Center for 3D Ferroelectric Microelectronics

A DOE EFRC

3D FeM

# Current and Potential Future BES Contributions to CHIPS and Science Act

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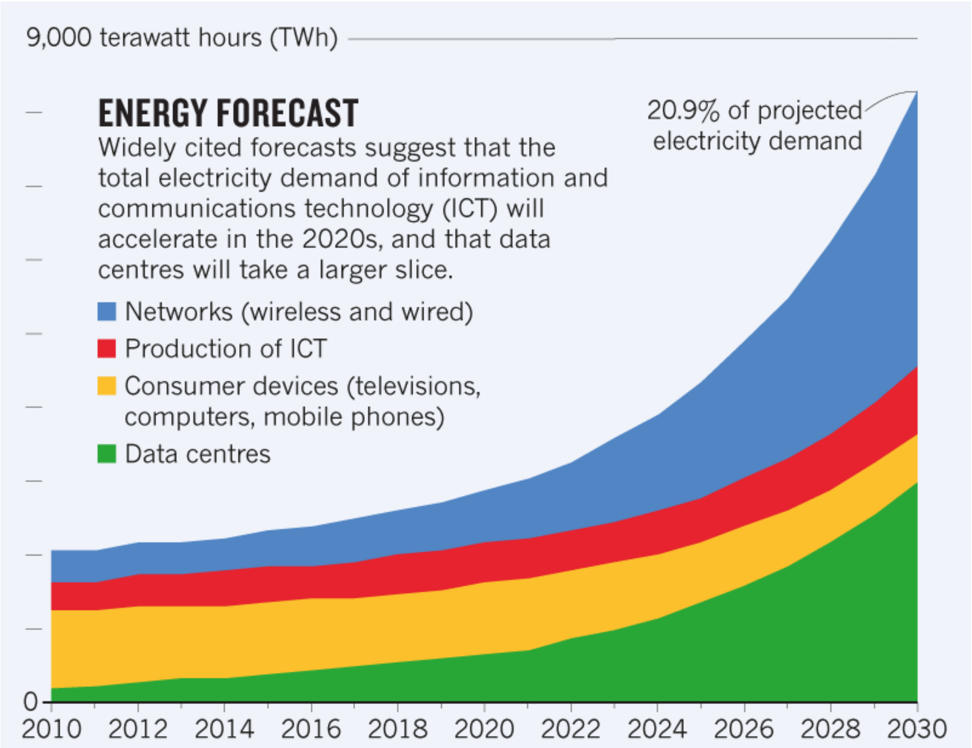
# Where Can BES Help?: Identifying and Addressing Challenges Like Computational Energy Consumption

- Computing accounts for 5 – 15% of worldwide energy consumption
- U.S. data centers alone consumed ~73 billion kWh in 2020
- Estimated energy demand from technology by 2030: 10 – 21%


- Edge computing for IoT demands low power

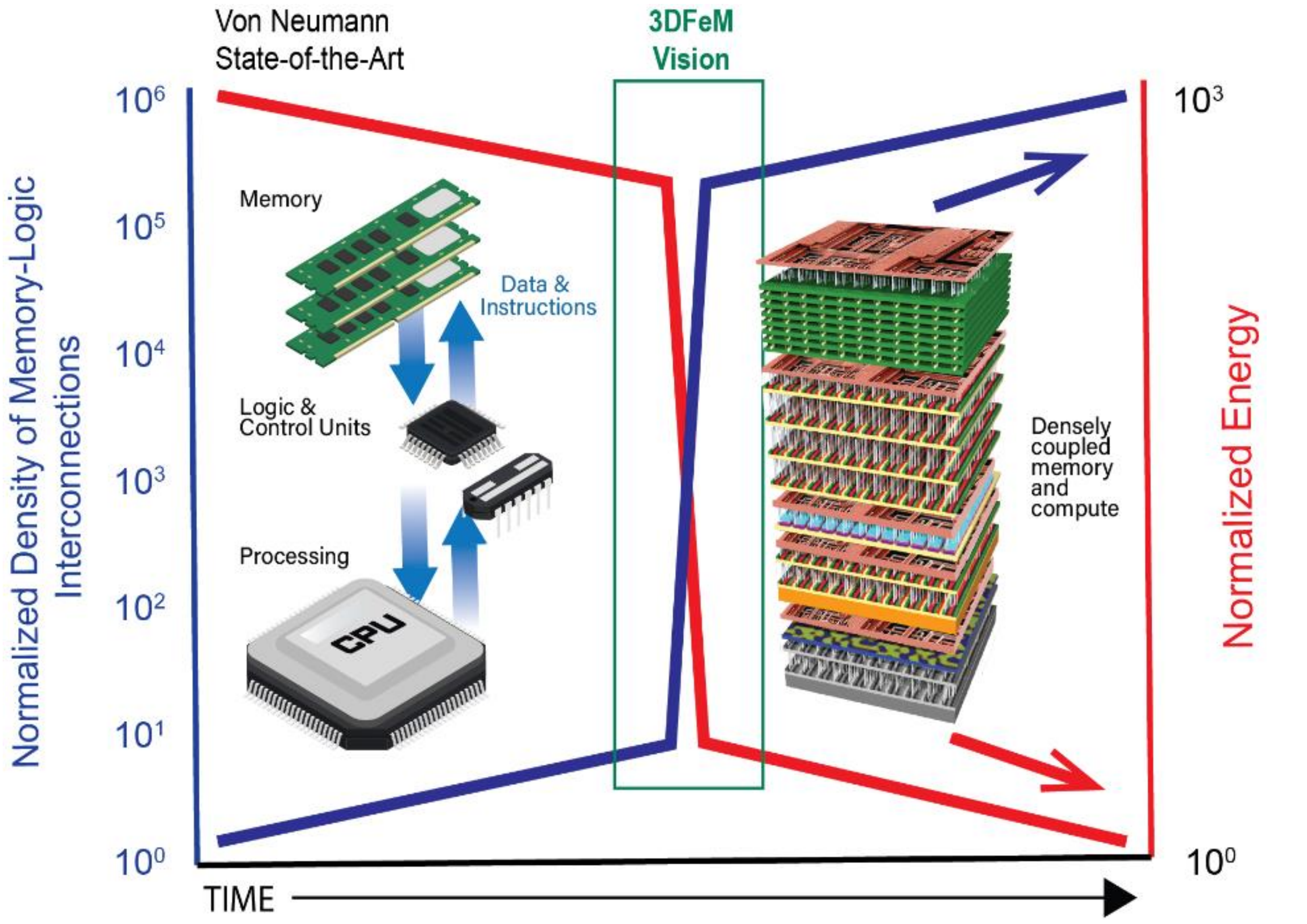



5% 15% 21%

Nicola Jones, Nature via: Anders A., Edler T., *On Global Electricity Usage of Communication Technology: Trends to 2030.*, Challenges, **6**, 117-157 (2015)

# Motivation: non-von Neumann Computing

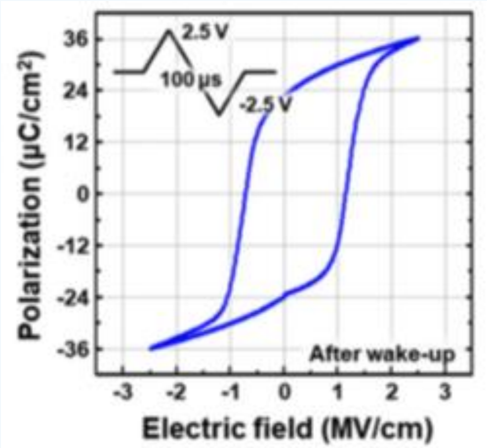
- Von Neumann architecture separates memory  and logic
  - Introduces delay
  - Significant energy penalty
- Solution:
  - Integrable, low power ferroelectric non-volatile memory
  - Dense interconnections between logic and memory
- BES can help re-assert US leadership in microelectronics



# BES Support – Developing New Materials

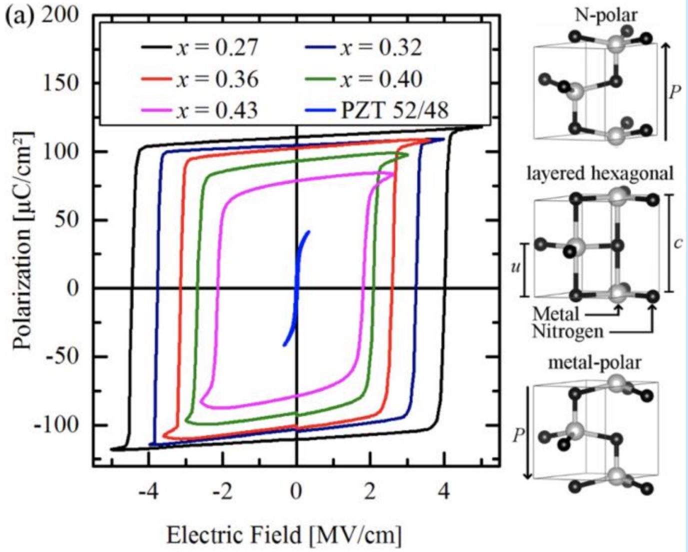
**Common link:** Electromechanical property **boost** at verge of composition **instability**

## $Hf_{1-x}Zr_xO_2$



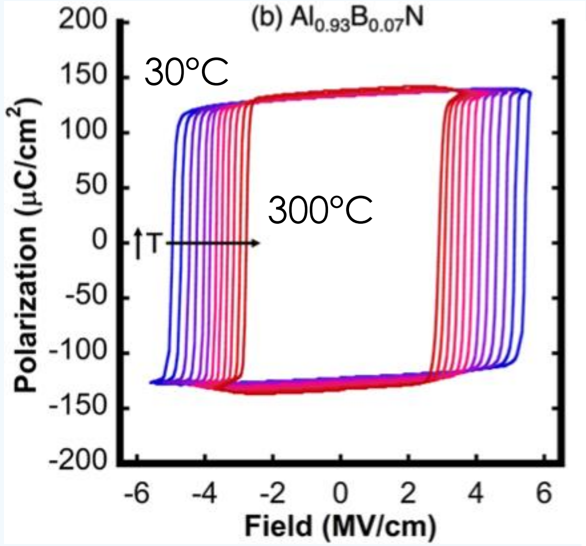

Muller et al., IEDM Proc., and APL (2011)

## $Al_{1-x}Sc_xN$



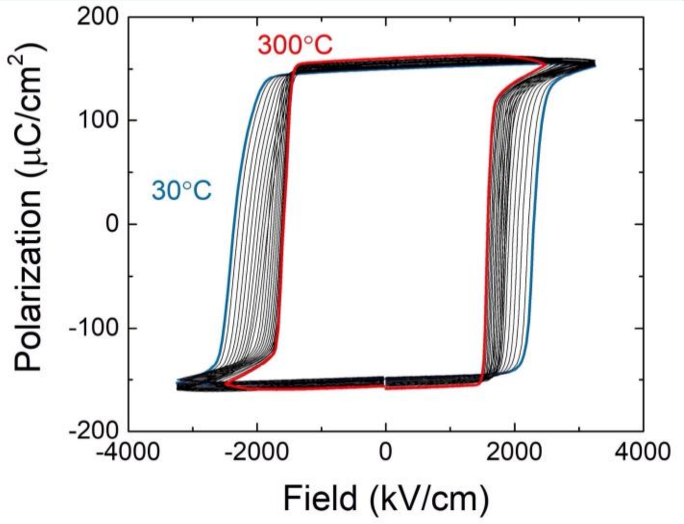

Fichtner et al., J. Appl. Phys. 125, 114103 (2019)

## $Al_{1-x}B_xN$




Hayden et al., Phys. Rev. Mat. (2021)

## $Zn_{1-x}Mg_xO$




Ferri et al., JAP (2021)

**3DFeM Exploration:** $V_2O_5$, ε-$Ga_2O_3$, $PbNb_2O_6$, $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$, γ-InSe

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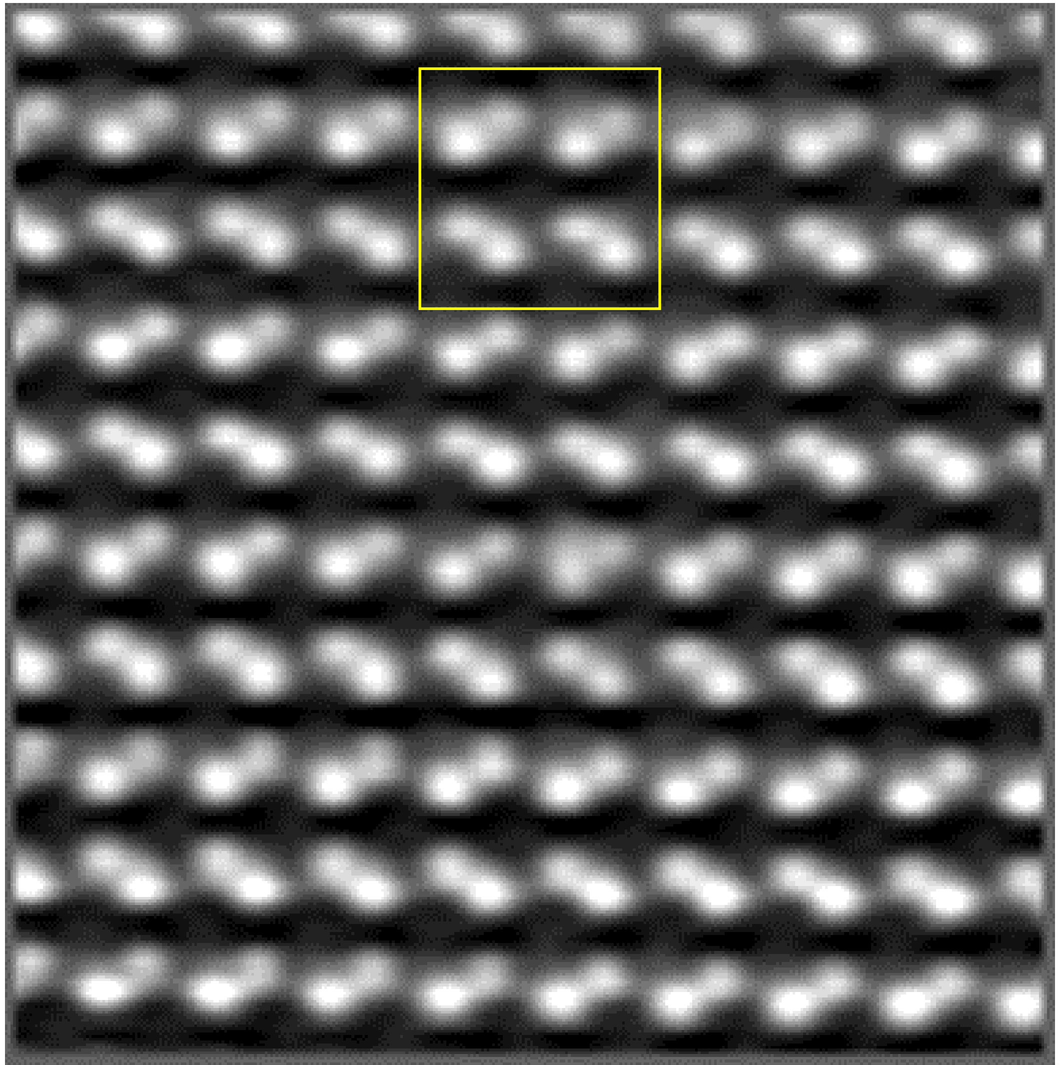
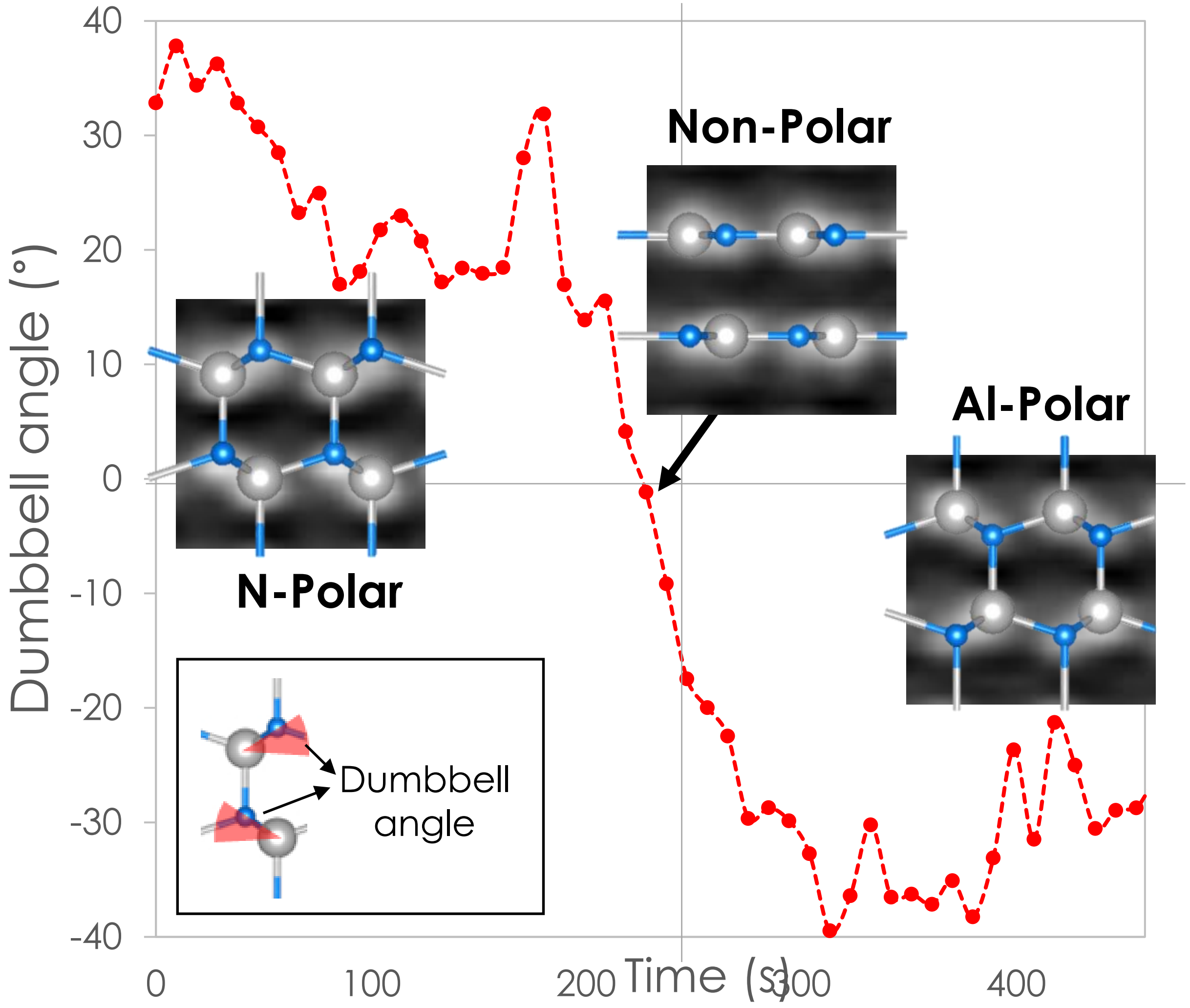
# Attacking the Underpinnings of New Behaviors: In-situ Observations of $Al_{1-x}B_xN$ Switching



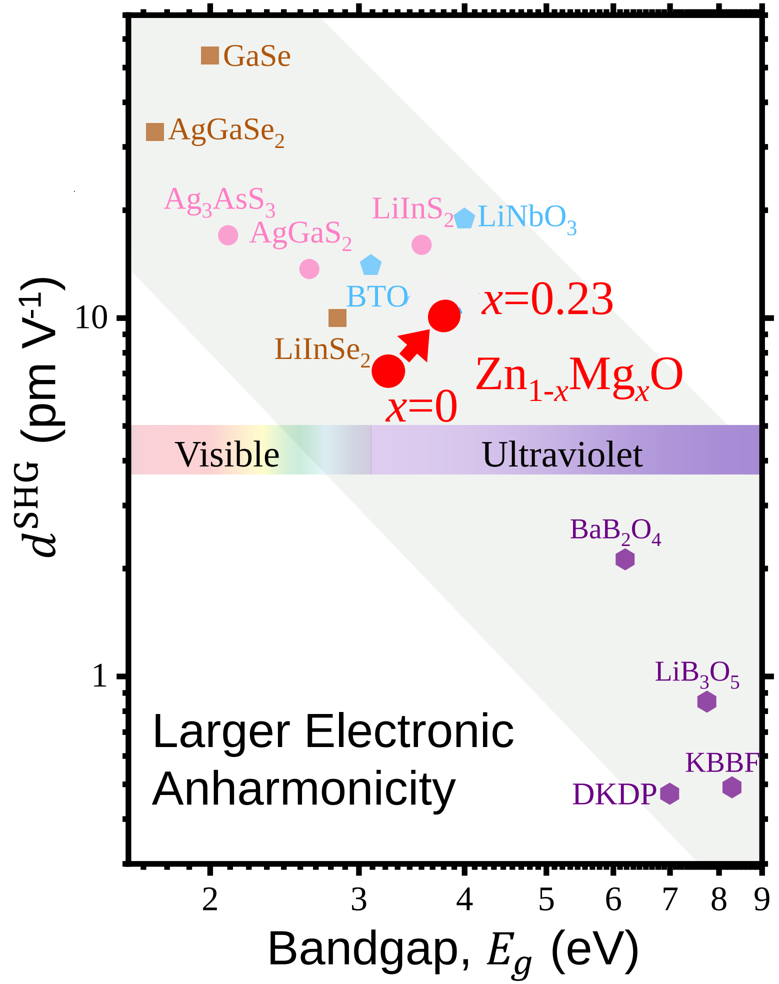



J. Calderon, E. Dickey

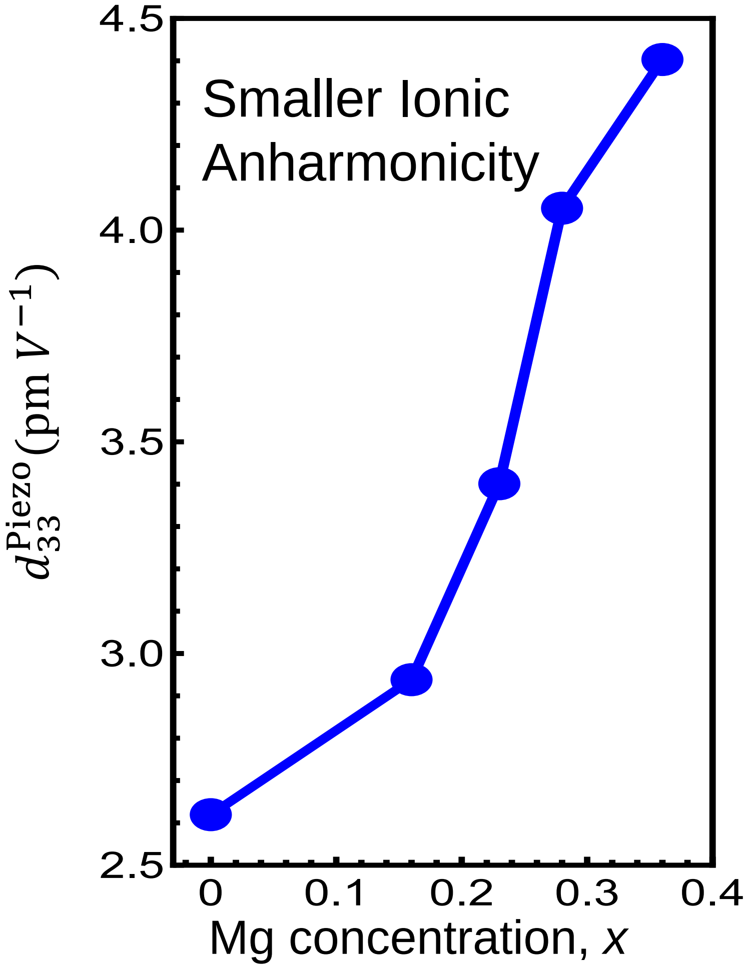
3D FeM

# Serendipitous Discovery: (Zn,Mg)O as a BEOL Compatible Electrooptic Material

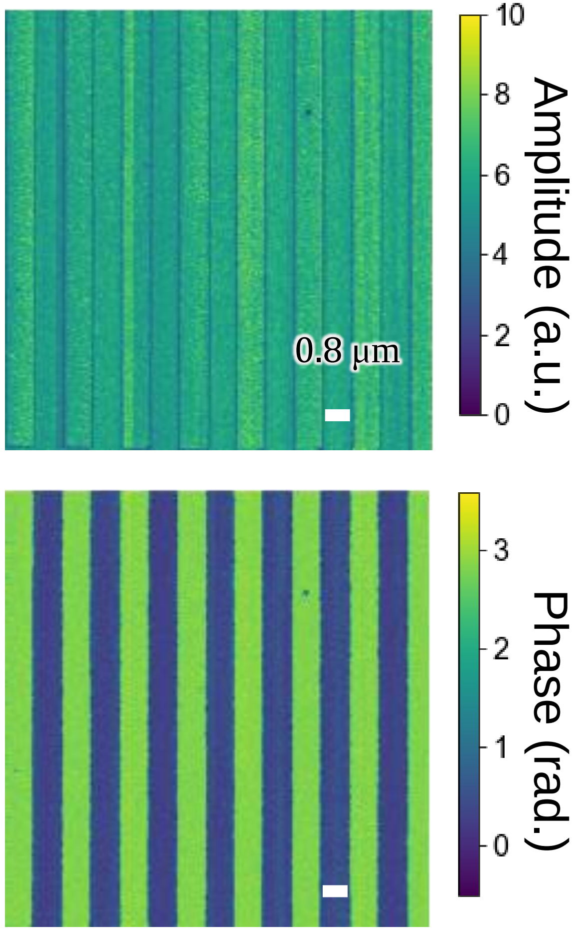
SHG coefficients and their band gaps



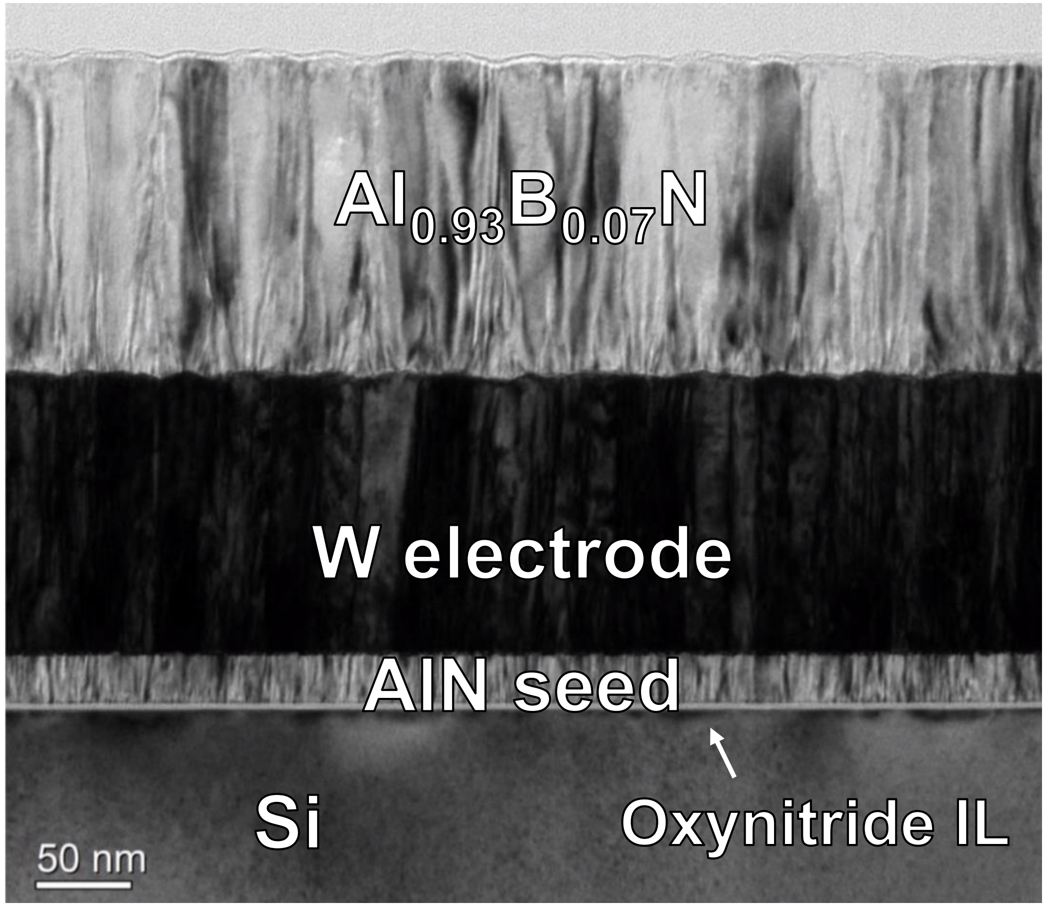

Piezoelectric Response

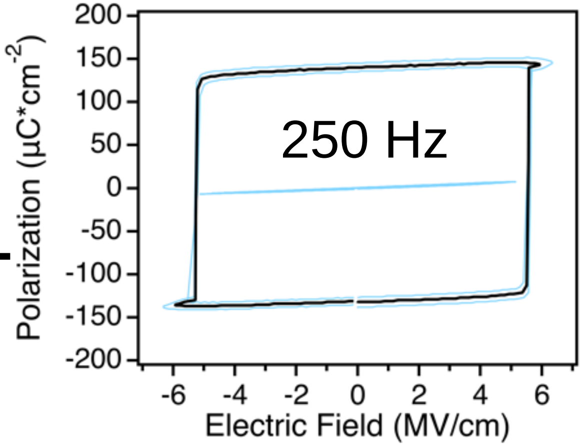



Ferroelectric Domain Grating

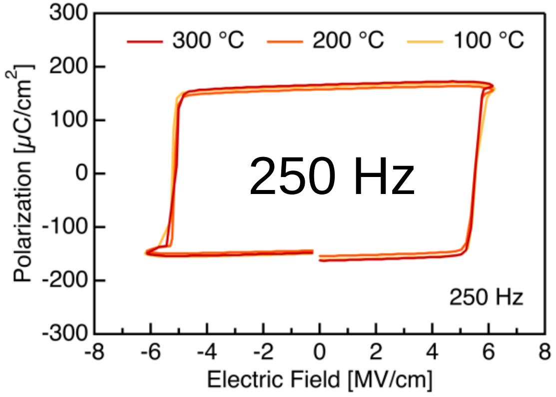


# BES Support: Addressing Hard Engineering Problems through Basic Science

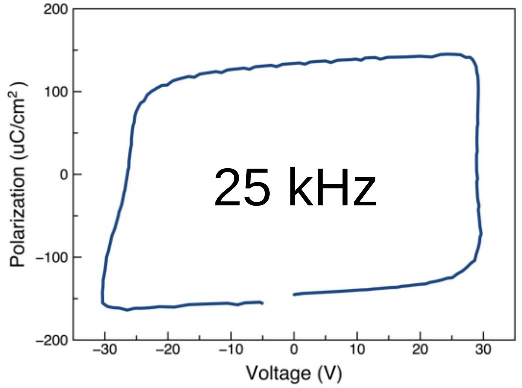



200$^{+}$ nm




90 nm




**36 nm**
**250 μm**

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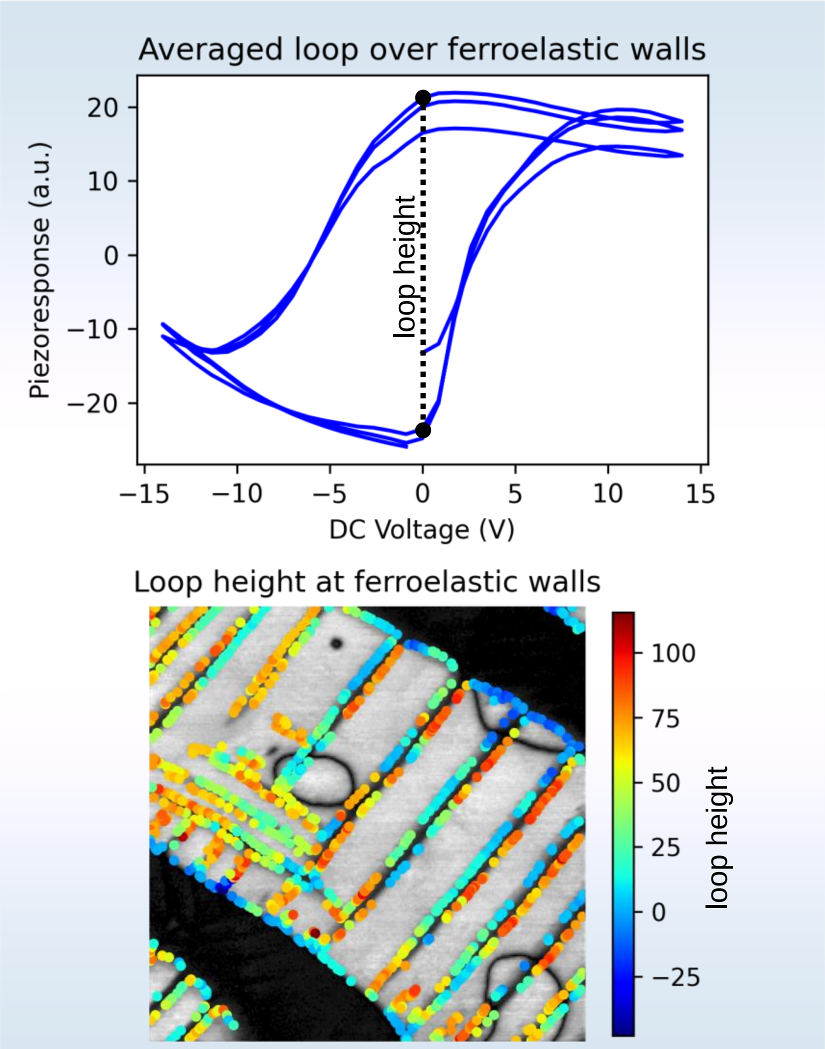
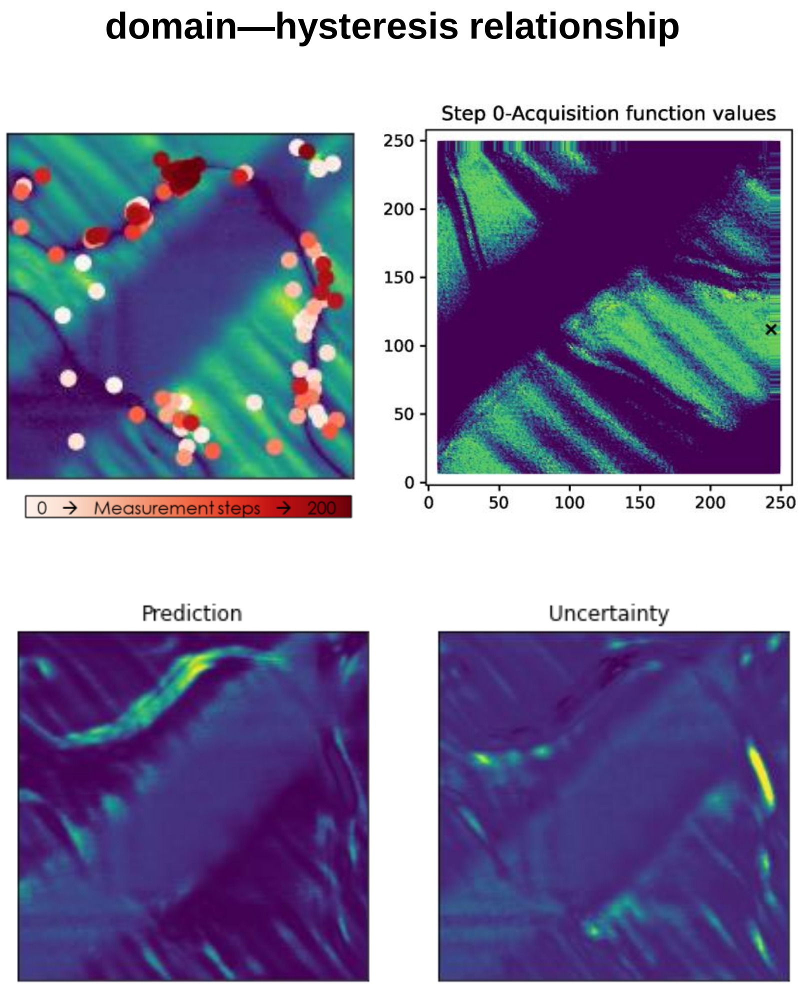
# BES Support: Developing Automated Microscopy

## *Ensembled DCNN*



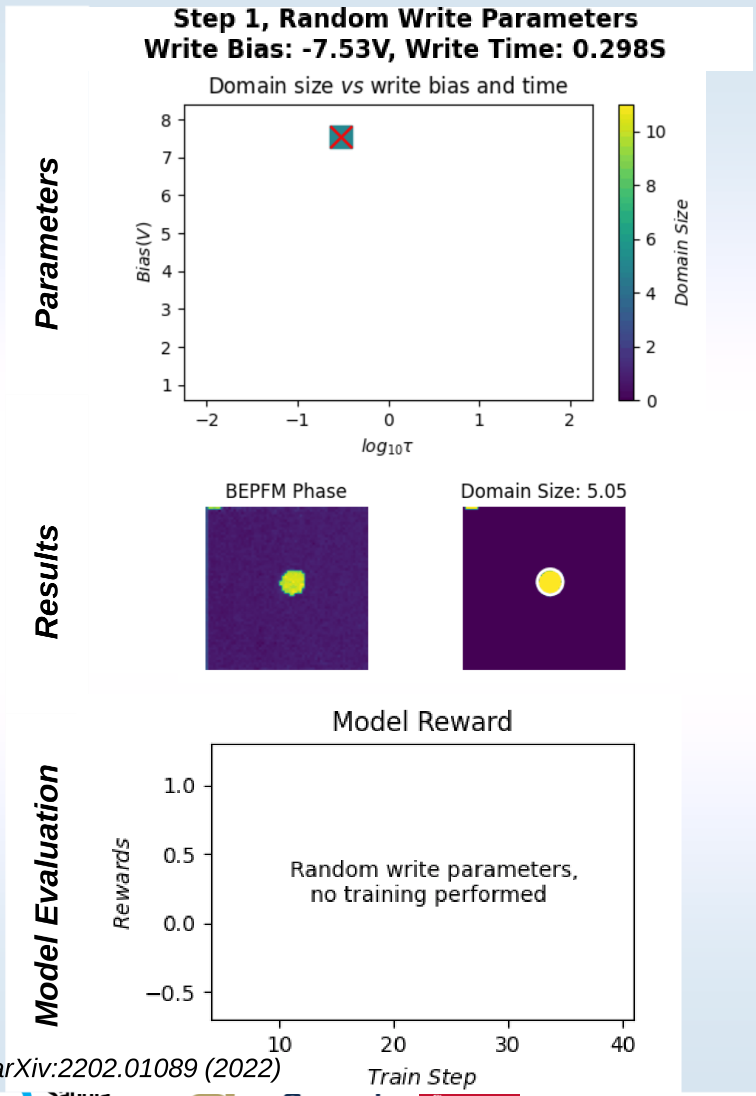

*Advanced Science (2022): 2203957*

## *Active Learning*




*Nature Machine Intelligence 4.4 (2022): 341-350.*

## *Hypothesis Learning*




*arXiv:2202.01089 (2022)*

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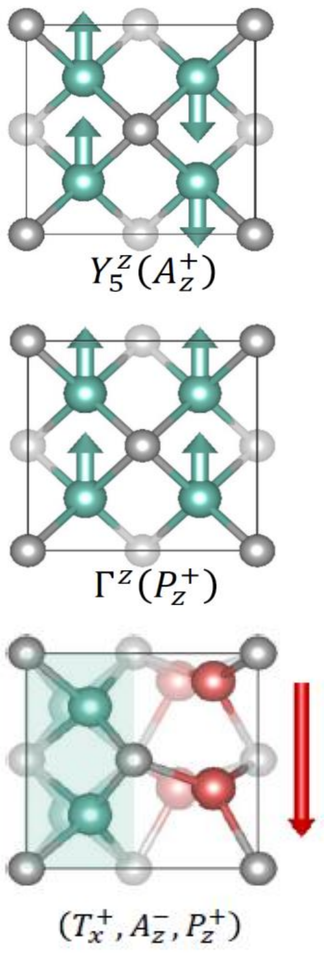
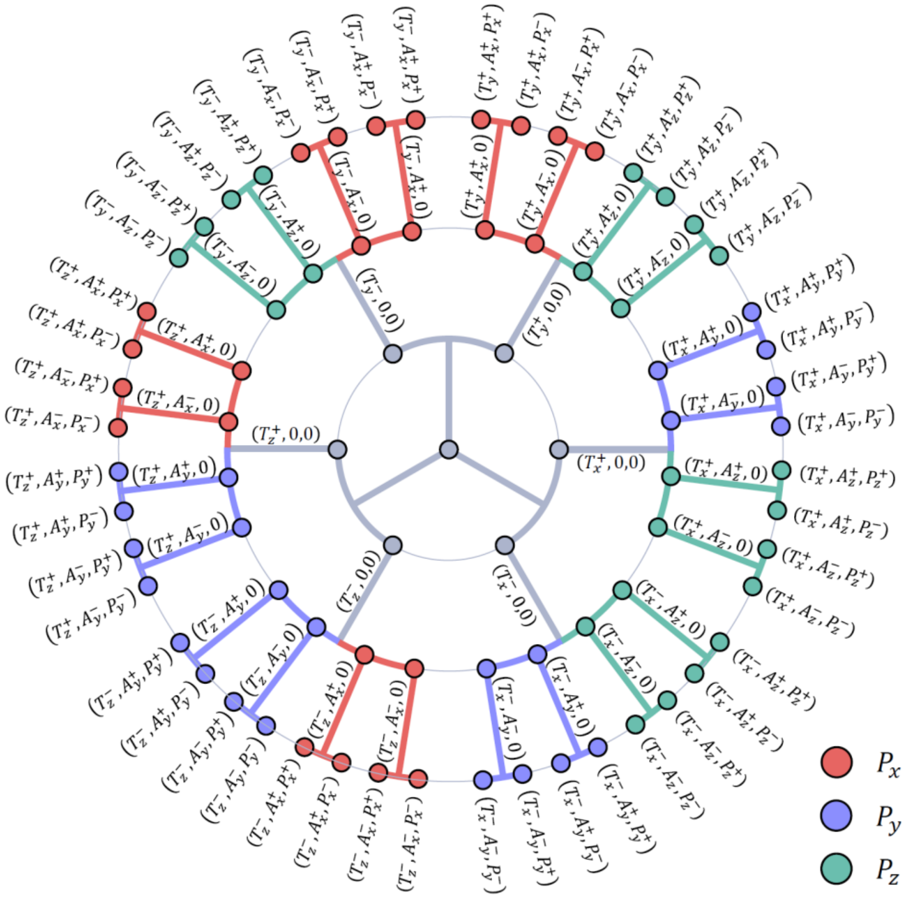
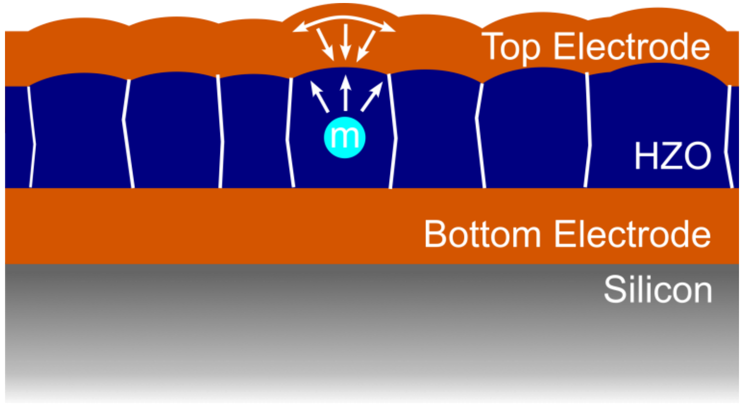
# BES Support: Understanding the Fundamentals of Existing Materials Like $Hf_{1-x}Zr_xO_2$



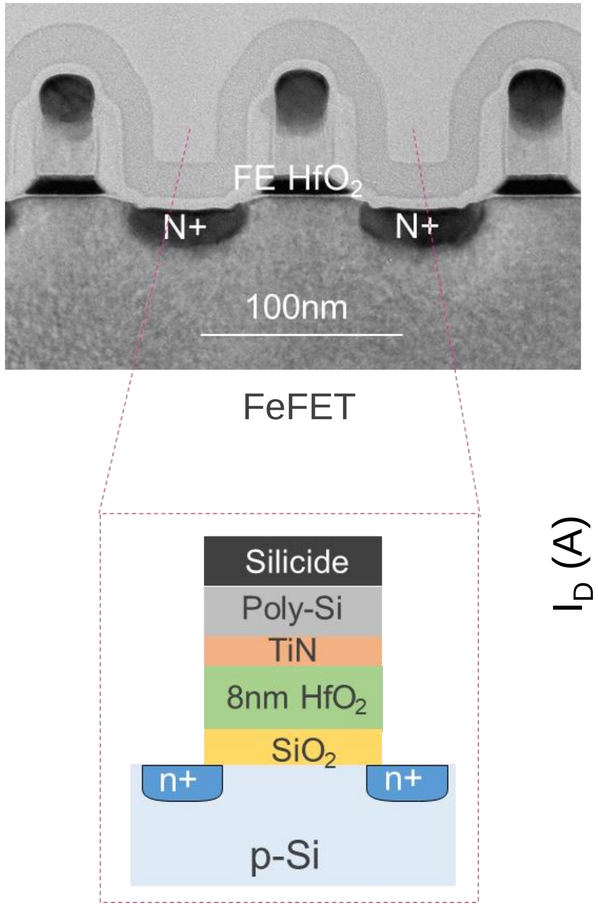



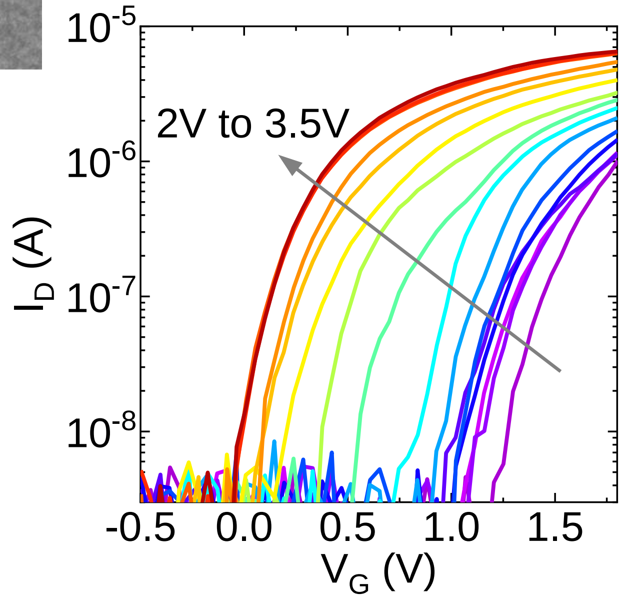




Top electrode serves as an out-of-plane mechanical constraint stabilizing the ferroelectric phase

S. Zhou, J. Zhang, A.M. Rappe, Strain-induced antipolar phase in hafnia stabilizes robust thin-film ferroelectricity, Advanced Science.

# BES Support Enables Co-Design: Intrinsic Synaptic Plasticity of Ferroelectric Field Effect Transistors (FeFETs)



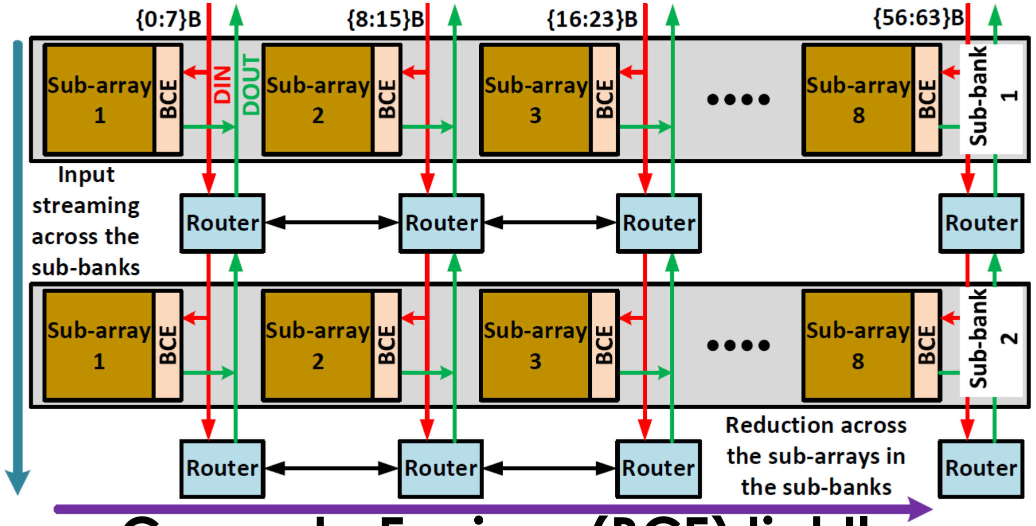

- "***Let physics do the computing***": Embrace inherent non-linearity and device programming history
- FeFETs enable brain-inspired in-memory compute processors that learn unsupervised representations online
- FeFET dynamics requires 33.3% fewer training samples (and 1/3 less power!) to converge compared to a network using the Standard STDP rule: **advantageous for few-shot learning, minimizes costly programming event**

Global Foundries Dresden provided FeFET devices.

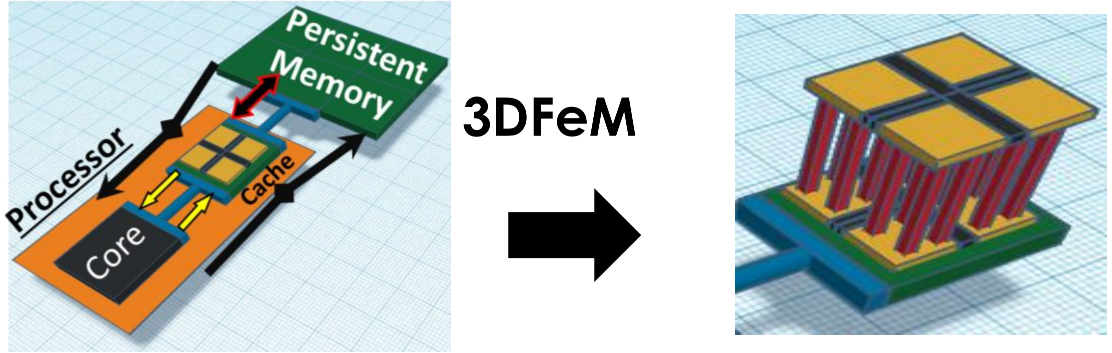
Arnob Saha, *et al*. Applied Physics Letters, Vol. 119 (13) 133701, 2021.

# Co-Design of Materials, Circuits, and Architectures for Data-intensive Applications

- Big Data: Machine Learning, Personalized Health, Data Analytics
  - In-situ compute with non-volatile weights
- Fast Back up and Restore: Servers: checkpointing transactions, Internet of Things: wakeup speed

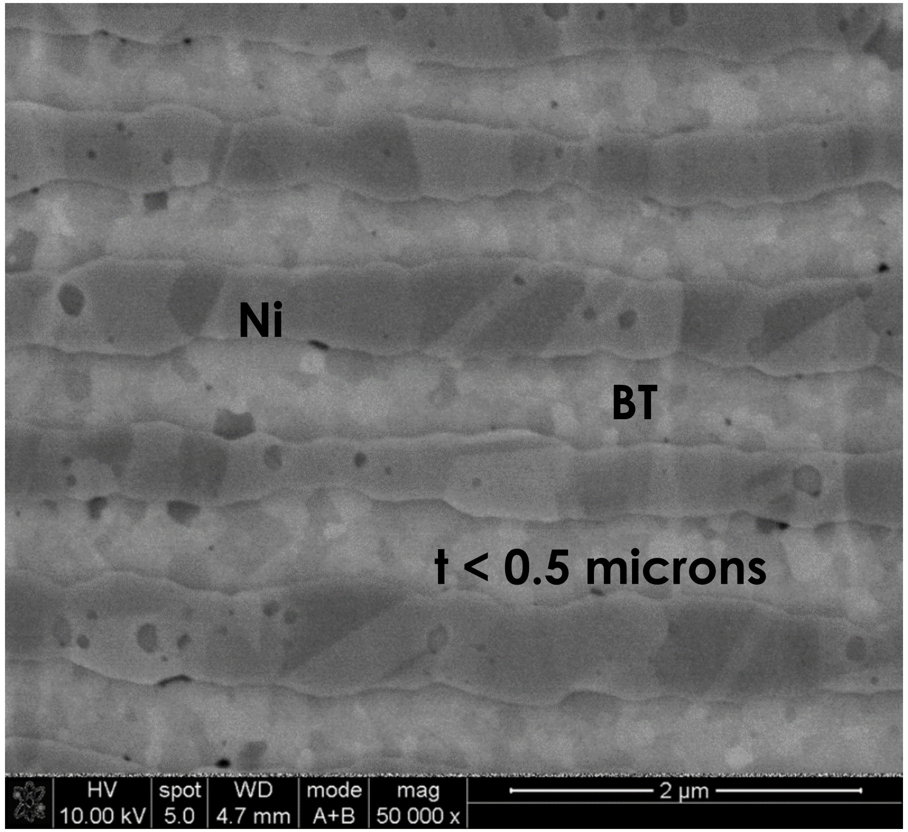



**Compute Engines (BCE) tightly integrated in memory**




**Persistent memory stacked on top of cache**
**Bandwidth between non-volatile and volatile memory**

# How Else can BES Help?: Support the Other Parts of the Electronics Infrastructure

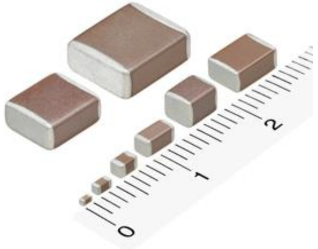



- Last major US producers (Kemet, AVX) have been acquired by international entities
- Some Japanese suppliers will not sell parts for US military applications

Multilayer Ceramic Capacitors

**Automobile X7R**

| Case Size | Voltage | Capacitance |
|---|---|---|
| 1005 | 10V | 1.0 µF |
| 3216 | 25V | 10 µF |
| 3225 | 25 V | 22µF |
| 3225 | 6.3V | 47 µF |




Operation Fields

**15V/µm to >30 V/µm**

**Application Examples**

**Typical ICE** 2900 pcs/Vehicle ICE +ADAS 4200 pcs/ Vehicle
(Advanced Driving Assistance System)

2000 mF/ Vehicle 8200 mF/ Vehicle
(Power Train, Safety, Information (Sat-Nav) and Entertainment)

EV 15,000 pcs/ Vehicle 40,000 mF/ Vehicle **48 volts and above**

**Cell Phones X5R**

| **2017 year** | **2018** | **2019** |
|---|---|---|
| 600 pcs/set | 720 pcs/set | 1,040 pcs/set |
| 2100 µF/set | 2500 µF/set | 3300 µF/set |

Trends: Size, Low ESL, and Low Profile

# Potential Areas of Interest

- Developing materials and processes for More Moore
  - Quantum computing
  - Advanced patterning approaches
  - …
- Developing materials, processes, and tools that enable More-than-Moore functionality
- Catching up to investments in foundry capabilities in Asia and Europe
- Recognizing that all electronic systems require passive components and packaging
- Facilitating lab-to-fab and fab-to-lab transitions