situ monitoring of V_{TH} during sustained double-pulsed switching operation. The circuit diagram is shown in Figure 1a. By using a gate driver design with separate gate resistors for turn-on and -off (Figure 1b.), the user can fine-tune the turn-on speed to optimize the extraction of V_{TH} (Figure 1c,d). This study will contribute to understanding the impact of hard switching on dynamic V_{TH} shifts and dynamic $R_{DS(ON)}$ of GaN power transistors.



▲ Figure 1: (a) Schematic for the double-pulse test setup. (b) Gate driver design to enable selecting the right gate resistor to tune the turn-on slew rate. (c) Simulation for various R_{GON} in gate driver showing that: (d) extracted V_{TH} is within specs.

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Ising Machine Based on Electrically Coupled Spin Hall Nano-Oscillators

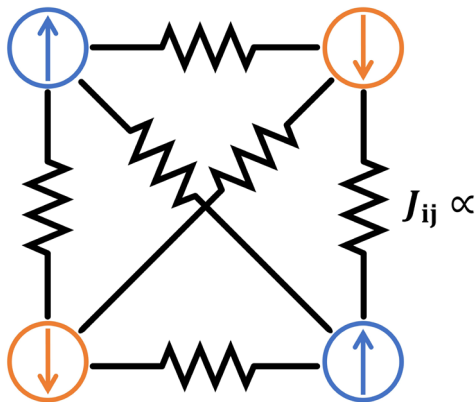
B. C. McGoldrick, J. Z. Sun, L. Liu
Sponsorship: MIT-IBM Watson AI Lab

Combinatorial optimization (CO) problems are ubiquitous in real-world applications, such as computer networking, very large-scale integration (VLSI) circuit design, and operations research. However, most of these problems remain unsolvable on traditional von Neumann computing architectures. These architectures suffer from a “bus bottleneck” whereby the shuffling of data between separate memory and computing units results in high latency. Unconventional computing architectures such as Ising machines have been proposed based on new hardware systems with novel physics that are better-suited for solving CO problems.

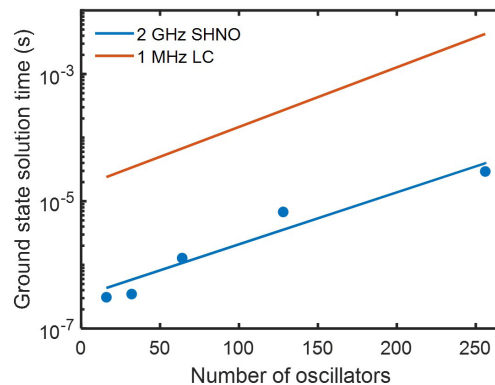
The Ising machine is composed of a coupled network of nonlinear oscillators, shown in Figure 1, on which CO problems can be mapped and subsequently solved using the natural phase synchronization dynamics. GHz spin Hall nano-oscillators (SHNOs) are a particularly attractive technology for building fast,

energy-efficient, and scalable computing systems; however, due to a lack of general modeling tools, the performance of Ising machines based on electrically coupled SHNOs has not yet been studied in detail.

In this work, we develop a new analytical framework describing SHNO synchronization that is integrated into an efficient device model for scalable circuit-level simulations of the Ising machine. We study the performance of the SHNO-based Ising machine using networks up to hundreds of coupled oscillators. As seen in Figure 2, we predict that the SHNO network can solve CO problems orders of magnitude faster than previous approaches and with ultralow power and a small footprint thanks to the devices’ nanoscale size. Our results illuminate important considerations in designing an Ising machine based on SHNOs that can efficiently solve full-scale CO problems with widely useful applications.



▲ Figure 1: Electrically coupled network of four oscillators that can be used to solve CO problems encoded by coupling weights J_{ij} .



▲ Figure 2: Solution time of SHNO Ising machine (blue) compared to previously proposed LC oscillator Ising machine (orange).

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Nanoscale Protonic Programmable Resistors for Analog Deep Learning

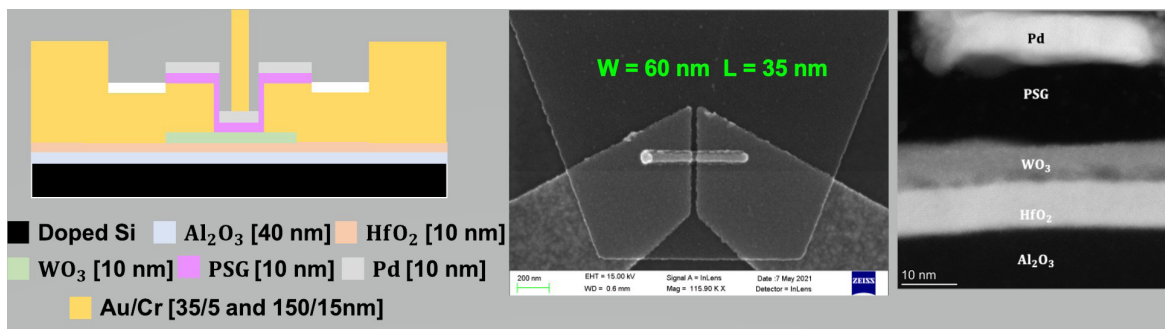
M. Onen, N. Emond, B. Wang, D. Zhang, F. M. Ross, J. Li, B. Yildiz, J. A. del Alamo
Sponsorship: MIT-IBM Watson AI Lab

Interest in engineering the ideal programmable resistor for analog deep learning applications has skyrocketed due to increasing workloads of deep learning problems. Ion intercalation-based programmable resistors have emerged as a potential next-generation technology for analog deep learning applications. While there have been previous successful demonstrations using Li^+ and O_2^- as the working ion, the former is incompatible with Si-integration whereas the latter is too large and heavy to be moved around, limiting the operation speeds and energy efficiency. In this regard, H^+ as the lightest ion available and eminently CMOS compatible is an interesting candidate.

Previously, we demonstrated the first back-end CMOS-compatible non-volatile protonic programmable resistor enabled by the integration of phosphosilicate glass (PSG) as the proton solid electrolyte layer. PSG is an outstanding solid electrolyte material that displays

both excellent protonic conduction and electronic insulation characteristics. Moreover, it is a well-known material within conventional Si fabrication, which enables precise deposition control and scalability.

In this work, we further optimize the material stack and fabrication process to realize nanoscale devices. The devices show excellent modulation characteristics by means of dynamic range, the number of states, modulation symmetry, retention, endurance, and energy efficiency. Furthermore, we provide a theoretical framework for room temperature ionics, based on electrical characterization under different operation conditions and metrological evidence obtained via TEM. This new device technology presents all-desirable characteristics to realize analog accelerators for deep learning applications and can serve as a platform to further explore ultrafast ionics.



▲ Figure 1: Cross section, scanning electron microscopic, and transmission electron microscope images of a nanoscale protonic programmable resistor

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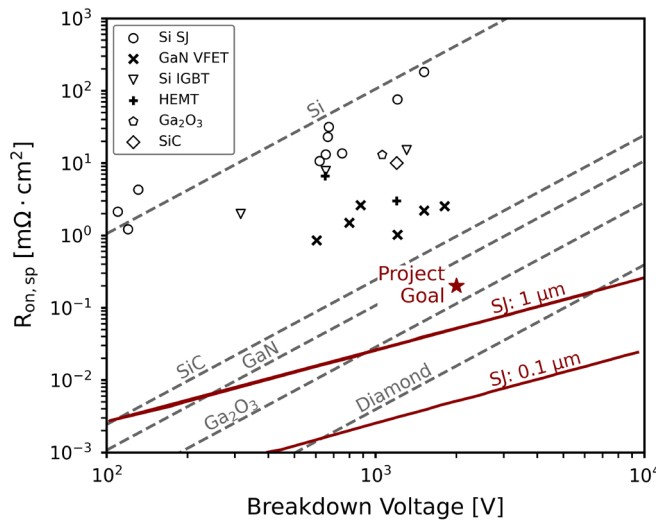
Vertical GaN Superjunction Transistors

J. Perozek, A. Zubair, R. Molnar, T. Palacios

Sponsorship: Advanced Research Projects Agency-Energy Power Nitride Doping Innovation Offers Devices Enabling SWITCHES

Increasing sustainable energy practices have spurred the need for next generation power conversion systems. At their core, these systems, which are essential for solar farms, data centers, and electric vehicles, require small, fast, and affordable power transistors. While gallium nitride (GaN) as a material is uniquely suited for these applications, existing transistors are far from optimized. Their inability to control the electric fields within the device have prevented commercial transistors from achieving the performance promised by theoretical studies.

We aim to use our expertise in fabricating vertical GaN fin field-effect transistors (FinFETs) to push beyond the unipolar limit and create the first GaN superjunction transistors. These transistors use alternating n- and p-type regions to optimize the electric field profile within the transistor to reach the theoretical limits of semiconductor performance. As shown by the red lines in Figure. 1, such devices could outperform existing tech by 50-100× and significantly improve energy conversion efficiency.



▲ Figure 1: Theoretical limits for the specific on-resistance and breakdown voltages of several material system for both unipolar (gray) and super-junction (red) based devices of varying column widths.

Nanoporous Gadolinium-doped Ceria-based Protonic Solid-state Electrochemical Synapse for CMOS-compatible Neuromorphic Computing

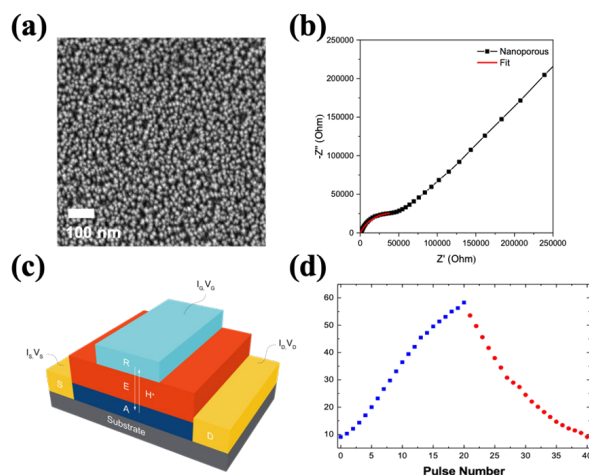
S. Ryu, H. G. Seo, M. Huang, J. A. del Alamo, J. Li, B. Yildiz
Sponsorship: MIT-IBM Watson AI Lab

Artificial neural networks offer great opportunities in artificial intelligence application. However, the hardware structures must overcome the decreasing scaling effectiveness of transistors and the intrinsic inefficiency of employing transistors in von-Neumann computing architectures. Diverse physical neural networks have demonstrated promising implementation of machine learning algorithms. However, currently developed physical processors suffer from poor device-to-device uniformity or high energy dissipation.

To address the issue, we mainly focus on protonic electrochemical artificial synapses. Protons are the smallest ions requiring low energy for transport, and the protonic synapse modulates conductance states via electrochemical proton intercalation. Therefore, the protonic electrochemical memristors can realize low energy computation using shuffling of protons. Also, uniform switching properties can be obtained by

controlling a fixed number of protons and electrons into active switching channel materials.

However, most conventional protonic electrochemical artificial synapses are incompatible with complementary metal-oxide-semiconductor (CMOS) fabrication due to polymeric proton electrolytes. Inspired by our former research demonstrating a CMOS-compatible protonic programmable resistor, we developed nanoporous Gd-doped ceria as an inorganic solid proton electrolyte, which provides efficient proton transport at room temperature via physisorbed water channels at the open pores. Controlling microstructures enables higher proton conductivities in the electrolytes and low energy computation based on controlling proton movement. This work provides a path to solution of CMOS-compatible energy efficient computing.



▲ Figure 1. (a) Top view scanning electron microscope image of nanoporous Gd:CeO₂ proton electrolytes. (b) Electrochemical impedance spectroscopic analysis of nanoporous Gd:CeO₂ electrolytes. (c) Device schematics of protonic electrochemical random access memory consist of proton reservoir (R), proton electrolytes (E), and active switching channel (A), source and drain (S & D). (d): Representative conductance modulation characteristics of the device.

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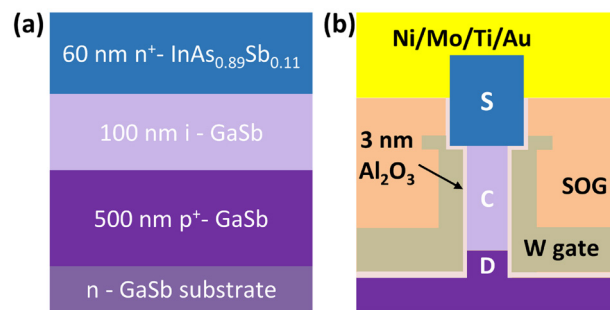
Sub-10-nm Diameter Vertical Nanowire p-Type GaSb/InAsSb Tunnel FETs

Y. Shao, J. A. del Alamo
Sponsorship: Intel Corporation

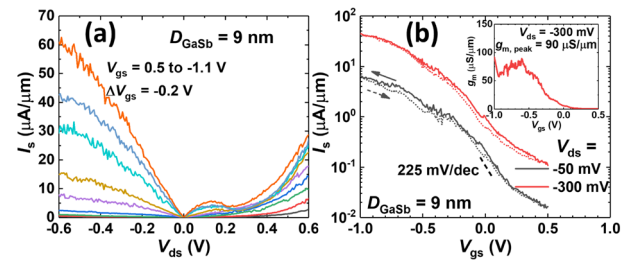
Tunnel field-effect transistors (TFETs) have attracted great attention due to their ability to operate with a sub-thermal subthreshold swing (S), which promises significant reduction in supply voltage and static power consumption in logic circuits. III-V materials are of particular interest in designing TFETs, thanks to the flexibility of band engineering and their superior transport properties. To date, III-V n-type TFETs with $S < 60$ mV/dec and decent drive current have been demonstrated. Nevertheless, for application in logic circuits, a complementary p-type III-V TFET is needed, preferably with similar performance to that of the n-type devices.

In this work, we have fabricated sub-10-nm

diameter vertical nanowire (VNW) GaSb/InAsSb broken-band p-type TFETs through a top-down approach. One of our devices demonstrates a peak transconductance of $90 \mu\text{S}/\mu\text{m}$ at $|V_{ds}| = 0.3$ V, which improves the state-of-the-art 3-D p-type TFETs by 100%. A linear S_{min} of 225 mV/dec is obtained in the same device, demonstrating a good balance between on-state and subthreshold regime. Clear negative differential resistance is observed at room temperature, a first in any III-V p-type TFETs, with the highest peak-to-valley-current-ratio being 3.1. This work shows the great potential of ultra-scaled III-V VNW TFETs on future complementary logic circuit applications.



▲ Figure 1: Schematics of (a) starting heterostructure and (b) device cross-sectional view.



▲ Figure 2: (a) Output and (b) transfer characteristics of a $D = 9$ nm device. Inset in (b) shows the smoothed transconductance extracted at $V_{ds} = -0.3$ V.

FURTHER READING

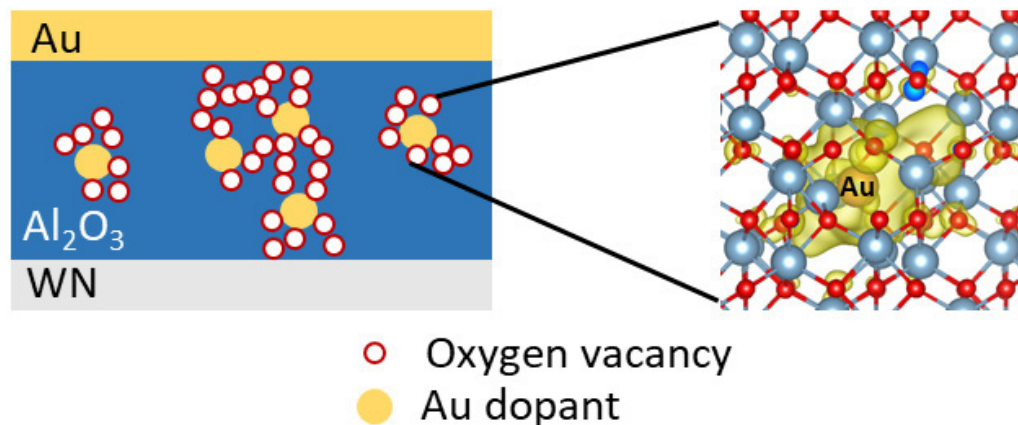
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Electronegative Metal Dopants Reduce Switching Variability in Al_2O_3 -resistive Switching Devices

V. Somjit, Z. J. Tan, C. Toparli, N. Fang, B. Yildiz

Brain-inspired or neuromorphic hardware holds great promise to reduce energy consumption and accelerate training and inference of deep neural networks. In particular, oxide-based electronics can emulate long- and short-term memory and spiking neurons of the brain by switching the oxide's resistive state via the strength and number of conductive networks. However, high variability of these resistive switching devices is a key drawback hindering reliable training of physical neural networks. In this study, we show that doping an oxide electrolyte, Al_2O_3 , with electronegative metals makes resistive switching significantly more reproducible, surpassing the reproducibility requirements for obtaining reliable hardware neuromorphic circuits. Using first principles calculations, we identify that the under-

lying mechanism is the ease of creating oxygen vacancies in the vicinity of electronegative dopants, due to the capture of the associated electrons by dopant mid-gap states and the weakening of Al-O bonds. These oxygen vacancies and vacancy clusters also bind significantly to the dopant, thereby serving as preferential sites and building blocks in the formation of conductive oxygen vacancy networks. We validate this theory experimentally by implanting multiple dopants over a range of electronegativities and find superior repeatability with highly electronegative metals, Au, Pt, and Pd. These results establish dopant electronegativity as a descriptor for predicting the ease of oxygen vacancy formation in an insulating oxide, with implications for reducing switching variability.



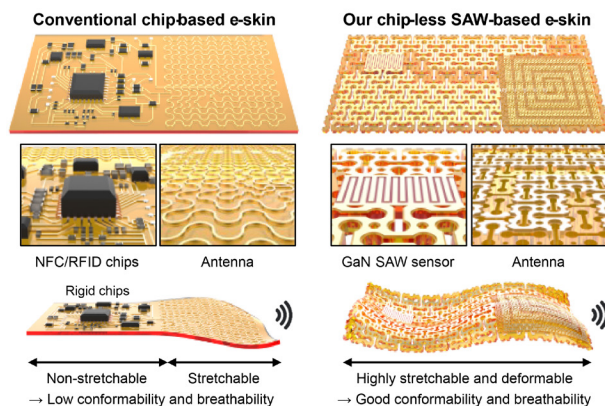
▲ Figure 1: Schematic of proposed switching mechanism in Au-doped Al_2O_3 : presence of Au reduces oxygen vacancy formation energy, giving rise to oxygen vacancy clusters preferentially formed around Au, improving switching consistency

Chip-less Wireless Electronic Skins Enabled by Epitaxial Freestanding Compound Semiconductors

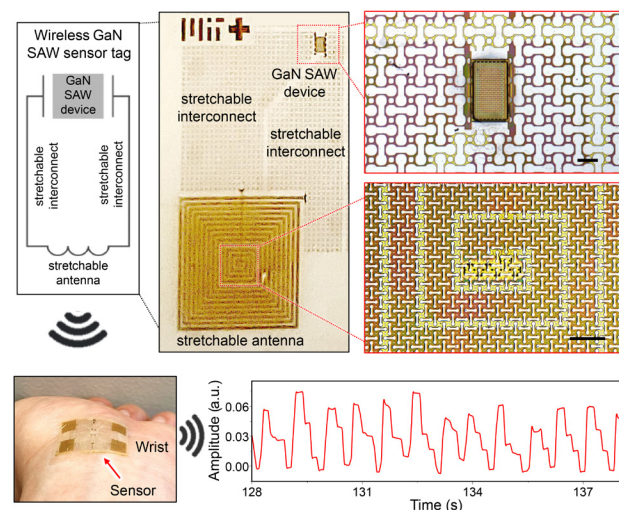
Y. Kim, J. M. Suh, Y. Liu, J. Shin, J. Kim
Sponsorship: Amore Pacific

Electronic skin (e-skin) has been developed with a goal to obtain a non-invasive human health monitoring electronic system with its imperceptibility. So far, one of the major shortcomings in this field is the bulky wireless communication system that severely affects its wearability (Figure 1). In this paper, we introduce a single-crystalline non-Si-based e-skin system where fully conformable, ultrathin, piezoelectric, compound semiconductor membranes are incorporated as power-efficient wireless communication modules and extremely high sensitivity sensors without needing bulky chips and batteries. The developed GaN surface

acoustic wave (SAW)-based device successfully measured wirelessly three different inputs including strain, ultraviolet light, and ion concentrations (Figure 2). The consistency and accuracy of the measured heart rate and pulse waveforms over a 7-day period, during which the e-skin was re-attached 7 times, strongly demonstrate the reusability and long-term wearability of our device. This study will change the paradigm of e-skins by providing versatile wireless platforms for fully imperceptible e-skins with very high sensitivity and low power consumption.



▲ Figure 1: Comparison between (left) conventional wireless e-skin based on integrated circuit chips and (right) chip-less wireless e-skin based on SAW devices made of GaN freestanding membranes.



▲ Figure 2: Schematic and optical images of our wireless GaN SAW e-skin strain sensor and wireless pulse measurements using GaN SAW e-skin strain sensors. Scale bars indicate 200 μm .

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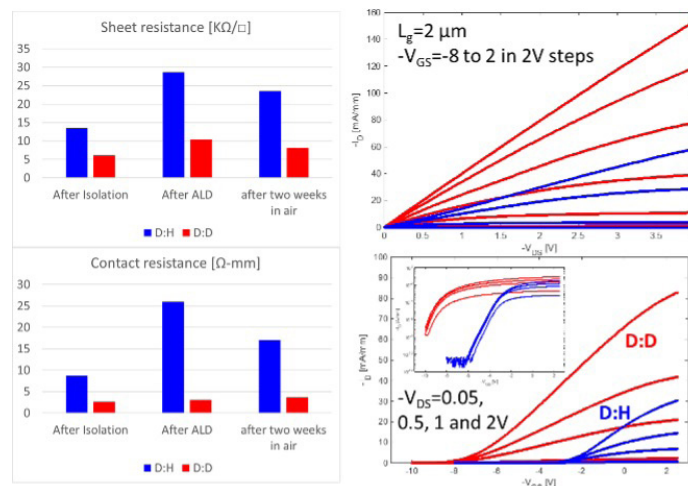
Deuterium-terminated Diamond Field-effect Transistor

A. Vardi, M. Geis, B. Zhang, J. A. del Alamo
Sponsorship: DARPA, Bose Fellowship

Due to its extraordinary thermal conductivity, wide bandgap, and large saturation velocity, diamond is a very promising semiconductor for high-power/high-frequency applications. The standard way to form a conducting channel on diamond is by exposing it to hydrogen plasma in a so-called hydrogen termination (D:H) process. This enables the formation of a two-dimensional-hole-gas which can form the basis of a field-effect transistor (FET).

Although the carbon-hydrogen bonds that form on the diamond surface after hydrogenation are stable, it is often observed that during the fabrication process of diamond FETs that there is severe degradation in the channel conductivity and contact resistance. In this work, we explore deuterium termination, diamond-

deuterium (D:D), as a way to increase the device stability during the fabrication process. Figure 1 shows the result of the experiment. Initially, D:D gives better results than diamond:hydrogen (D:H), but more significantly, throughout the process, D:H shows a dramatic increase in sheet and contact resistance that persists after the process is completed, while D:D exhibits a lower and stable sheet and contact resistances that are retained well after the process is completed. The figure also compares the transistor characteristics; notably, D:D devices show higher current and deeper depletion-mode characteristics. This all suggests that the available 2D hole concentration in the D:D device is higher and more stable than in the standard D:H device.



▲ Figure 1: Left: sheet and contact resistance of D:H and D:D throughout and after the process. Right: output, transfer, and sub-threshold (inset) characteristics of D:H and D:D FETs.

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NbN-Gated GaN Transistor Technology for Applications in Quantum Computing Systems

Q. Xie, N. Chowdhury, A. Zubair, M. S. Lozano, J. Lemettinen, M. Colangelo, O. Medeiros, I. Charaev, K. K. Berggren, T. Palacios
Sponsorship: IBM

High-performance and scalable cryogenic electronics is an essential component of future quantum information systems, which typically operate below 4 K. Superconducting qubits need advanced radio frequency (RF) and pulse-shaping electronics, which typically occupy large instrumentation racks operating at room temperature. Today's approach to the RF control electronics is not scalable to the millions of physical qubits needed in future fault-tolerant quantum systems.

This work explores the use of wide band gap electronics, specifically the AlGaN/GaN high-electron-mobility transistor (HEMT), for cryogenic low-noise applications. These structures take advantage of the polarization-induced two-dimensional electron gas to create a high mobility channel, hence eliminating the heavy doping needed in the other semiconductor technologies. Epitaxially-grown GaN-on-silicon wafers have been demonstrated in large (300 mm) substrates, therefore making the technology an excellent candidate for scalable RF electronics in quantum computing systems.

Furthermore, the use of electrodes using superconducting materials is proposed to significantly reduce the parasitic components and therefore push the RF performance of cryogenic transistors. Short-channel transistors with NbN gates of length 250 nm have been demonstrated with promising performance at 4.2 K.

In the next step, we will study the effect of the superconducting gate on the RF characteristics of the transistors, with the eventual goal of pushing the frequency performance of these transistors to new limits. Improvements to the NbN gate fabrication technology is underway. These transistors will be integrated into low noise amplifier circuits for applications in readout and control electronics at cryogenic temperature. Furthermore, the demonstrated NbN-gated GaN transistor paves the way for the application of high-frequency GaN technology in cryogenic electronics, notably in scalable quantum computing systems, and brings us one step closer to an all-nitride integrated electronics-quantum device platform.

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Self-aligned Enhancement-mode GaN p-Channel FinFET with $I_{ON} > 100$ mA/mm and $I_{ON}/I_{OFF} > 10^7$

N. Chowdhury, Q. Xie, T. Palacios
Sponsorship: Intel Corporation

This work demonstrates self-aligned p-channel fin field-effect transistors (FinFETs) based on a GaN-on-Si wafer. While the self-aligned gate process helps to achieve shortest possible source-to-drain distance to compensate for low hole mobility in GaN (~ 20 cm²/V·s), the FinFET architecture provides strong electrostatic control over the channel. Our fabricated transistors with 40-nm fin width, LSD=120 nm, and LG=90 nm exhibits an $I_{ON} \approx 140$ mA/mm, $I_{ON}/I_{OFF} > 10^7$, $V_{TH} = 1$ V, $SS = 150$ mV/dec, $g_{m,max} = 14$ mS/mm, and $RON = 61$ Ω ·mm. By precisely controlling the recess depth, enhancement-mode (E-mode) operation was also achieved. Our best E-mode device shows an $I_{ON} \approx 125$ mA/mm, $I_{ON}/I_{OFF} > 10^7$, $V_{TH} = -0.3$ V, and $RON = 69$ Ω ·mm. In addition, record low subthreshold swing of 80 mV/dec for devices with fin width of 40 nm and LSD=240 nm attests to the strong gate control over the p-channel achieved by the FinFET-architecture.

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Tungsten-gated GaN/AlGaN p-FET with $I_{max} > 120$ mA/mm on GaN-on-Si

N. Chowdhury, Q. Xie, T. Palacios
Sponsorship: Intel Corporation

This work demonstrates tungsten (W)-gated p-channel GaN/AlGaN heterostructure field-effect transistors (FETs) on a GaN-on-Si wafer grown by metal organic chemical vapor deposition (MOCVD). The choice of W as the gate metal over the more commonly used Mo induces larger turn-on voltage and lower gate leakage current. An annealing step at 500 °C in N₂ ambient was introduced to heal the damage introduced during the gate recess step, which resulted in lower channel resistance. Long-channel W-gated p-FETs with LSD=5.5 μm

and LG=1.5 μm exhibit an $I_{ON} \approx 25$ mA/mm and $I_{ON}/I_{OFF} > 103$. A scaled transistor of dimensions LSD=1.2 μm and LG=100 nm demonstrates an $I_{ON} \approx 125$ mA/mm, $I_{ON}/I_{OFF} \approx 104$, and RON=170 Ω·mm. To the best of the authors' knowledge, the reported device performance represents the state-of-the-art of all planar GaN/AlGaN p-FETs and is comparable with high voltage Si FET on the 65-nm node.

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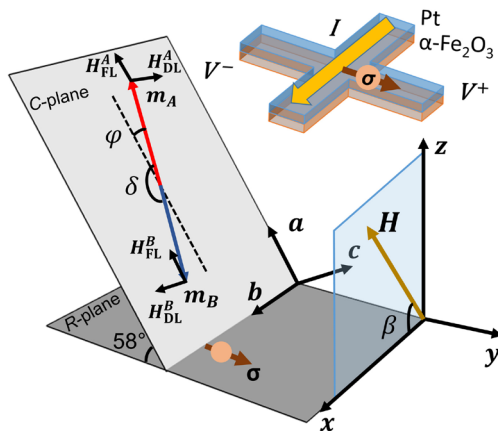
Efficient Spin-orbit Torques in an Antiferromagnetic Insulator with a Tilted Easy Plane

P. Zhang, C.-T. Chou, H. Yun, B. C. McGoldrick, J. T. Hou, K. A. Mkhoyan, L. Liu

Sponsorship: NSF, U.S. Air Force Office of Scientific Research, Taiwan Semiconductor Manufacturing Company, Semiconductor Research Corporation SMART Center, Mathworks Fellowship

Electrical manipulation of spin textures inside antiferromagnets represents a new opportunity for developing spintronics with superior speed and high device density. Injecting spin currents into antiferromagnets and realizing efficient spin-orbit-torque-induced switching is, however, still challenging due to the complicated interactions from different sublattices. Meanwhile, because of the diminishing magnetic susceptibility, the nature and the magnitude of current-induced magnetic dynamics remain poorly characterized in antiferromagnets, whereas spurious effects further complicate experimental interpretations.

In this work, by growing a thin film antiferromagnetic insulator, α -Fe₂O₃, along its non-basal plane orientation, we realize a configuration where an injected spin current can robustly rotate the Néel vector within the tilted easy plane, with an



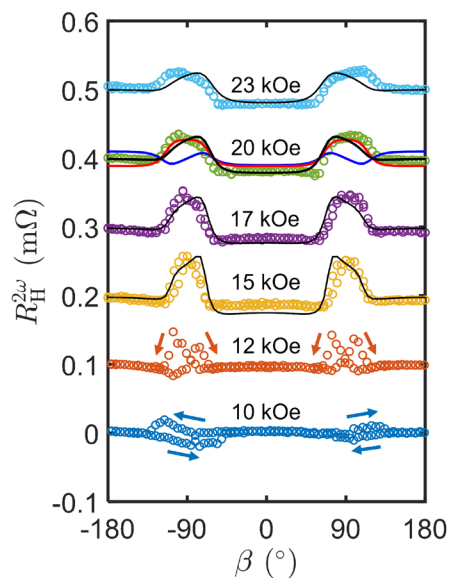
▲ Figure 1: 30 nm of α -Fe₂O₃ layer was epitaxially grown on an α -Al₂O₃ R-plane (0112) substrate and further covered by 5 nm of Pt, and patterned into Hall bar devices. Inset: The current channel is parallel to the axis, and the generated spin magnetic moment is parallel to the χ [2110] axis and generated spin magnetic moment is parallel to γ axis. The magnetic easy plane of α -Fe₂O₃ is the tilted C-plane (0001). The external magnetic field is rotated within the xz plane, with the angle defined as β . Damping-like torque effective fields H_{DL} rotate the antiferromagnetic sublattice moments m_A and m_B constructively, while the field-like torque H_{FL} does not.

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efficiency comparable to that of classical ferromagnets. The experimental configuration is illustrated in Figure 1. By measuring the second-harmonic Hall resistance, as shown in Figure 2, we find that the spin-orbit torque effect stands out among competing mechanisms and leads to clear switching dynamics. Thanks to this new mechanism, in contrast to the usually employed orthogonal switching geometry, we achieve bipolar antiferromagnetic switching by applying positive and negative currents along the same channel, a geometry that is more practical for device applications.

By enabling efficient spin-orbit torque control on the antiferromagnetic ordering, the tilted easy plane geometry introduces a new platform for quantitatively understanding switching and oscillation dynamics in antiferromagnets.



▲ Figure 2: The angle-dependent second-harmonic Hall resistance $R_H^{2\omega}$ as a function of β , at different external fields. The current is 4 mA (root mean square value). H_{DL} (red) and H_{FL} (blue) contributions to $R_H^{2\omega}$ at $H = 20$ kOe are separately plotted. H_{DL} corresponds to a damping-like torque efficiency $\xi_{DL} = 0.015$ comparable to the value of Pt - Ferrimagnetic Insulator bilayers.