Purdue ECE MN Area Research

Muhammad Ashraful Alam, Joerg Appenzeller, Zhihong Chen, Supriyo Datta, Sumeet Gupta,

David Janes, Gerhard Klimeck, Mark Lundstrom, Dana Weinstein, Pramey Upadhyaya, Peide Ye

Microelectronics and Nanotechnology Area

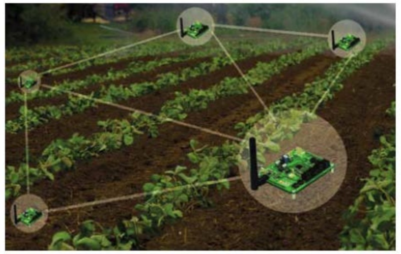
School of Electrical and Computer Engineering

PURDUE UNIVERSITY

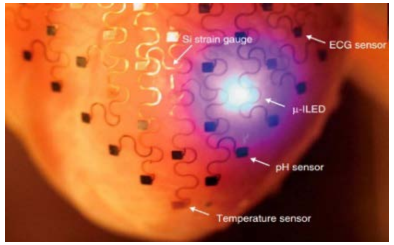
Reliability Physics of Classical and Emerging Electronic Devices (CEED)

Muhammad A. Alam

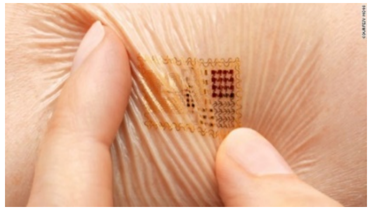
Power Electronics



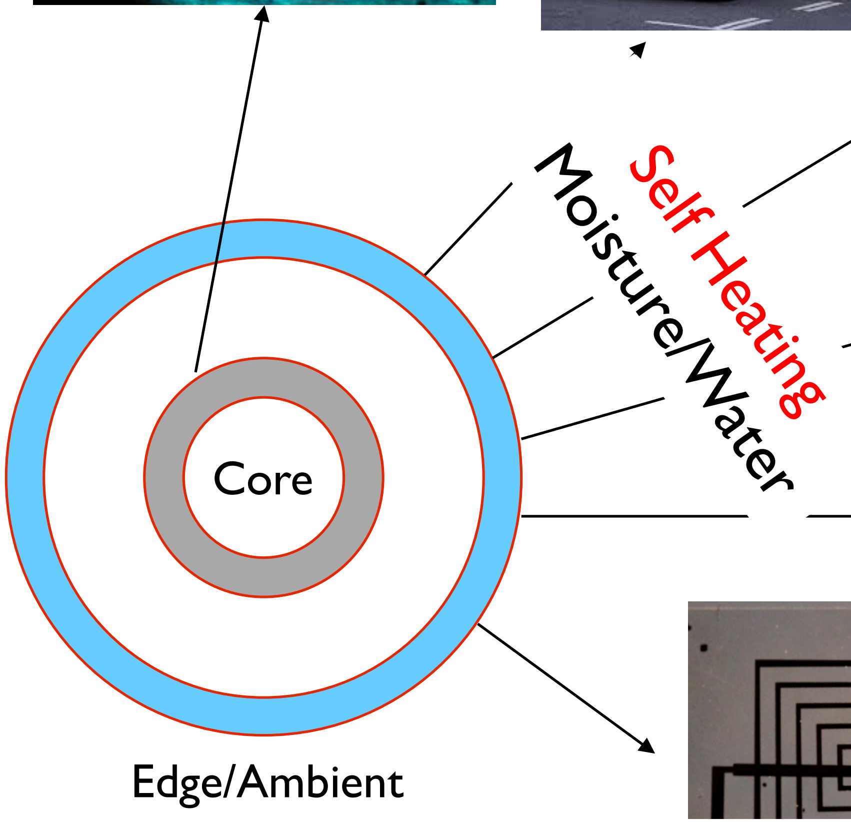
Precision Agriculture

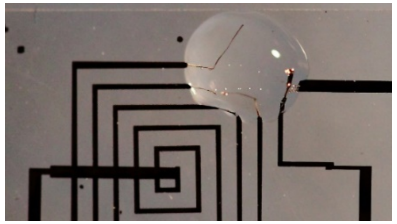


Implantable Electronics



Flexible Electronics

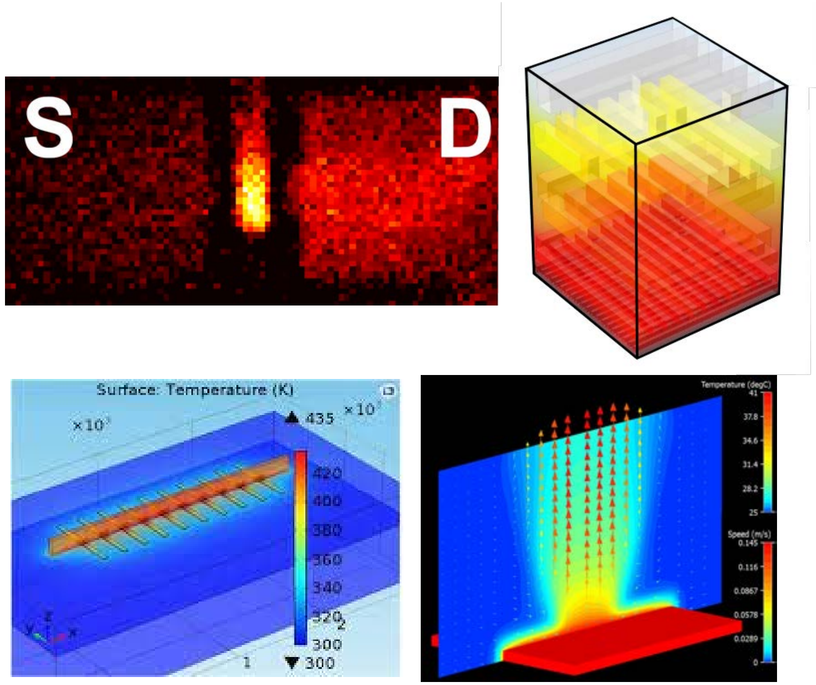




Programmable reliability
Self healing

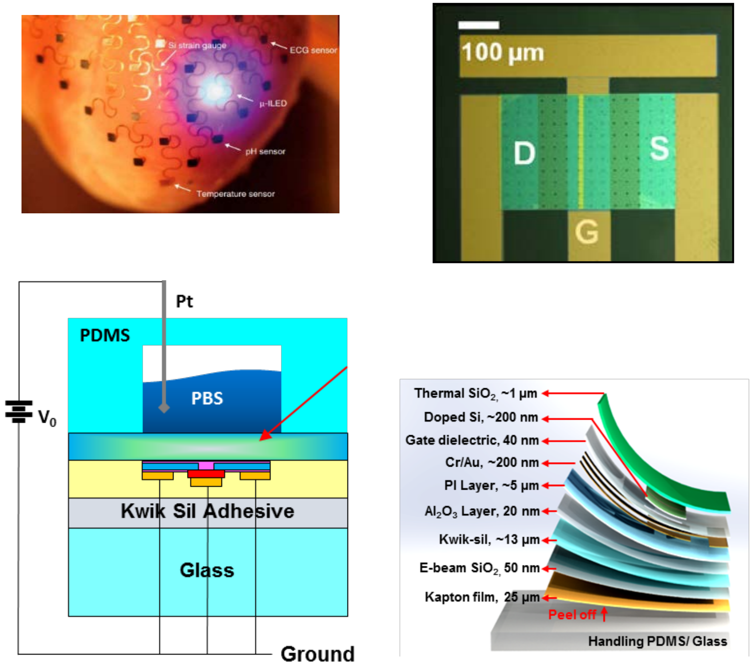
CEED: Challenges and Opportunities

Integrated Circuits
IC and Mission-specific Self-heating
FEOL/BEOL/Mold-compound interactions
Reliability as a design variable



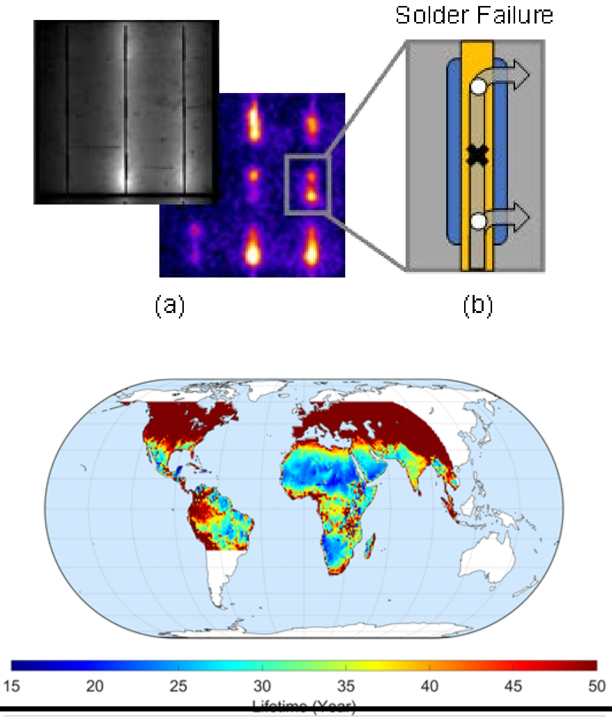
IEEE TED 2017, 2018, 2020

Biosensors
Calibration-drift in harsh/uncontrolled
Environment; Next generation packaging,
Reliable sensing in unreliable environment



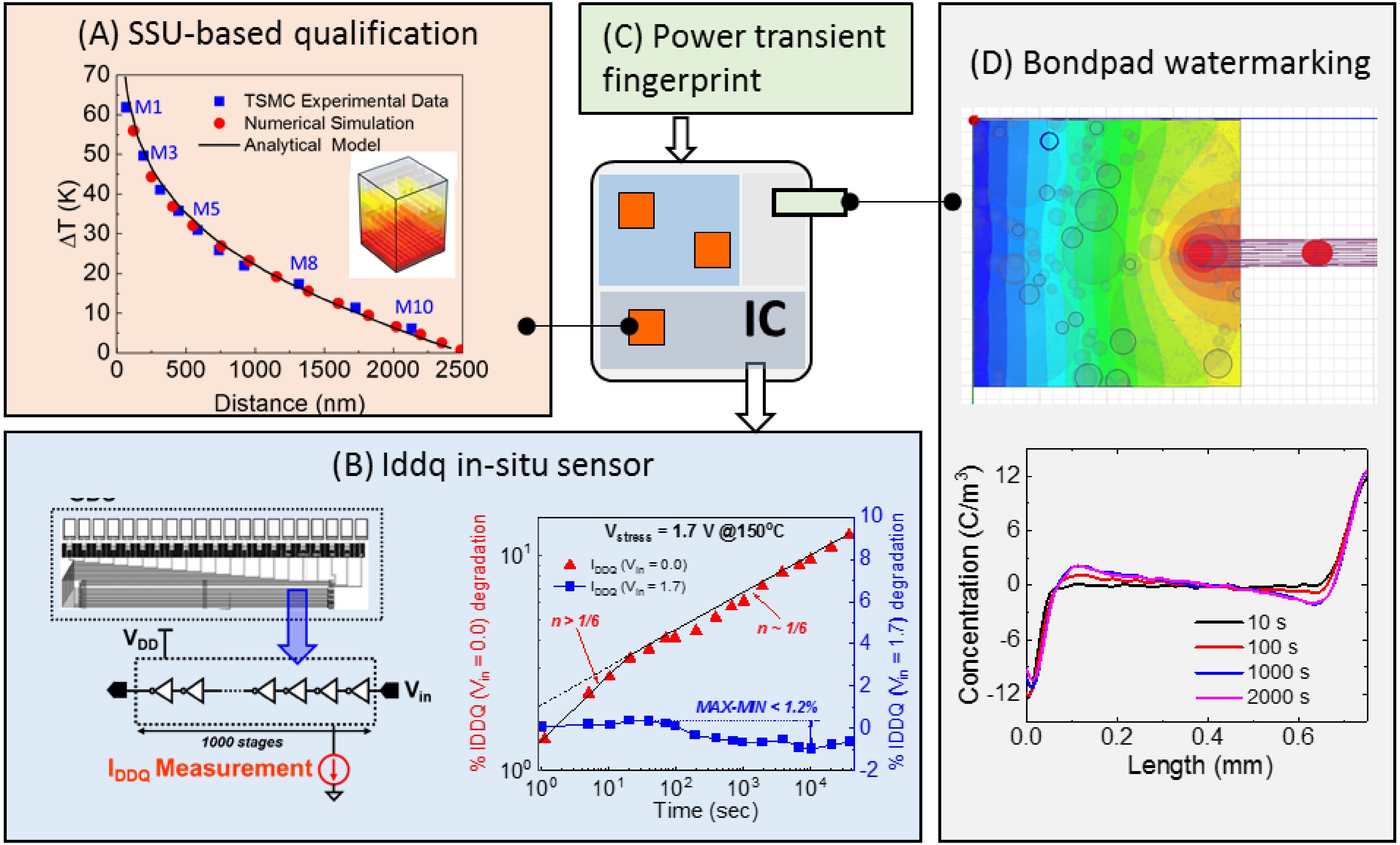
IEEE TED 2020, PNAS 2019

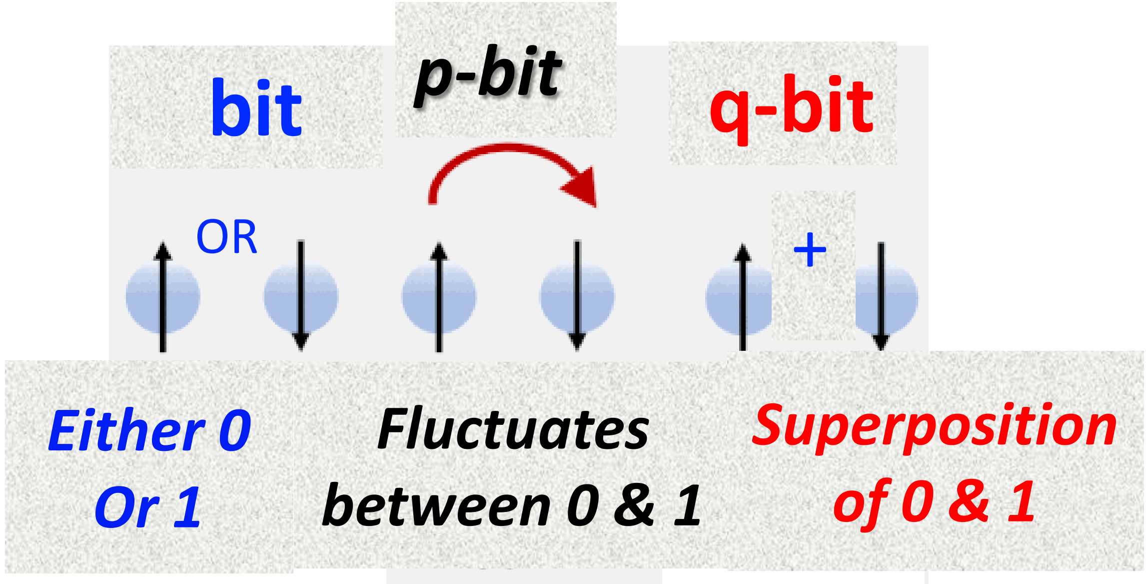
Energy harvesters
Technology suitable for highly
Variable weather conditions
Location-aware reliability



JPV 2019, Applied Energy 2021

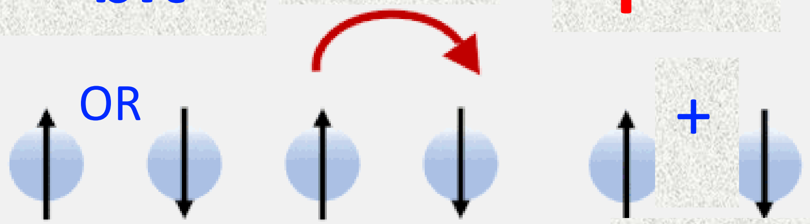
“Intrinsic Odometers” for Secure Electronics





Supriyo Datta

bit | ***p-bit*** | **q-bit**



Either 0 Or 1

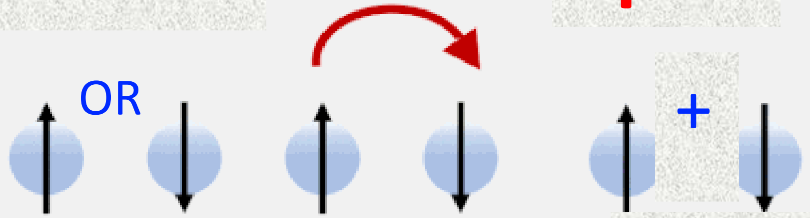
Fluctuates between 0 & 1

Superposition of 0 & 1

Digital Computing

Quantum Computing

bit	p-bit	q-bit



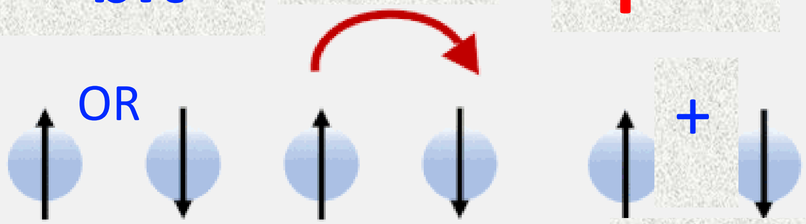
Either 0 Or 1	***Fluctuates between 0 & 1***	***Superposition of 0 & 1***

Digital Computing

Quantum Computing

Building Block
Probabilistic Computing

bit **p-bit** **q-bit**



Either 0 Or 1	*Fluctuates between 0 & 1*	*Superposition of 0 & 1*
Digital Computing		*Quantum Computing*

Building Block

Probabilistic Computing

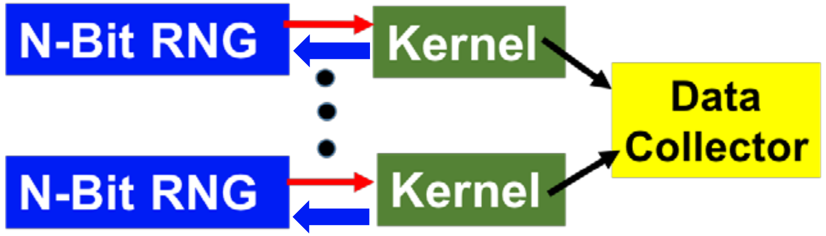
Stochastic Algorithms

Monte Carlo

Optimization

Markov Chain Monte Carlo

Multi-Dimensional Integration | Matrix Multiplication | Quantum Monte Carlo | • • | Drug Discovery | Molecular Dynamics



Easy to parallelize

"Architecture"

Building Block

Probabilistic Computing

Stochastic Algorithms

Monte Carlo

Optimization

Markov Chain Monte Carlo

Multi-Dimensional Integration

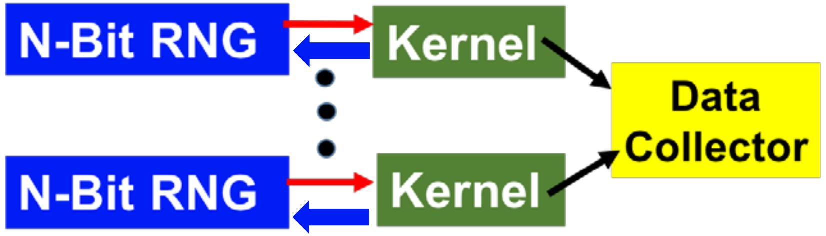
Matrix Multiplication

Quantum Monte Carlo

• •

Drug Discovery

Molecular Dynamics



125 MHz FPGA

Available for public use at https://www.purdue.edu/p-bit/

IEEE Access 8, 157238 (2020)

Easy to parallelize

"Architecture"

Building Block
Probabilistic Computing

Stochastic Algorithms

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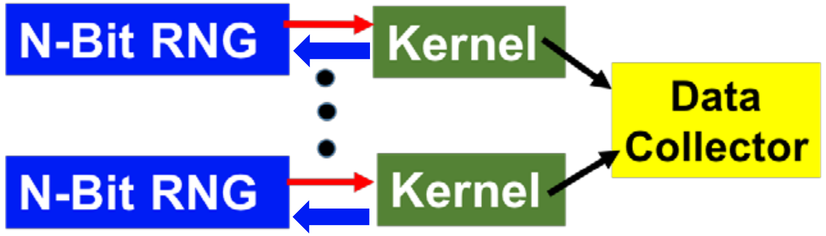
Multi-Dimensional Integration | **Matrix Multiplication** | **Quantum Monte Carlo** | • • | **Drug Discovery** | **Molecular Dynamics**



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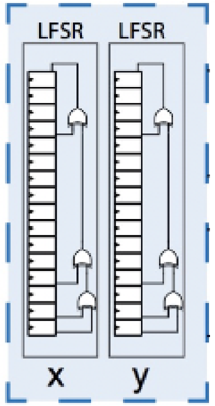
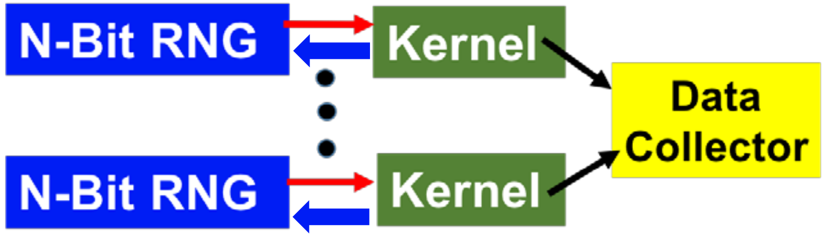
Easy to parallelize

"Architecture"

Physics-Based Drop-in Replacement

1000's of transistors





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IEEE Access 8, 157238 (2020)

Easy to parallelize

"Architecture"

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Nature 573, *7774 (2019)*

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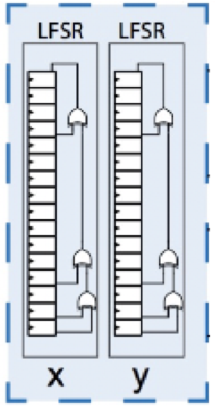
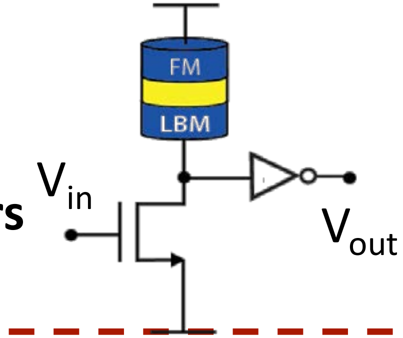
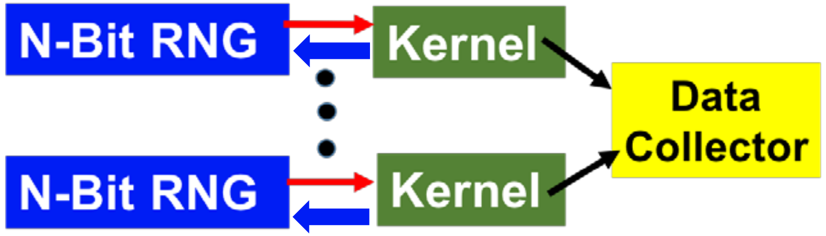


3 transistors + 1 s-MTJ





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IEEE Access 8, 157238 (2020)

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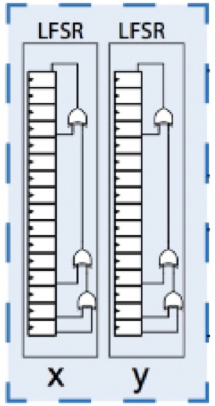

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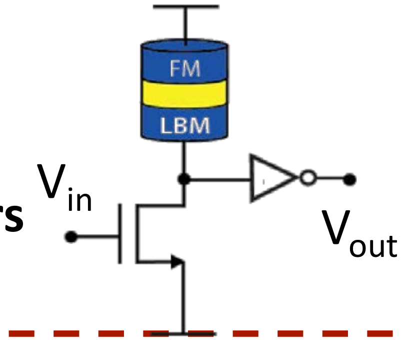
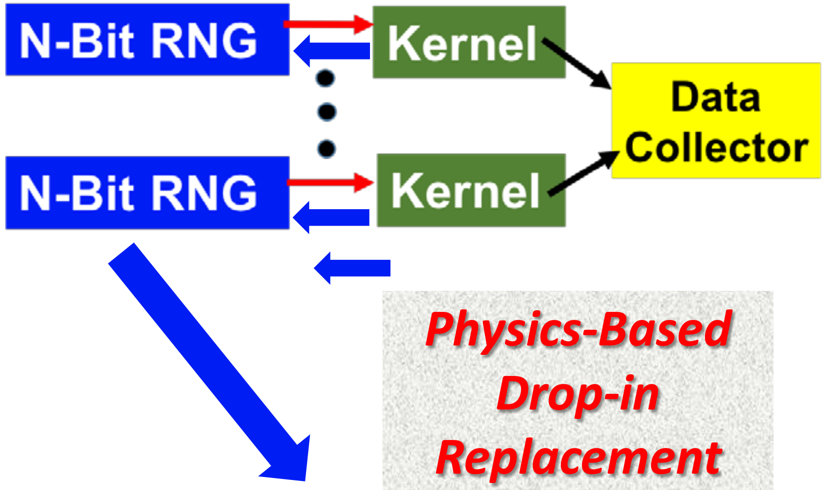


Nanosecond fluctuations in resistance

Experimentally demonstrated



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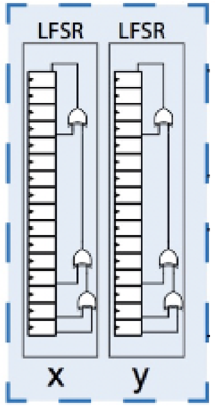

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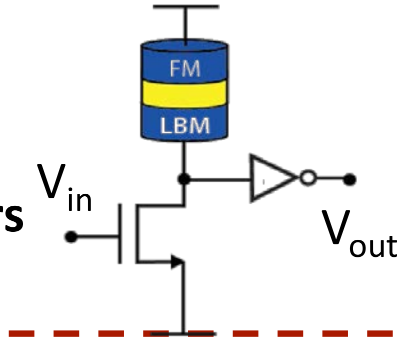


Nanosecond fluctuations in resistance

Experimentally demonstrated

Monte Carlo

Optimization

Markov Chain Monte Carlo

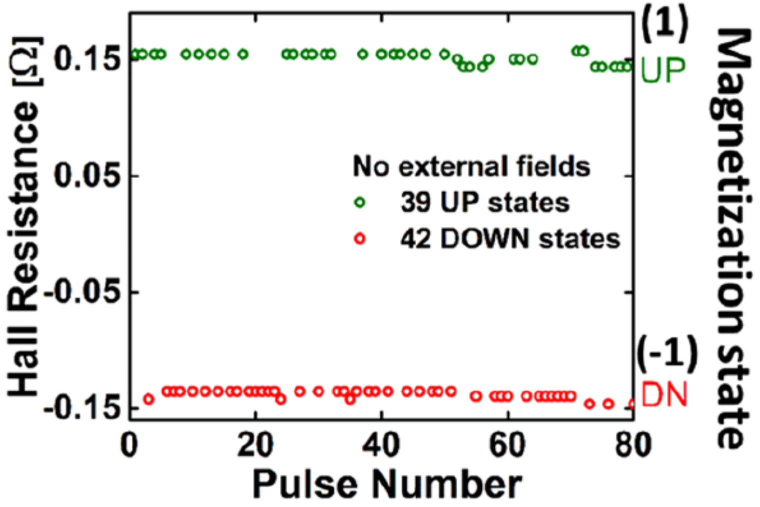
Multi-Dimensional Integration	Matrix Multiplication	Quantum Monte Carlo	• •	Drug Discovery	Molecular Dynamics

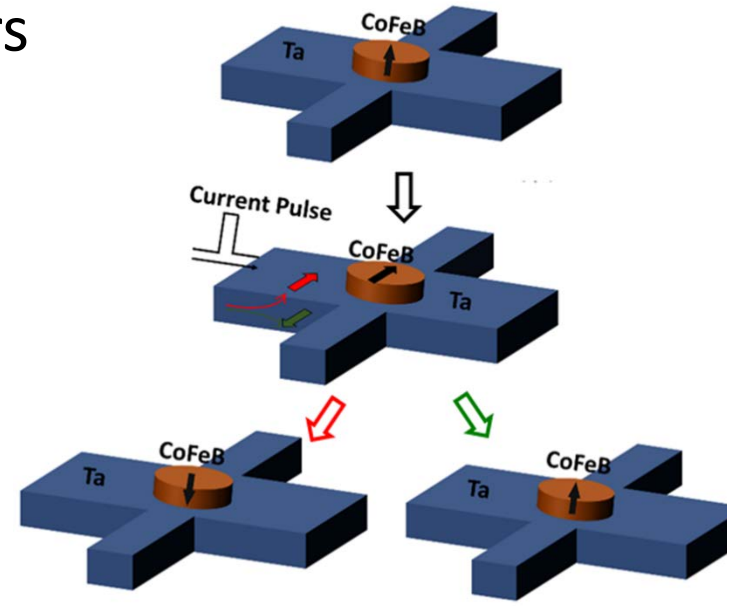
Experimental work on p-bits and circuits

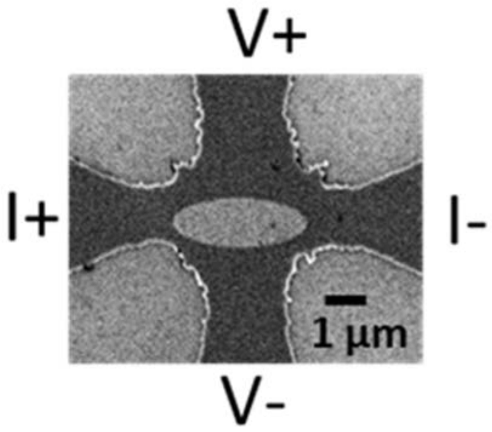
Joerg Appenzeller

Tunable random number generators

1. Spin Orbit Torque (SOT) current pulse for hard axis initialization (*clock*)







PMA magnet on GSHE material

For sufficiently large current pulses the magnet is found in its up and down state with a 50% / 50% probability!

Figures adapted from V. Ostwal, P. Debashis, R. Faria, Z. Chen, and J. Appenzeller, *Spin-torque devices with hard axis initialization as Stochastic Binary Neurons*, Scientific Reports 8, 16689 (2018). DOI:10.1038/s41598-018-34996-2, under the terms of the Creative Commons Attribution 4.0 International license.

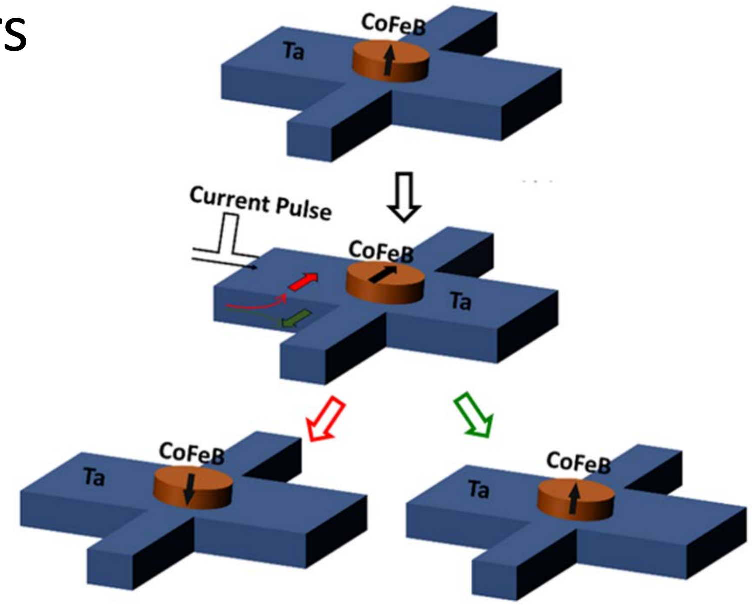
Experimental work on p-bits and circuits

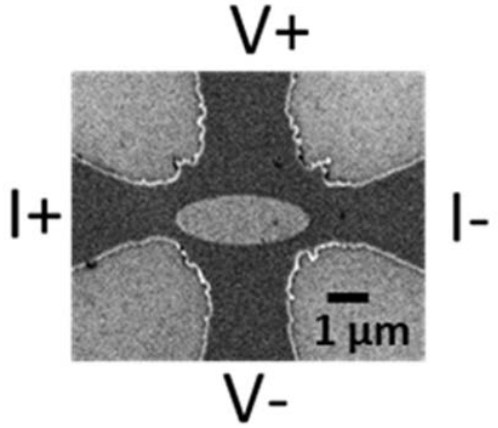
Tunable random number generators

1. Spin Orbit Torque (SOT) current pulse for hard axis initialization (*clock*)

2. Input current through Oersted ring (*write*)

3. Read out through Anomalous Hall Effect (AHE) (*read*)





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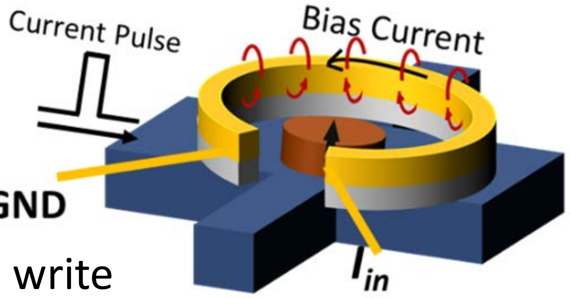
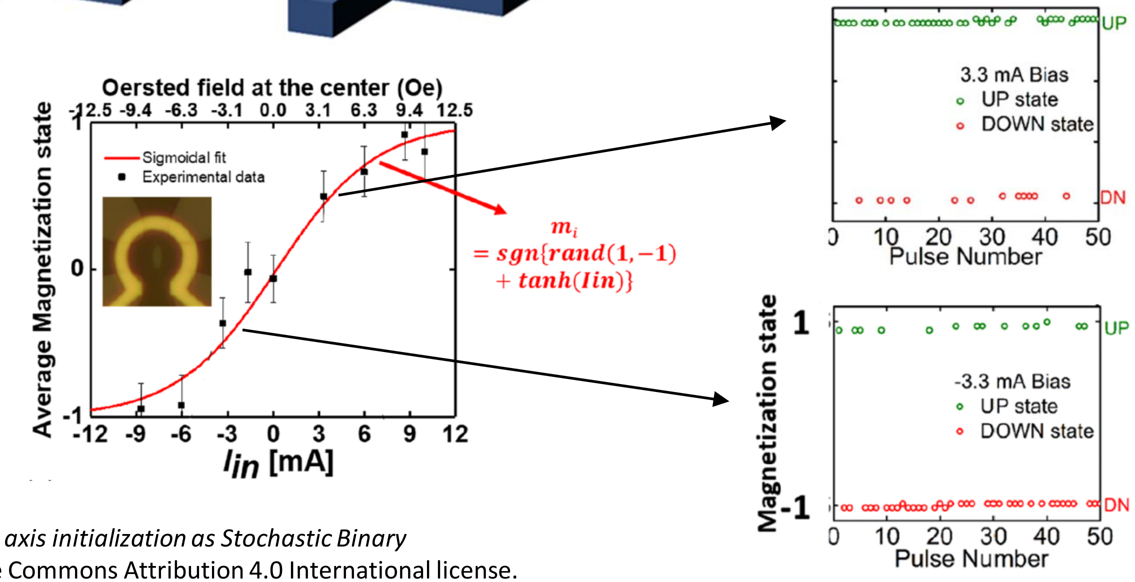


Separate read and write



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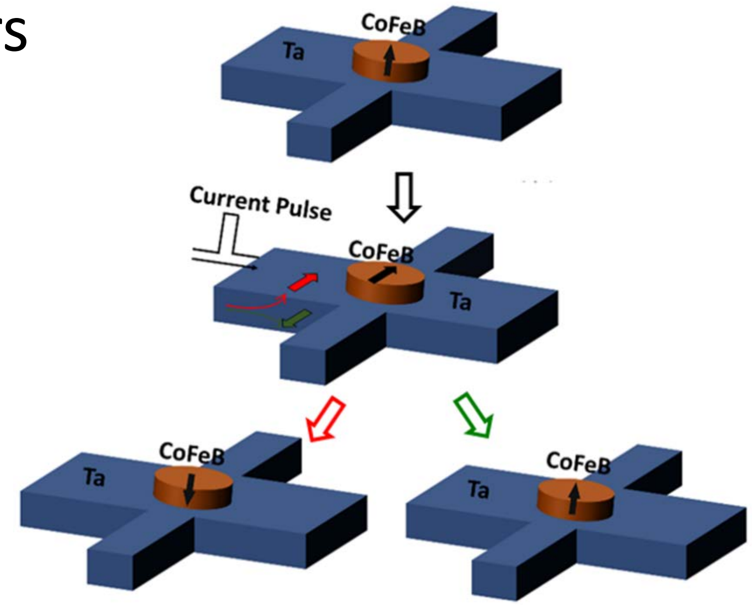

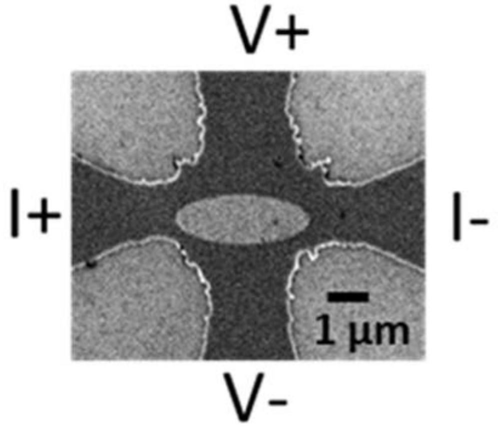

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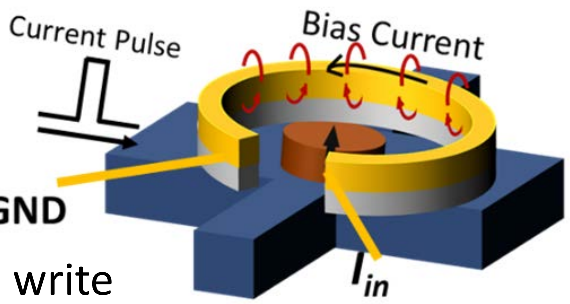

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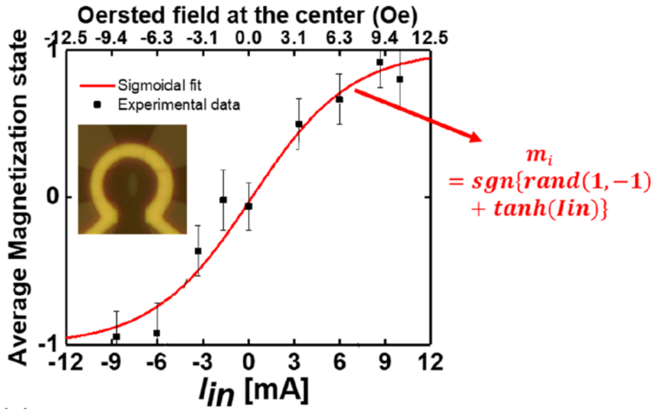


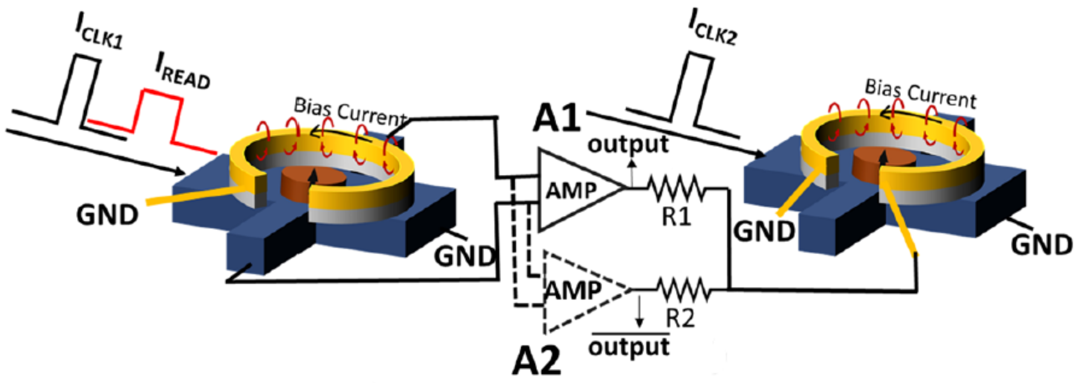
Demonstration of an all-electrical p-bit with field generating metal ring!

Experimental work on p-bits and circuits

Correlations in connected p-circuits

- Each node exhibits a sigmoidal activation function
- Nodes are connected through resistors R1 and R2, allowing for different weights of the interconnect

- During measurement devices are clocked, an input pulse is provided, and the state of the two magnet nodes N1 and N2 are read by AHE



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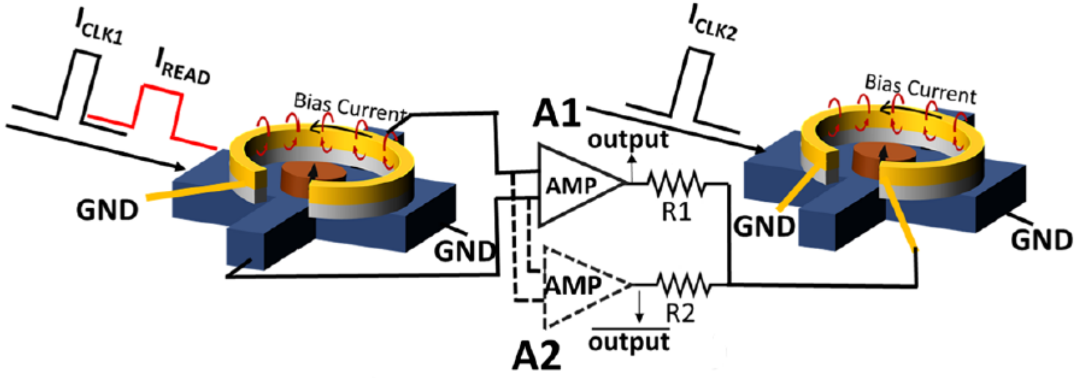

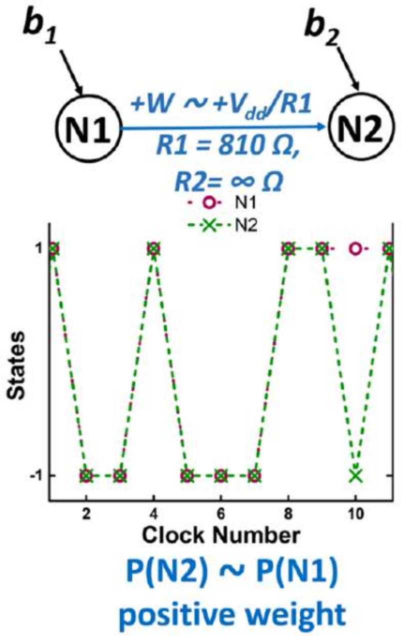

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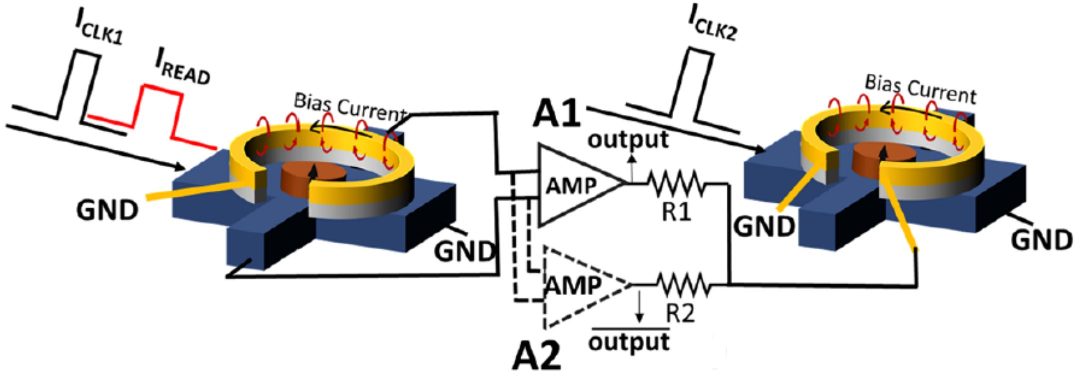

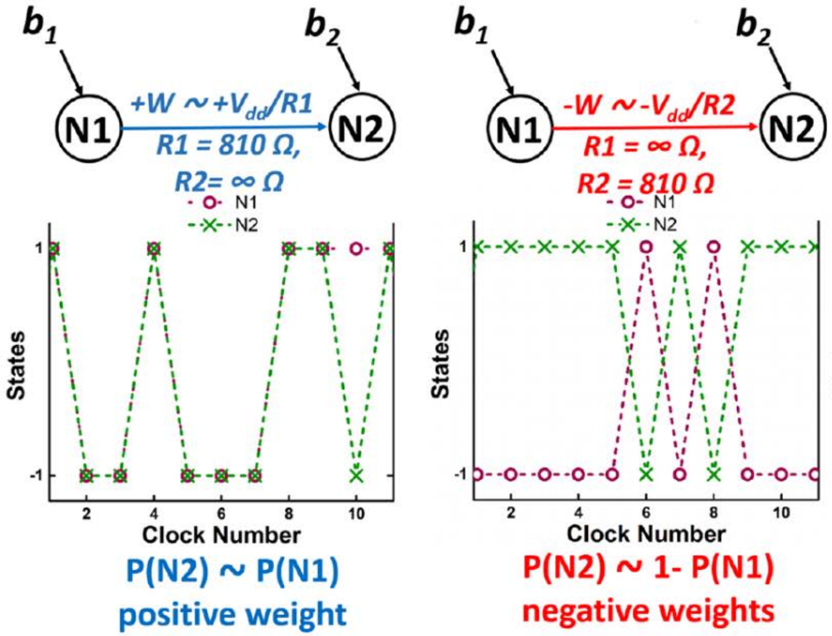

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Experimental work on p-bits and circuits

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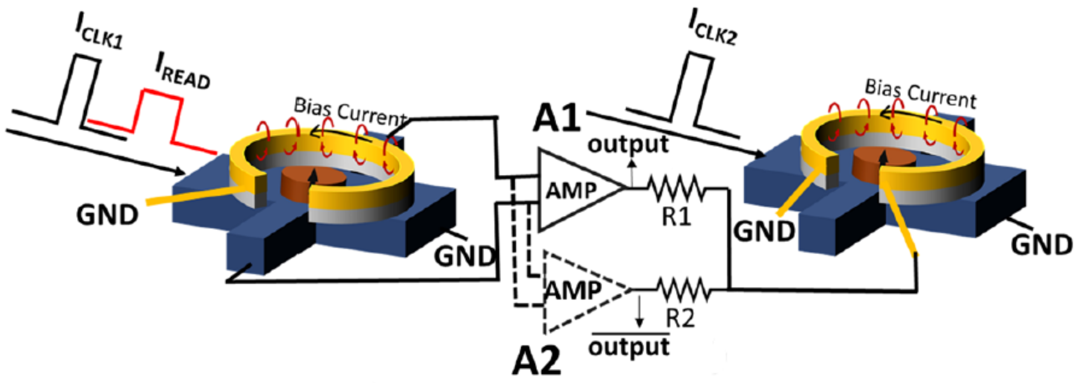
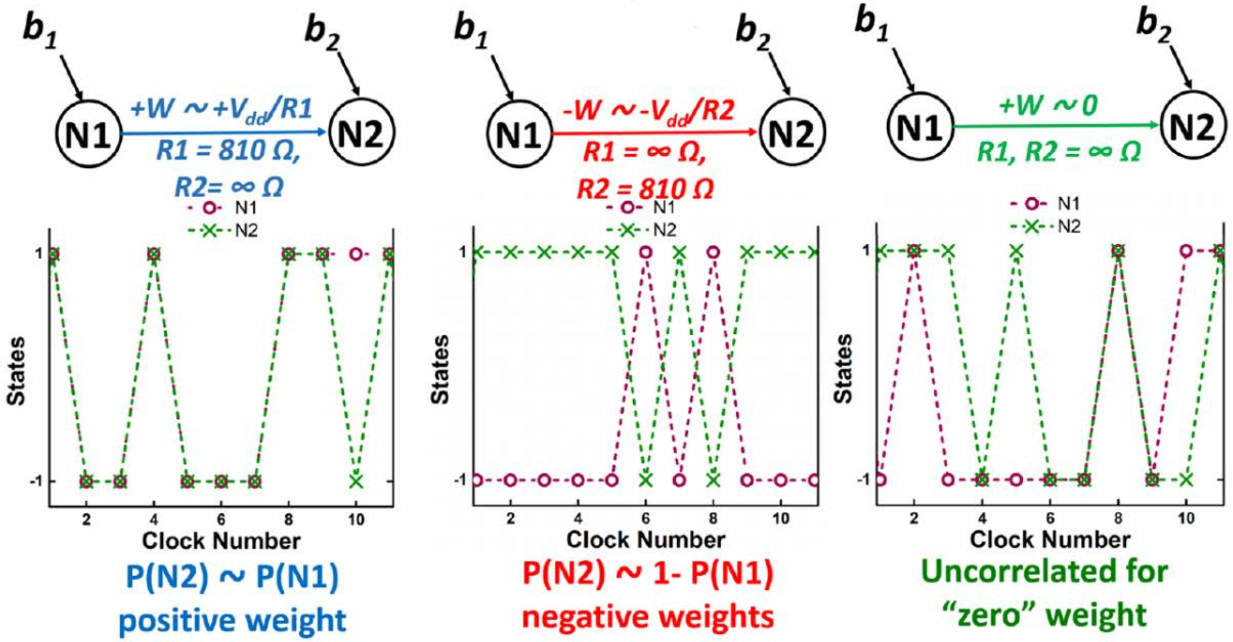
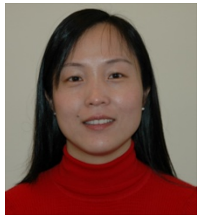




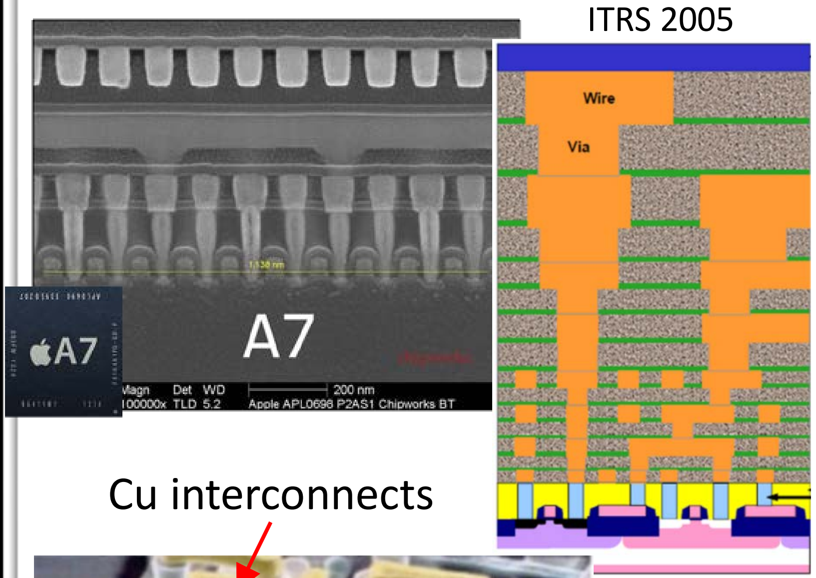
Demonstration of a weighted 2 p-bit circuit!

Figures adapted from V. Ostwal, P. Debashis, R. Faria, Z. Chen, and J. Appenzeller, *Spin-torque devices with hard axis initialization as Stochastic Binary Neurons*, Scientific Reports 8, 16689 (2018). DOI:10.1038/s41598-018-34996-2,

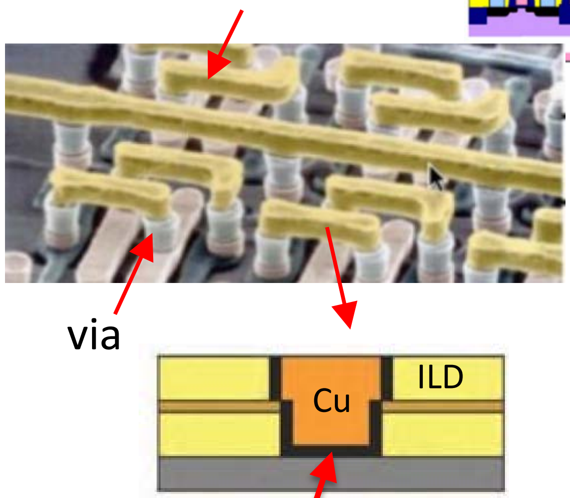
2D Materials for BEOL Interconnect Technologies

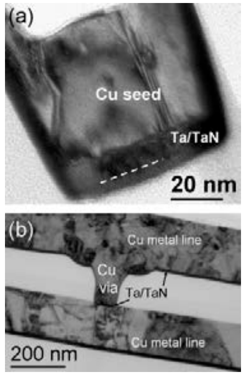


Zhihong Chen



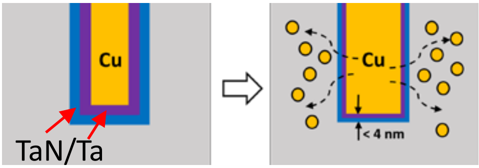
Cu interconnects

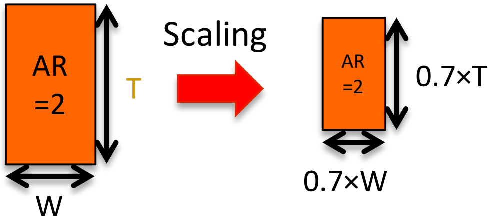


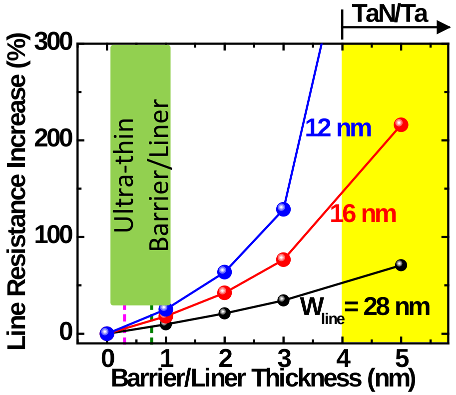


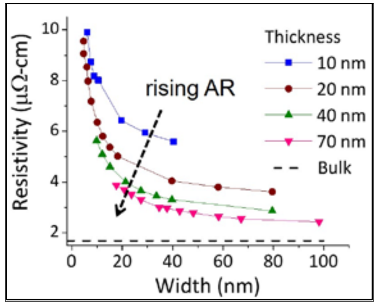
Mat. Sci. Semi. Proc, **27**, 860 (2014)

Diffusion Barrier/Liner Bilayer (TaN/Ta)



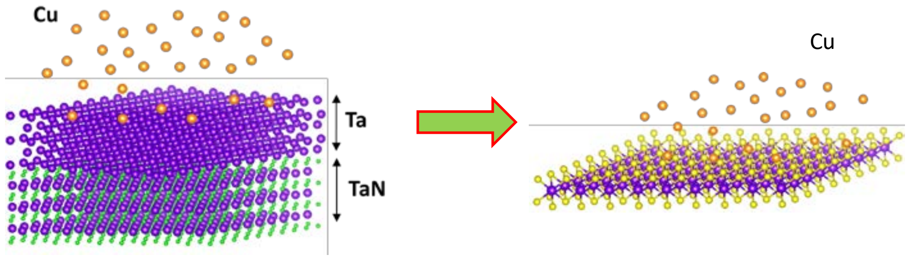


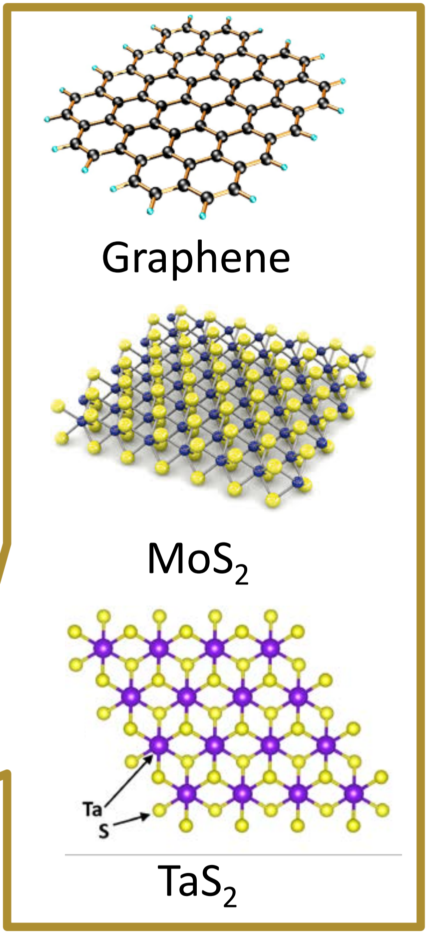




- Conventional barrier/liner > 4nm
- Increasing Cu resistivity at scaled dimensions

Line resistance⬆ electromigration⬆ Joule heating⬆

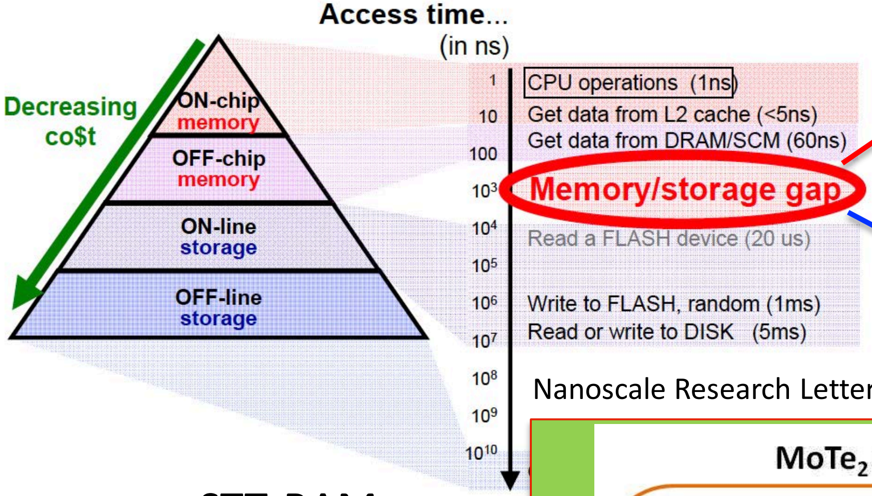




Atomically thin 2D materials as diffusion barrier, liner and capping layer

J. Appl. Phys. **128**, 080903 (2020)

2D Materials for High-speed Non-volatile Memory

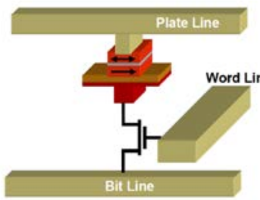


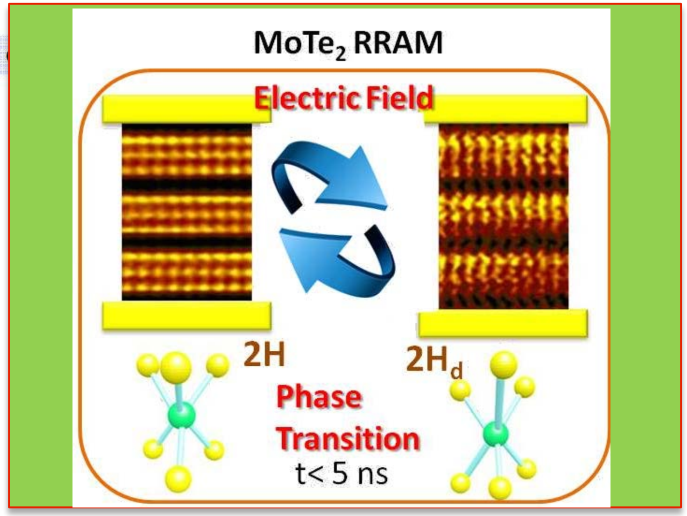
Embedded Non-volatile Memory <<1µs

Embedded Storage 1-10µs

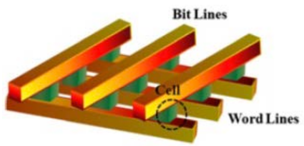
Nanoscale Research Letters, **9**, 526 (2014)

STT-RAM

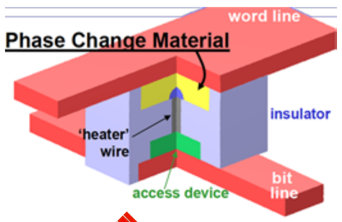




RRAM

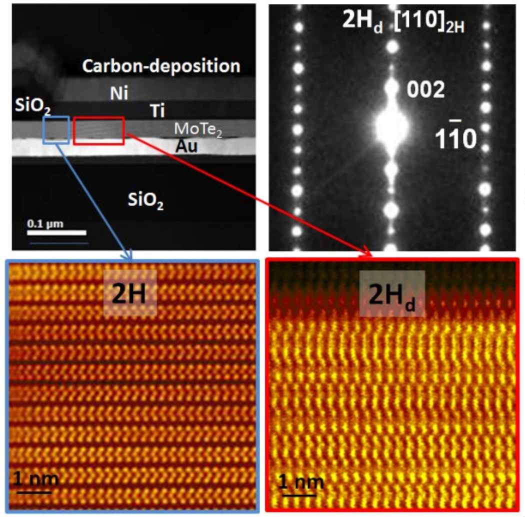


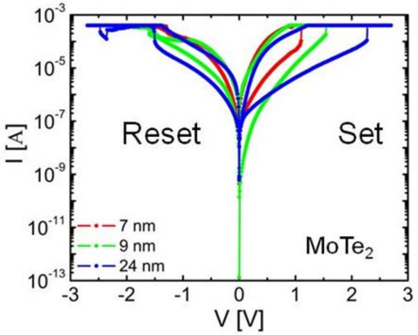
PCM

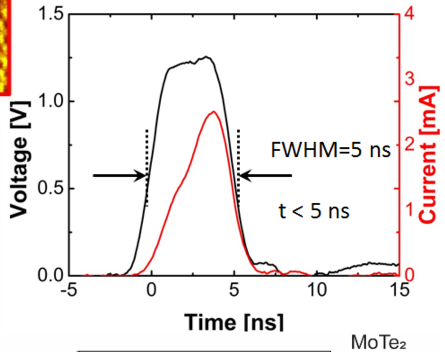


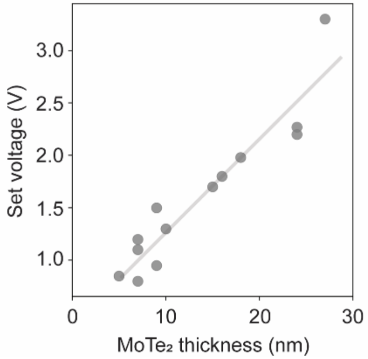
Higher Density

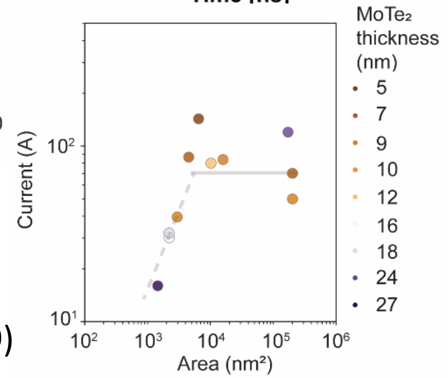
Faster







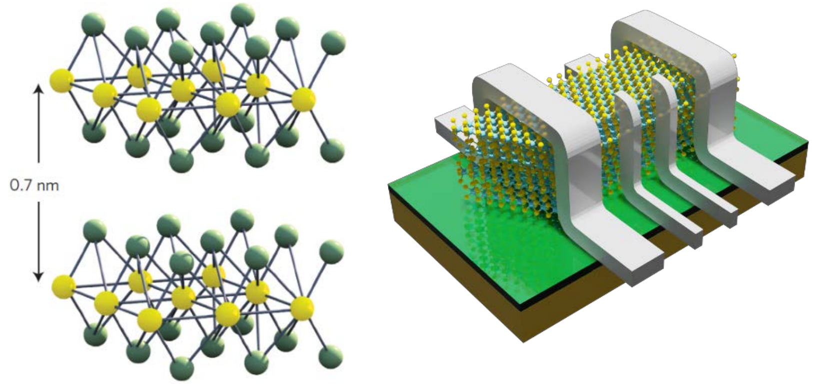


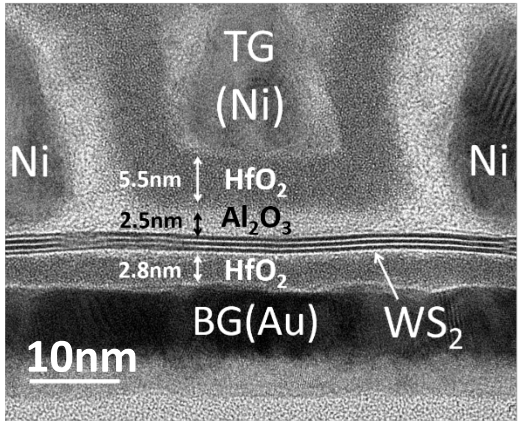


Nature Mater. **18**, 55 (2019)

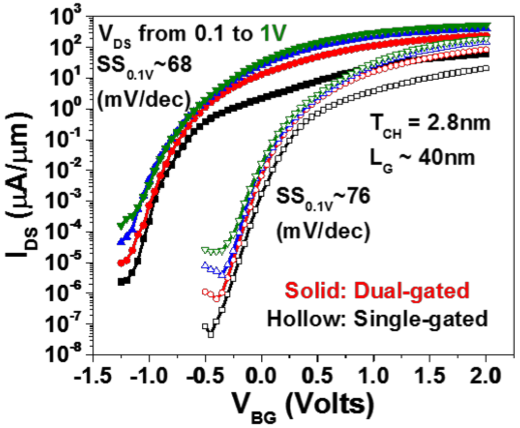
Electric field induced phase change in 2D materials for high speed, low energy, non-volatile memory – combined RRAM+PCM

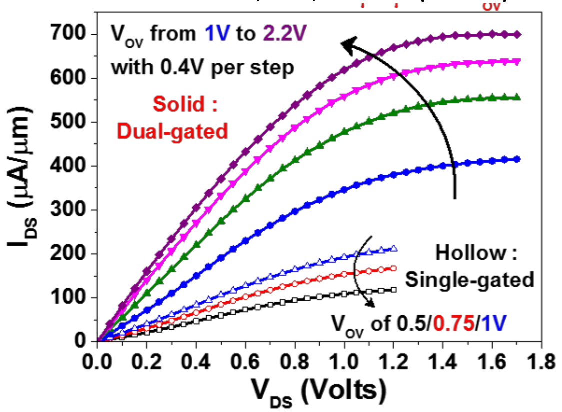
2D TMD Materials for Beyond CMOS Applications





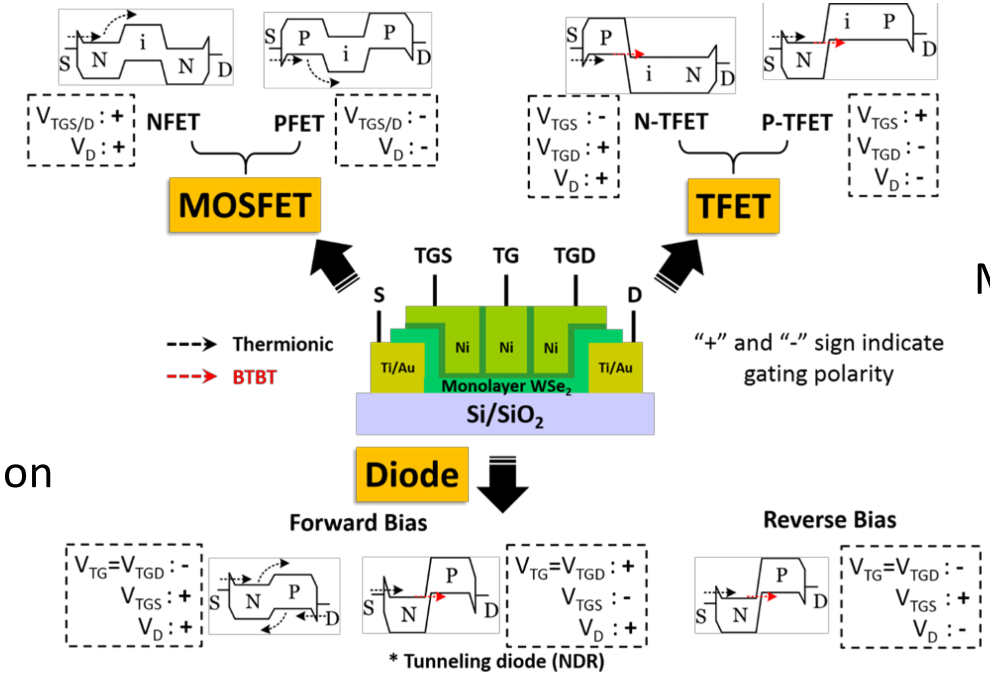
IEEE TED, **68**, 2123 (2021)

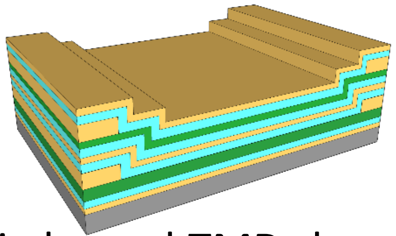




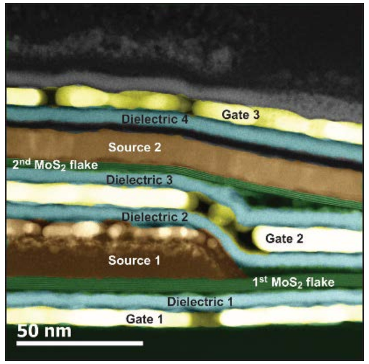
- Ultra-thin body for aggressive scaling
- Comparable field-effect mobility
- Thickness-dependent E_g from 1-2 eV
- Access of both electron and hole injection

Small **15**, 1902770 (2019)





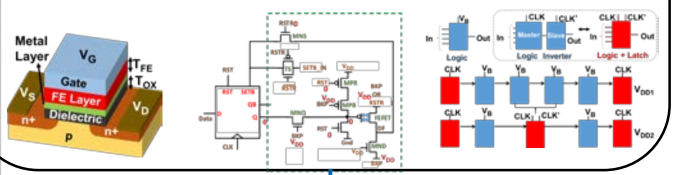
Multi-channel TMD sheet FETs



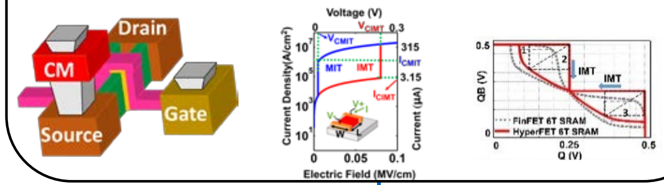
Demonstrations of 2D TMD based MOSFETs, Tunneling FETs, reconfigurable FETs, and 3D integration of multi-channel FETs

Research Overview – Sumeet Gupta

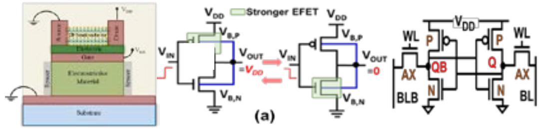
Ferroelectric FETs
- Non-volatile memories
- Logic-Memory Reconfigurability
- Non-volatile Computing
- In-Memory Computing



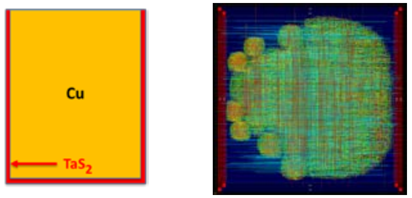
Correlated-Material Enhanced Electronics
- Phase FETs: Steep Switching Devices
- Logic and SRAM Design
- Selectors for Cross-point Memories



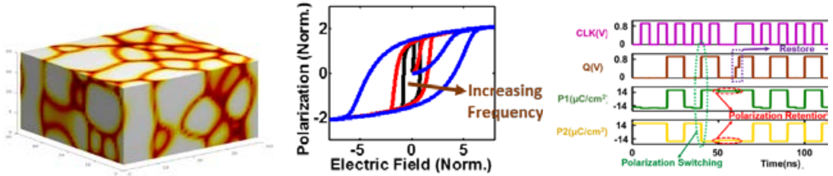
Piezoelectric FETs
- Logic based on steep switching FETs
- Non-volatile memories
- In-memory computing



TMD based Electronics
- Interconnects
- Logic and Memory Design



Modeling and Simulation
- Phase field and Compact model for Ferroelectrics and FEFETs
- Models for spin devices
- SPICE model for correlated materials and HyperFETs
- Models for PeFETs and TMD FETs



Device-Circuit Co-design of Charge-Based Technologies

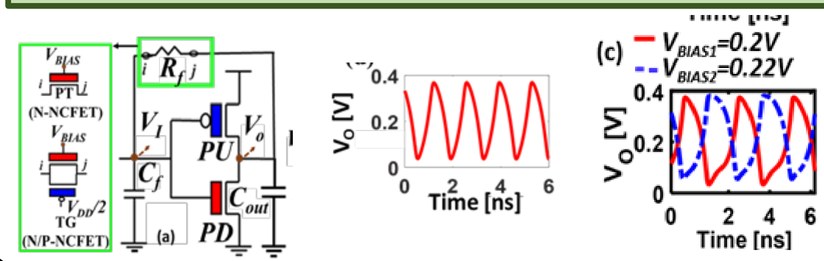
Modeling

Future Ultra-Low Power Computing Platforms

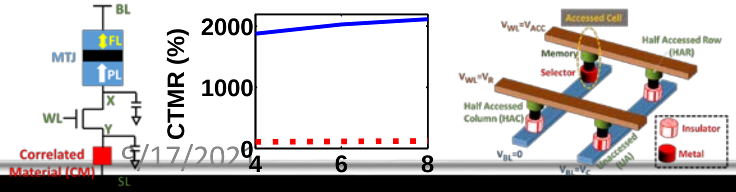
Non-Boolean

Spin-based Memories and Logic

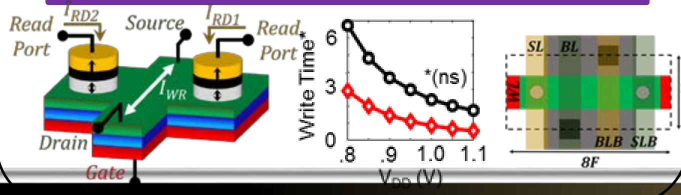
Associative Computing
- FEFET based Coupled Oscillators
- Applications in pattern matching, graph coloring



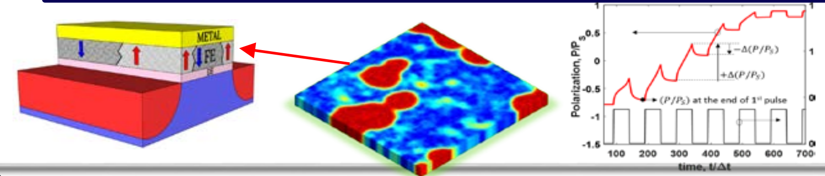
Correlated Materials Enhanced Spintronics
- MRAMs
- Sense Amplifiers
- Cross-point Architectures



TMD based Spintronics
- Valley coupled Spintronics using TMD
- Single-Ended/Differential Memories
- Non-volatile Flip-Flops



Neuromorphic Computing
- FEFET based Bio-Plausible Neurons and Synapses
- New adaptive learning mechanisms enabled by FEFET based neuro-mimetic devices

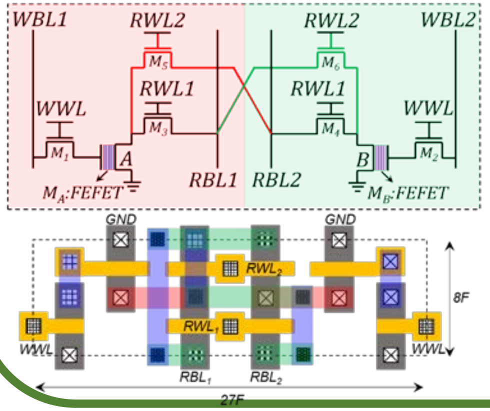


FeFETs: Modeling and Device-Circuit Co-Design

Deep Neural Network Architectures (A. Raghunathan)

Ultra-Low Precision Compute-Enabled Memories

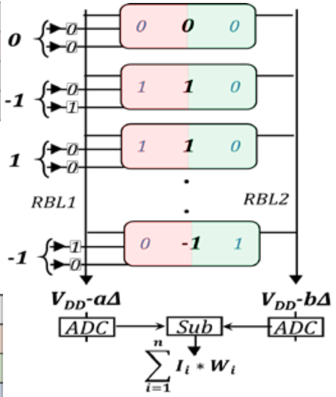
Cross-coupled Cells for Signed Low Precision In-Memory Computation



RWL$_1$	RWL$_2$	I.E
0	0	0
1	0	1
0	1	-1

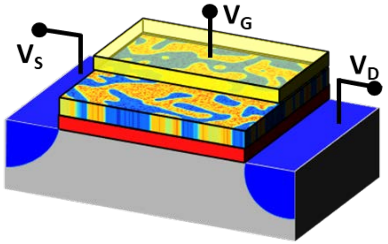
A	B	W.E
0	0	0
1	0	1
0	1	-1

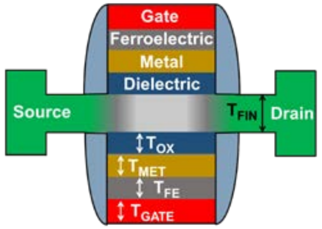
RBL$_1$	RBL$_2$	O.E
V_{DD}	V_{DD}	0
V_{DD}-Δ	V_{DD}	1
V_{DD}	V_{DD}-Δ	-1

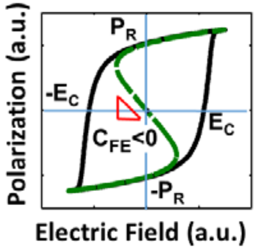


Thirumala *et al*, DATE 2020
Jain *et al*, TVLSI 2020

Ferroelectric Transistors (FEFET) Design







Phase Field Model based Simulation Framework

FEFET Variation Models

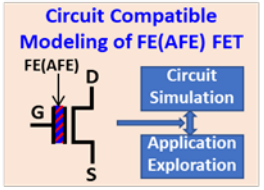
Circuit-Compatible Model

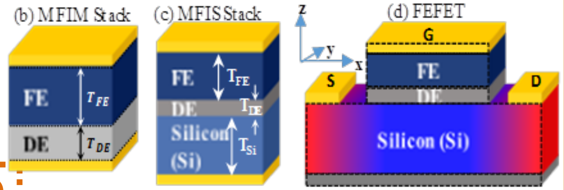
Landau Ginzburg Devonshire (LGD) Eq.

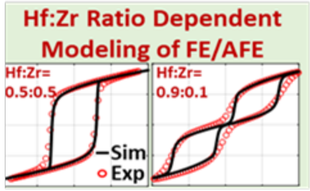
Poisson's Eq.

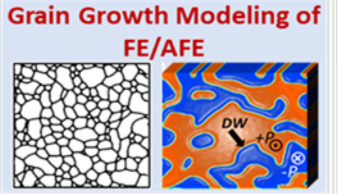
Charge/ Current Eq.

Saha *et al*, APL 2019
Saha *et al*, Scientific Reports 2020
Saha *et al*, IEDM 2020





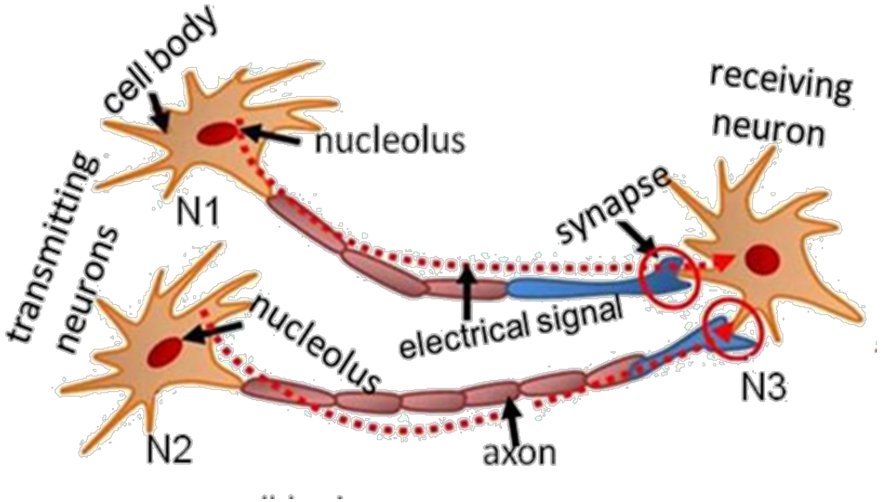


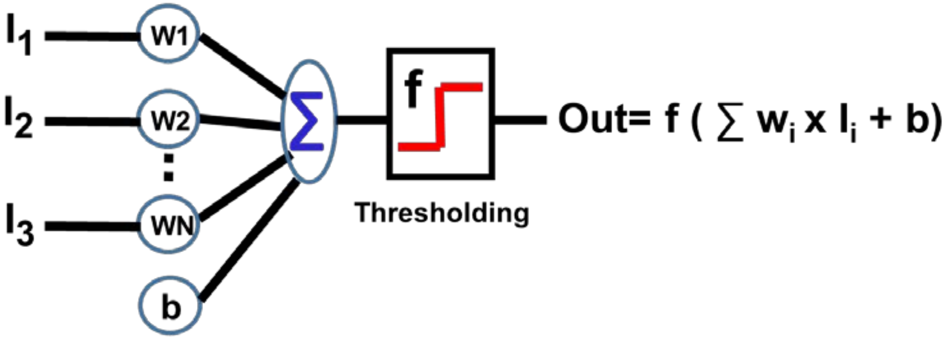


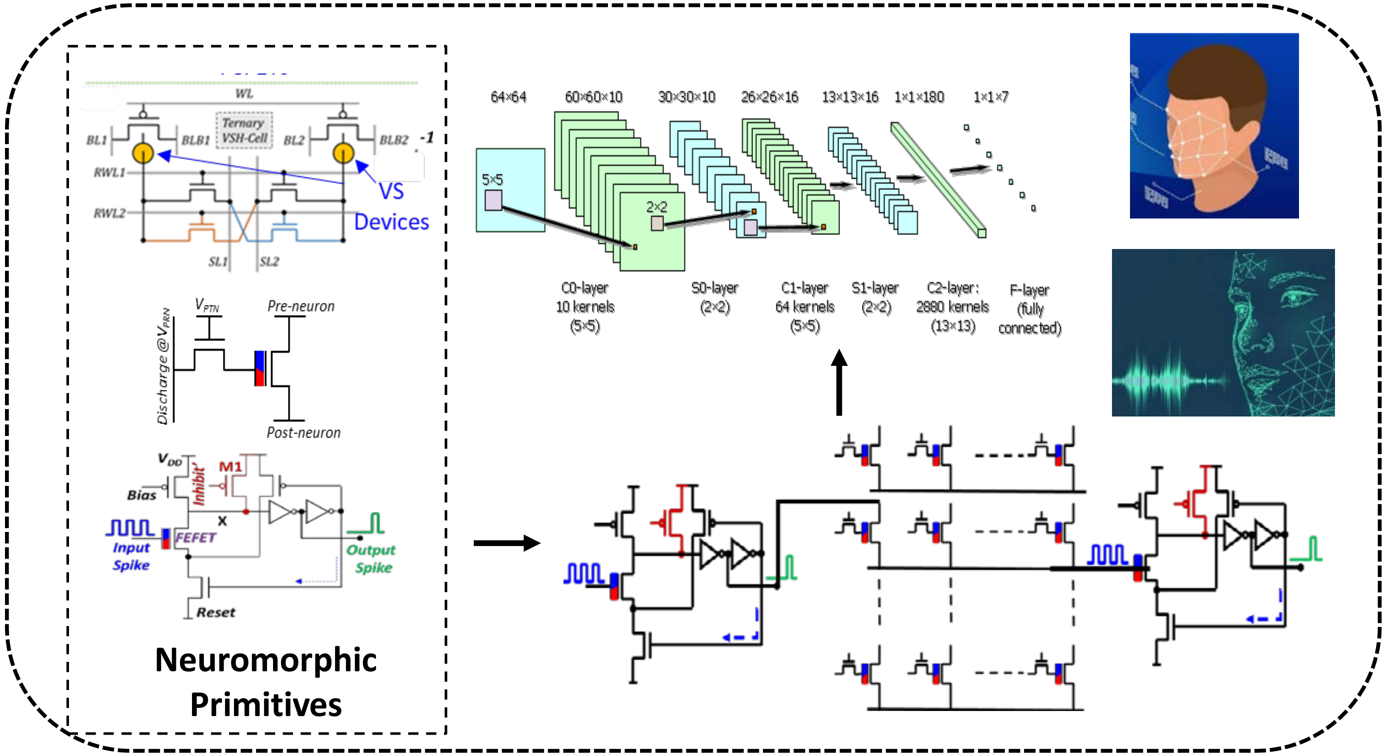
Calibration with Experiments from collaborators (Ye, Datta)

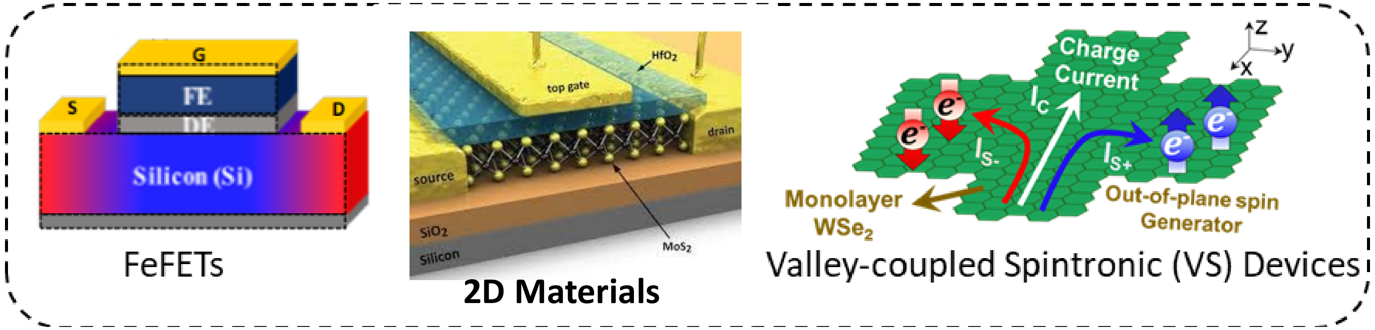
Future Research Directions

Heterogenous Integration of Neuro-mimetic Technologies for Secure and Low Power Edge AI

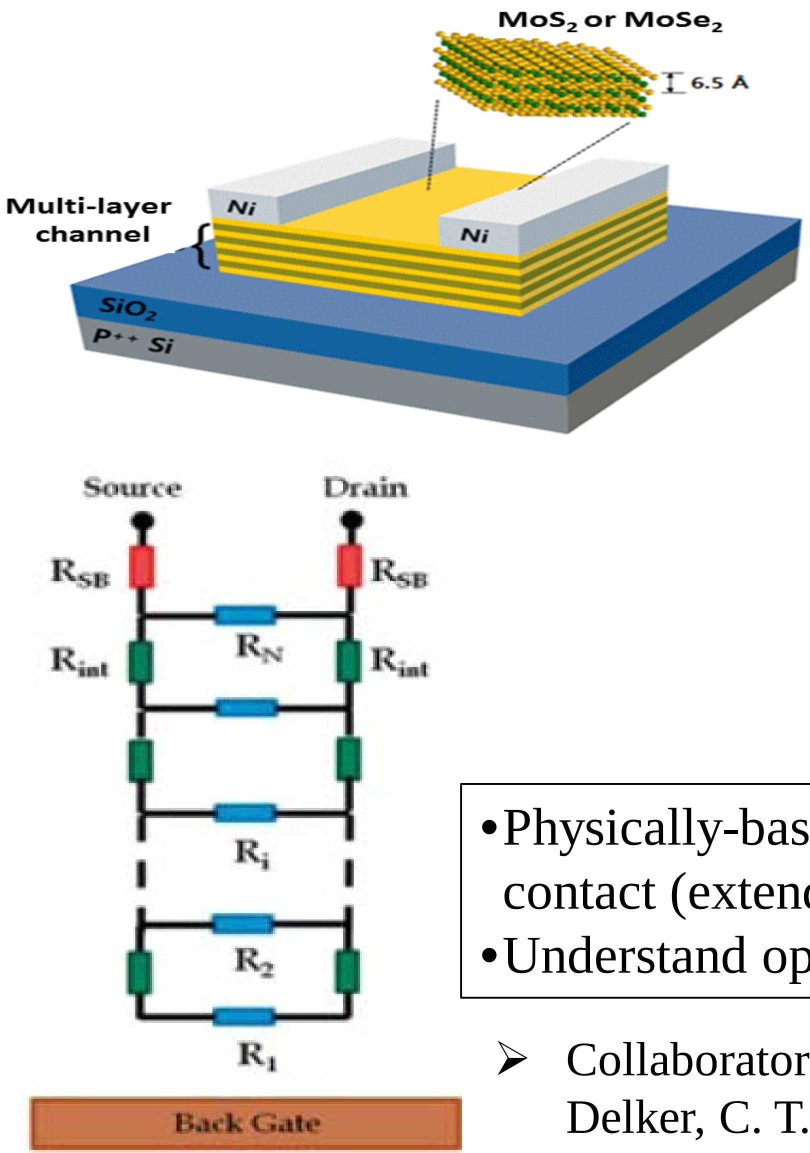


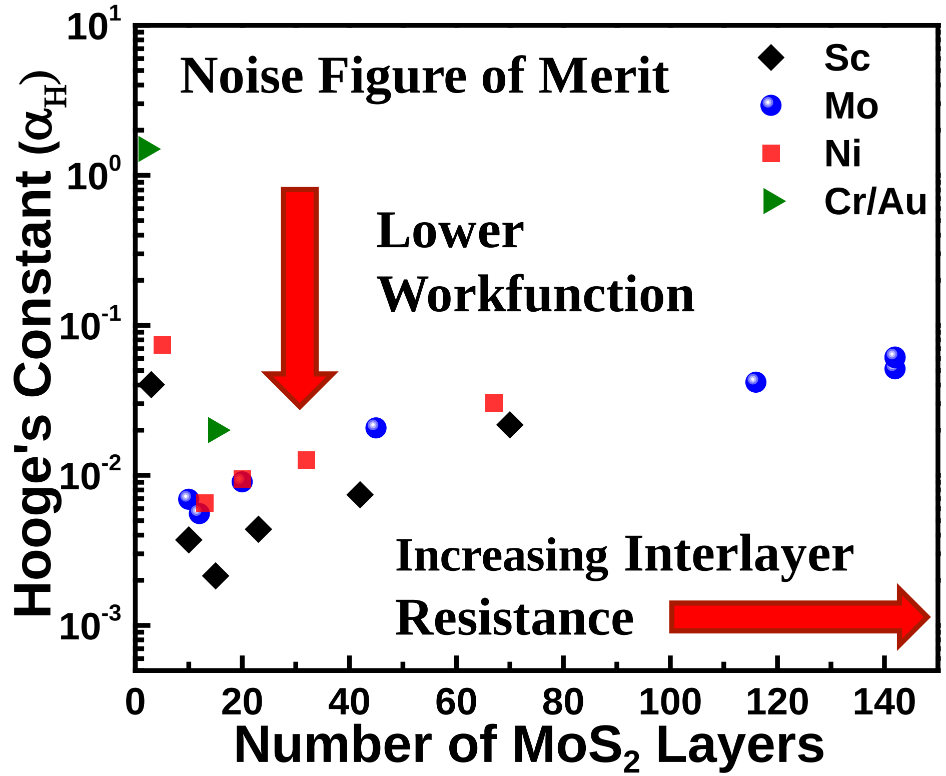






Mobility and 1/f Noise in 1-D and 2D FETs





David Janes

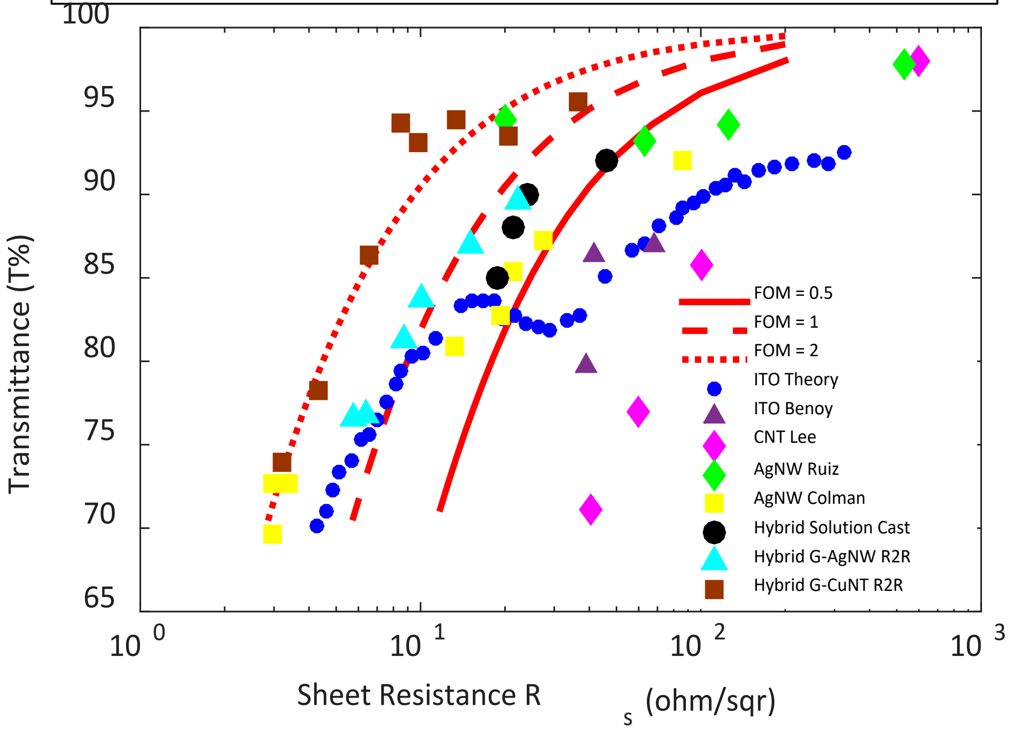
- Physically-based model of channel, interlayer resistance and contact (extending mobility approach of Appenzeller, et al)
- Understand optimal materials, channel thickness, contact

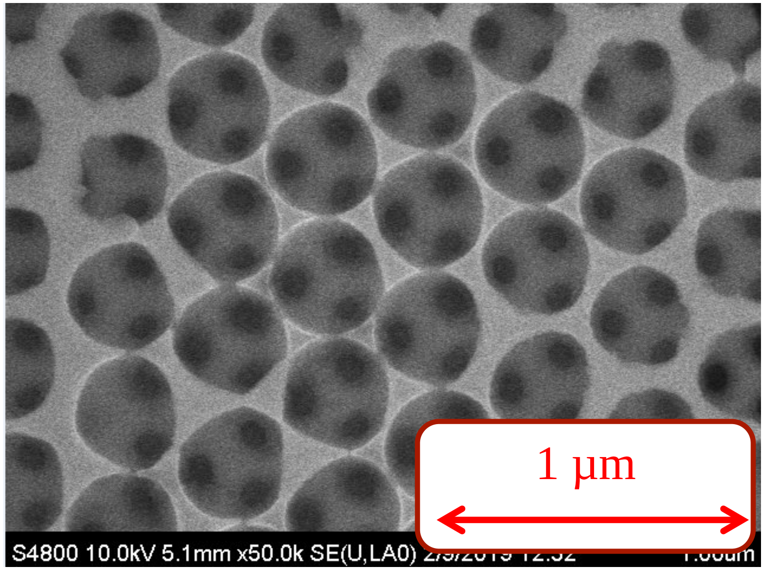
➢ Collaborators: S. Das, *Kansas State*, J. Appenzeller, *Purdue*, C. J. Delker, C. T. Harris, and B. Swartzentruber, *Sandia*

Nanostructured Transparent Conductors and Templated Self-Assembly of Photonic Materials

Transparent Conductors:
- 1D/2D Hybrids
- Low Resistance, High Transmittance

Nanostructured templates:
- Electrodeposition (metals, semicond.)
- Laser Annealing





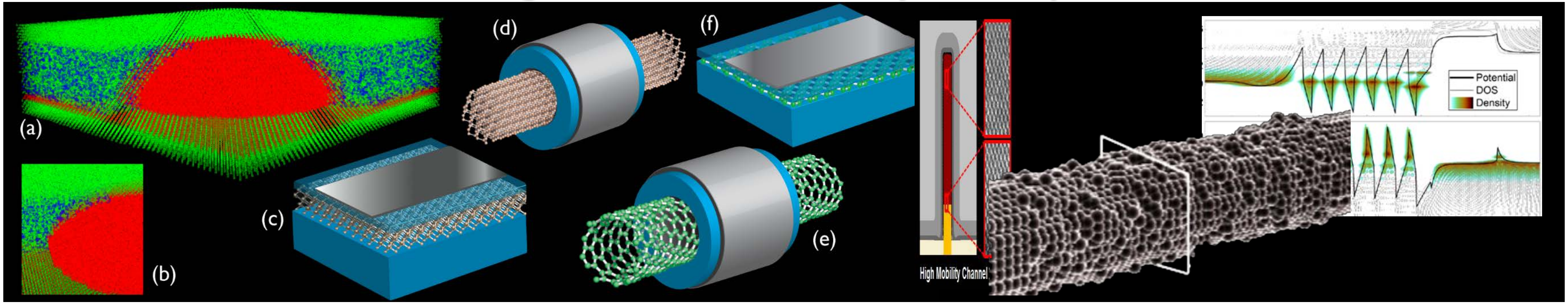
InSb Inverse Opal Structure

➢ Collaborators: M.A. Alam, A. Kildeshev, D. Warsinger, A. Marconnet, *Purdue*

Gerhard Klimeck

Nano Electronic Modeling – NEMO

Multi-Scale Modeling Framework Beyond Specific Devices



Available NEMO5 Capabilities:

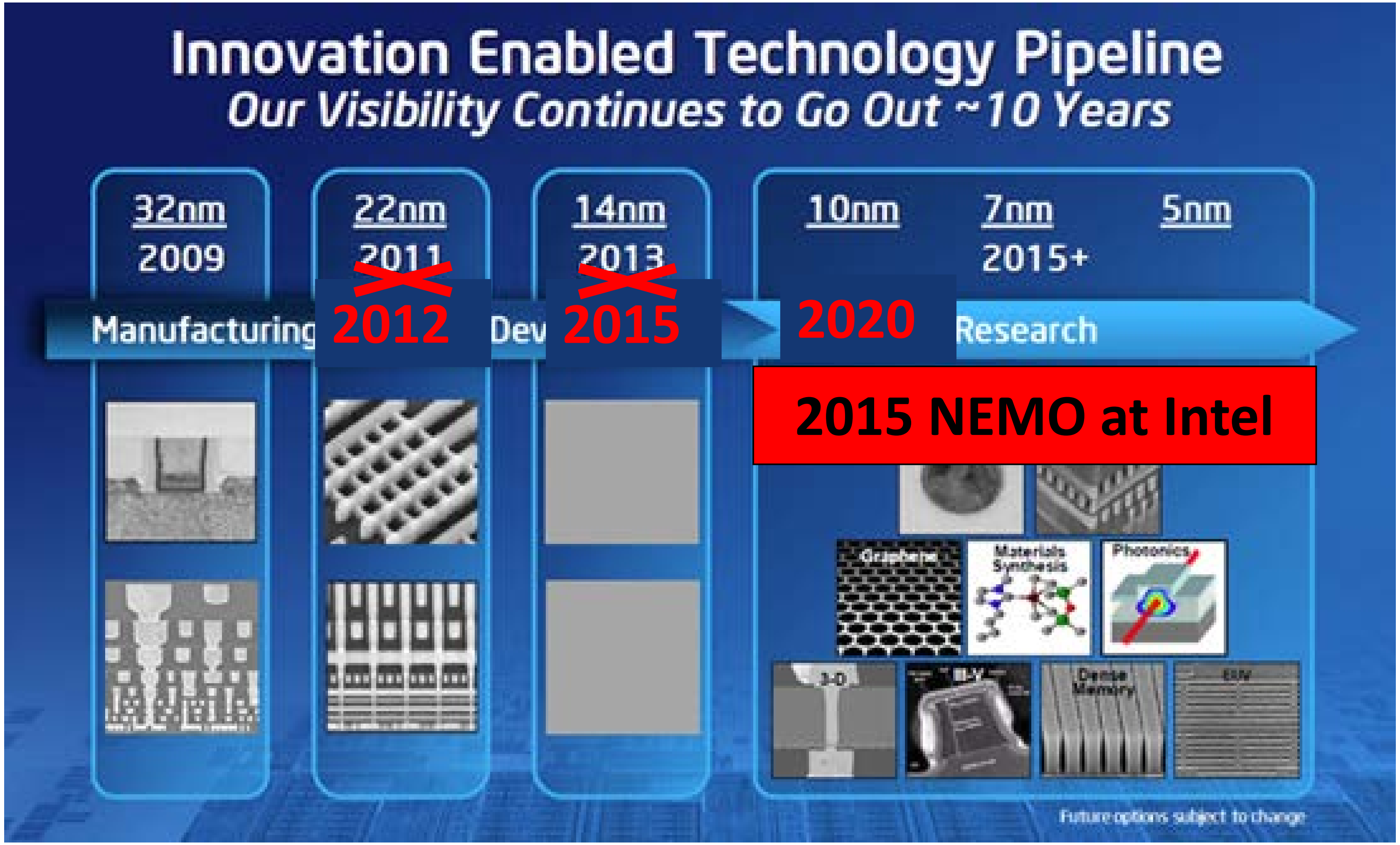
- 3D, 2D, 1D geometries -Atomic representation
- Realistically extended device sizes
- Nanowires, mosFET, tunnelFETs, quantum dots
- All semiconductors & metals: SiGe, III-V, 2D
- Roughness, impurities, alloys
- 50 Million atom structures
- Material science-MD structure input

Quantitative agreement w /Experiments:

- nanowires, 2D materials, InGaAs FETs
- million-atom InGaAs/GaAs optical quantum dots
- Single atom transistor design of P in Si
- Ultra-scaled – 4 atom wide, 1 atom nanowires
- LEDs
- Bulk Phonon dispersions,
- Thermal transport at nm-scale

A new and unique toolset that cannot (yet) be bought elsewhere

Moore's Law - 2009 Intel Road Map

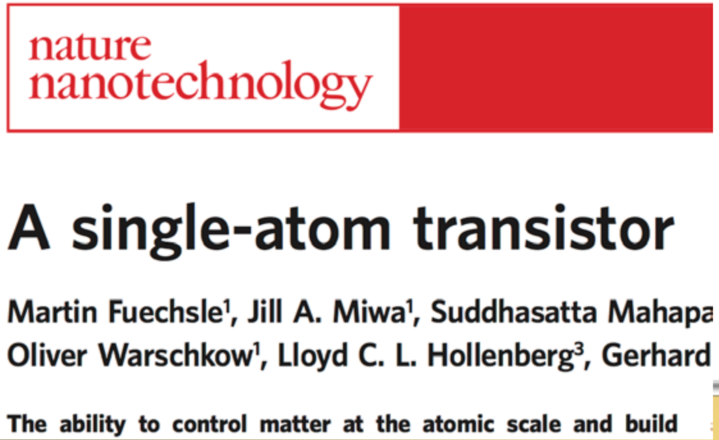


nm Node	22	14	10	7	5
Node atoms	176	122	80	56	40
Electrons	160-190	64-80	30-38	18-23	11-15

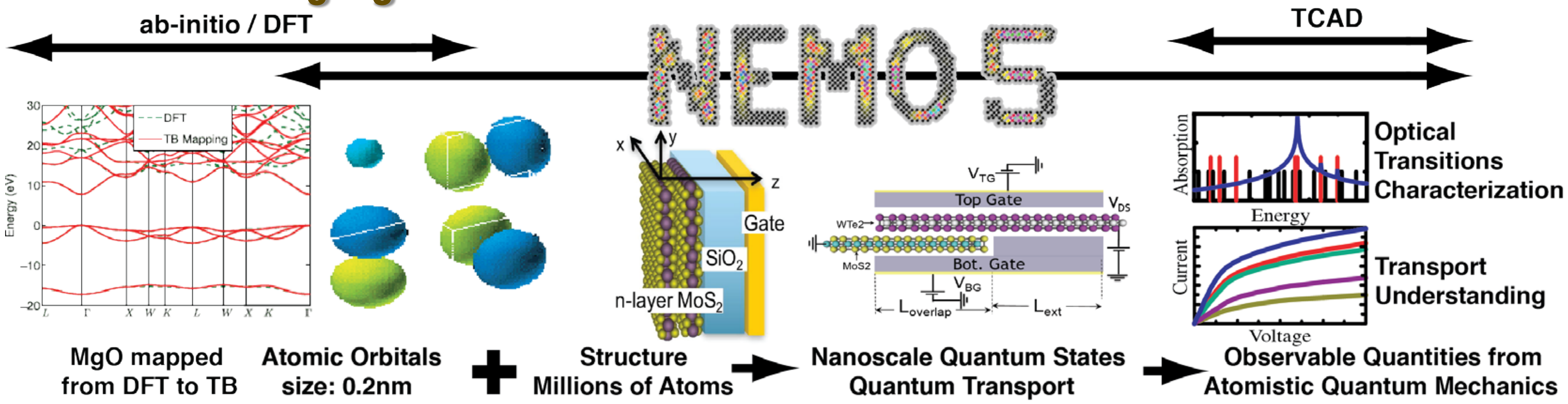
Intel Adoption of NEMO:

- 2009 initial engagement
- 2012-2017 co-development
- 2015 Intel buys a dedicated supercomputer to run NEMO
- 2019 Intel announces NEMO integration at IEDM
- 2015-2020 NEMO helps design 2 transistor generations

2018 - SILVACO licenses NEMO first industrial customers



Bridging the Scales - From Ab-Initio to Realistic Devices



Goal:

- Device performance with realistic extent, heterostructures, fields, etc. for many materials

Problems:

- TCAD does not contain any real material physics
- Need ab-initio to explore new material properties
  - Ab-initio cannot model non-equilibrium.
  - Heterostructures are step functions!
  - Infinite waves needed to resolve a step!
- Need a local basis

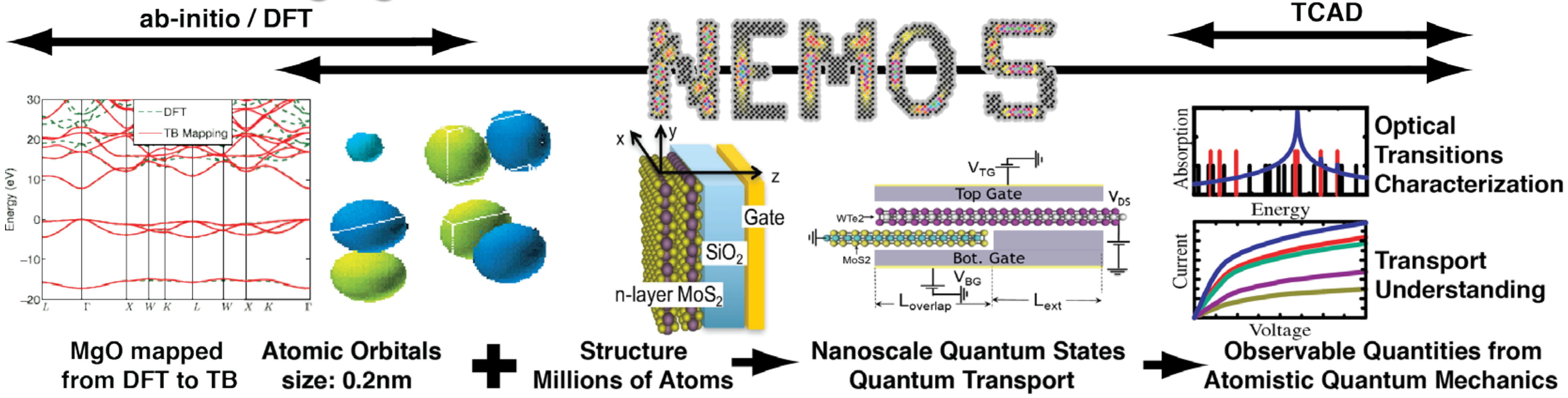
Atom Position Approach:

- Valence Force Fields
- Molecular Dynamics
- Ab-initio

Electronic Structure Approach:

- Ab-initio - bulk or small ideal superlattices
- Map ab-initio to tight binding
  - Local atomic basis
  - Transferrable parameters

Bridging the Scales - From Ab-Initio to Realistic Devices



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- Molecular Dynamics
- Ab-initio

Electronic Structure Approach:

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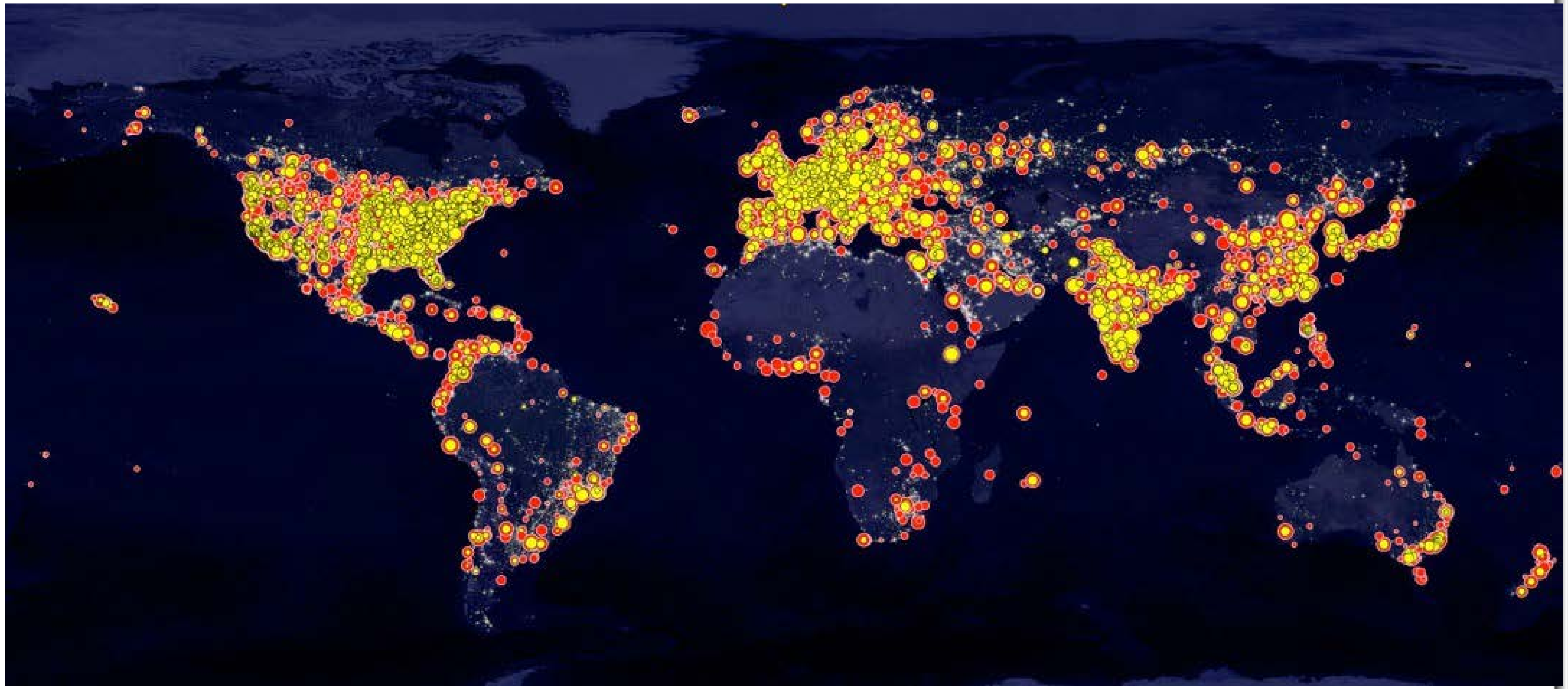
New virtual tool for qualitative and quantitative exploration.
Qualitatively like the introduction of physical MBE or ALD tools.
A new and unique toolset that cannot (yet) be bought elsewhere.

nanoHUB in a nutshell: translating traditional research to new paradigms in publishing, computing, research, & education



What ?
> 685 nano-Apps in the cloud
> 6,511 lectures and tutorials
> 170 courses => MOOC
Largest global nano-facility Cyberinfrastructure
24/7 operation with 99.4% uptime

Who?
> 1.8 million users annually
> 2,440 contributors
- 172 countries

- Faculty
- Students
- Industry practitioners

nanoHUB in a nutshell: translating traditional research to new paradigms in publishing, computing, research, & education

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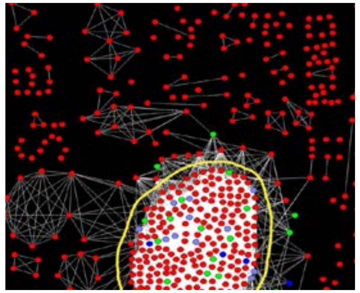

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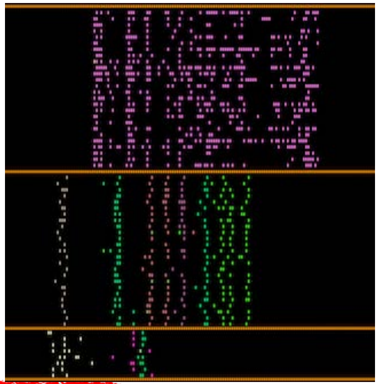
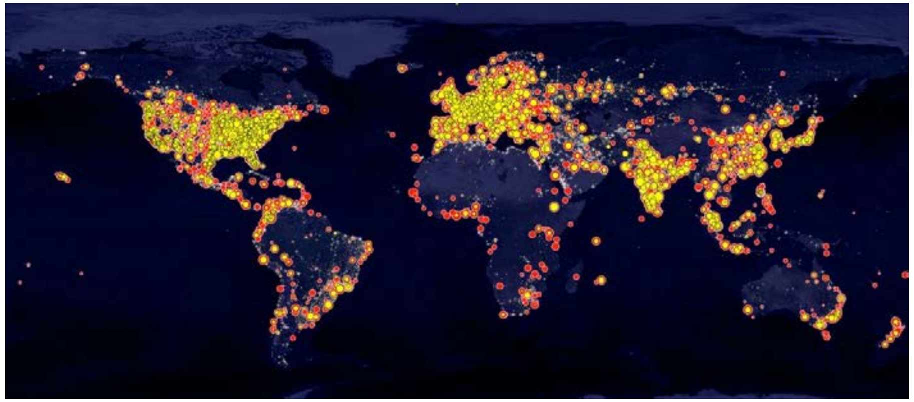


- Faculty
- Students
- Industry practitioners

Fundamental changes in approach or underlying assumptions



Research Impact:
- nanoHUB tools now listed in

WEB OF SCIENCE Google Scholar

- > 2,507 papers cite nanoHUB
- > 54,300 secondary citations
- h-index of 105

Educational Impact
- >89,730 students use tools in classrooms, >3,840 classes, 185 institutions
- Rapid curriculum change <6 months adoption rate

Next up: Prof. XYZ

HybridMEMS

Dana Weinstein

Vision:

Develop MEMS RF devices, transducers, and sensors in low-barrier-to-entry technology platforms for adaptive wireless communication, timing, and IoT applications.

Focus:

- MEMS-IC resonators, oscillators, and filters in UHF through Ka band frequencies
- III-V programmable RF and mm-Wave components
- Lithium Niobate gain, switchable, tunable devices
- Recent: Phase change and phase transition MEMS
- Recent: Ultrasonic transducers for biomedical applications and IoT

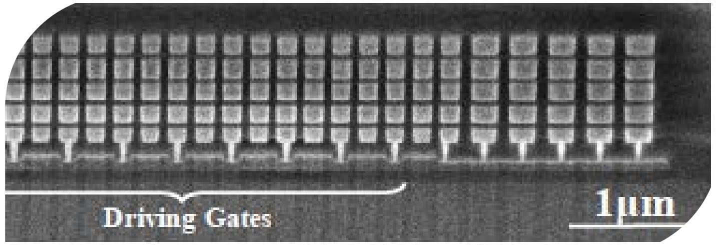
everythingrf.com

- Automotive applications, sensors
- 5G/6G communication
- mm-Wave imaging
- THz spectroscopy
- IoT / Smart infrastructure
- Neuromorphic computation
- Quantum computing above 4K

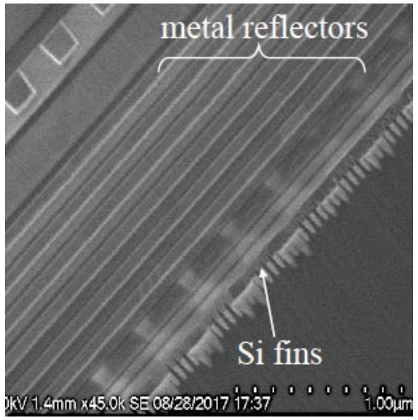
HybridMEMS – Research Focus

CMOS MEMS resonators and physical sensors

Seamless integration of electromechanical structures in standard CMOS technology. No post-processing or packaging required.



3 GHz SOI FET resonators
Q>13000 (Global Foundries 32nm SOI)

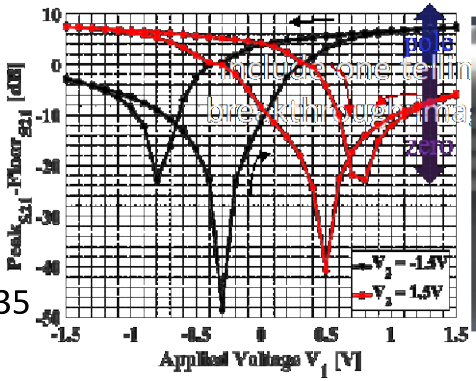


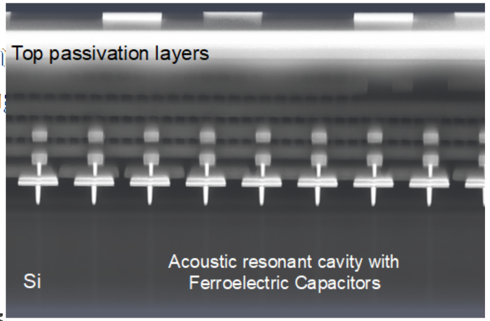
30+ GHz FinFET resonators
Q>1000 (GF 14LPP)

Ferroelectric Transducers

- Need for larger electromechanical coupling in CMOS-MEMS. Ferroelectrics are piezoelectric and can improve drive/sense efficiency by 100-1000x over capacitive transducers.
- Opportunities beyond CMOS for switchable 5G/6G filters

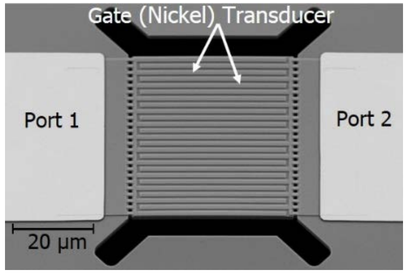
700 MHz resonators in TI E035 FeRAM technology

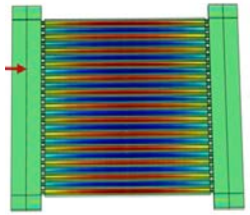




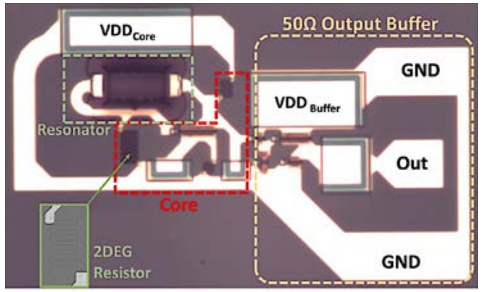
GaN MMIC-MEMS

GaN MEMS in monolithic microwave ICs (MMIC) leveraging HEMTs and 2D electron gas (2DEG) for high Q, high frequency RF components with programmable functionality





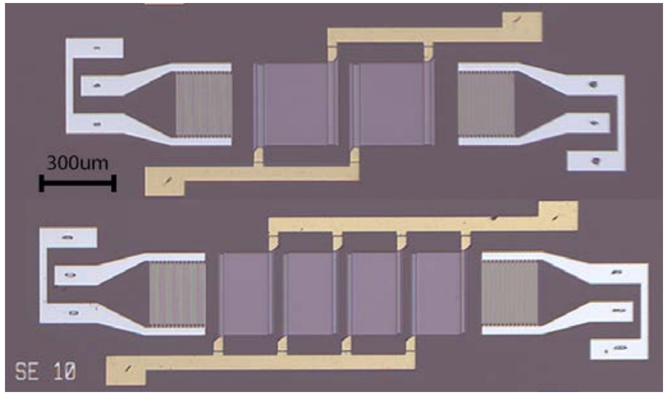
Lamb mode GaN resonators
Q = 8327, f = 1.87 GHz

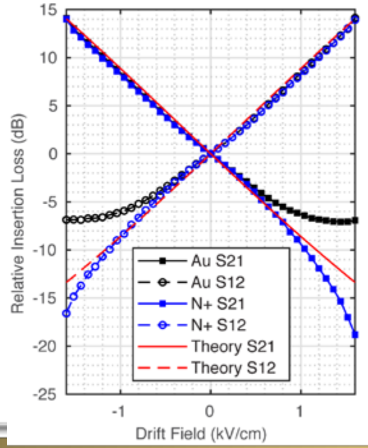


GaN MEMS oscillators and filters in MMIC technology

Acoustoelectric

Non-reciprocal amplification of acoustic waves for applications in RF circulators, isolators, and correlators.





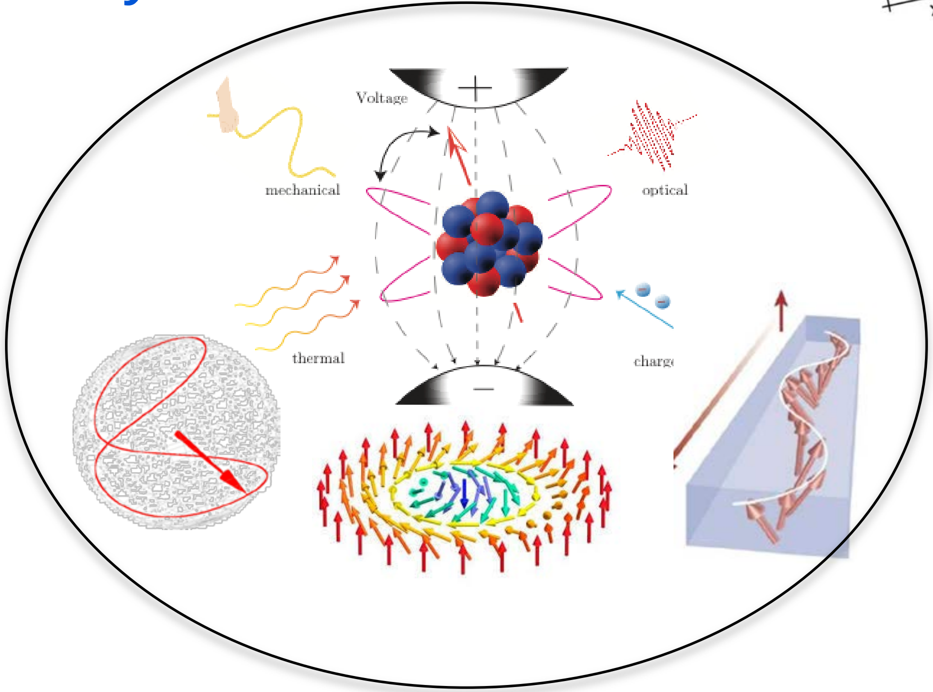
InGaAs/LN AE transmission lines with record-breaking terminal gain and non-reciprocity

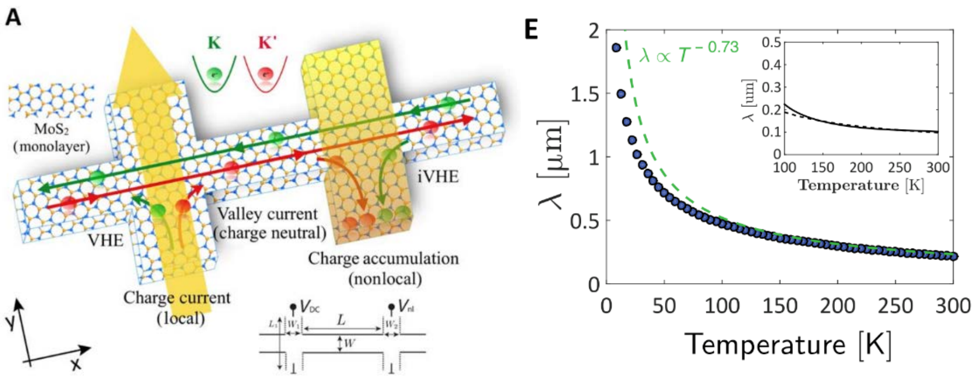
Novel Physics for Next-generation Microelectronics

Pramey Upadhyaya

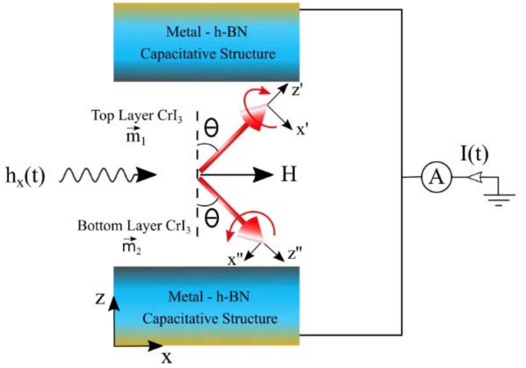
Memory, Computing & Sensing

Energy-efficient, compac tunable dynamical systems



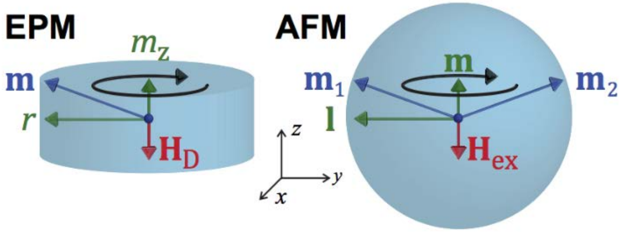


Chen/PU collab. **Sci. Adv.** (2019)



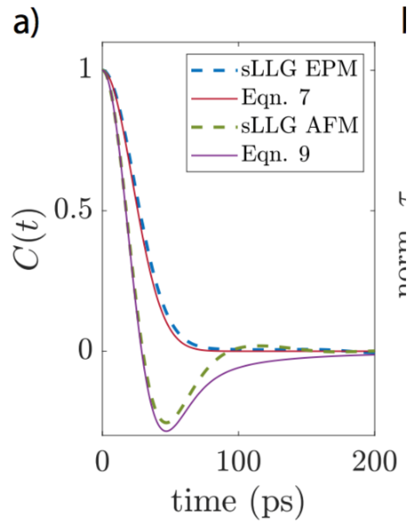
2d magnet, THz detector

PRB (2019)

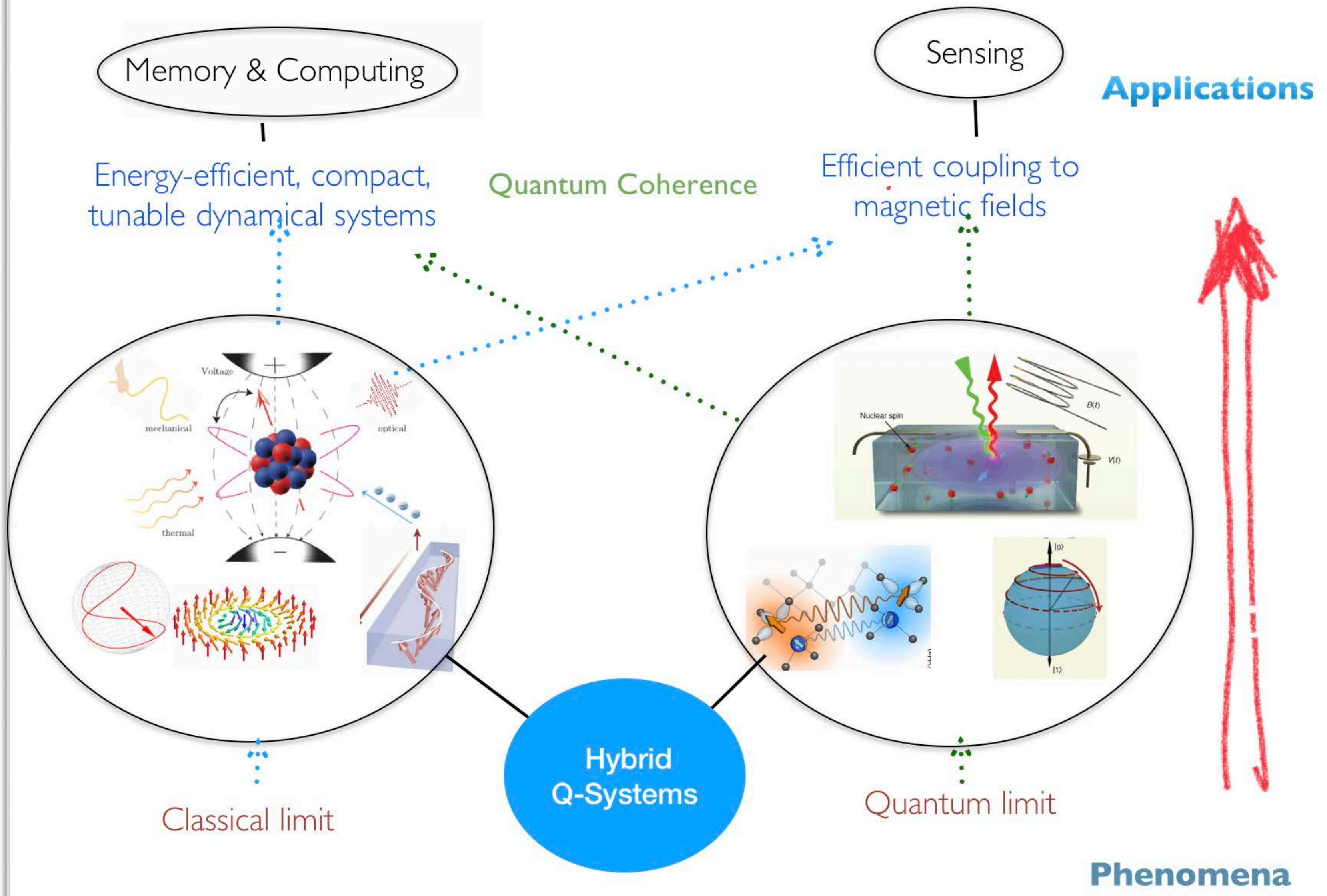


Sub ns P-bits

Datta/PU collab. **PR Applied** (2019)



Hybrid Quantum-Nano Systems for Microelectronics

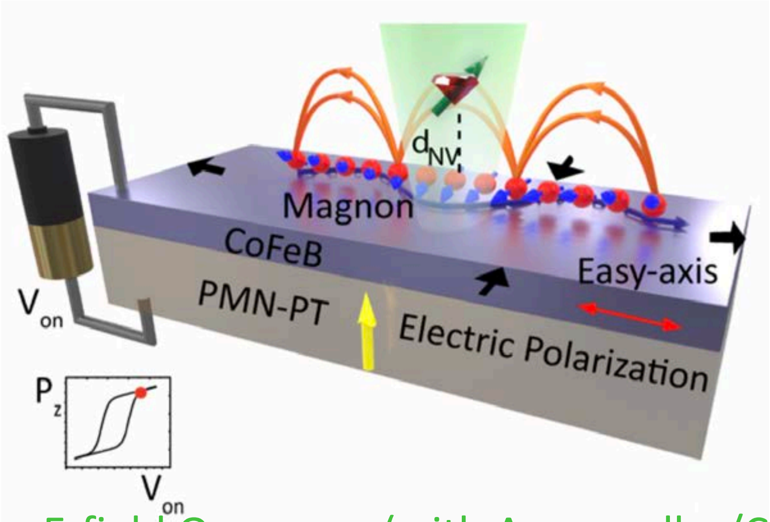


Motivation:

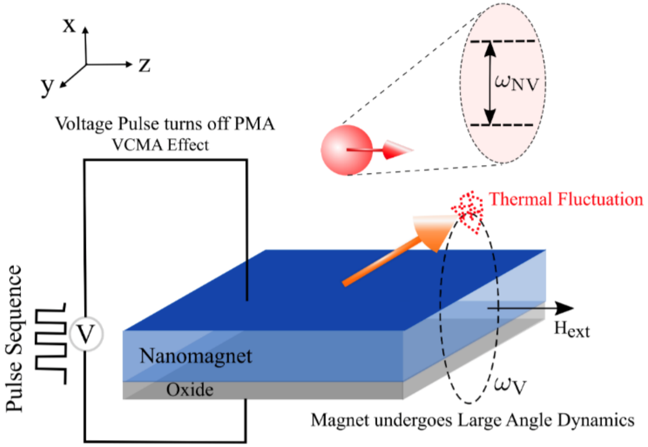
1. *Quantum* for advancing next-generation *classical* microelectronic platforms

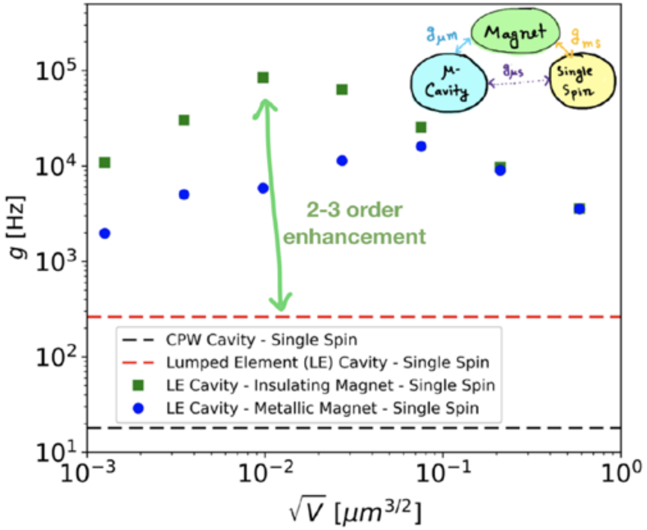
2. *Classical* for advancing next-generation *Quantum* platforms

Hybrid Quantum-Nano Systems for Microelectronics: Examples & Possibilities



E-field Q-sensors (with Appenzeller/Chen/Shalaev): arXiv:2012.01497 (2020)





Quantum for *classical* microelectronics

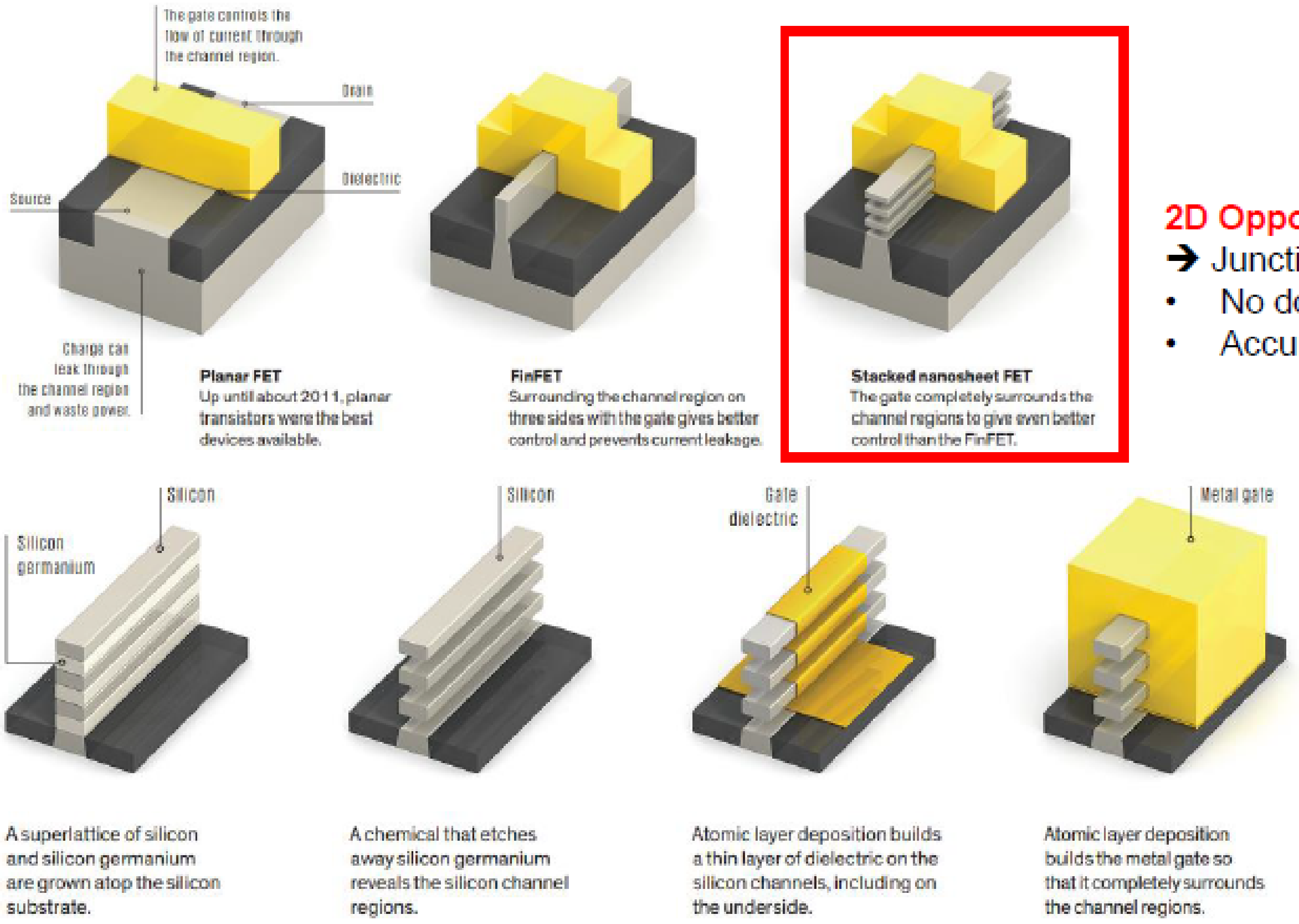
Classical for *quantum* platforms

Nanoscale, GHz-badwidth, noninvasive, ambient Q-sensors for electromagnetic fields and materials

Control fields and transducers for scalable Quantum systems

Nanosheet devices could be the final evolutionary step for Moore's Law. (The Last Silicon Transistor, IEEE Spectrum 2019)

Peide Ye



Si/Ge selective etching

ALD high-K dielectric

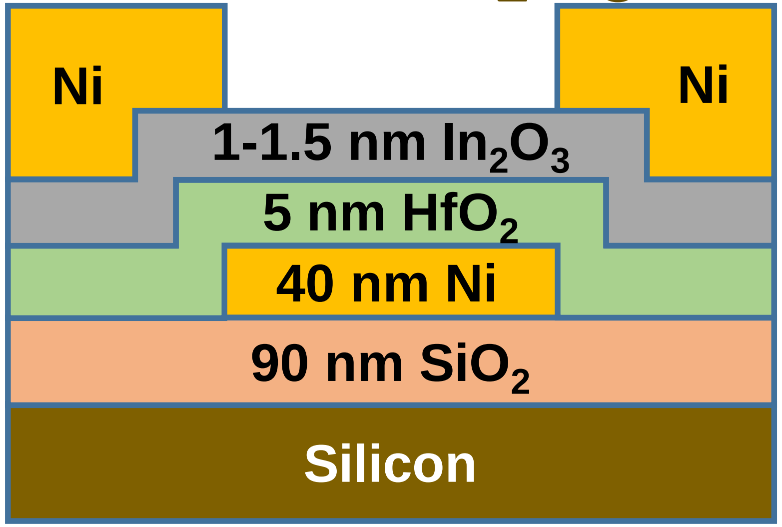
2D Opportunity?

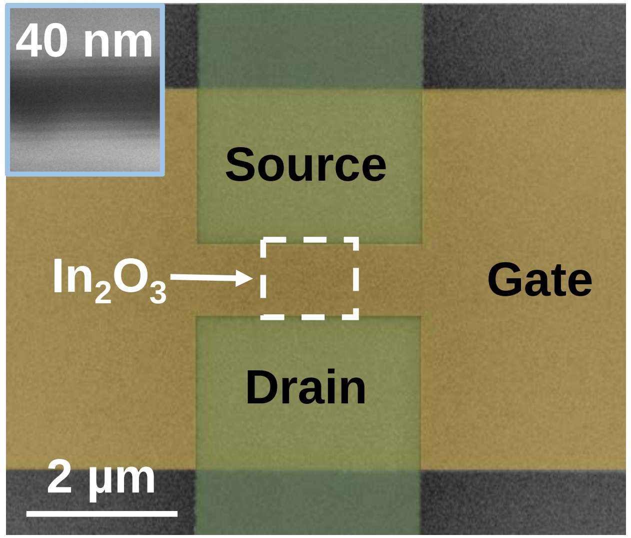
→ Junctionless FET

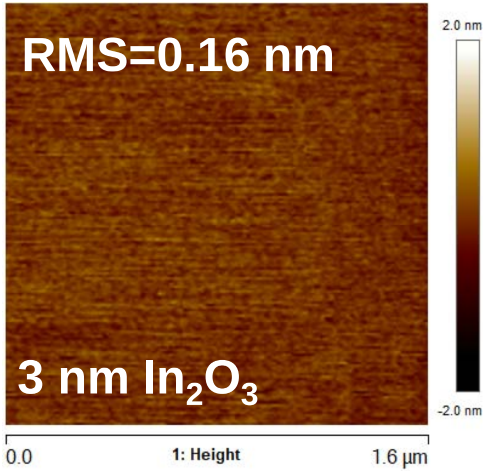
- No doping need?
- Accumulation-type

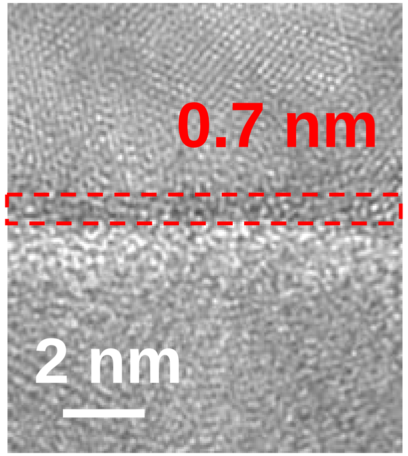
Atomic-Scale Ultra Precision Control for Future Ultra Efficient Microelectronics

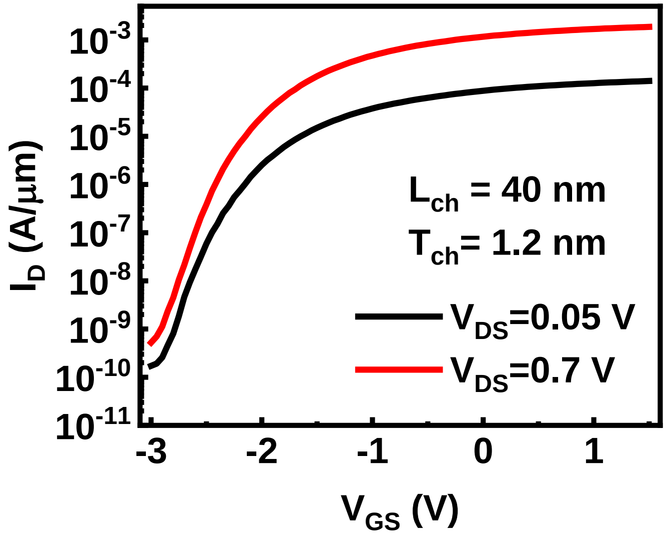
Ultrathin In_2O_3 Transistors by Atomic Layer Deposition



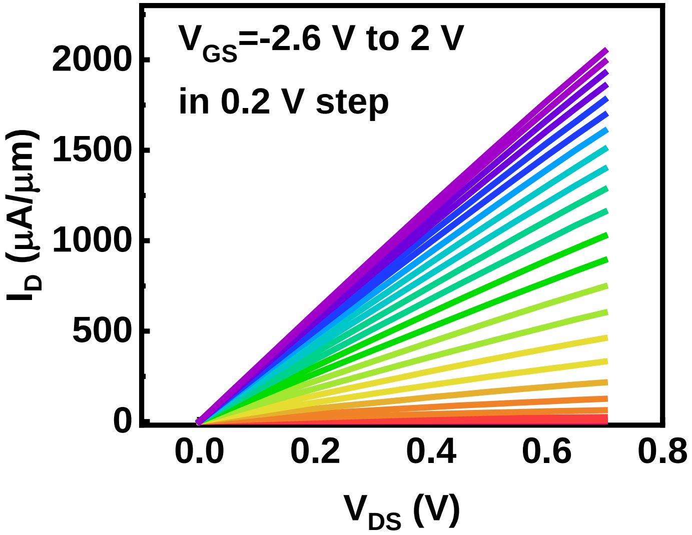




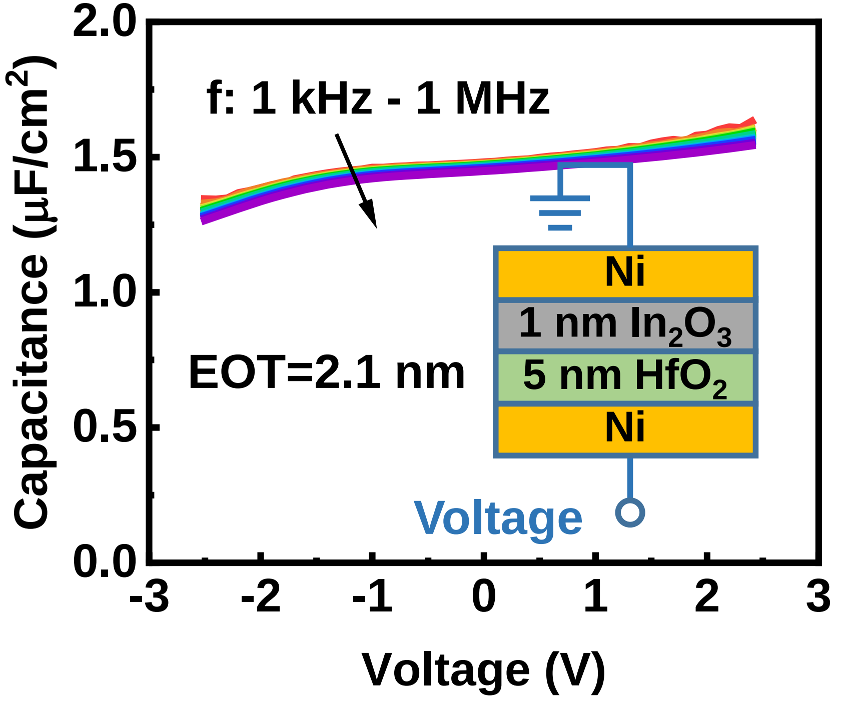




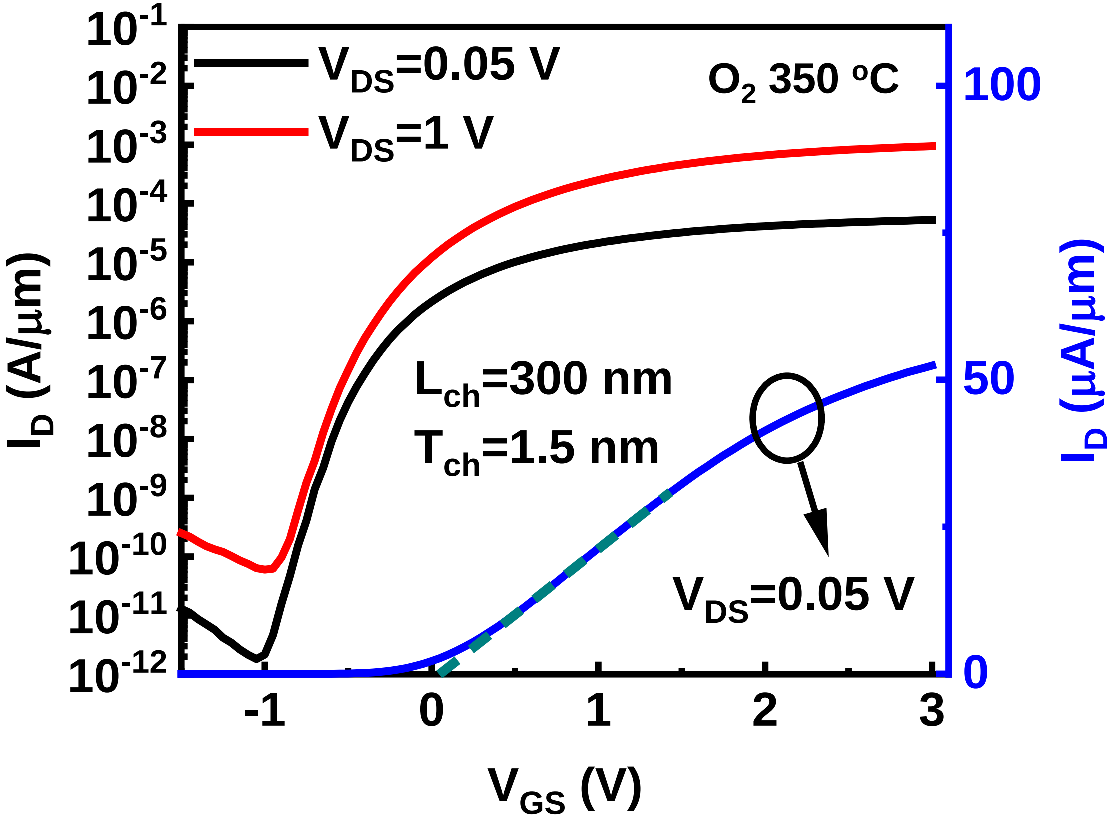
M. Si et al., IEEE EDL, 2020.
M. Si et al., Nano Lett., 2020.

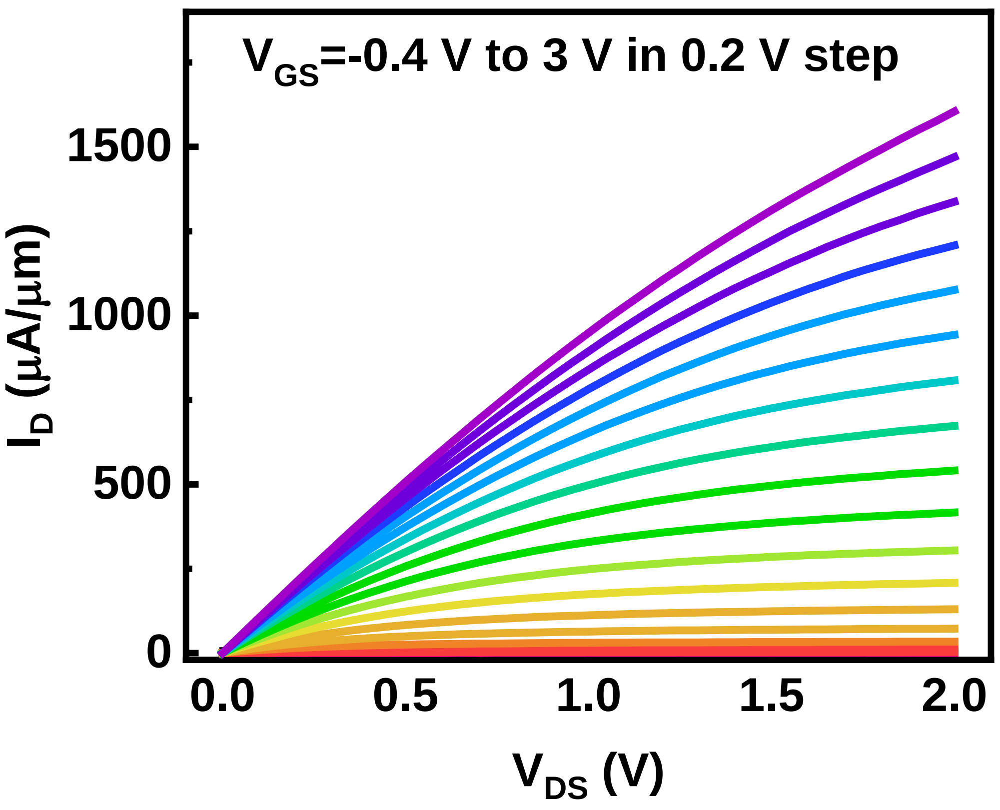


A. Charnas et al., APL, 2021.
M. Si et al., IEEE TED, 2021.



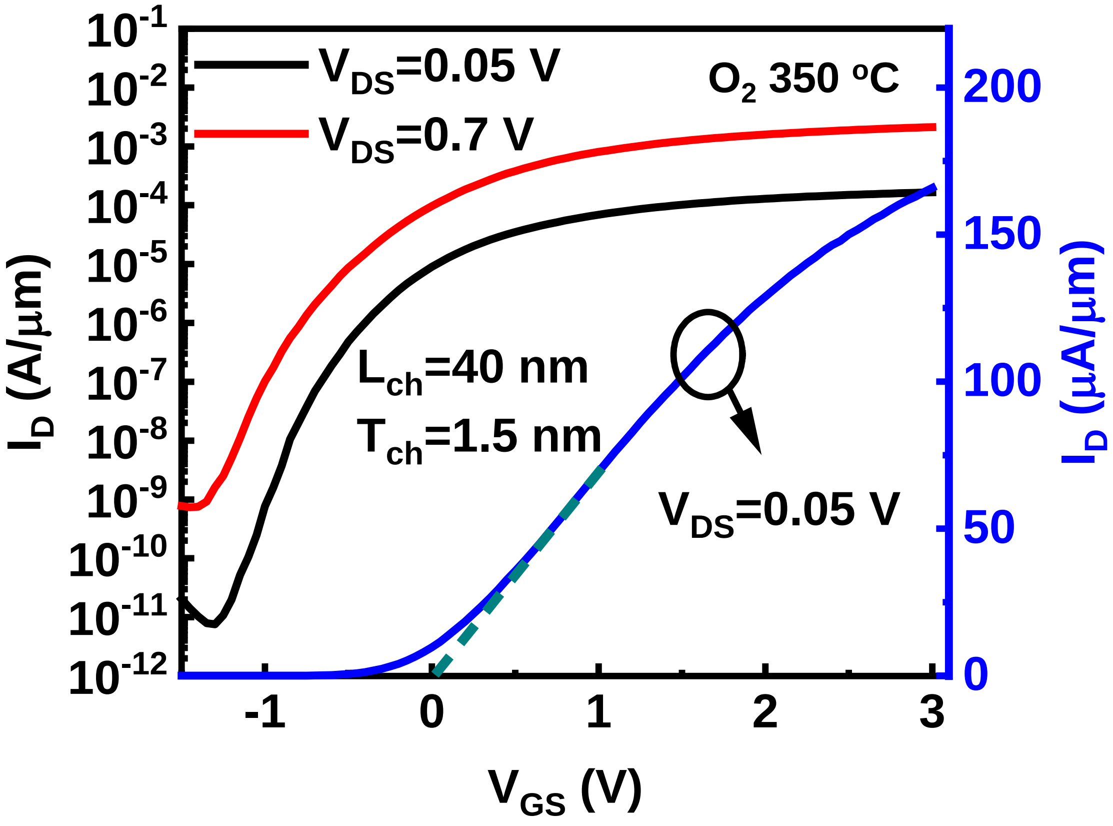
High-Performance Device by O_2 Annealing

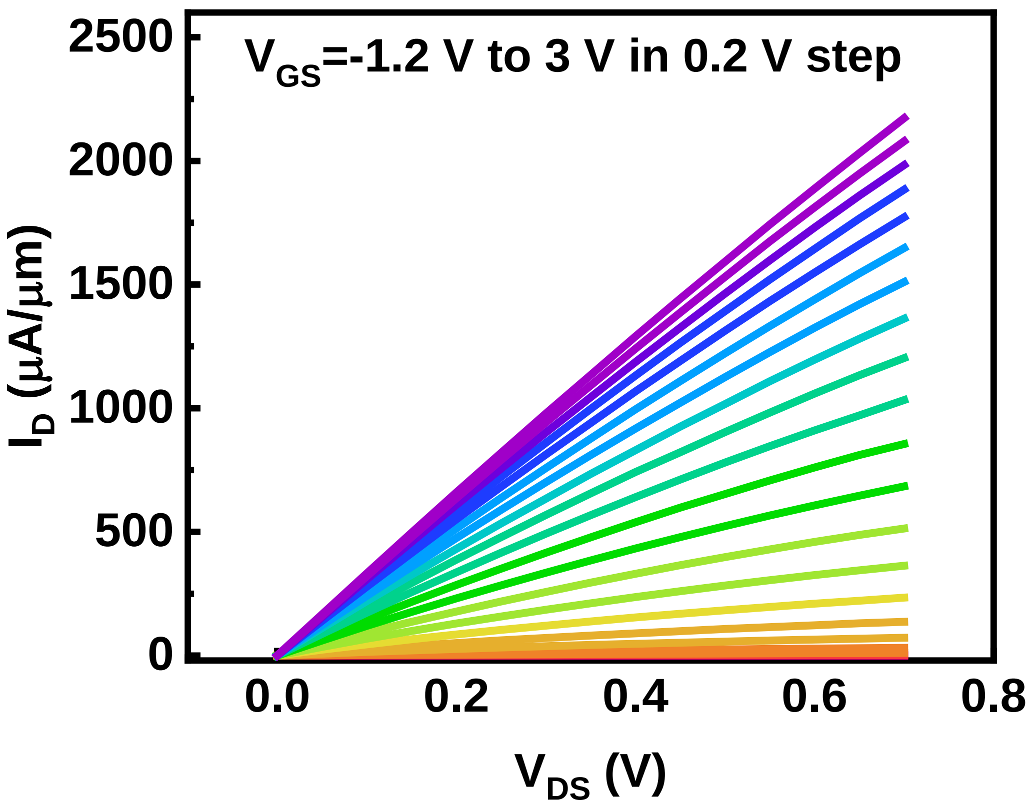




- ❑ Long channel device showing drain saturation.

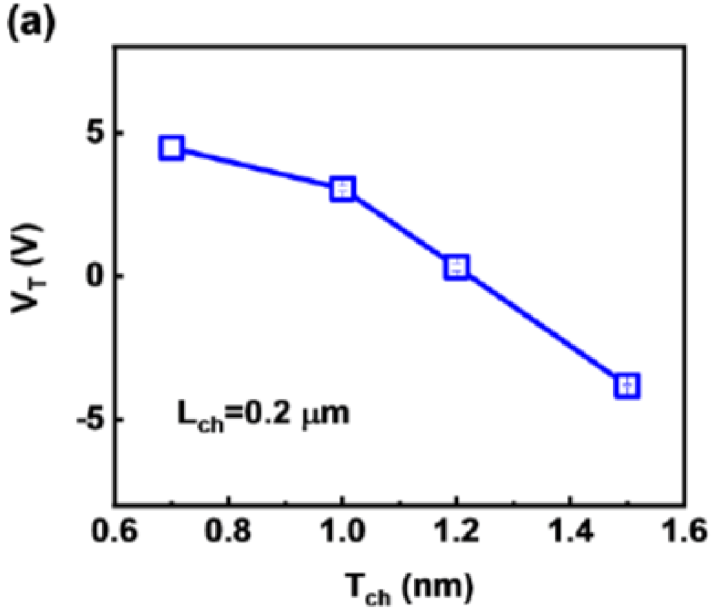
High-Performance Device by O_2 Annealing

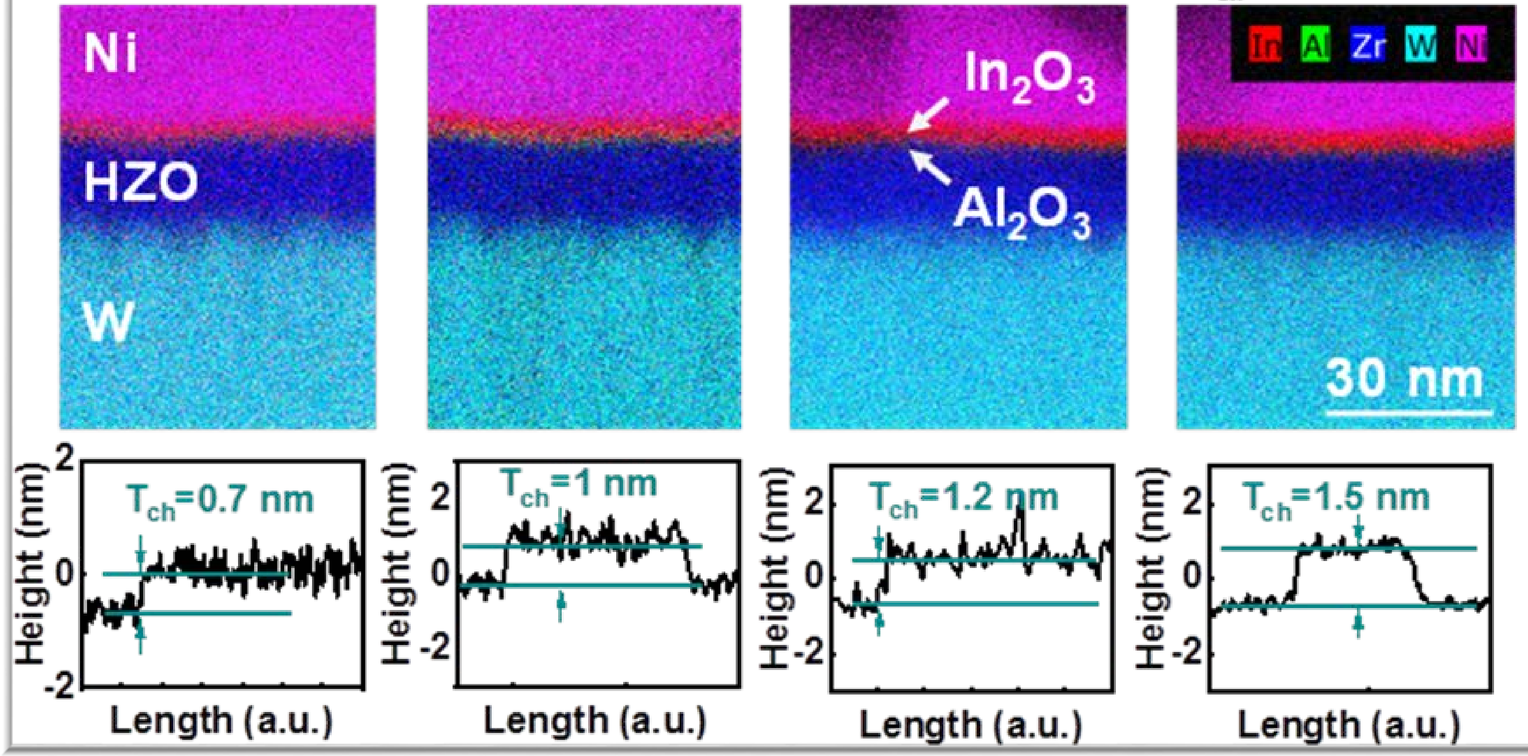


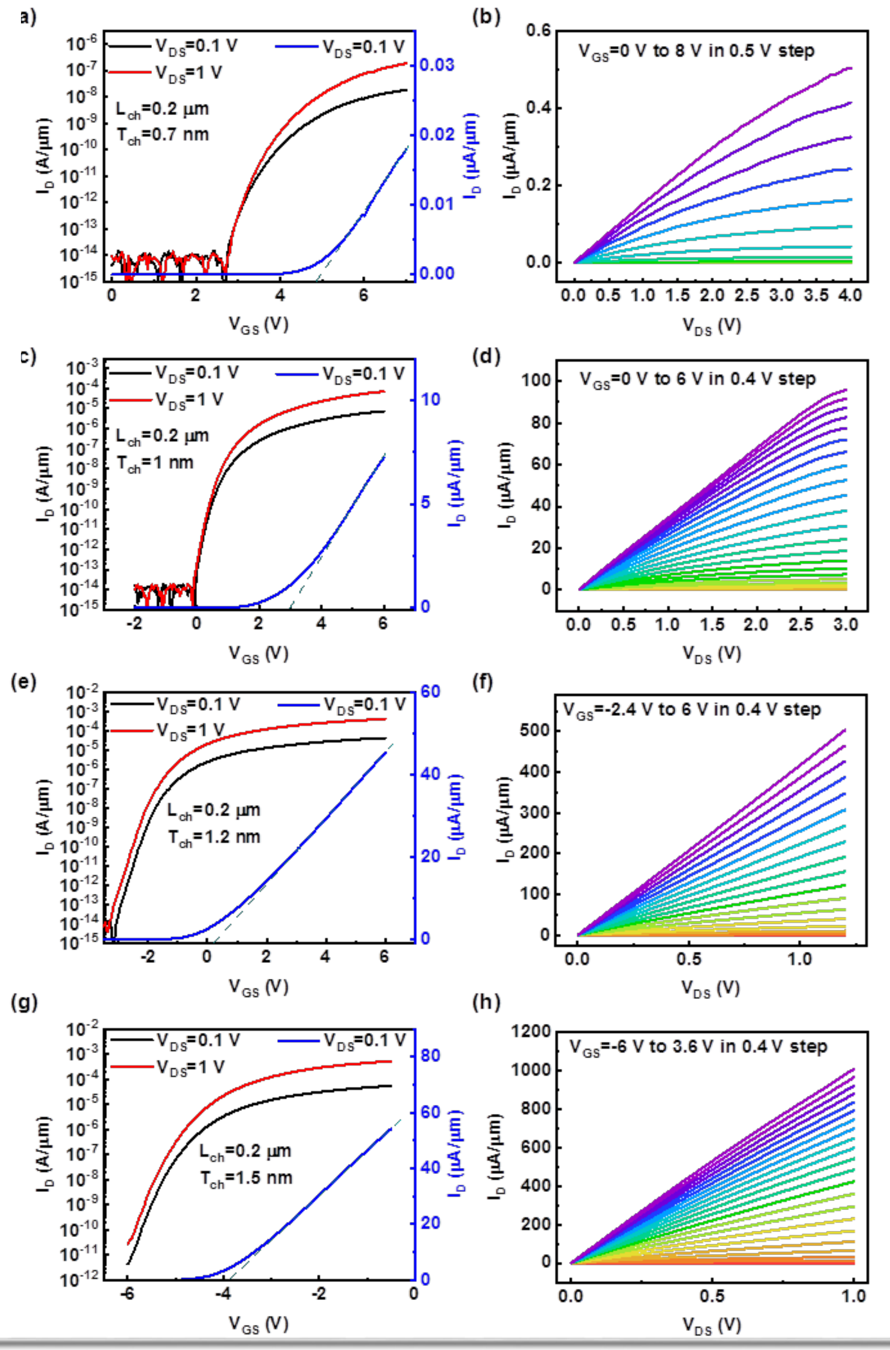


❑ On-current > 2 A/mm with enhancement-mode operation.

Threshold voltage (V_T) is controlled by the channel thickness at 0.1nm level (1 ALD cycle)

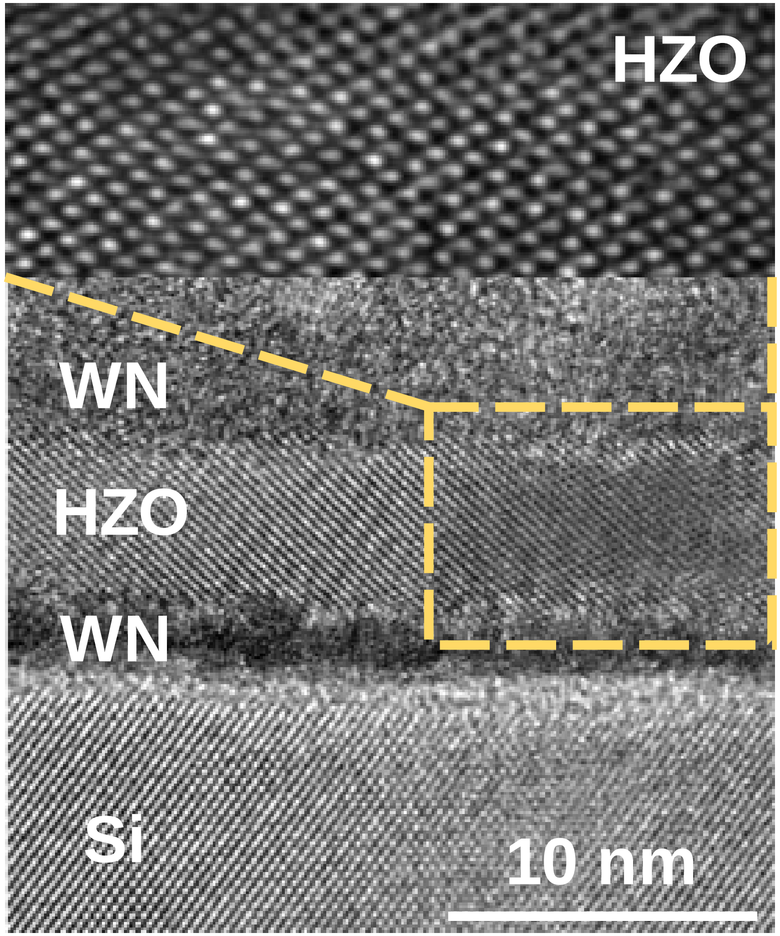


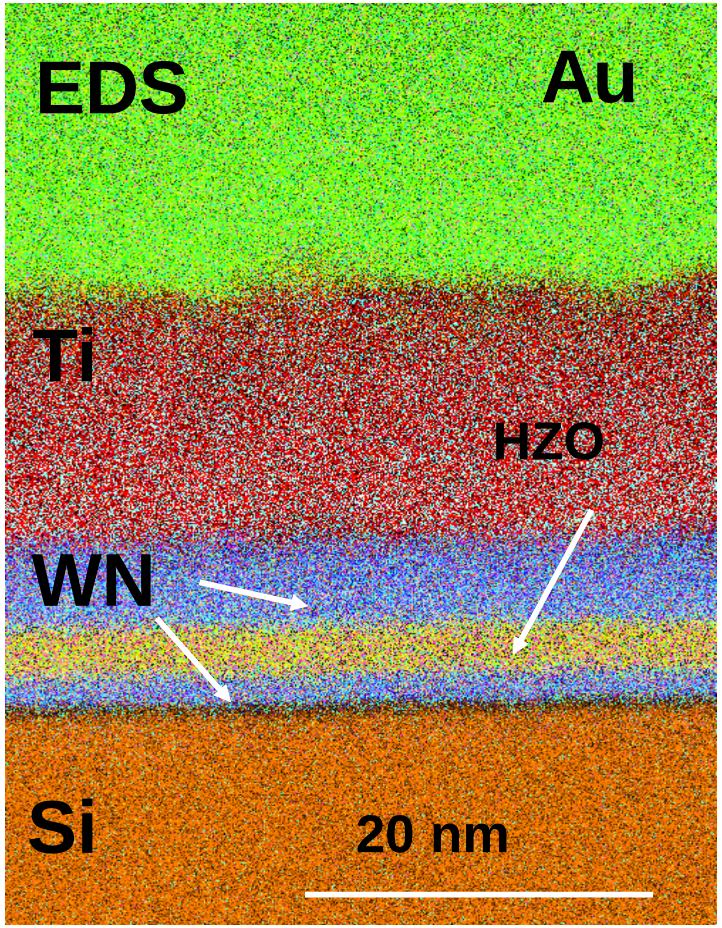




Atomic Layer Deposition of Ferroelectric and Anti-ferroelectric $HfZrO_2$

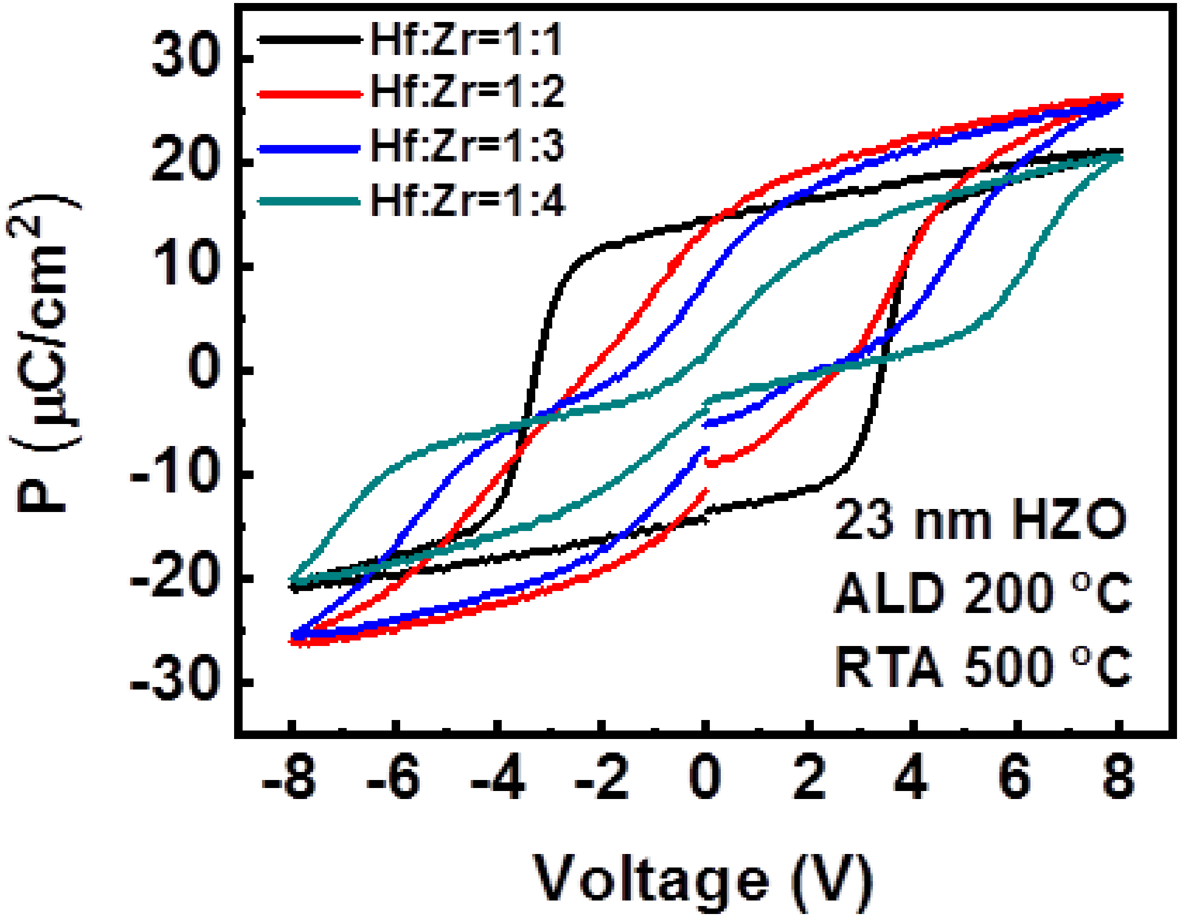
- Solvent Cleaning
- ALD WN
  - BTBMW, NH_3
  - 400 ºC
- ALD HZO
  - TDMAHf, TDMAZr, H_2O
  - 200 ºC
  - Hf:Zr=1:1 (FE)
    Hf:Zr=1:3 (AFE)
- ALD WN
- RTA 500 ºC in N_2 for 1 min
- Ti/Au Evaporation
- CF_4/Ar Dry Etching

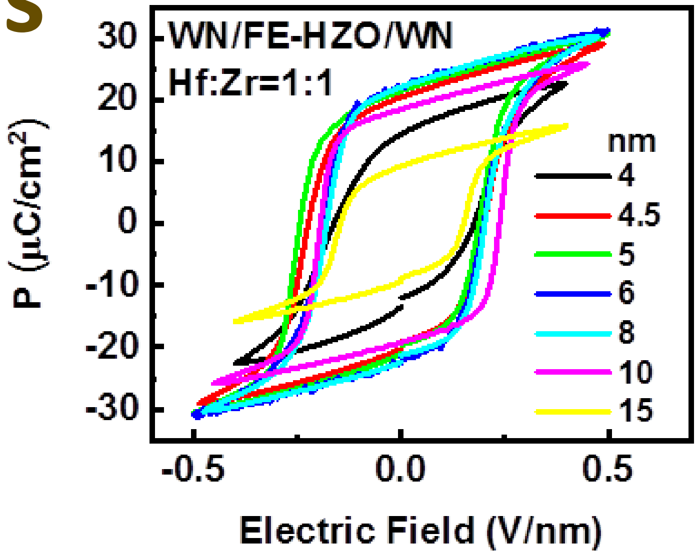


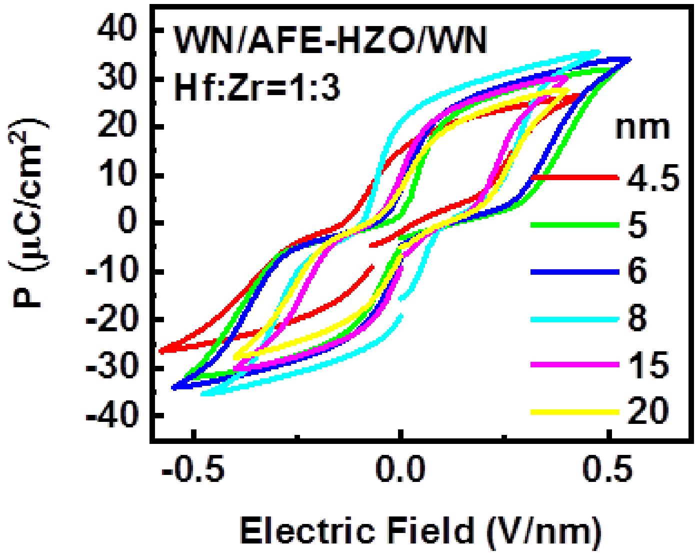


X. Lyu et al., VLSI, 2019

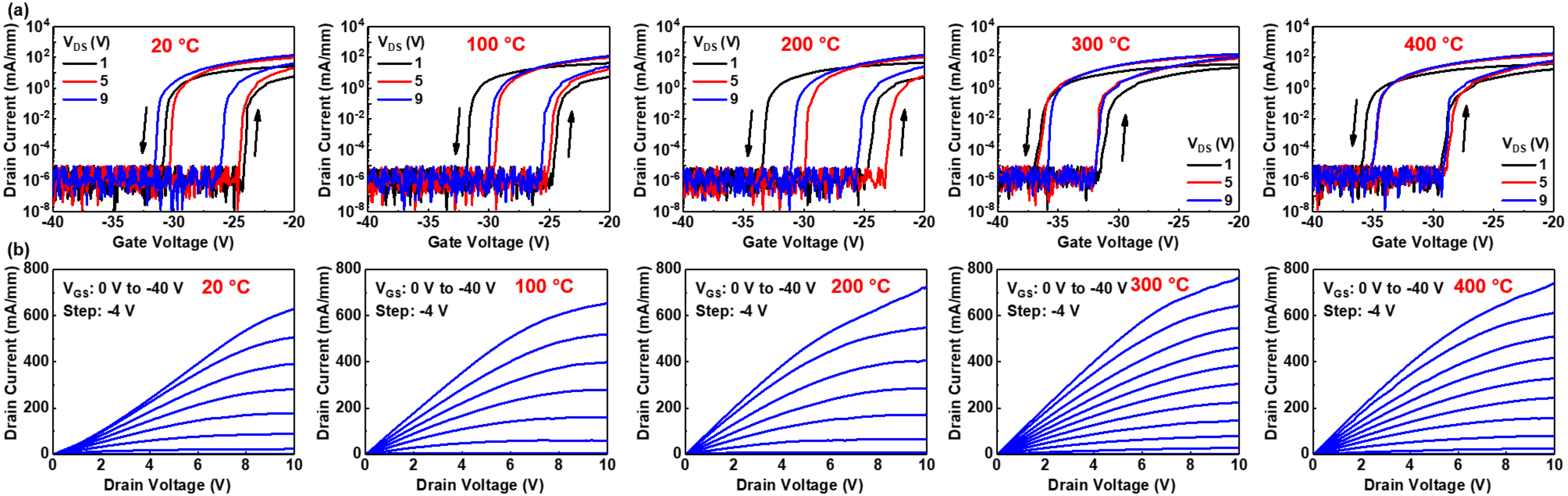
Ferroelectric vs. Anti-ferroelectric Controlled by Atomic Layer Cycles

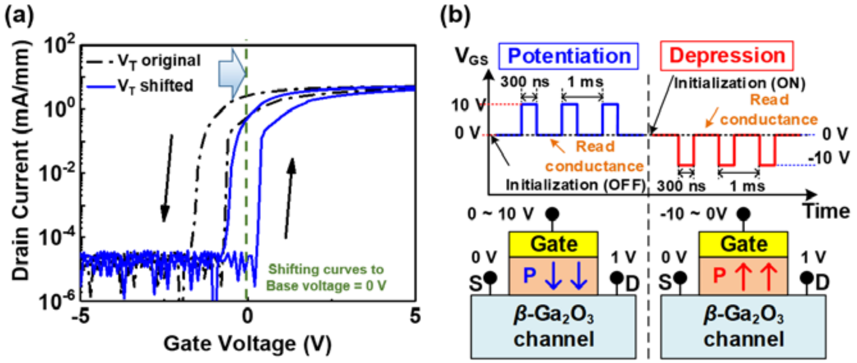


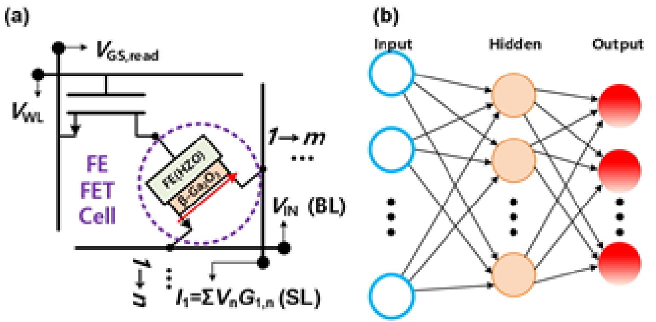


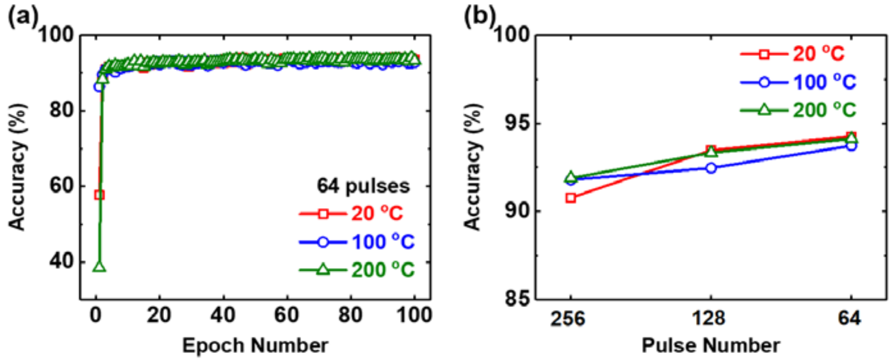


First Experimental Demonstration of Robust HZO/β-Ga_2O_3 Ferroelectric Field-Effect Transistors as Synaptic Devices for Artificial Intelligence Applications in a High Temperature Environment









J. Noh et al. IEEE TED 2021.

New Era Electronics

Mark Lundstrom

"This new electronics lives close to the frontiers of science, and requires a high level of technical competence. It grows by the development of new products. It is characterized by the transistor and other solid state electronic devices."
-- Frederick Terman, 1960.

21st Century Electronics:

-driven by applications
-inspired by new science
-enabled by new materials/heterogeneous integration
-accomplished by people with the right stuff

SCALE +
Lecture Notes on New Era Electronics
(World Scientific Publishing Company)

1960's

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Thank you!