

FERROELECTRIC MATERIALS FOR MICROELECTRONICS

*Addressing Grand Challenges in
Energy Consumption-Storage-Generation*



RESEARCH LABORATORY
OF ELECTRONICS AT MIT



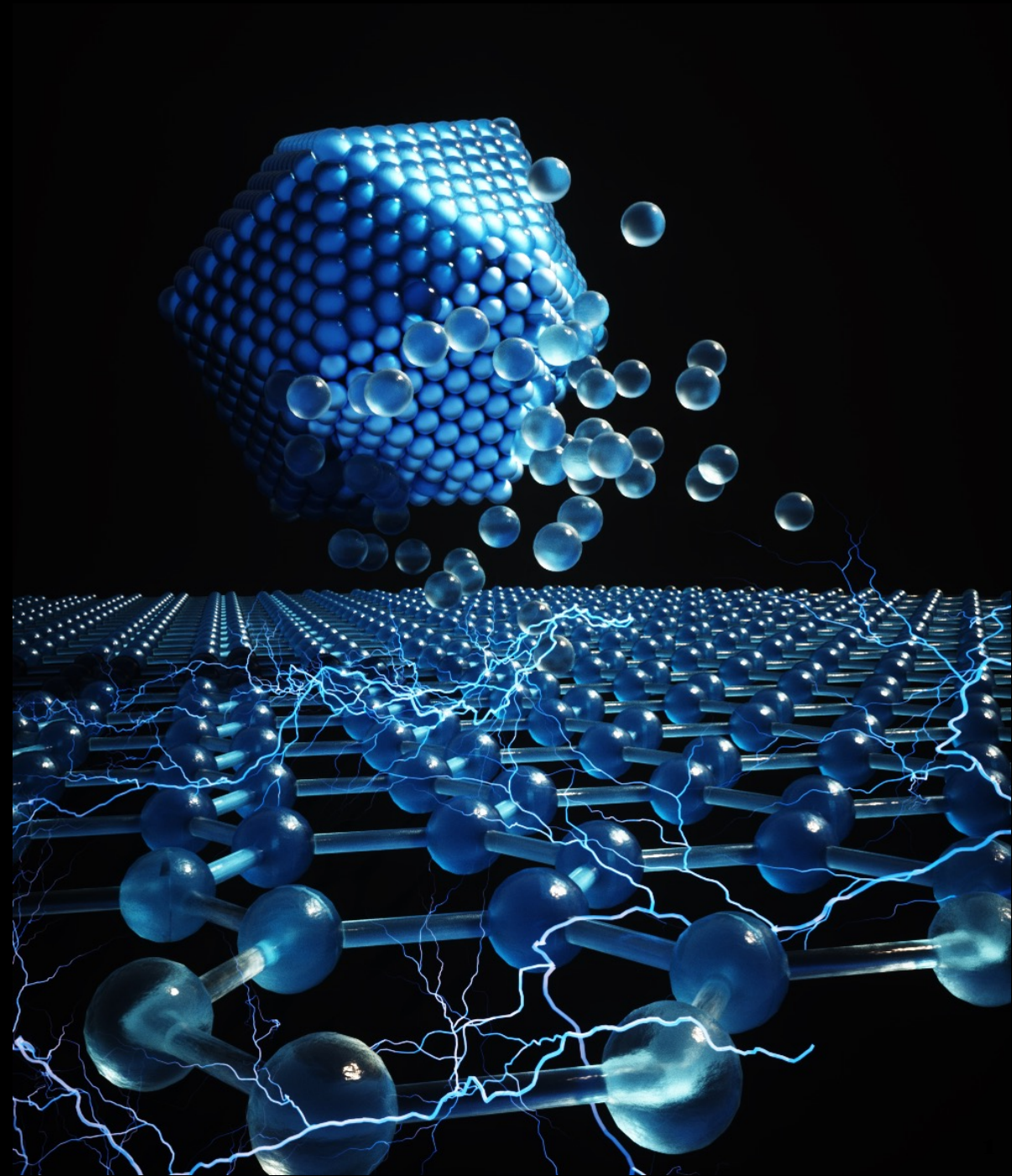
[Electronic Metamaterials & Devices Group](#)

Suraj Cheema | sscheema@mit.edu

Principal Investigator: RLE | MTL

Assistant Professor: DMSE | EECS

Massachusetts Institute Of Technology



Microelectronics | Energy Grand Challenge

Computing Energy Consumption

A Call for New Paradigms of Electronics

ENERGY SCALE

Global Electricity Demand

20,000 TWh

Information Technology

2,000 TWh

Data Centers

200 TWh

Computing Energy Consumption

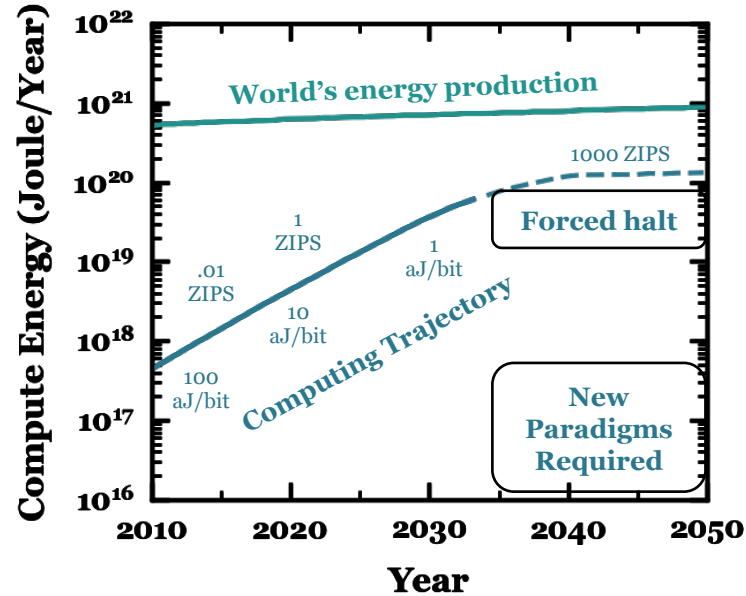
Currently: ~ 5-10 %

Jones. Data centres gobbling the world's electricity. *Nature* 561, 163 (2018)

Computing Energy Consumption

Projected: > 20 %

Semiconductor Research Corporation (SRC)
Decadal Plan for Semiconductors (2020)



Global Energy Demand from Electronics

Exponentially rising: ~ doubling every 3 years

Microelectronics | The “Angstrom” Era

Computing Energy Consumption A Call for New Paradigms of Electronics

ENERGY SCALE

Global Electricity Demand

20,000 TWh

Information Technology

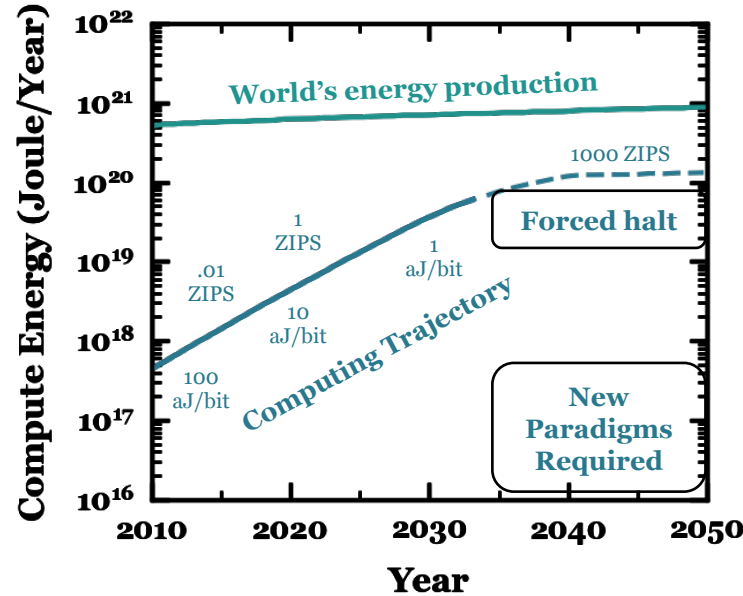
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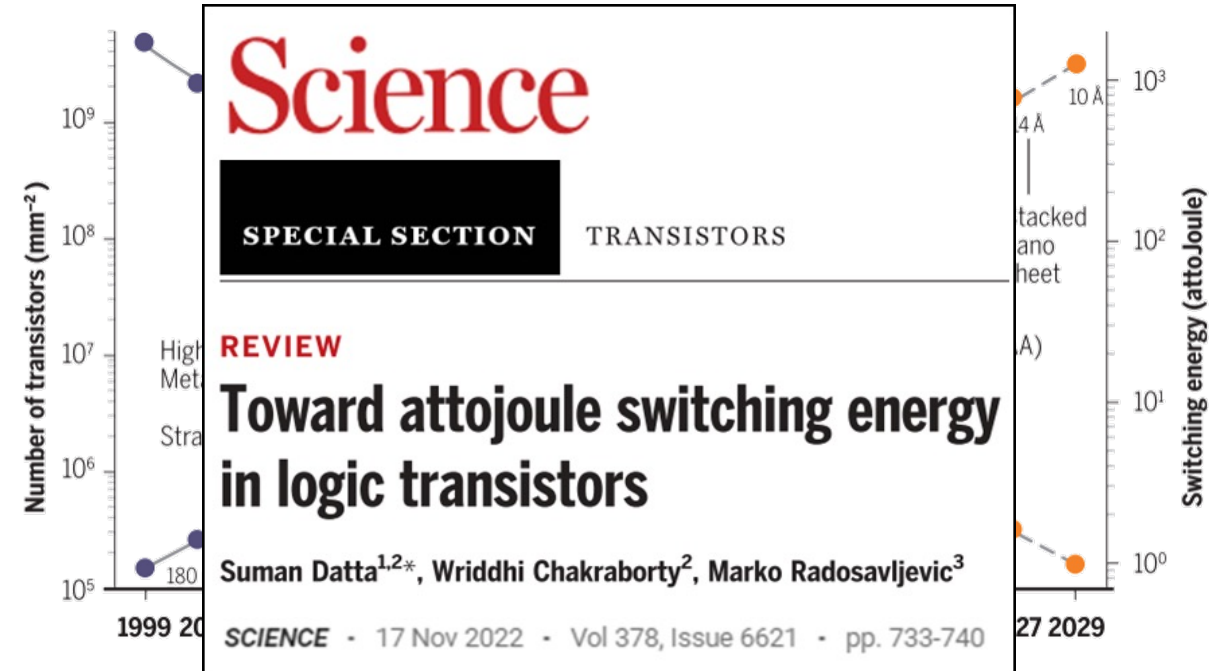
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Decadal Plan for Semiconductors (2020)

Solution I: Energy-Efficient Electronics [More Moore] Low Power Logic



Moore's Law & Dennard's Scaling
Road to Attojoule (1e-18 J) switching energy

Datta & Radosavljevic. Toward attojoule switching energy in logic transistors. *Science* 378, 733–740 (2022).

Global Energy Demand from Electronics
Exponentially rising: ~ doubling every 3 years

Overcome Fundamental Energy Limits
New Paradigm for Computing

Microelectronics | The “Angstrom” Era

Computing Energy Consumption A Call for New Paradigms of Electronics

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20,000 TWh

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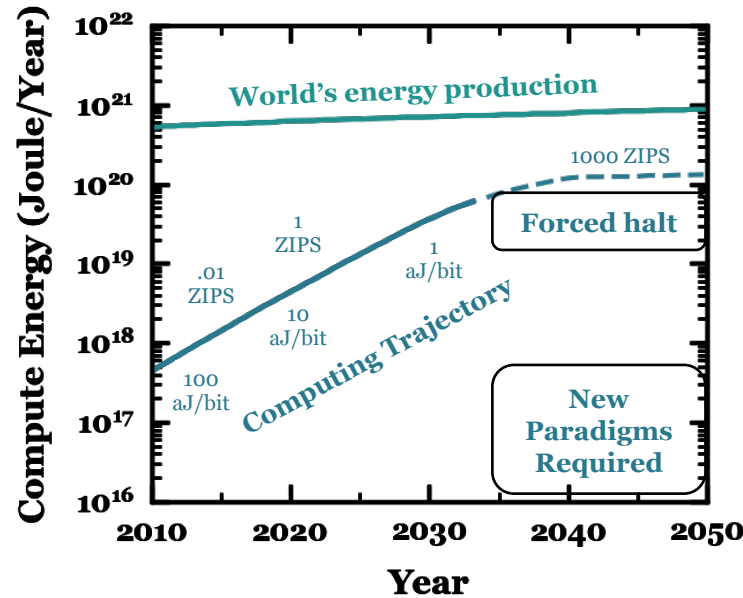
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Solution I: Energy-Efficient Electronics [More Moore] Logic

nature

More from Moore

Moore's law is approaching physical limits:
truly novel physics will be needed to extend it.

Nature 520, 408 (2015)

$$\frac{I_2}{I_1} = e^{\frac{q\Delta\psi}{k_B T}}$$

FE

Prob

π_{clas}

**In Quest of the “Next Switch”:
Prospects for Greatly Reduced
Power Dissipation in a
Successor to the Silicon
Field-Effect Transistor**

By THOMAS N. THEIS AND PAUL M. SOLOMON, *Fellow IEEE*

C_{ins}

ψ_s

C_s

Drain

ration

electrons

Zhirnov *et al.* Limits to binary logic switch scaling - A gedanken model.
Proc. IEEE 91, 1934–1939 (2003).

Collective Phenomena: Overcome Fundamental Energy Limits
New Paradigm for Logic Transistors

Microelectronics | The AI Era

Energy Grand Challenge Electronics Electricity Consumption

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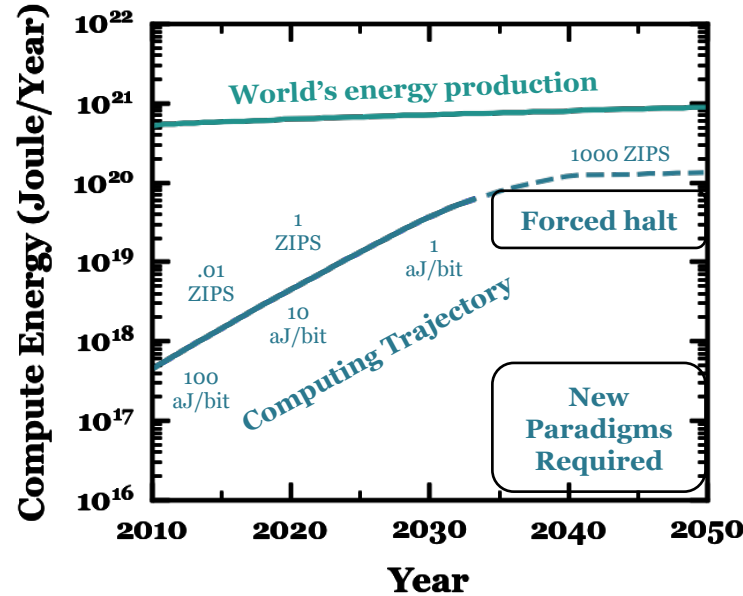
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Exponentially rising: ~ doubling every 3 years

Solution I: Energy-Efficient Electronics [More Moore] AI Hardware

nature

NEWS AND VIEWS | 23 August 2023

Analog chip paves the way for sustainable AI

As the resources required by artificial intelligence increase unsustainably, an analog design provides an energy-efficient alternative to digital computer chips – and one that is ideally suited to neural-network computations.

nature electronics

AI hardware has an energy problem

New energy-efficient electronic hardware will be required to sustain the development of machine learning and artificial intelligence.

[Nature Electronics](#) 6, 463 (2023) |

increasing demand for computing power
outpacing Moore's law scaling

Mehonic & Kenyon. Brain-inspired computing needs a master plan.
Nature 604, 255–260 (2022).

Need to improve more than transistors
New Paradigm for AI Hardware

Microelectronics | The IoT Era

Energy Grand Challenge Electronics Electricity Consumption

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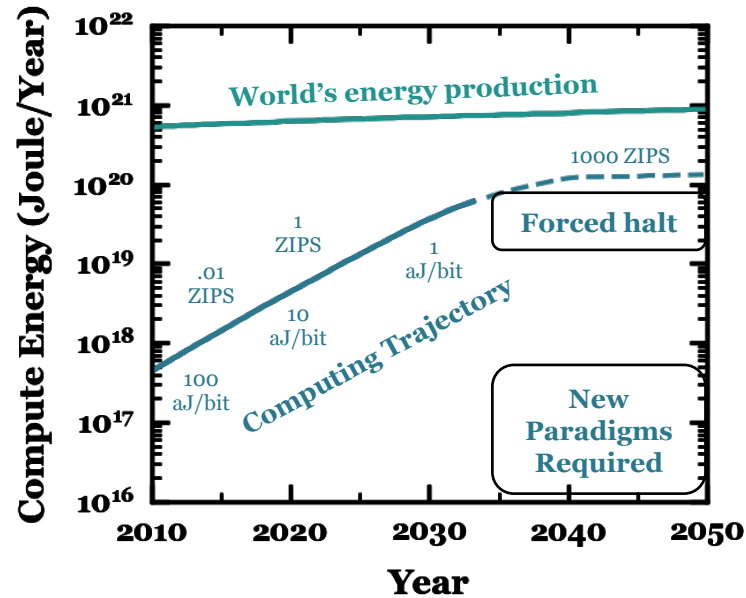
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Global Energy Demand from Electronics
Exponentially rising: ~ doubling every 3 years

Solution II: Energy-Autonomous Electronics [More-than-Moore] Processing via Harvested/Stored Energy

nature electronics

THREE-DIMENSIONAL INTEGRATION

Adding a new layer to 'more than Moore'

[Hendrik Faber](#) & [Thomas D. Anthopoulos](#)

Nature Electronics 2, 497–498 (2019)

nature nanotechnology

Microsupercapacitors as miniaturized energy-storage components for on-chip electronics

[Nana Amponsah Kyeremateng](#), [Thierry Brousse](#) & [David Pech](#)

Nature Nanotechnology 12, 7–15 (2017)

Next-generation Internet of Things (IoT)
2030: 100+ Billion smart connected IoT devices

Keshavarzi & van den Hoek. Edge Intelligence—On the Challenging Road to a Trillion Smart Connected IoT Devices. *IEEE Des. Test* 36, 41–64 (2019).

Energy-Efficiency Not Enough
New Paradigm for On-Chip Energy Technologies

Microelectronics | Edge Intelligence

Energy Grand Challenge Electronics Electricity Consumption

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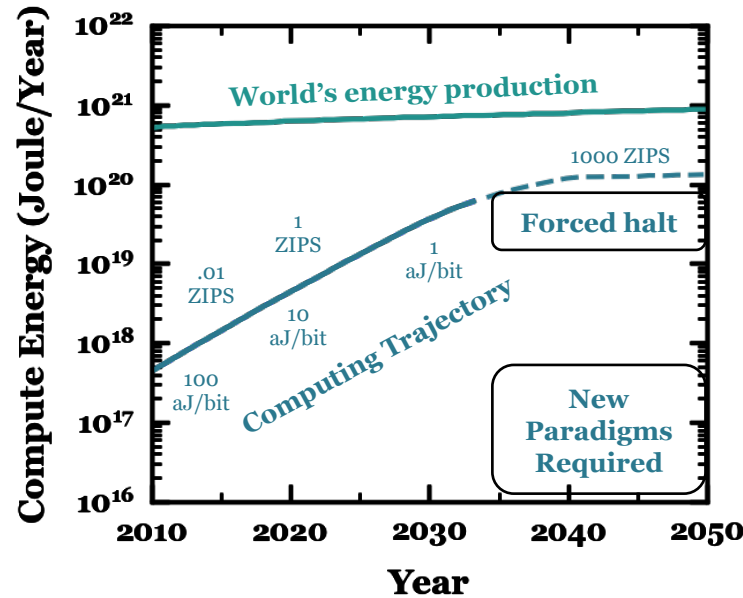
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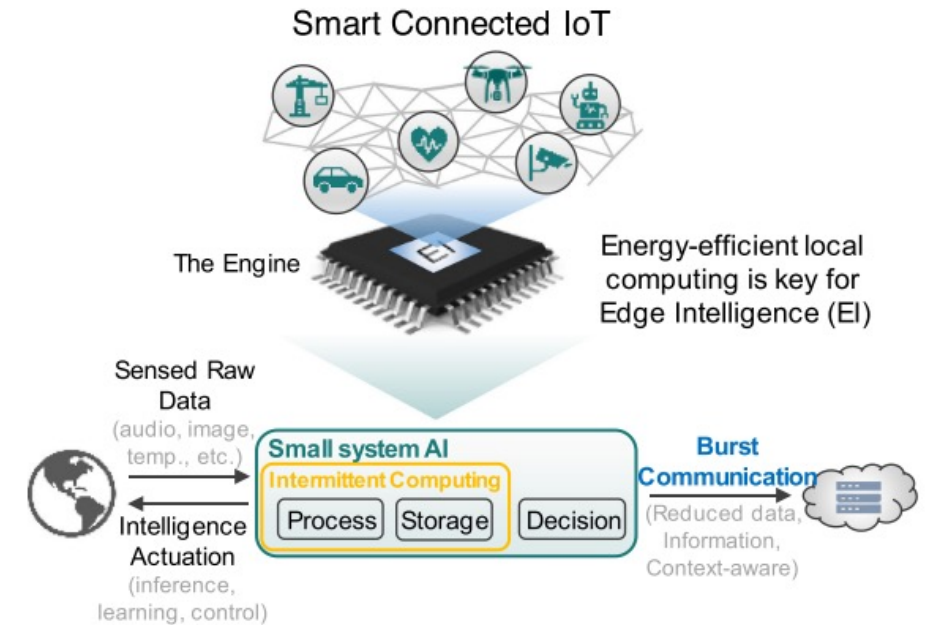


Computing Energy Consumption

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Energy-Efficient & Energy-Autonomous Electronics More-Moore & More-than-Moore Synergy



Edge Intelligent IoT Devices

1000X more compute- energy-efficient micro AI engines

A Keshavarzi, K Ni, W Van Den Hoek, S Datta, A Raychowdhury.
FerroElectronics for Edge Intelligence. *IEEE Micro* 40, 33–48 (2020).

Global Energy Demand from Electronics

Exponentially rising: ~ doubling every 3 years

From the Cloud to the Edge

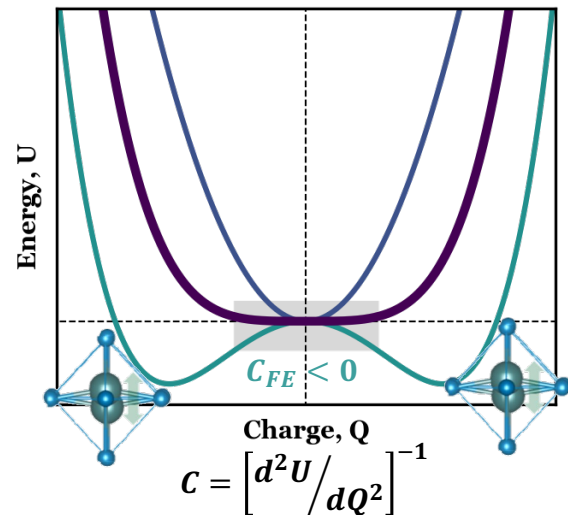
Self-powered edge computing with ferroelectric multifunctionalities

Goal: Energy-Efficient & Energy-Autonomous Electronics i.e. Sustainable Electronics

Atomic Scale Approach: Design novel “Beyond CMOS” electronic phenomena (in simple CMOS materials!) to overcome traditional limitations

Negative Capacitance | From Landau to Landauer

Phenomenological Model



Landau Model of Ferroelectric

$$U = \alpha P^2 + \beta P^4 + \gamma P^6$$

Landau. *Phys. Z. Sowjun.* 11, 545 (1937)

Devonshire. *Phil. Mag.* 40, 1040–1063 (1949)

Landauer. Can capacitance be negative. *Collect. Phenom.* 2, 167–170 (1976)

Conventional Insulator

$$U = Q^2/2C$$

Ferroelectric + Dielectric

Total system stable @ $Q=0$

$$1/C_{Total} = 1/C_{DE} - 1/|C_{FE}|$$

$$C_{Total} = \frac{|C_{FE}|C_{DE}}{|C_{FE}| - C_{DE}} > C_{DE}$$

if $|C_{FE}| > C_{DE}$

Metal

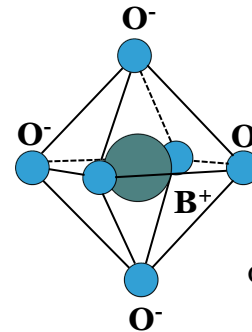
Dielectric

Ferroelectric

Metal

Capacitance Boost via Neg.-κ Dielectric

Lattice & Electrostatic Energies



Perovskite Lattice
Cation (B) displaced in z

$$P \propto q_B \bar{z}_B$$

Cation displacement (z) $\propto$
dipole moment & polarization (P)

Dipole fields: tend to polarize ferroelectric

Dipole Forces

$$F_p(R_B) = q_B E_p \approx q_B \left(-\frac{P}{\epsilon_0} + \frac{P}{3\epsilon_0} + \frac{15P}{4\pi\epsilon_0} \right)$$

JC Slater.
Phys. Rev.
78, 748–761
(1950)

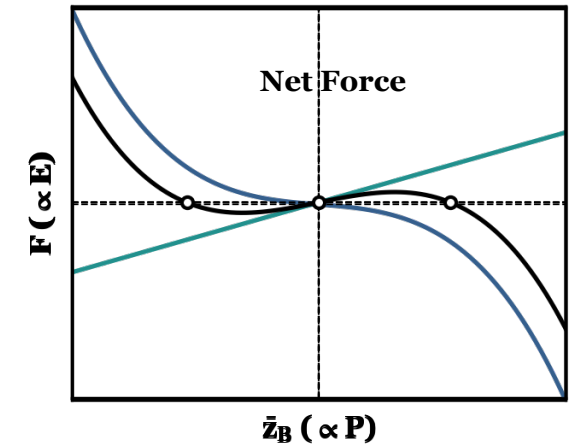
Ionic potentials: restore to zero distortion

Interatomic Potential

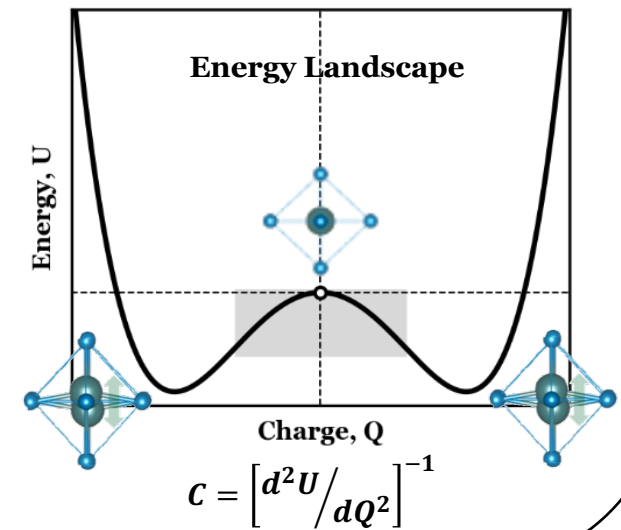
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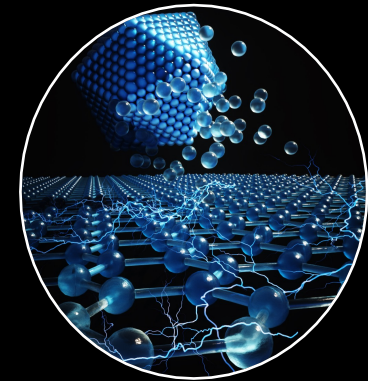
$$U = - \int E \cdot dP$$



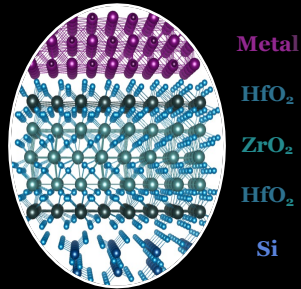
Energy Landscape: Directly maps to microscopic atomic configuration

Novel Phenomena in Simple Systems Can we atomically engineer ferroelectricity & NC in today's CMOS dielectrics (HfO₂-ZrO₂ on Si)?

Ferroelectrics | A Novel Platform for Computing & Energy Technologies

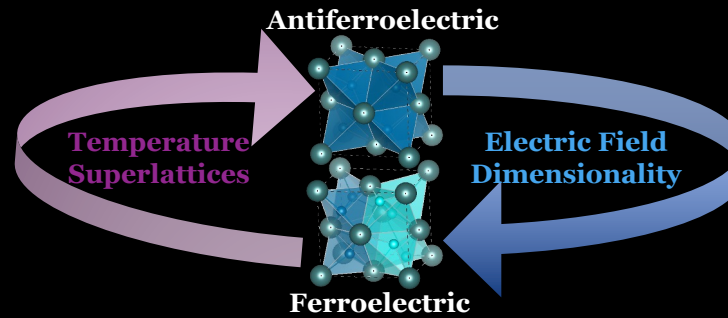


Atomic Layer
Synthesis

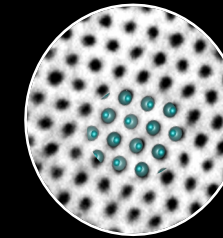


Stacking-dependent
Sub-Unit Cell Superlattices

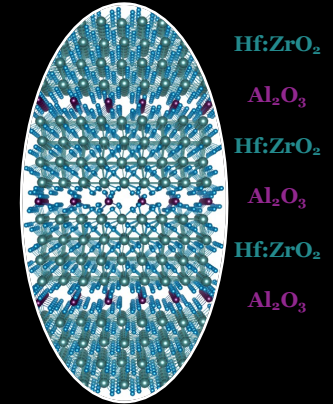
Ferroelectrics: Building Blocks
competing polar-nonpolar crystal structures
platform for emergent (negative) electronic phenomena



[HfO₂] Cheema *et al.* Enhanced ferroelectricity in ultrathin films grown directly on silicon. *Nature* (2020).
[ZrO₂] Cheema *et al.* Emergent ferroelectricity in sub-nanometer binary oxide films on silicon. *Science* (2022).

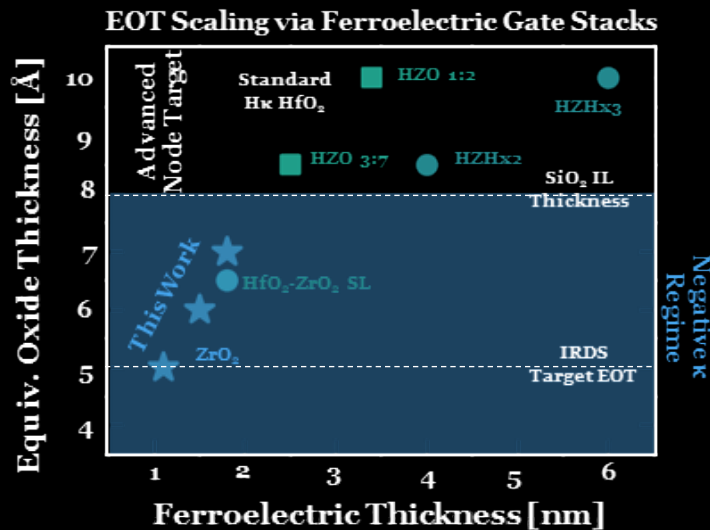


Crystal Symmetry
Manipulation



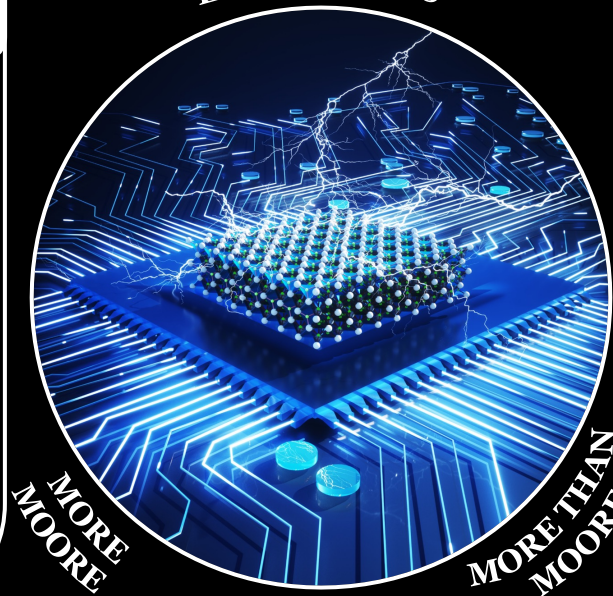
Crystalline-Amorphous
Superlattices

Ferroelectrics: New paradigm for Logic & Memory
high- κ dielectrics $\rightarrow$ negative- κ ferroelectrics
defective $\rightarrow$ collective switching



[HfO₂-ZrO₂] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors. *Nature* (2022).
[ZrO₂] Cheema *et al.* Ultralow electrical thickness via one nanometer negative capacitance. *In prep.*

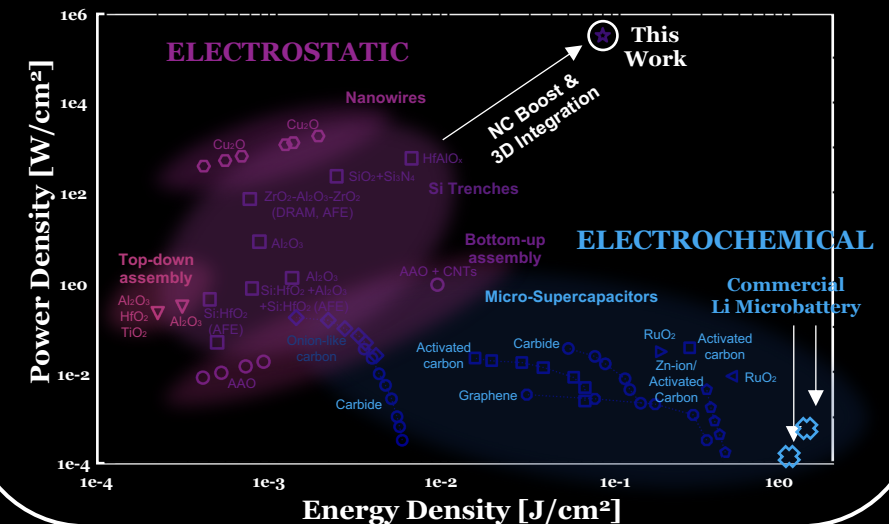
FERRO-ELECTRONICS



MORE
MOORE

MORE THAN
MOORE

Ferroelectrics: New paradigm for Energy Tech
electrochemical $\rightarrow$ electrostatic energy storage
thermoelectric $\rightarrow$ pyroelectric energy harvesting

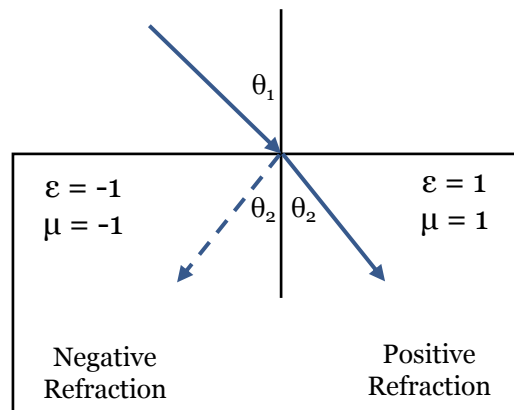


[ZrO₂-Al₂O₃] Cheema *et al.* Giant energy storage & power density neg. capacitance superlattices. *Nature* (2024)

Emergent Negative Phenomena in Materials

Optical Metamaterials

Negative refractive index (n)



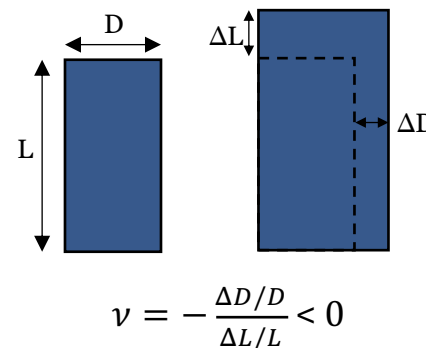
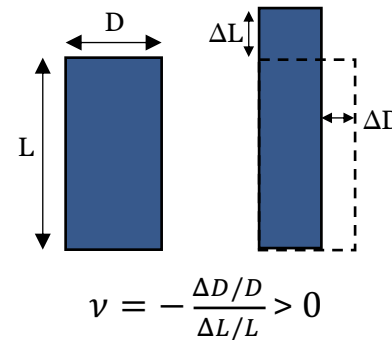
$$n = \sqrt{\epsilon\mu}$$

ϵ : electric permittivity
 μ : magnetic permeability

ϵ & μ negative
 $\rightarrow$ transparent to light

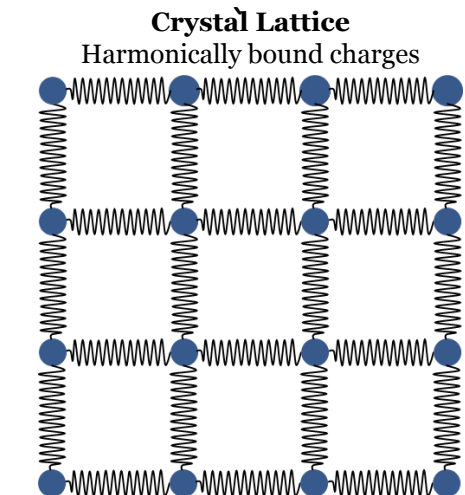
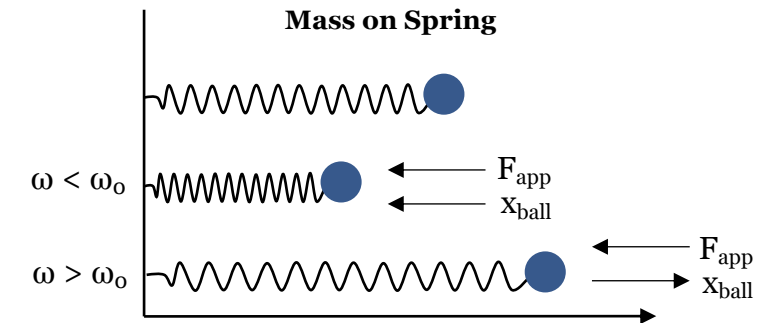
Mechanical Metamaterials

Negative Poisson's ratio (ν)



Electronic Metamaterials

Negative capacitance? (dQ/dV)



Shelby. Experimental Verification of a Negative Index of Refraction. *Science* 292, 77–79 (2001).
 Smith. Metamaterials and Negative Refractive Index. *Science* 305, 788–792 (2004).

Lakes. Foam Structures with a Negative Poisson's Ratio. *Science* 235, 1038–1040 (1987).
 Greaves. Poisson's ratio and modern materials. *Nat. Mater.* 10, 823–837 (2011).

Rolf Landauer. Can Capacitance Be Negative? *Collective Phenomena* 2, 167–170 (1976)

Negative Refraction
 Negative permeability & permittivity

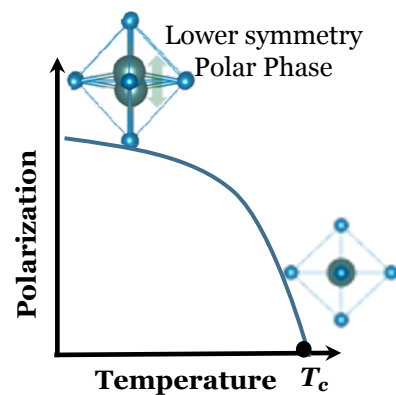
Negative Poisson's Ratio
 Transverse & longitudinal strain: same sign

Negative Capacitance
 Applied E-field drive “reverse” dipole response?

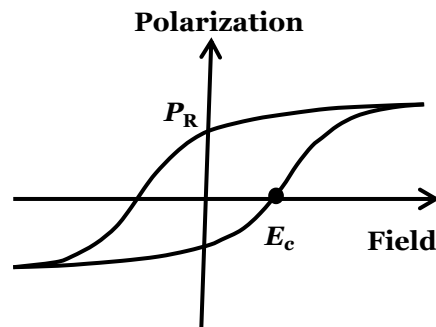
Open Question: Can we stabilize the negative capacitance effect in dielectrics?
Electronic Metamaterials Building Blocks: What kind of electronic system displays such dipoles?

Our Approach | Ferroelectric Materials & Functionalities

Ferroelectricity



Symmetry-lowering
phase transition



Hysteretic reversible
electric dipoles

Crystallographic
classification

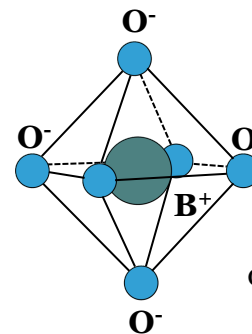
Dielectrics
[32 crystal
classes]

Piezoelectric
non-centrosymmetric
[20]

Pyroelectric
polar axis
[10]

Ferroelectric
reversible
polarization

Lattice & Electrostatic Energies



Perovskite Lattice
Cation (B) displaced in z

$$P \propto q_B \bar{z}_B$$

Cation displacement (z) $\propto$
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Dipole fields: tend to polarize ferroelectric

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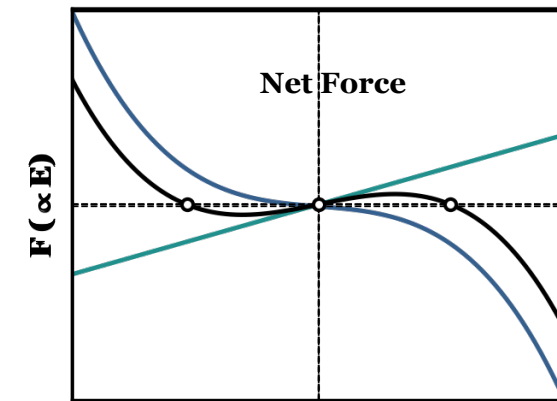
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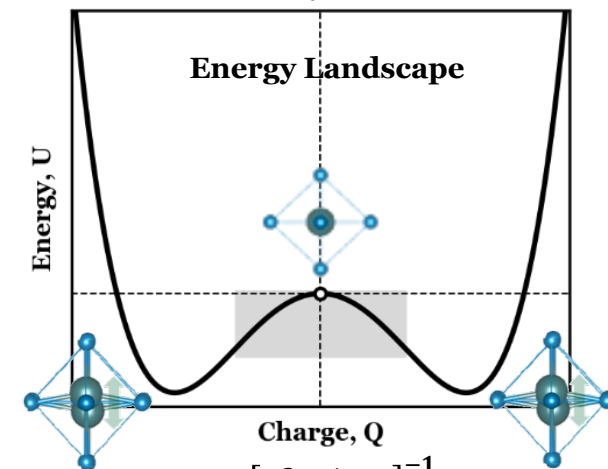
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$$c = \left[d^2 U / dQ^2 \right]^{-1}$$

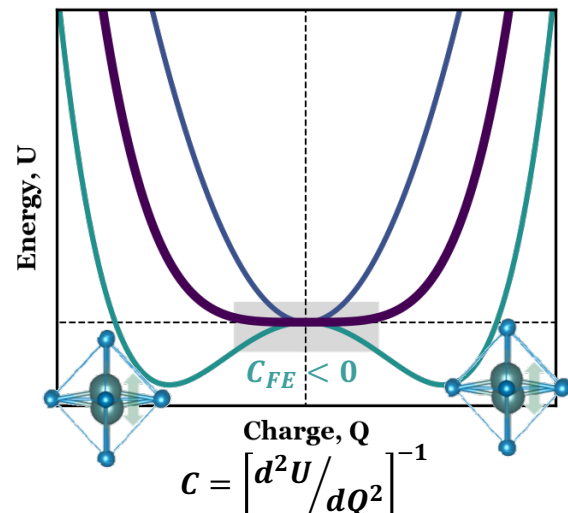
Spontaneous & switchable electric dipole

Energy Landscape: Directly maps to microscopic atomic configuration

Multifunctional Ferroelectric Platform High- κ (logic, e-storage), nonvolatility (memory, AI HW), piezo-/pyroelectric (e-harvesting, sensing)

Negative Capacitance | From Landau to Landauer

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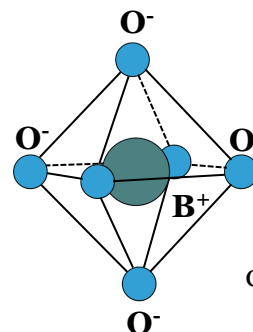
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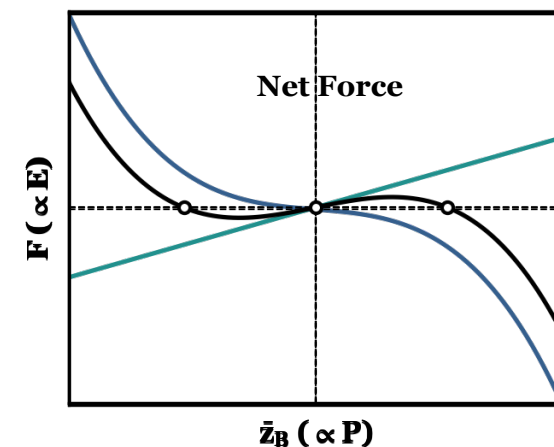
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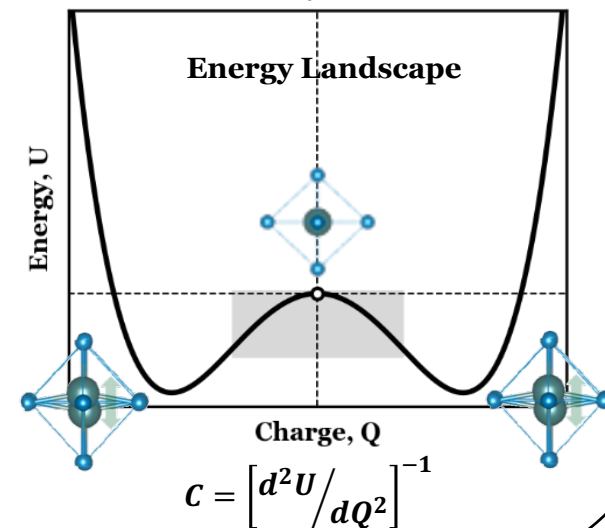
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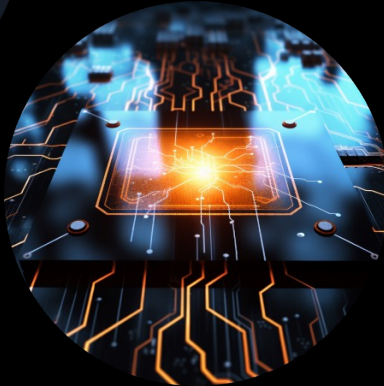
Ferroelectronics | A New Paradigm for Sustainable Microelectronics

Energy-Autonomous Electronics

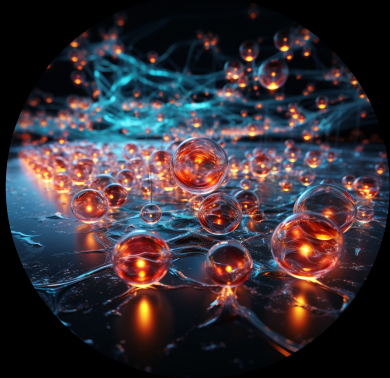


**Energy Storage
& Power Delivery**
NC ultra-capacitors

**Energy Harvesting &
Thermal Management**
pyro & electrocaloric
capacitors



Sensing
Piezo FeNEMS
Pyro IR sensors



More-than-Moore
Energy Harvesting | Energy Storage |
Thermal Mgmt | Sensing | Power Delivery

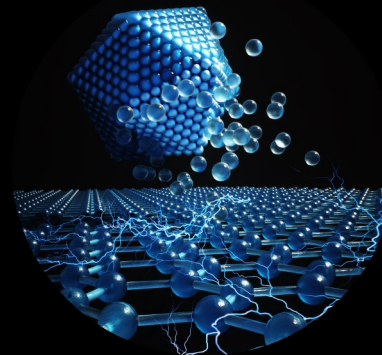
Electronic Metamaterials



**Atomic
Layer Deposition**
Atomic-precision |
Superlattices |
Composition |
Dimensionality |
Conformal 3D |
Wafer scale



**Electronic Building
Blocks**
Exploiting novel
electronic phenomena:
(anti) ferroelectric order |
phase transitions |
2D 3D materials



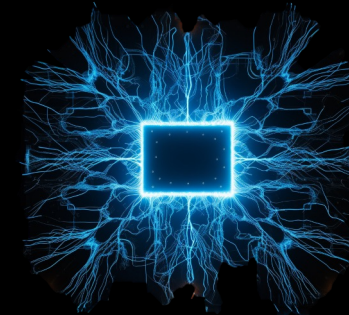
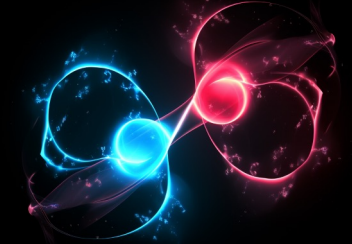
**Unprecedented
Electronic Properties**
Negative capacitance &
piezoelectricity |
Overcoming fundamental
material trade-offs

Energy-Efficient Electronics



Memory & AI Hardware
Next-gen DRAM & Flash
Analog NNs: FeTFTs | FTJs | FeCaps

Cryo CMOS
Ferroelectric
superconducting hardware



Logic
Negative capacitance
transistors

More Moore
Logic | Memory | AI Hardware |
Superconducting Electronics

Cheema et al. Giant energy storage & power density neg. capacitance superlattices. *Nature* (2024)

Cheema et al. Enhanced ferroelectricity in ultrathin films directly on Si. *Nature* (2020)
Cheema et al. Emergent ferroelectricity in sub-nm binary oxide on Si. *Science* (2022)

Cheema et al. Ultrathin ferroic superlattice for advanced transistors. *Nature* (2022)
Cheema et al. Ultralow electrical thickness via 1-nm negative capacitance. (2024)

Sustainable Microelectronics Vision: Computing & Energy Tech Monolithically-Integrated & Synergistically-Operated
Challenging but Possible : All IC components enhanced via $\text{HfO}_2\text{-ZrO}_2$ ferroelectric platform

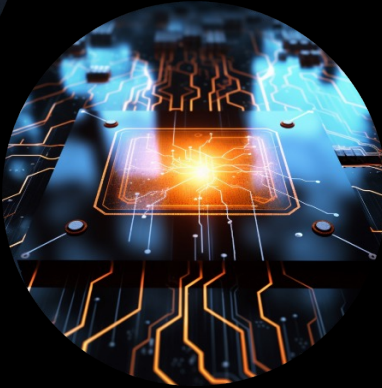
Ferroelectronics | A New Paradigm for Sustainable Microelectronics

Energy-Autonomous Electronics

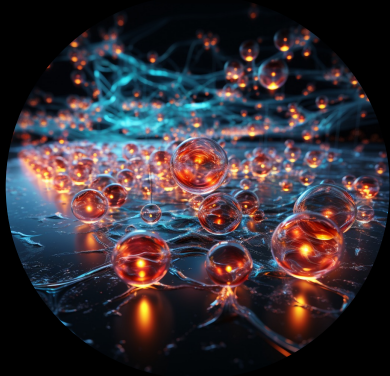


**Energy Storage
& Power Delivery**
NC ultra-capacitors

**Energy Harvesting &
Thermal Management**
pyro & electrocaloric
capacitors



Sensing
Piezo FeNEMS
Pyro IR sensors



More-than-Moore
Energy Harvesting | Energy Storage |
Thermal Mgmt | Sensing | Power Delivery

Lab to Fab



Federal CHIPS & Science Act
Translate lab discoveries to government &
semiconductor foundries

MIT Lincoln Laboratory

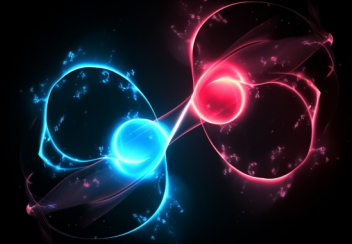
Cheema et al. Ultrathin ferroic superlattice for advanced transistors. *Nature* (2022)
Cheema et al. Giant energy storage & power density neg. capacitance superlattices. *Nature* (2024)

Energy-Efficient Electronics

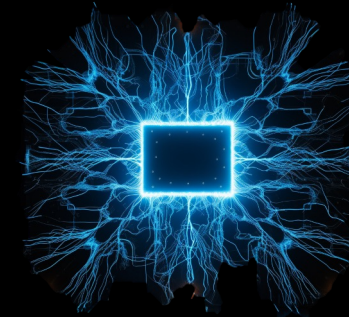


Memory & AI Hardware
Next-gen DRAM & Flash
Analog NNs: FeTFTs | FTJs | FeCaps

Cryo CMOS
Ferroelectric
superconducting hardware



Logic
Negative capacitance
transistors



More Moore
Logic | Memory | AI Hardware |
Superconducting Electronics

Sustainable Microelectronics Vision: Computing & Energy Tech Monolithically-Integrated & Synergistically-Operated
Challenging but Possible : All IC components enhanced via $\text{HfO}_2\text{-ZrO}_2$ ferroelectric platform

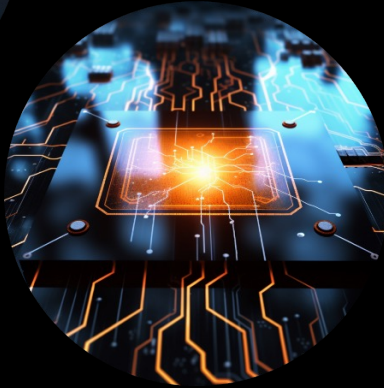
Ferroelectronics | A New Paradigm for Sustainable Microelectronics

Energy-Autonomous Electronics

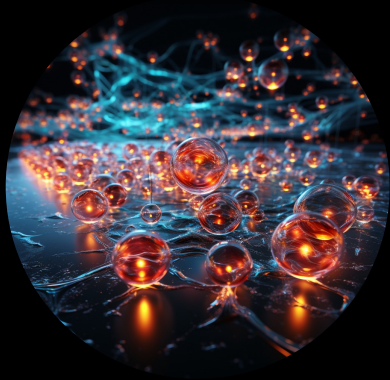


**Energy Storage
& Power Delivery**
NC ultra-capacitors

**Energy Harvesting &
Thermal Management**
pyro & electrocaloric
capacitors



Sensing
Piezo FeNEMS
Pyro IR sensors



More-than-Moore
Energy Harvesting | Energy Storage |
Thermal Mgmt | Sensing | Power Delivery

Ferroelectric 3D Processor



from Cloud to Edge Intelligence

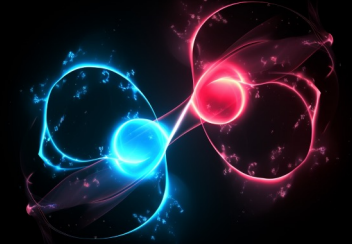
Monolithic 3D-integration of
compute + memory + energy + sensing
micro-AI-engines
for autonomous data processing

Energy-Efficient Electronics

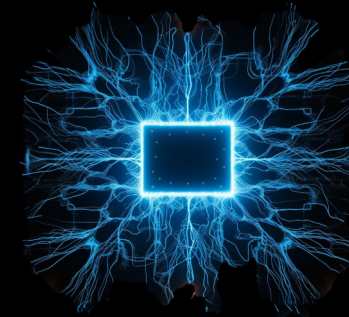


Memory & AI Hardware
Next-gen DRAM & Flash
Analog NNs: FeTFTs | FTJs | FeCaps

Cryo CMOS
Ferroelectric
superconducting hardware



Logic
Negative capacitance
transistors

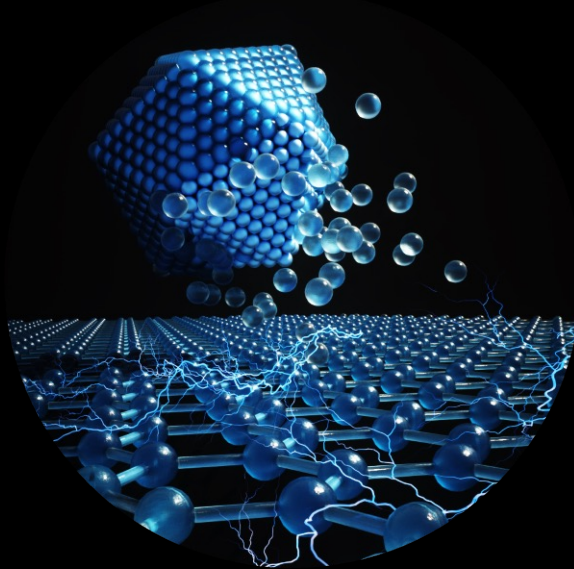


More Moore
Logic | Memory | AI Hardware |
Superconducting Electronics

Sustainable Microelectronics Vision: Computing & Energy Tech Monolithically-Integrated & Synergistically-Operated
Challenging but Possible : All IC components enhanced via $\text{HfO}_2\text{-ZrO}_2$ ferroelectric platform

Ferroelectric Materials & Devices | Materials Design

Atomic Layer Synthesis



Atomically-precise bottom-up stacking of materials via Atomic Layer Deposition (ALD)

Lab-to-Fab Large-Area Wafer Scale
Nature 2022 | Nature 2024

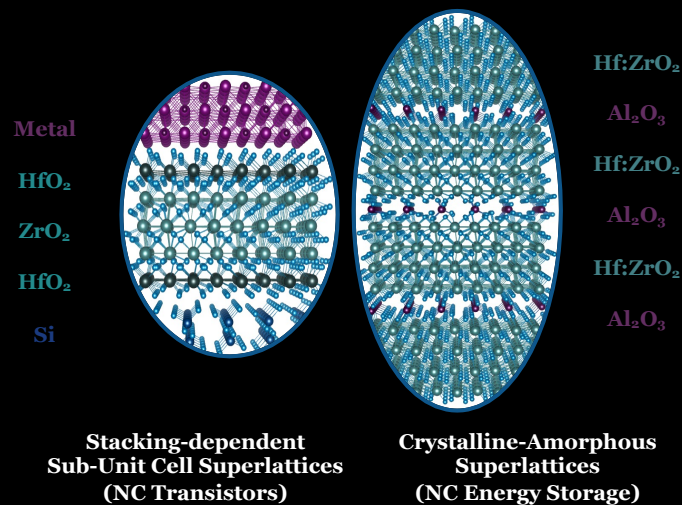
Template-free amorpho-taxy
Nature 2020 | Science 2022

Atomic-scale stacking of materials (superlattices)
Nature 2022 | Nature 2024

3D conformal growth
Nature 2024

Accelerated wafer-scale materials discovery

Atomic Engineering



Manipulating crystal symmetry to stabilize metastable polymorphs

3D materials to 2D limit: ferroelectric stabilization
Science 2022 | Nature 2020

Dimensionality & Superlattices: neg. capacitance stabilization
Nature 2022 | InReview 2023

Composition control: ferroic phase transitions
Nature 2024

Electric field control: ferroic phase transitions
Nature 2024

Temperature control: ferroic phase transitions
Science 2022

Electronic Building Blocks



Stabilizing negative electronic phenomena to overcome fundamental material trade-offs

Negative Capacitance
Nature 2022 | Nature 2024

Negative Piezoelectricity
Nature 2020 | Science 2022

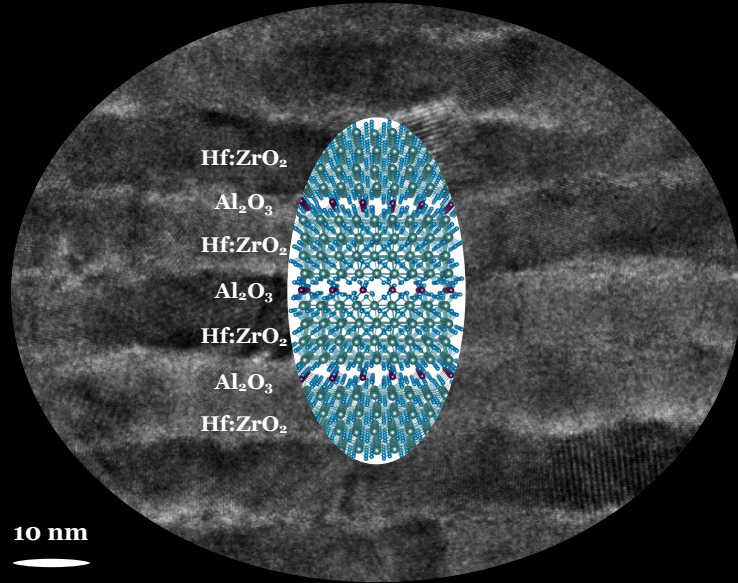
Reverse ferroelectric size effects
Nature 2020 | Science 2022

Leakage-EOT
Nature 2022

Permittivity-Breakdown
Nature 2024

Ferroelectric Materials & Devices | Toolbox

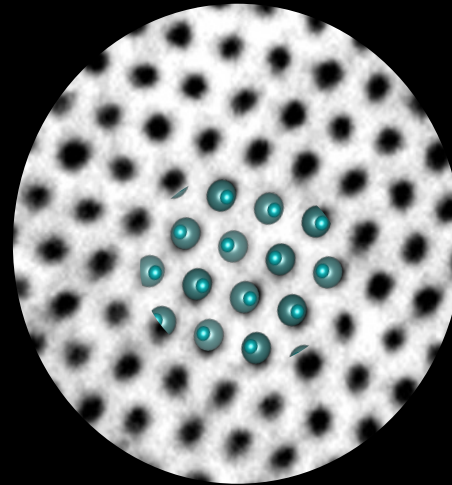
Synthesis



To stabilize emergent phenomena beyond the standard unit cell, we utilize Atomic Layer Deposition (ALD) to manufacture hierarchical “super-cells”

ALD, used in today's microelectronics, deposits atomically-precise films across wafers to enable large-scale integration and Lab-to-Fab translation

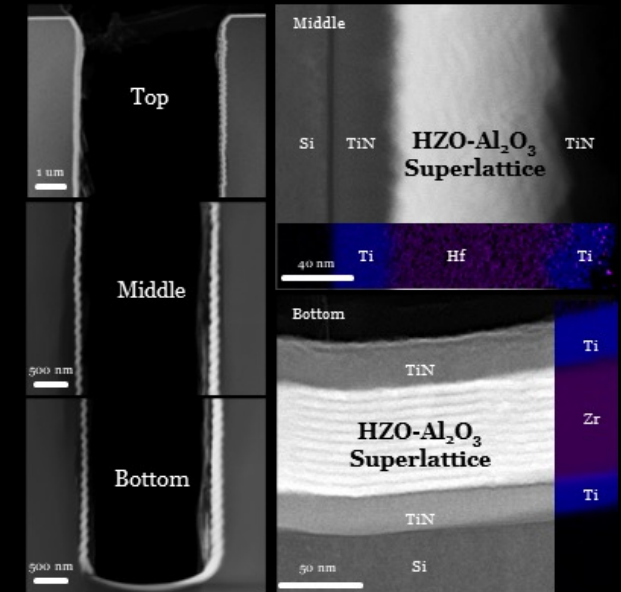
Characterization



To understand the microscopic origins underlying electronic metamaterials:

- (i) synchrotron x-rays: diffraction, spectroscopy,
 - (ii) microscopy: x-ray, electron, scanning probe
 - (iii) transport: ultrafast, cryogenic, etc
- at National Labs, MIT.nano facilities, and in-house setups

Devices +



To realize the enhanced performance derived from their emergent phenomena, we integrate electronic metamaterials into relevant device structures – e.g. 3D capacitors, transistors, crossbar arrays – fabricated at

- (i) MIT.nano
- (ii) MIT Lincoln Laboratory
- (iii) Semiconductor Foundries

MIT.nano

MTL
microsystems technology laboratories

MIT.nano

Ferroelectronics | Research Highlights

Re-imaging the (mem)resistor



Result

From defective to collective resistive switching via ferroelectricity down to the atomic-scale limit

Cheema *et al* *Nature* 2020 | Cheema *et al* *Science* 2022

Impact

Samsung Electronics: Samsung Advanced Institute of Technology (SAIT) confirmation of ferroelectricity in ultrathin $\text{HfO}_2\text{-ZrO}_2$

Nature Electronics 2023 | *ACS AMI* 2021

US Defense Foundry: MIT Lincoln Laboratory confirmation of ferroelectricity and negative capacitance in ultrathin $\text{HfO}_2\text{-ZrO}_2$

IEDM 2022

Cheema *et al*. Enhanced ferroelectricity in ultrathin films directly on Si. *Nature* (2020)
Cheema *et al*. Emergent ferroelectricity in sub-nm binary oxide on Si. *Science* (2022)

Re-imagining the capacitor



Result

From electrochemistry to electrostatic energy storage to overcome the capacity-speed trade-off: 8 (1) orders of magnitude higher (lower) power (energy) density than commercial Li-ion microbattery

Cheema *et al* *Nature* 2024

Impact

US Defense Foundry: MIT Lincoln Lab confirmation & integration into their 3D foundry process (on-chip battery & power delivery)

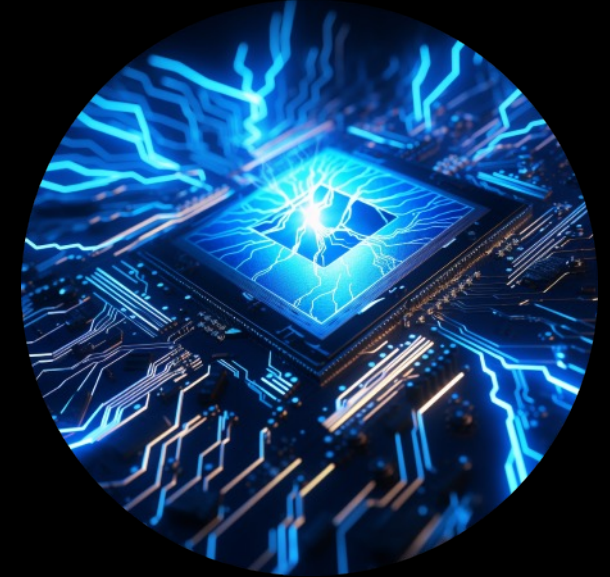
Nature 2024

The Pentagon invited to present this energy storage technology to US military decision-makers at the Pentagon (space electronics)

DARPA Demo Day 2023

Cheema *et al*. Giant energy storage & power density neg. capacitance superlattices. *Nature* (2024)

Re-imaging the transistor



Result

From high-k dielectrics to negative-k ferroelectrics for ultra-low power transistor operation

Cheema *et al* *Nature* 2022

Impact

US Defense Foundry MIT Lincoln Laboratory confirmation & integration into their Defense Foundry transistor technology

IEDM 2022

Samsung Electronics SAIT confirmation & integration of my NC gate stack into their FinFET technology; on logic tech roadmap

Nature Electronics 2023 | *IEDM Plenary* 2022

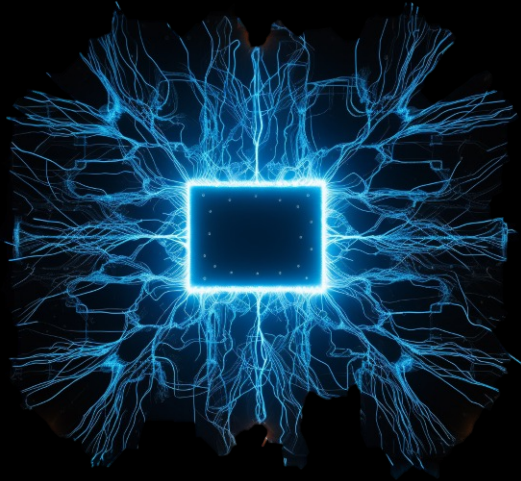
Intel Science's 75th Anniversary of the Transistor highlighted my NC technology as a future for energy-efficient computing

Science 2022

Cheema *et al*. Ultrathin ferroic superlattice for advanced transistors. *Nature* (2022)
Cheema *et al*. Ultralow electrical thickness via 1-nm negative capacitance. (2024)

Ferroelectronics | Advanced Computing

Logic



Advanced Transistors for Next-Gen Computing

from high-k dielectric to negative-k ferroelectric transistor gate stacks

- (i) Materials design: pushing the physical and electrical limits of negative capacitance towards ultra-low power operation
- (ii) Next-generation materials: new channel materials (e.g. oxides) and dielectrics for back-end-of-the-line (BEOL) transistors

Negative Electrical Thickness

Discovery of Negative EOT

Negative Capacitance Gate-All-Around Transistors

Outperforms semiconductor industry GAA technology

Memory & AI Hardware



Analog AI Hardware for Edge Computing

from defective (ionic) to collective (ferroic) nonvolatile switching

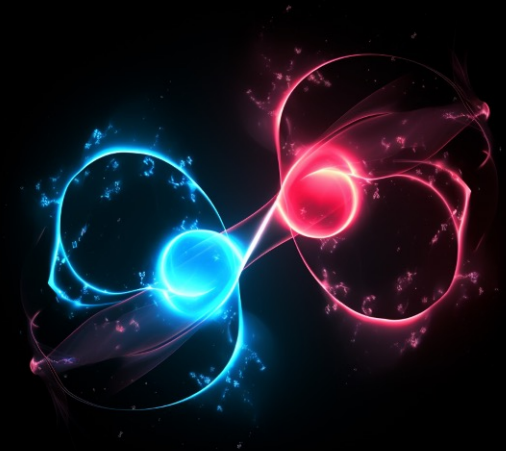
Ultralow-power, ultrafast-switching, ultrahigh-density ferroelectric HW

- (i) Embedded nonvolatile memory: next-gen DRAM & Flash
- (ii) Artificial synapses and neurons for analog computing

Ferroelectric HW Analog Neural Networks

High-density M3D-integration of BEOL ferroelectric synaptic arrays and neurons

Superconducting Electronics



Ferroelectronics for Cryo-Computing

from normal to superconducting electron transport for low temperature computing paradigms

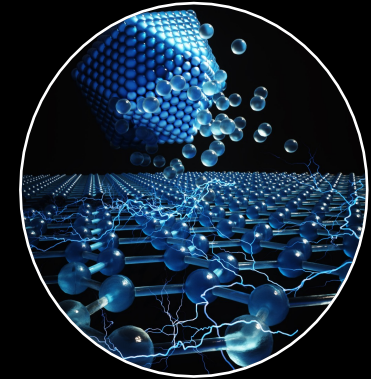
- (i) Ferroelectric cryo-CMOS for steep slope transistors & high-performance cryo-computing
- (ii) Ferroelectric superconducting hardware for dissipationless cryo-electronics

Ferroelectric superconducting switch

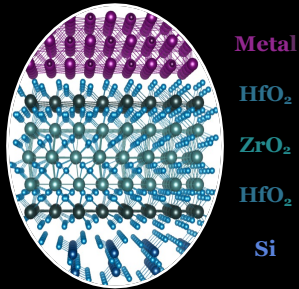
Superconducting nonvolatile memory via ferroelectric josephson junctions

CMOS Ferroelectric Platform: realize “beyond-CMOS” paradigms for orders magnitude improvement in performance & energy consumption

Ferroelectronics | A Novel Platform for Computing & Energy Technologies

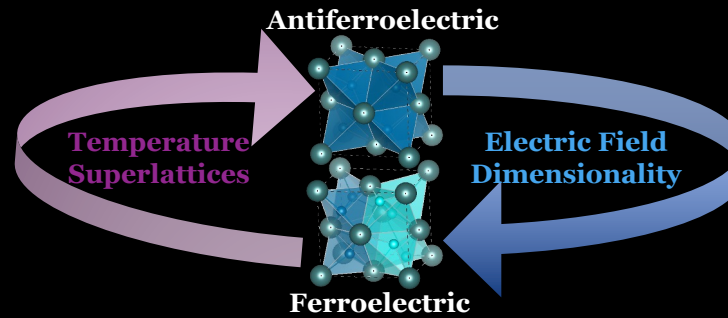


Atomic Layer Synthesis

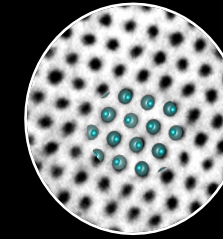


Stacking-dependent Sub-Unit Cell Superlattices

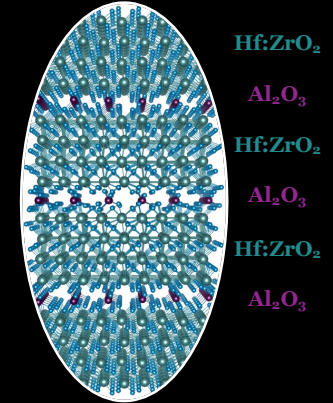
Ferroelectrics: Building Blocks
competing polar-nonpolar crystal structures
platform for emergent (negative) electronic phenomena



[HfO₂] [Cheema *et al.*](#) Enhanced ferroelectricity in ultrathin films grown directly on silicon. *Nature* (2020).
[ZrO₂] [Cheema *et al.*](#) Emergent ferroelectricity in sub-nanometer binary oxide films on silicon. *Science* (2022).



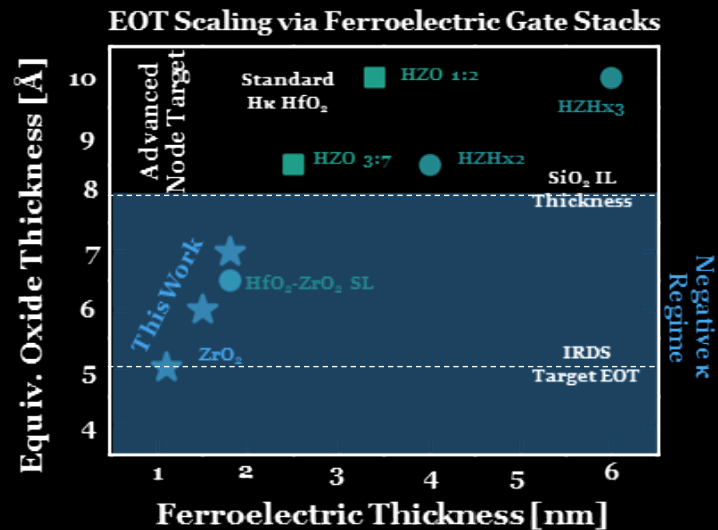
Crystal Symmetry Manipulation



Crystalline-Amorphous Superlattices

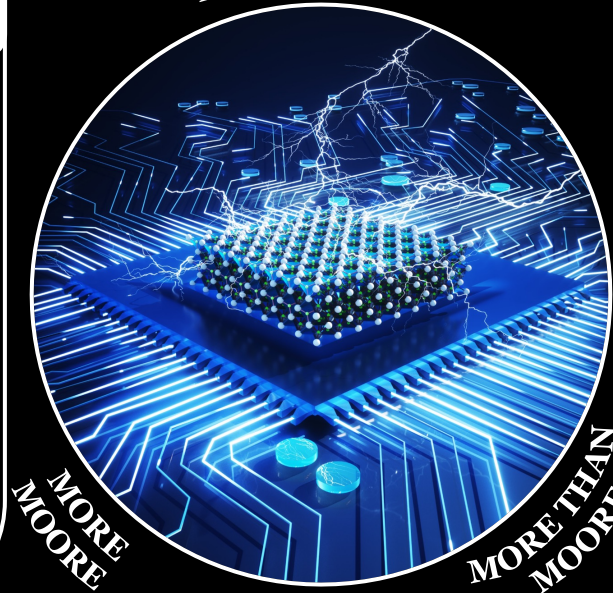
Ferroelectrics: New paradigm for Logic & Memory

high- κ dielectrics $\rightarrow$ negative- κ ferroelectrics
defective $\rightarrow$ collective switching



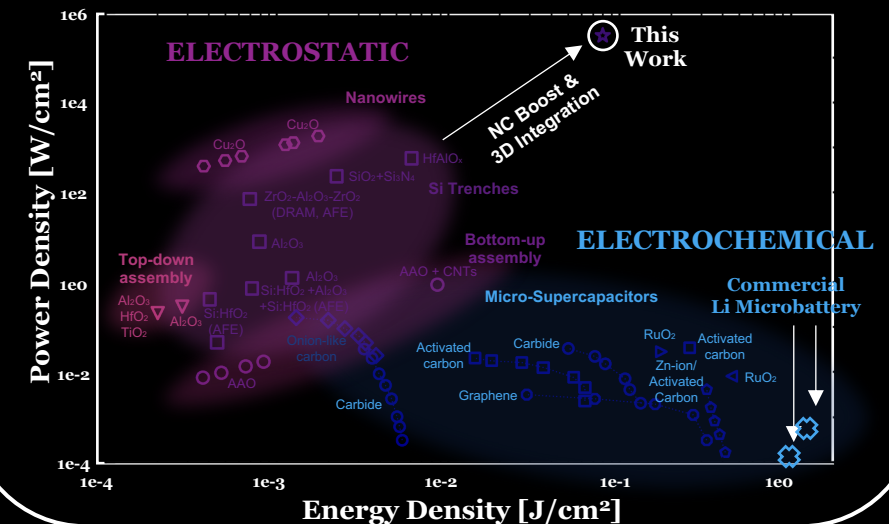
[HfO₂-ZrO₂] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors. *Nature* (2022).
[ZrO₂] Cheema *et al.* Ultralow electrical thickness via one nanometer negative capacitance. (2024)

FERRO-ELECTRONICS



Ferroelectrics: New paradigm for Energy Tech

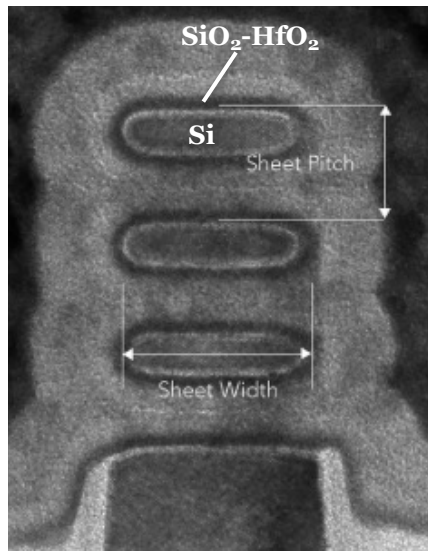
electrochemical $\rightarrow$ electrostatic energy storage
thermoelectric $\rightarrow$ pyroelectric energy harvesting



[ZrO₂-Al₂O₃] Cheema *et al.* Giant energy storage & power density neg. capacitance superlattices. *Nature* (2024)

Materials Design | Ferroelectricity in $\text{HfO}_2\text{-ZrO}_2$ on Si

Technological Constraints



IBM Nanosheet FET

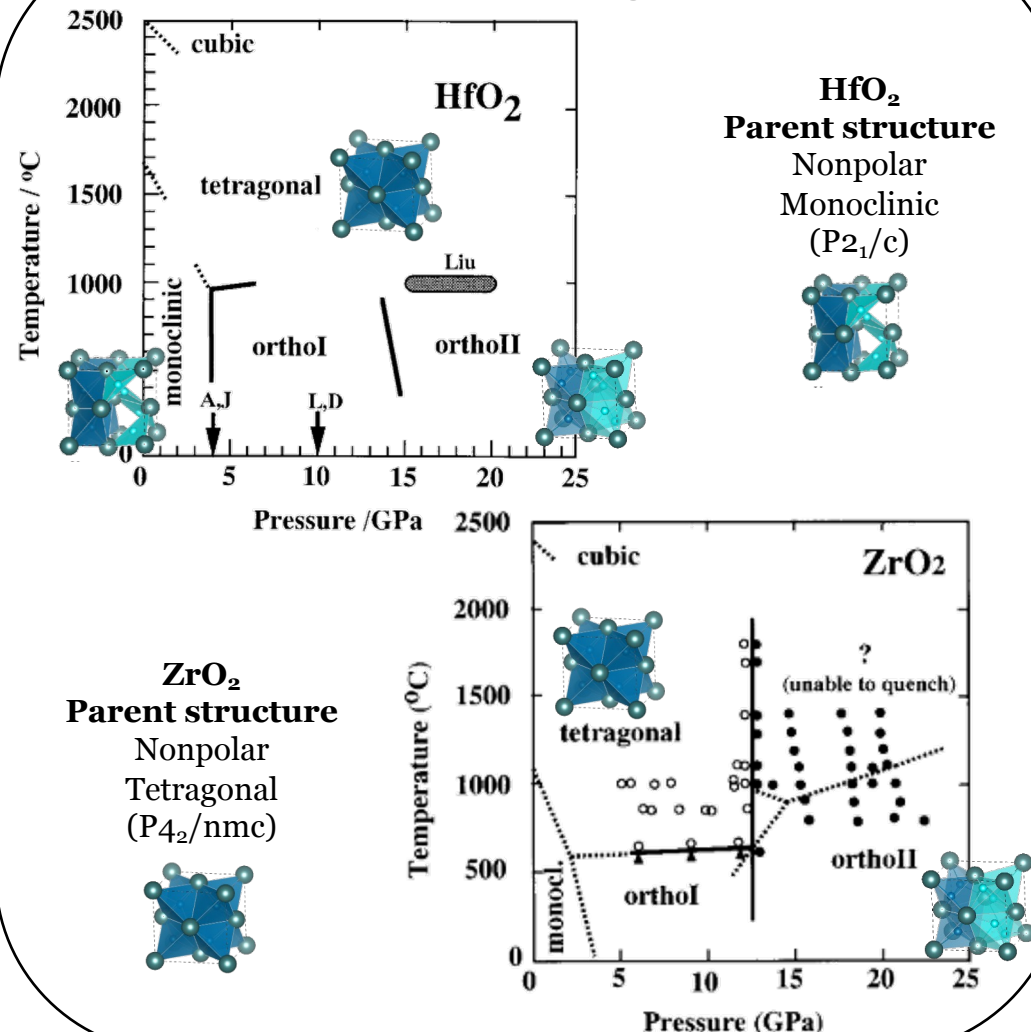
Advanced transistors
No room for the gate oxide!
< 1.5 nm

Materials Challenge
Ferroelectricity vanishes
< 2 nm!

Junquera & Ghosez. Critical thickness for ferroelectricity in perovskite ultrathin films. *Nature* 422, 506–509 (2003).

Challenge
FE order in ultrathin $\text{HfO}_2\text{-ZrO}_2$

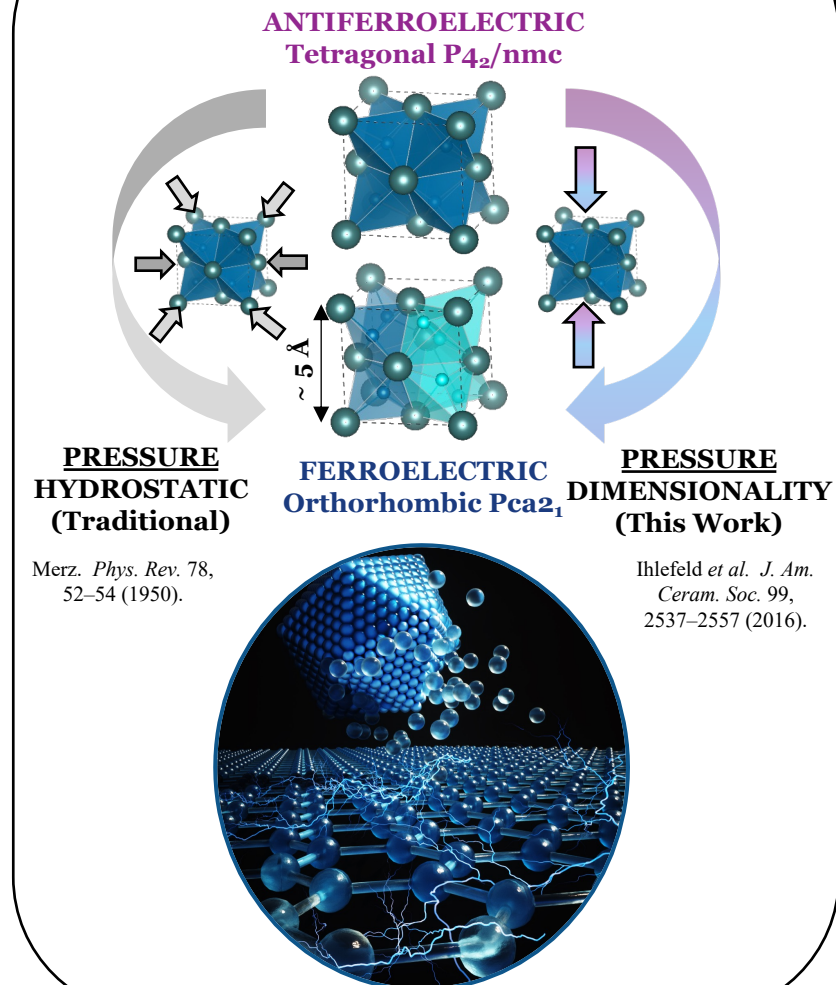
Bulk Phase Diagram



[HfO_2] Ohtaka *et al.* *J. Am. Ceram. Soc.* 84, 1369–1373 (2004).
[ZrO_2] Ohtaka *et al.* *Phys. Rev. B* 63, 174108 (2001)

Polar Orthorhombic Phase
Stabilized under high pressure

Thin Film Approach



Merz. *Phys. Rev.* 78, 52–54 (1950).

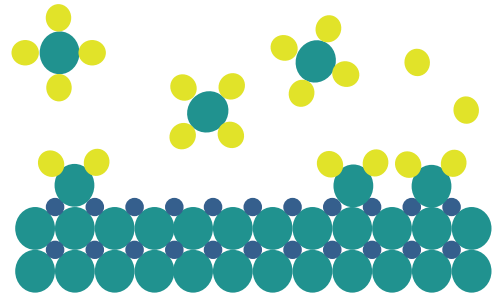
Ihlefeld *et al.* *J. Am. Ceram. Soc.* 99, 2537–2557 (2016).

[HfO_2] Cheema *et al.* Enhanced ferroelectricity in ultrathin films on Si. *Nature* 580 (2020)
[ZrO_2] Cheema *et al.* Emergent ferroelectricity in sub-nanometer films on Si. *Science* 376 (2022)

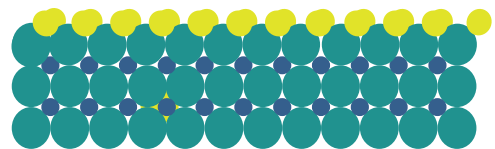
Reduced Dimensionality
FE order stabilized in atomically-thin regime

Materials Synthesis | Atomic Layer Deposition

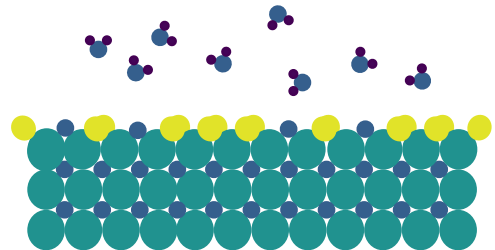
Sequential Half-Reactions



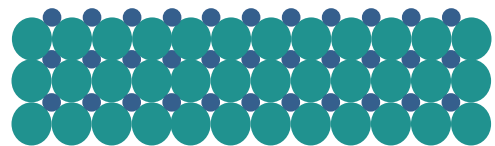
Metal
Organic



Purge



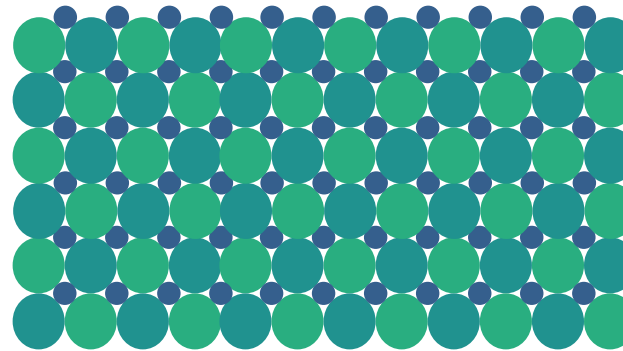
Oxidant



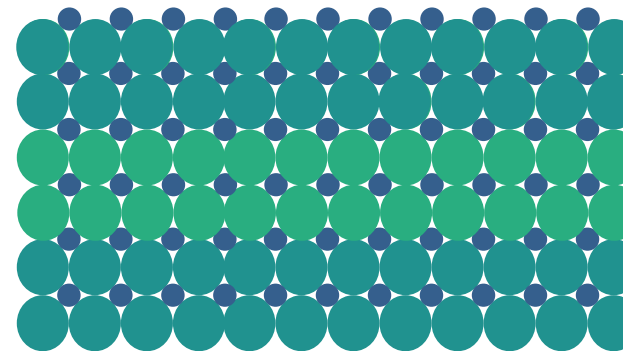
Purge

● Cation ● Organic ● O ● H

Tunable Film Composition

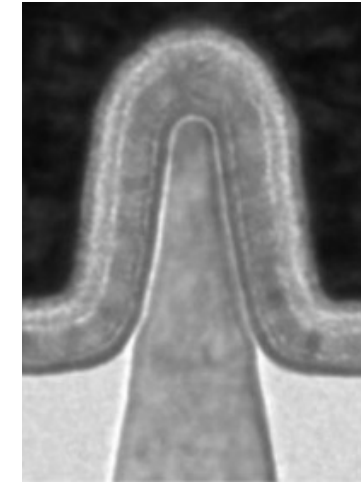


Solid Solution



Multilayers

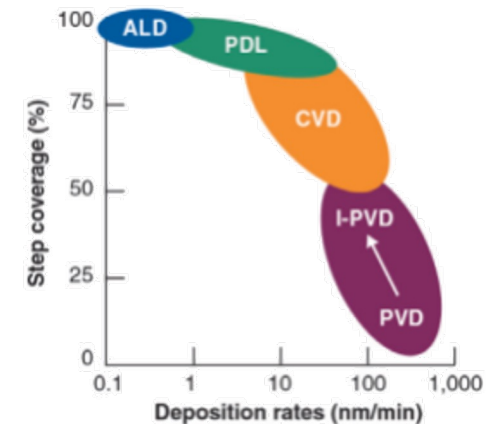
Conformality & Uniformity



**Conformal
High-Aspect
Ratio**

Intel 22nm node
FinFET

Johnson *et al. Mater. Today* 17,
236–246 (2014).



**Conformal
slow
deposition**

Kunene *et al. Mater. Today
Proc.* (2022)

Self-Limiting Reactions

Ideal for atomically-thin films

Multi-Component Composition

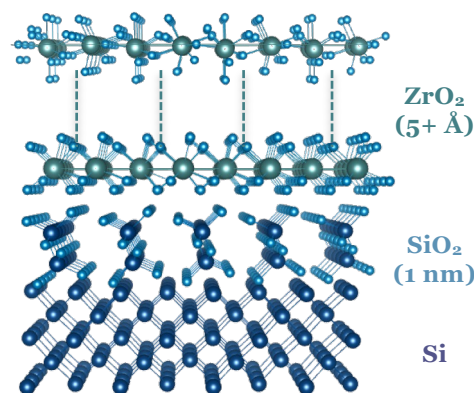
Controlling “super-cycles”

Conformal Deposition

Can coat sidewalls for 3D structures

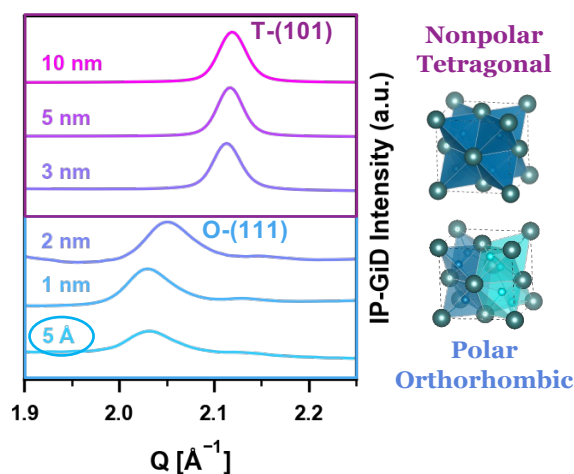
Materials Design | Ferroic Phase Identification

Thickness Series



Atomic Layer Deposition

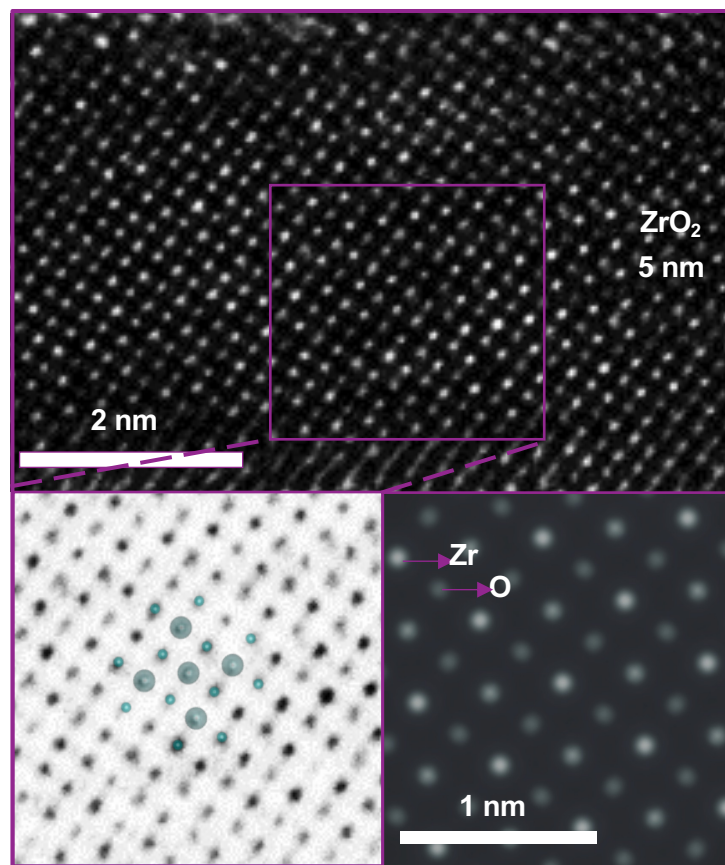
0.5 nm – 10 nm ZrO₂



In-plane Grazing Incidence Diffraction

Suggests T $\rightarrow$ O phase transition $\leq$ 2 nm

Nonpolar Tetragonal Phase



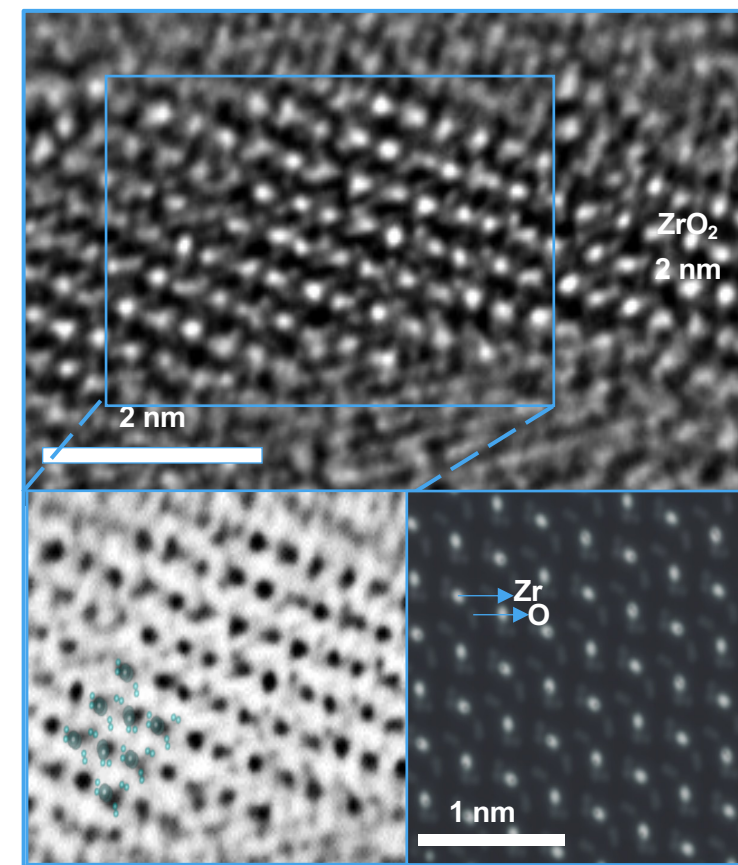
Inverted Contrast
Overlay: Tetragonal P4₂/nmc

HR-TEM simulation
Tetragonal P4₂/nmc [001]

Transmission Electron Microscopy

Centered oxygen anion

Polar Orthorhombic Phase



Inverted Contrast
Overlay: Orthorhombic Pca2₁

HR-TEM simulation
Orthorhombic Pca2₁ [110]

Transmission Electron Microscopy

Acentric oxygen distortion

Size dependent phase transition

Below 2 nm thickness

Centrosymmetric crystal structure

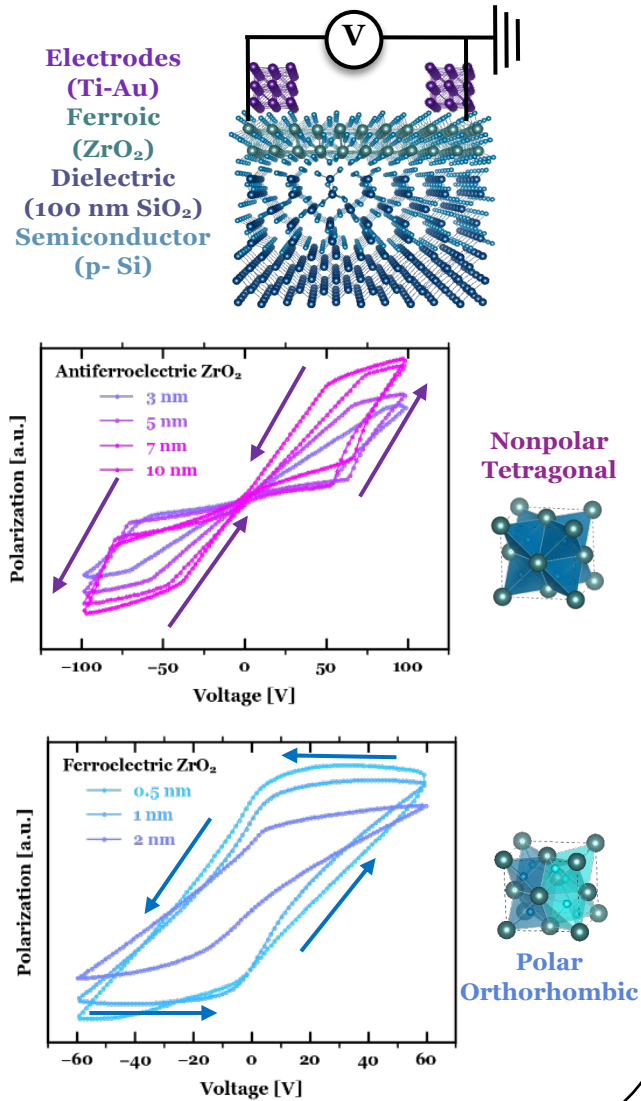
> 2 nm: Tetragonal symmetry

Noncentrosymmetric crystal structure

$\leq$ 2 nm: Orthorhombic symmetry

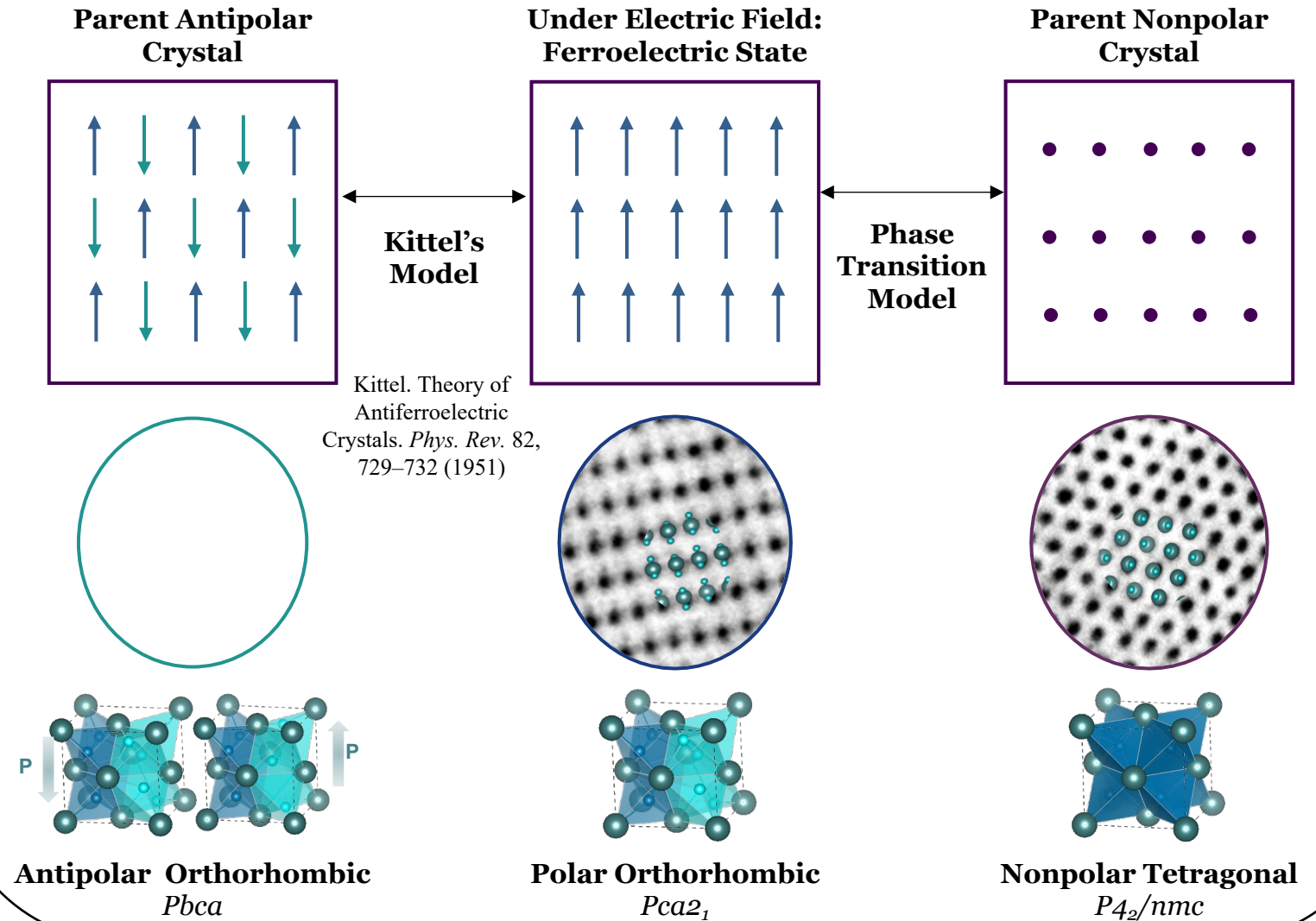
Materials Design | Ferroelectric Polarization Switching

Polarization Switching



< 2 nm ZrO_2
 Ferroelectricity emerges from unusual state

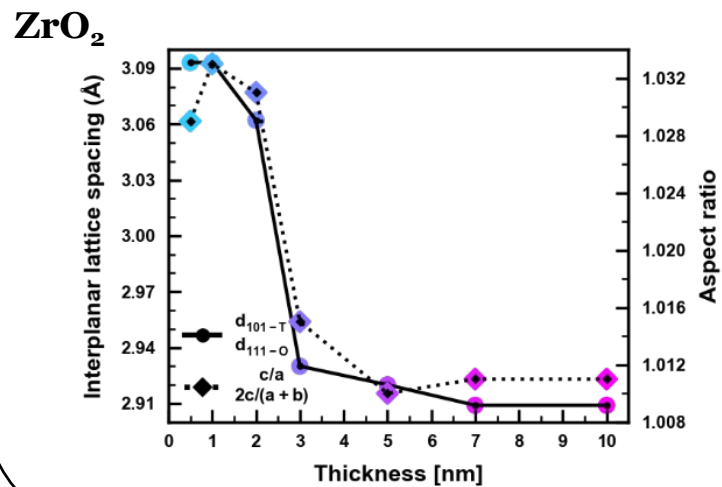
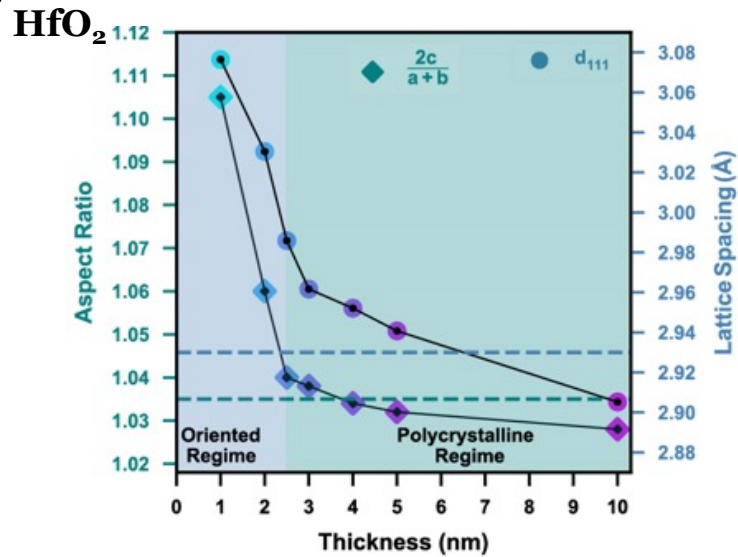
Antiferroelectricity: Microscopic Models



Electric Field Control of Inversion Symmetry
 Field-induced nonpolar $\rightarrow$ polar phase transition

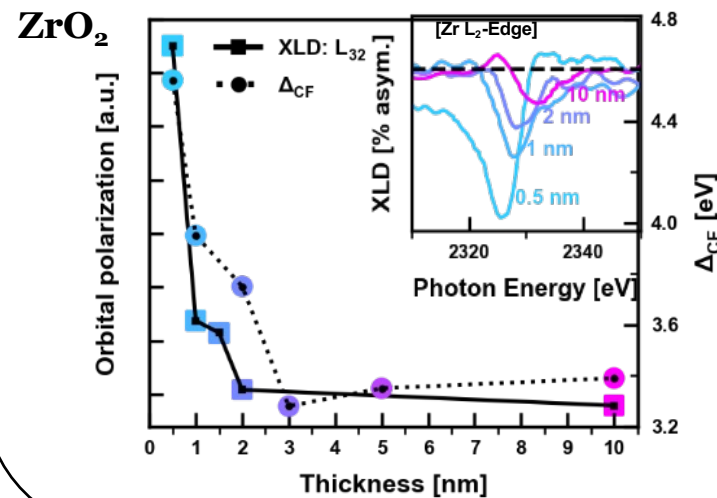
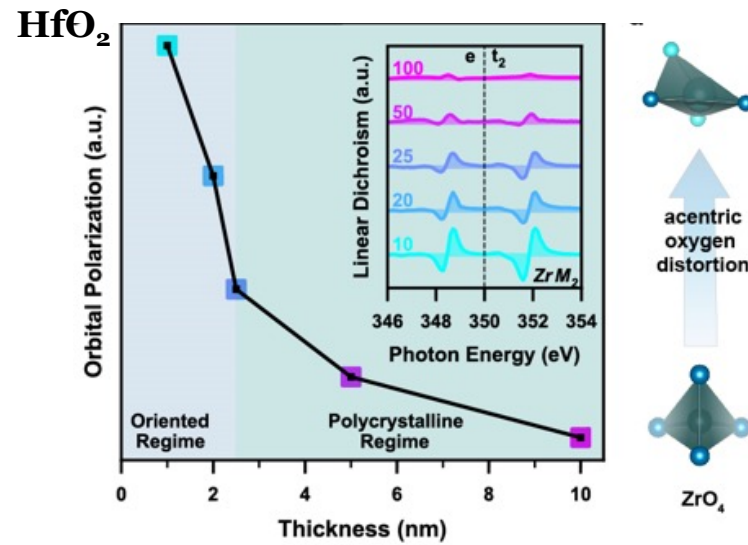
Materials Design | Ultrathin Enhanced Polarization

Diffraction



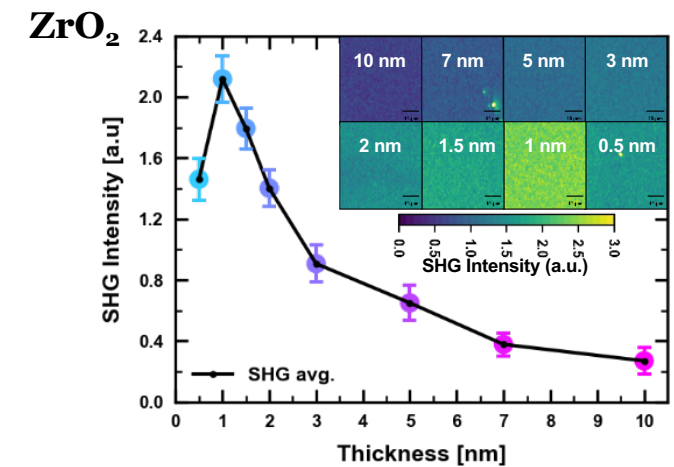
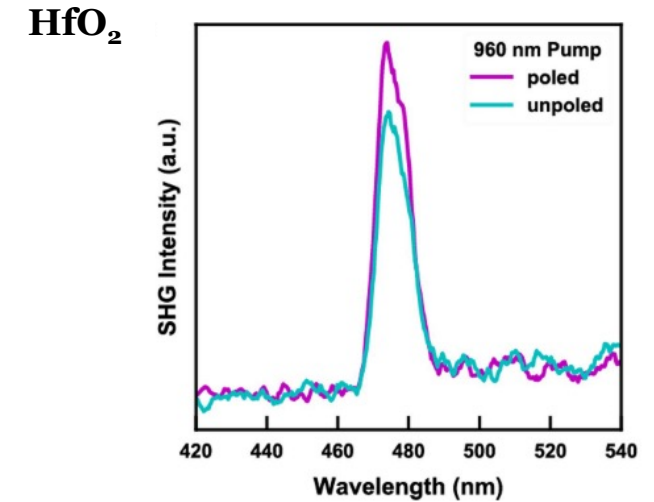
Distortion markers via diffraction
Ultrathin enhanced polar distortion

Spectroscopy



Polarization markers via spectroscopy
Ultrathin enhanced orbital polarization

Optical

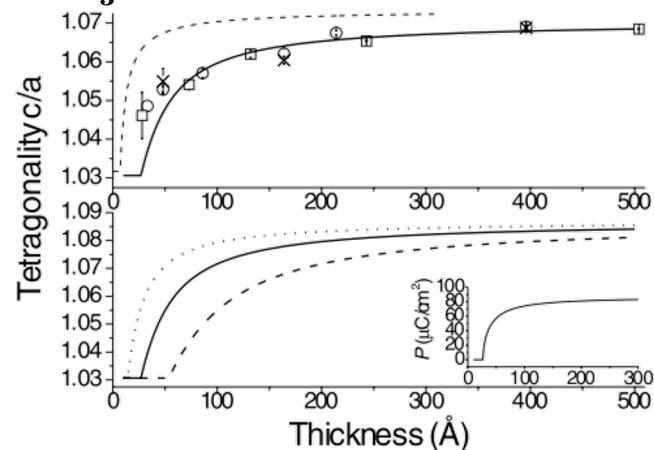


Polarization markers via SHG
Ultrathin enhanced symmetry breaking

Materials Design | “Inverse” Ferroelectric Size Effects

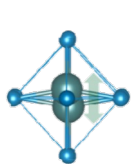
Conventional Ferroelectrics

PbTiO₃

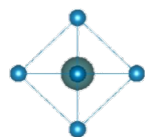


Lichtensteiger *et al. Phys. Rev. Lett.* 94, 047603 (2005)

Perovskite-Structure



Reduced
Dimensions



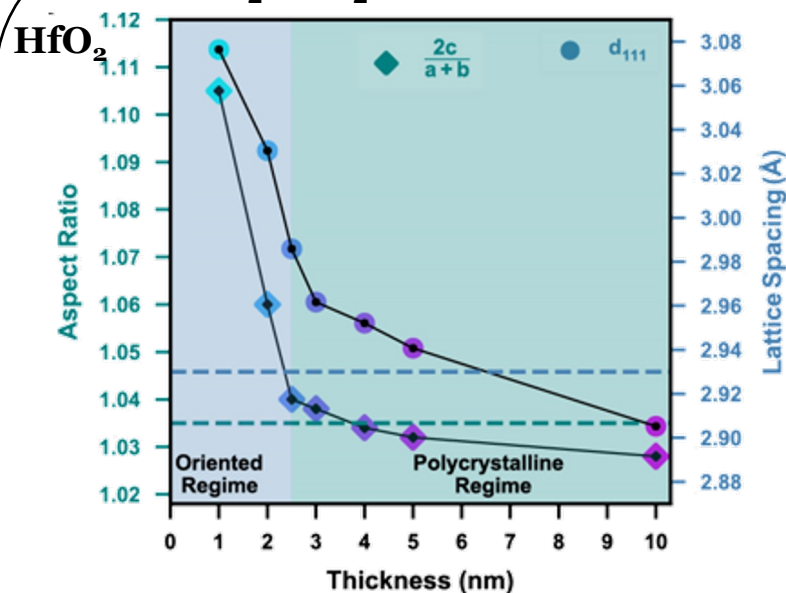
Polar Tetragonal

Nonpolar Cubic

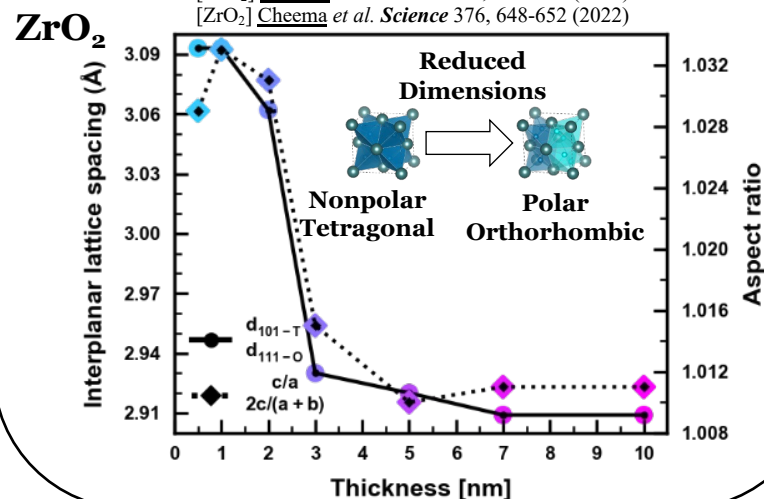
Junquera & Ghosez. *Nature* 422, 506–509 (2003).

Ultrathin-Diminished Polarization
Conventional Perovskite Ferroelectrics

HfO₂-ZrO₂ Ferroelectrics

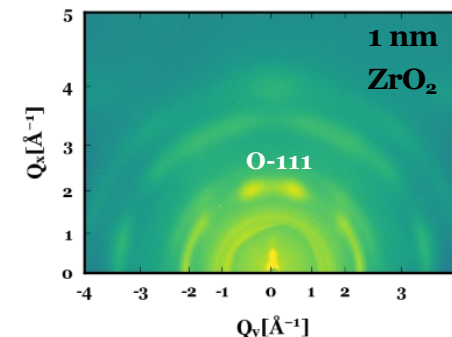


[HfO₂] Cheema *et al. Nature* 580, 478–482 (2020)
[ZrO₂] Cheema *et al. Science* 376, 648–652 (2022)

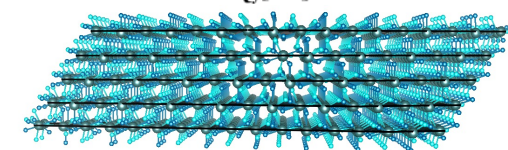


Ultrathin-Enhanced Polarization
New Fluorite Ferroelectrics

Potential Origins



OOP Diffraction
Films highly-oriented
in 111-direction:
HZO & ZrO₂



Pca2₁ (111)
P // [001]
In-plane projection

Textured films: In-plane P & less cancellation

Cheema *et al. Science* 376, 648 (2022); Cheema *et al. Nature* 580, 478 (2020)
H Lee, DH Choe, S Jo *et al. ACS AMI* 13 (2021)

Negative Piezoelectric & Electric Auxetic Effect

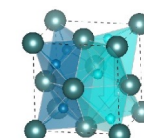
Phys. Rev. Appl. 12, 034032 (2019) ; *Phys. Rev. Lett.* 125, 197601 (2020) ;
Nat. Commun. 12, 7301 (2021)

Flexoelectricity: Strain gradient

Chen *et al. Europhys. Lett.* 369, 1343 (2022)

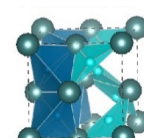
Improper Ferroelectricity

Lee *et al. Science* 369, 1343 (2020)



**Nonpolar
Monoclinic**

Reduced
Dimensions

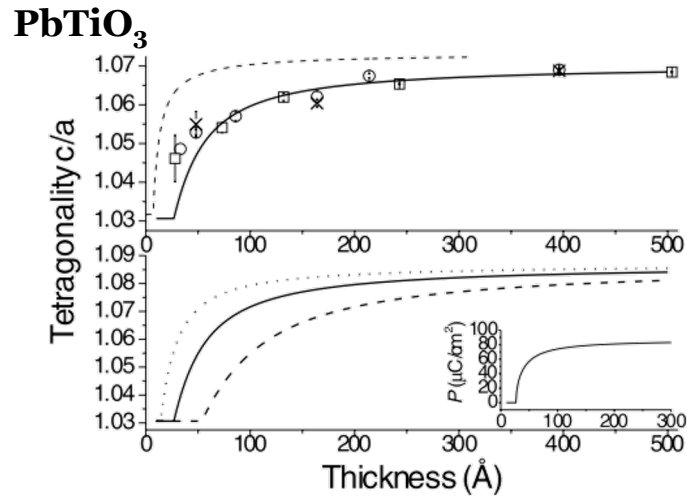


**Polar
Orthorhombic**

Negative Piezoelectric Effect
Explains pressure-enhanced ferroelectricity

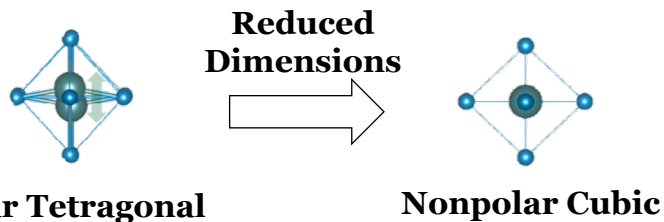
Materials Design | “Inverse” Ferroelectric Size Effects

Conventional Ferroelectrics



Lichtensteiger *et al. Phys. Rev. Lett.* 94, 047603 (2005)

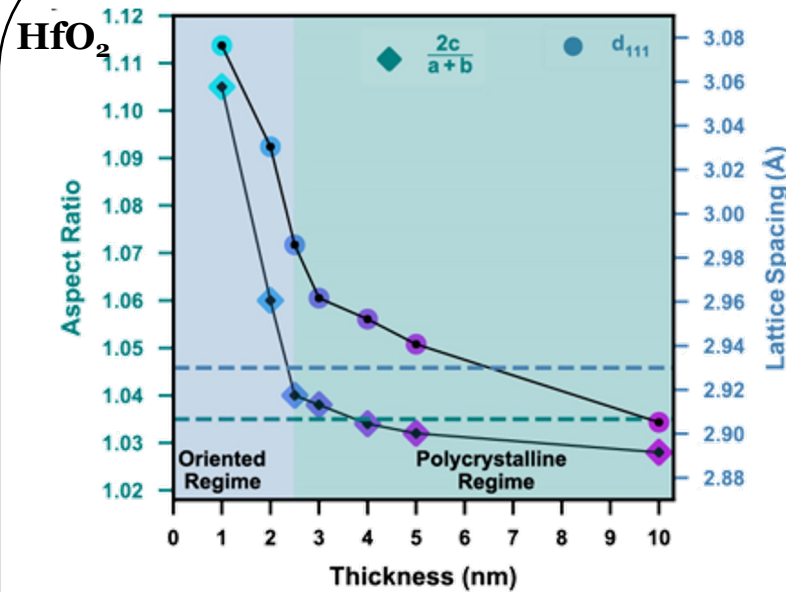
Perovskite-Structure



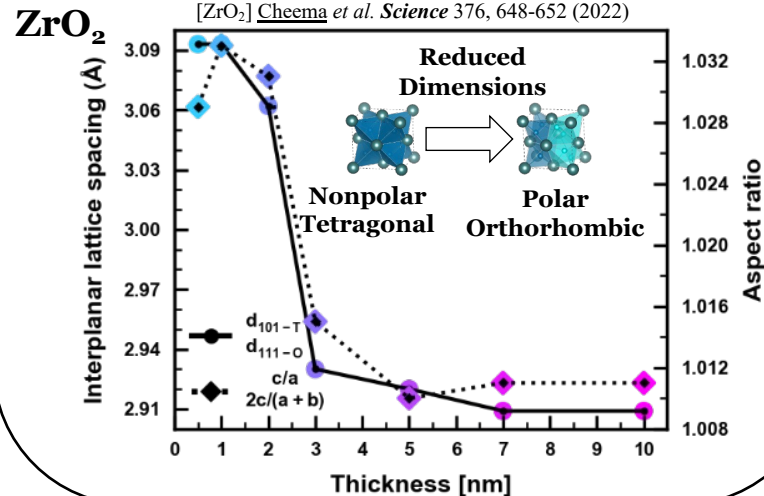
Junquera & Ghosez. *Nature* 422, 506–509 (2003).

Ultrathin-Diminished Polarization
Conventional Perovskite Ferroelectrics

HfO₂-ZrO₂ Ferroelectrics



[HfO₂] Cheema *et al. Nature* 580, 478–482 (2020)
[ZrO₂] Cheema *et al. Science* 376, 648–652 (2022)

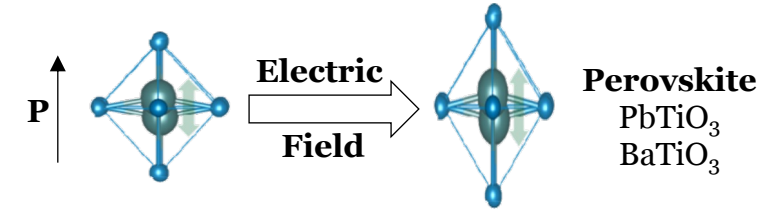


Ultrathin-Enhanced Polarization
New Fluorite Ferroelectrics

Negative Piezoelectricity

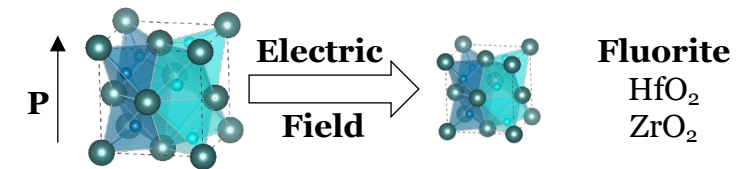
Positive Piezoelectricity

Conventional deformation driven by E-field



Negative Piezoelectricity

Neg. deformation driven by E-field



[Theory] Negative Piezoelectricity in HfO₂-ZrO₂

Liu & Cohen. Origin of Negative Piezoelectric Effect. *PRL* 119, 207601 (2017)
[HZO] Liu *et al.* Electric Auxetic Effect in Piezoelectrics. *PRL* 125, 197601 (2020)
[HfO₂] Dutta *et al.* Piezoelectricity in hafnia. *Nat. Commun.* 12, 7301 (2021)
[ZrO₂] Ganser *et al.* Piezo- and Pyroelectricity in Zirconia. *PRA* 18, 054066 (2022)

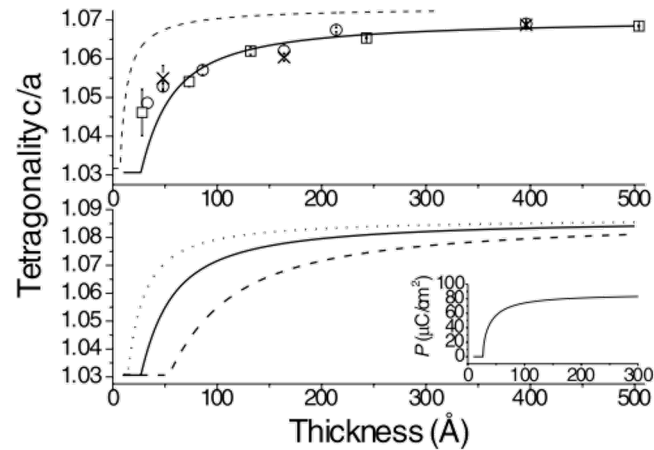
[Experiment] Negative Piezoelectricity in HfO₂-ZrO₂

[HfO₂] Buragohain *et al. Adv. Mater.* 34, 2206237 (2022)
[ZrO₂] Silva *et al. Appl. Mater. Today* 30, 101708 (2023)
[HZO] Stylianidis *et al. arXiv*:2212.01680

Negative Piezoelectric Effect
Explains pressure-enhanced ferroelectricity

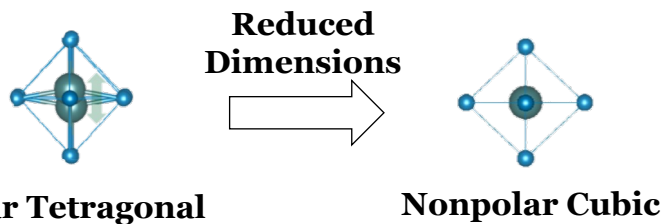
Ferroelectric Thickness Scaling | “Negative” Ferroelectric Size Effects

Conventional Ferroelectrics



[PTO] Lichtensteiger *et al. Phys. Rev. Lett.* 94, 047603 (2005)

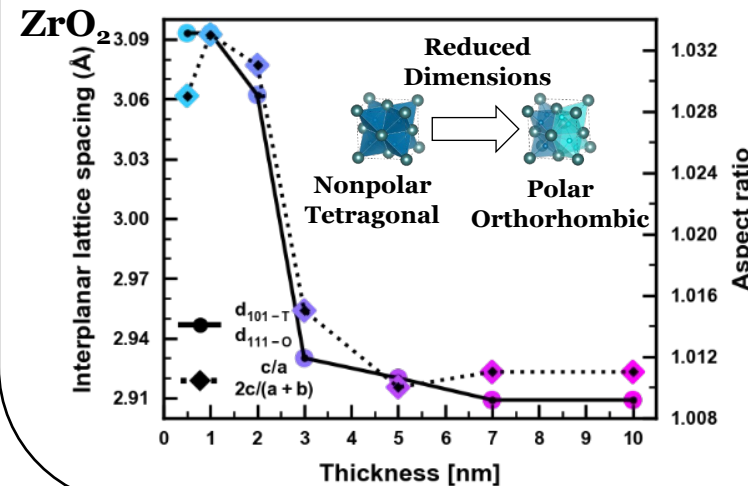
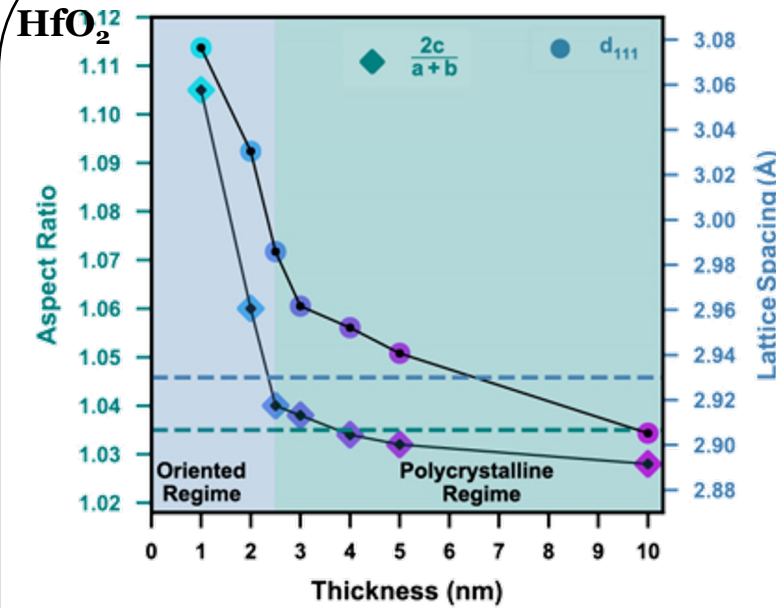
Perovskite-Structure



Junquera & Ghosez Critical thickness for ferroelectricity in perovskite ultrathin films. *Nature* 422, 506–509 (2003).

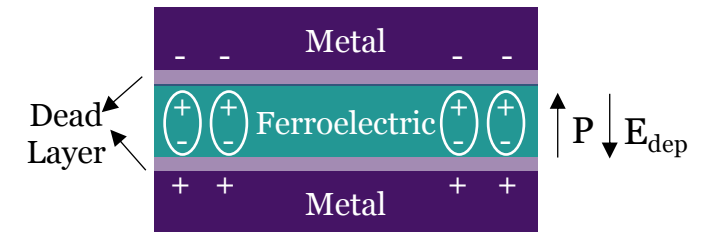
Ultrathin-Diminished Polarization
Conventional Perovskite Ferroelectrics

HfO₂-ZrO₂ Ferroelectrics



Ultrathin-Enhanced Polarization
New Fluorite Ferroelectrics

Depolarization Fields



Charge Conservation

$$Q_{FE} = \epsilon_o E_{FE} + P = \epsilon_r \epsilon_o E_{DE} = Q_{DE}$$

Short Circuit Boundary Condition

$$0 = E_{FE} t_{FE} + E_{DE} t_{DE}$$

Depolarization Field

$$E_{FE,dep} = - \frac{P/\epsilon_o}{1 + \epsilon_r \left(\frac{t_{FE}}{t_{DE}} \right)} \propto \frac{1}{t_{FE}}$$

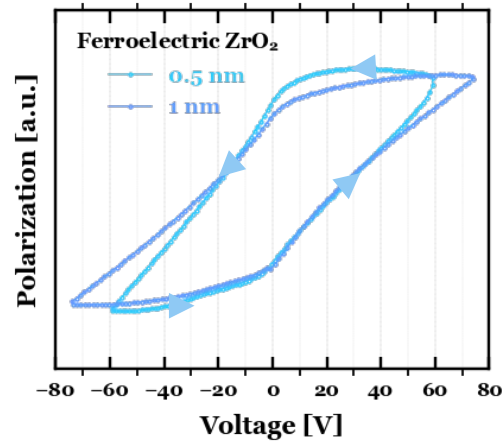
Depolarization fields increase with decreasing thickness
→ Polarization vanishes in the ultrathin limit

Wurfel & Batra. Depolarization-Field-Induced Instability in Thin Ferroelectric Films. *Phys. Rev. B* 8, 5126–5133 (1973).

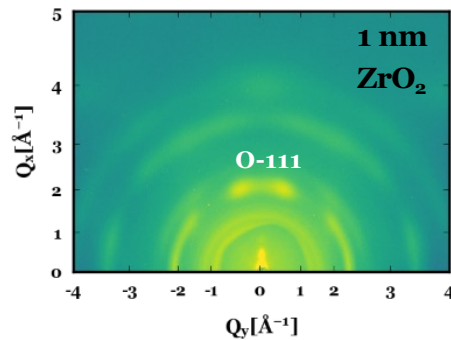
Depolarization Fields
How does HfO₂-ZrO₂ overcome this?

Ferroelectric Thickness Scaling | “Negative” Ferroelectric Size Effects

In-plane Polarization



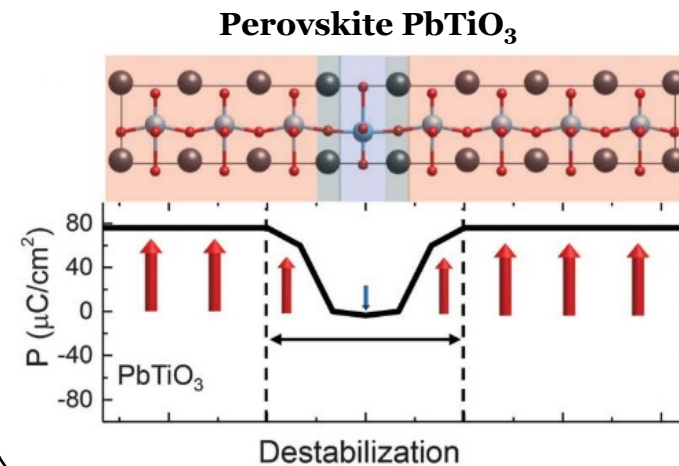
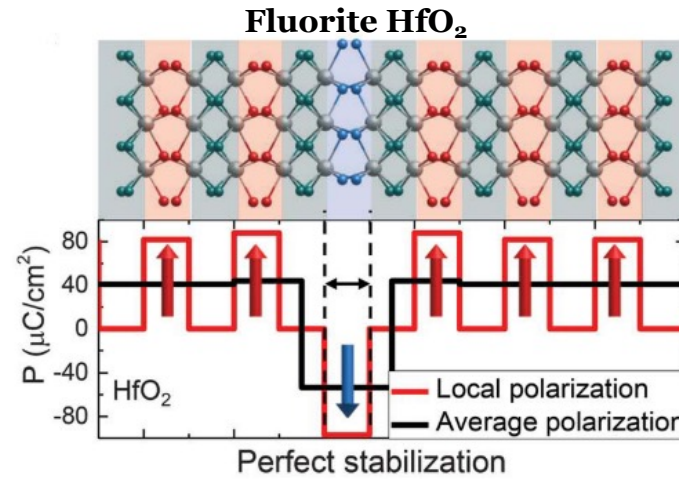
In-plane P switching



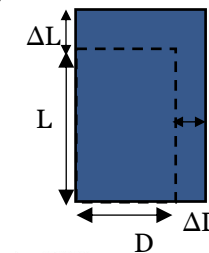
OOP Diffraction
Films highly-oriented in 111-direction

Pca2₁ (111)
P // [001]
In-plane projection

Scale-Free Ferroelectricity

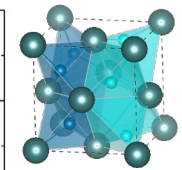
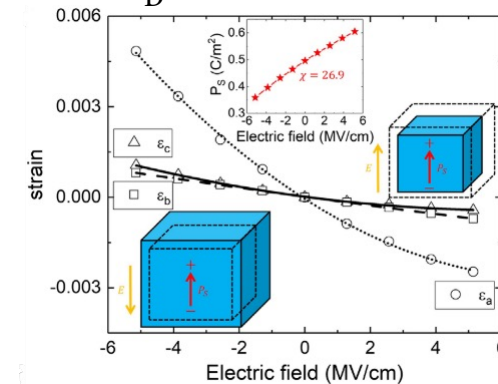


Negative Piezoelectricity



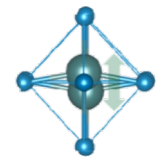
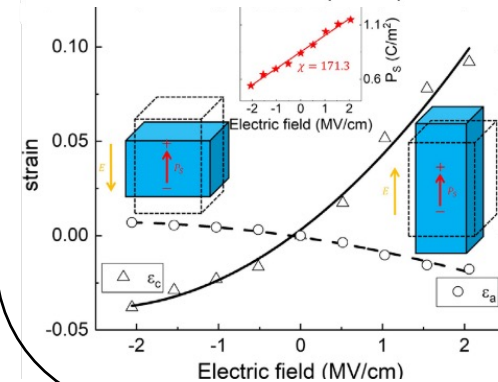
$$\nu = -\frac{\Delta D/D}{\Delta L/L} < 0$$

Neg. Poisson's
Deformation driven by stress



Fluorite HfO₂

Negative Piezoelectricity
Deformation driven by E-field



Perovskite PbTiO₃

[HfO₂] Cheema *et al.* Enhanced ferroelectricity in ultrathin films on Si. *Nature* 580 (2020)
[ZrO₂] Cheema *et al.* Emergent ferroelectricity in sub-nanometer films on Si. *Science* 376 (2022)

Lee *et al.* Scale-free ferroelectricity induced by flat phonon bands in HfO₂. *Science* 369, 1343 (2020)

Liu & Cohen. Origin of Negative Piezoelectric Effect. *Phys. Rev. Lett.* 119, 207601 (2017).
Liu *et al.* Electric Auxetic Effect in Piezoelectrics. *Phys. Rev. Lett.* 125, 197601 (2020).

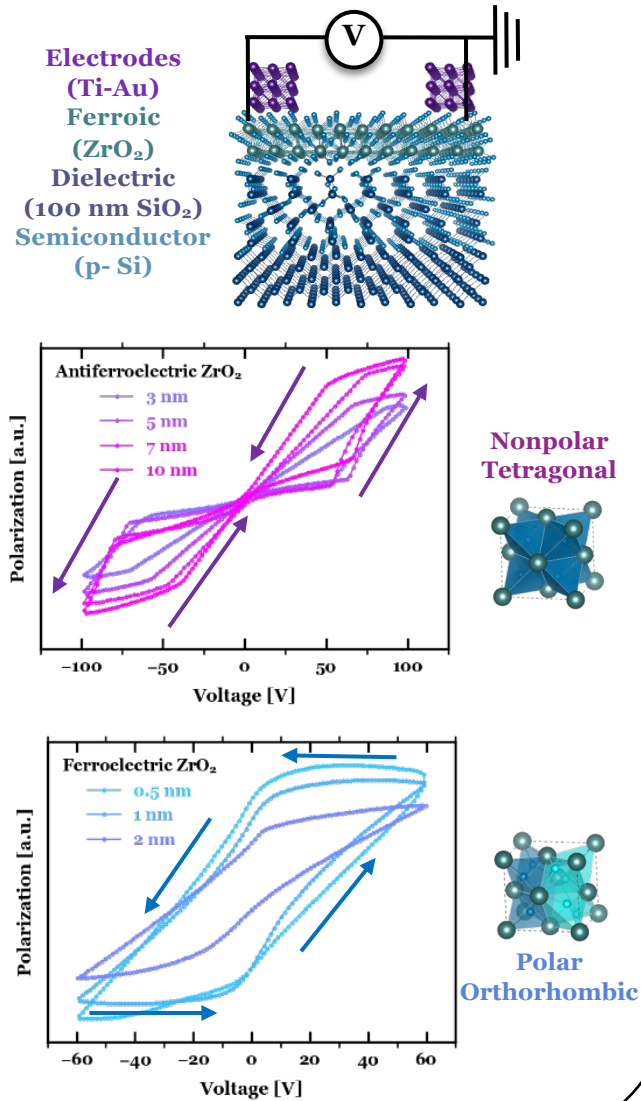
In-plane Polarization
Bypasses depolarization fields

Negative Domain Wall Energy
Domains avoids depolarization

Negative Piezoelectric Effect
Explains pressure-enhanced ferroelectricity

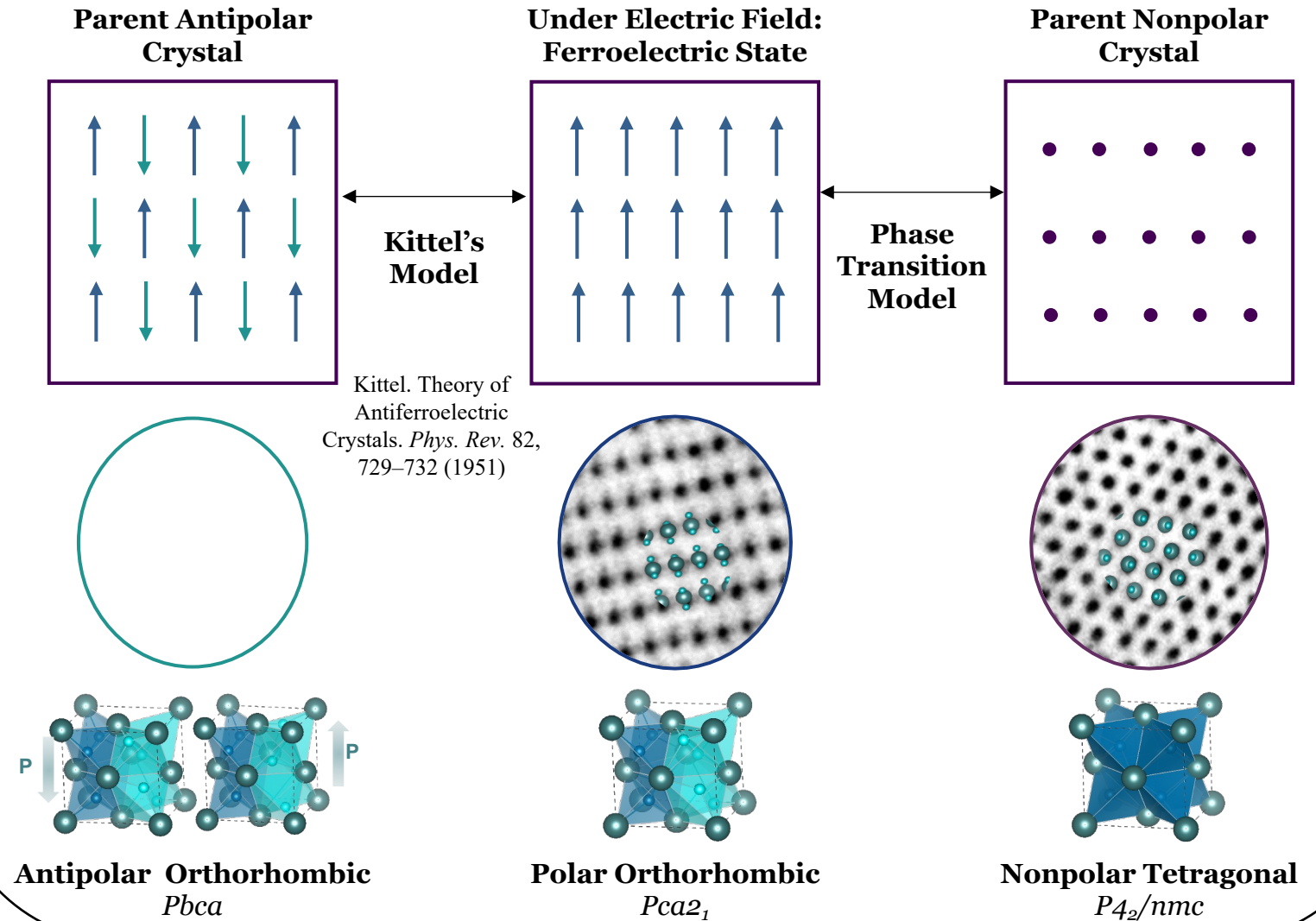
Materials Design | Symmetry Control Knobs

Polarization Switching



Thickness Control of Symmetry
 Size-driven nonpolar $\rightarrow$ polar transition

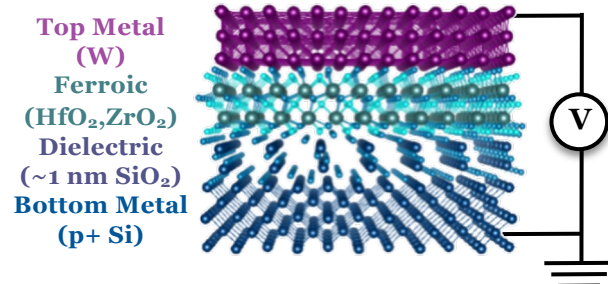
Antiferroelectricity: Microscopic Models



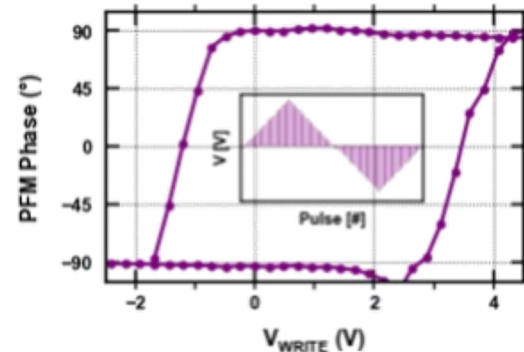
Electric Field Control of Inversion Symmetry
 Field-induced nonpolar $\rightarrow$ polar phase transition

Ferroelectric Memory| Atomic Switch

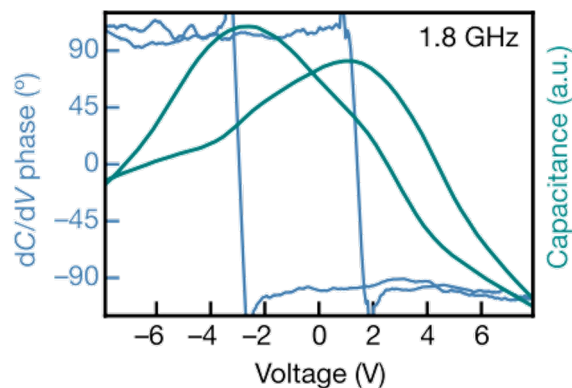
Scanning Probe Microscopy



Piezoresponse Force Microscopy

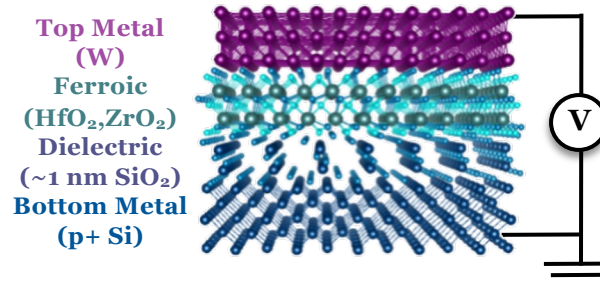


Scanning Capacitance Microscopy

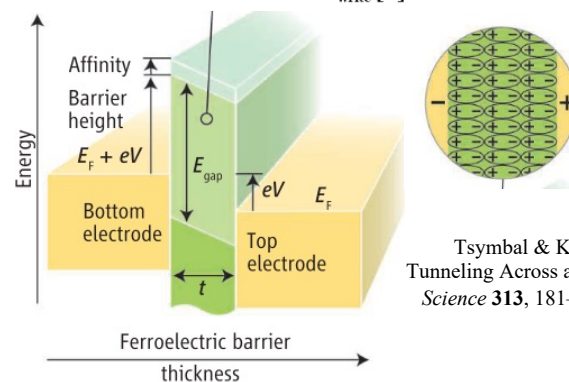
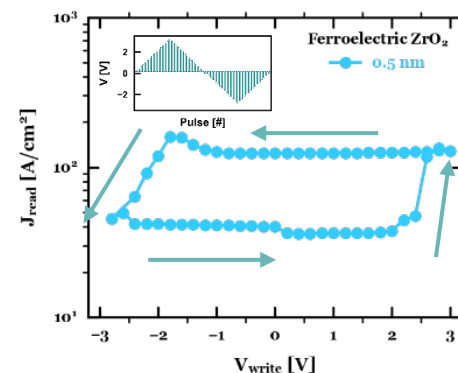


5 Å ZrO₂ & 1 nm HfO₂
Polarization switching ~ unit cell thickness

Transport



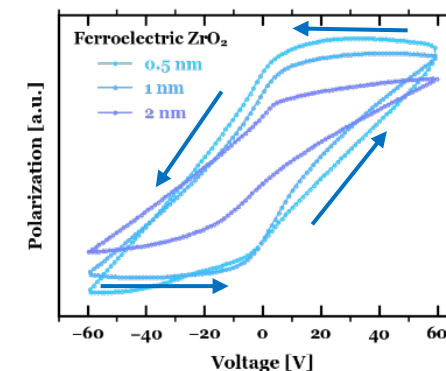
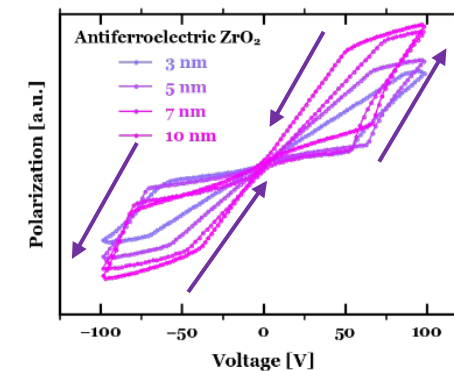
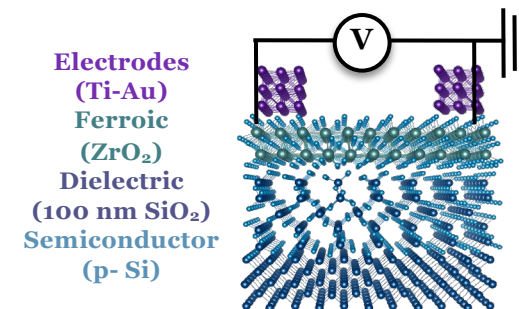
Ferroelectric Tunnel Junctions



Tsymbal & Kohlstedt.
Tunneling Across a Ferroelectric.
Science **313**, 181–183 (2006).

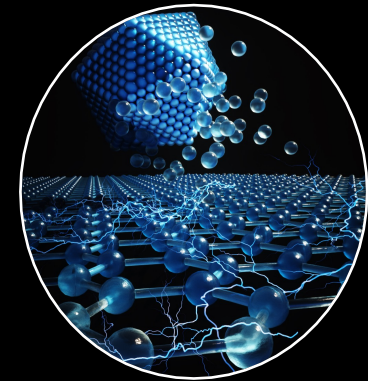
5 Å ZrO₂ & 1 nm HfO₂
Polarization-dependent tunnel current

In-plane Devices

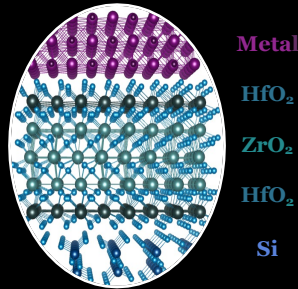


< 2 nm ZrO₂
Ferroelectricity emerges from unusual state

Ferroelectrics | A Novel Platform for Computing & Energy Technologies

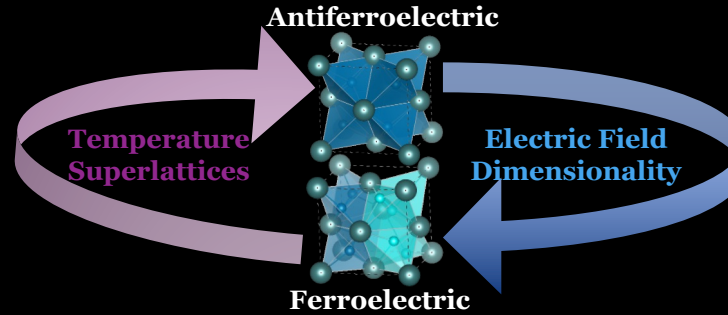


Atomic Layer
Synthesis

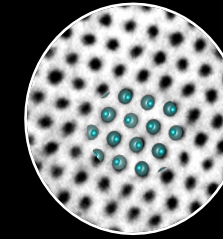


Stacking-dependent
Sub-Unit Cell Superlattices

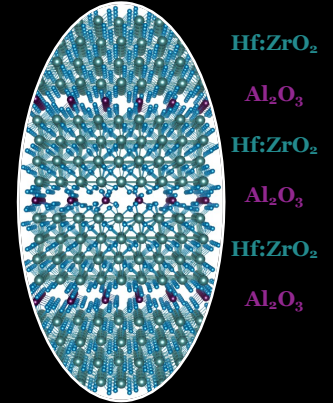
Ferroelectrics: Building Blocks
competing polar-nonpolar crystal structures
platform for emergent (negative) electronic phenomena



[HfO₂] Cheema *et al.* Enhanced ferroelectricity in ultrathin films grown directly on silicon. *Nature* (2020).
[ZrO₂] Cheema *et al.* Emergent ferroelectricity in sub-nanometer binary oxide films on silicon. *Science* (2022).

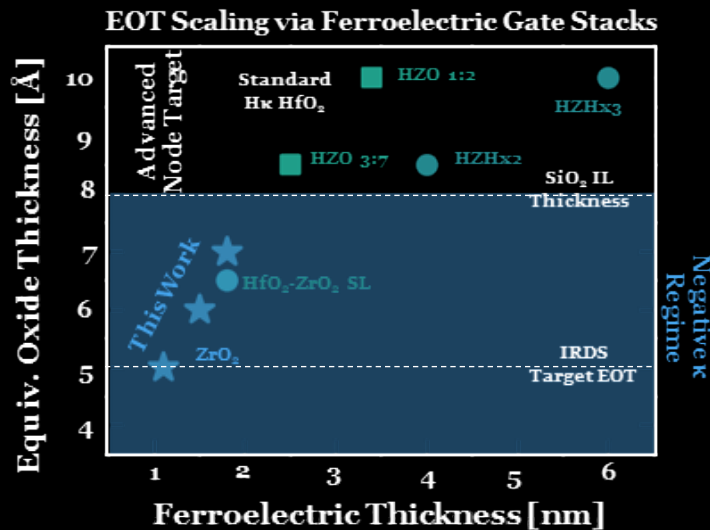


Crystal Symmetry
Manipulation



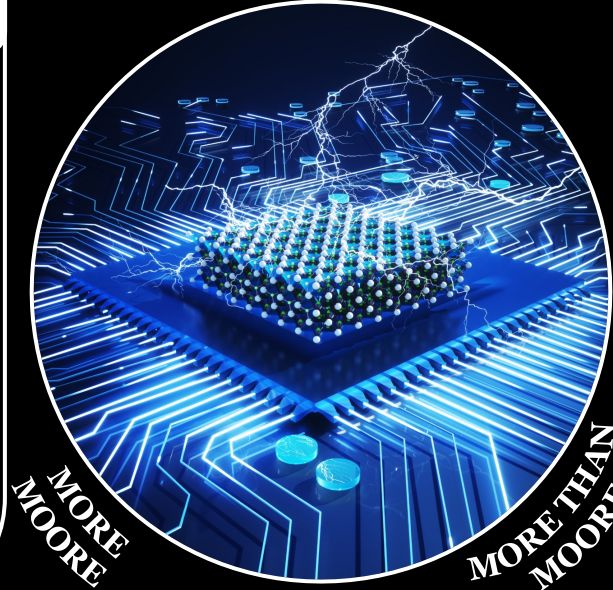
Crystalline-Amorphous
Superlattices

Ferroelectrics: New paradigm for Logic & Memory
high- κ dielectrics $\rightarrow$ negative- κ ferroelectrics
defective $\rightarrow$ collective switching



[HfO₂-ZrO₂] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors. *Nature* (2022).
[ZrO₂] Cheema *et al.* Ultralow electrical thickness via one nanometer negative capacitance. (2024)

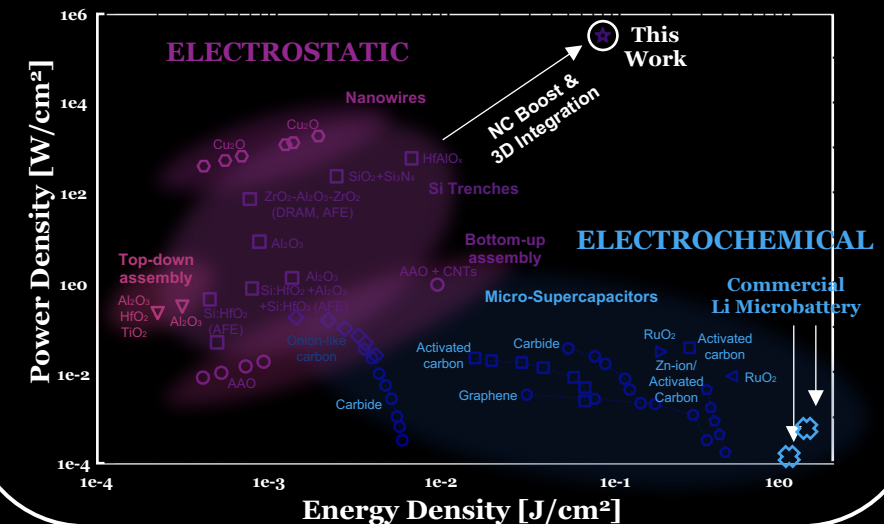
FERRO-ELECTRONICS



MORE
MOORE

MORE THAN
MOORE

Ferroelectrics: New paradigm for Energy Tech
electrochemical $\rightarrow$ electrostatic energy storage
thermoelectric $\rightarrow$ pyroelectric energy harvesting



[ZrO₂-Al₂O₃] Cheema *et al.* Giant energy storage & power density neg. capacitance superlattices. *Nature* (2024)

Negative Capacitance for Computing | Logic Transistor Roadmap

PERSPECTIVE

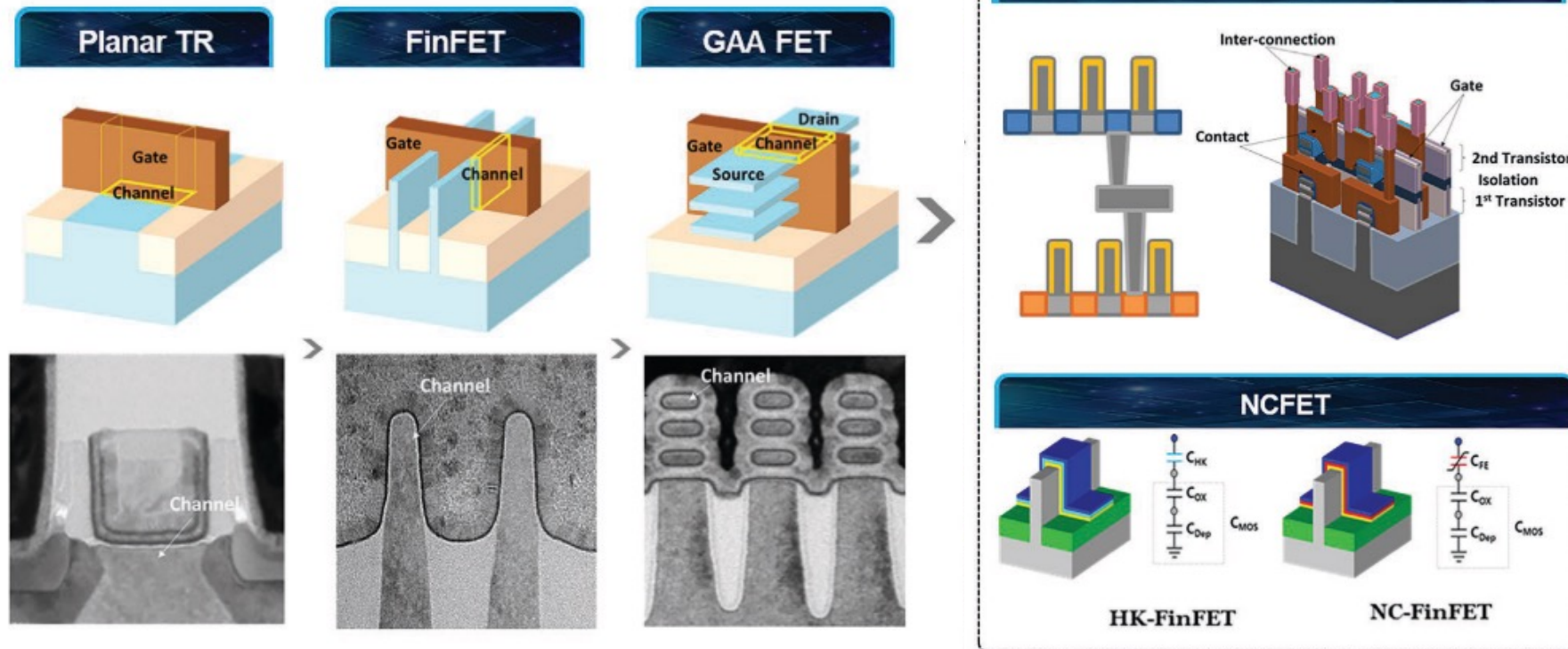
ADVANCED
MATERIALS
TECHNOLOGIES

www.advmattechnol.de

Creating the Future with Silicon

ES Jung

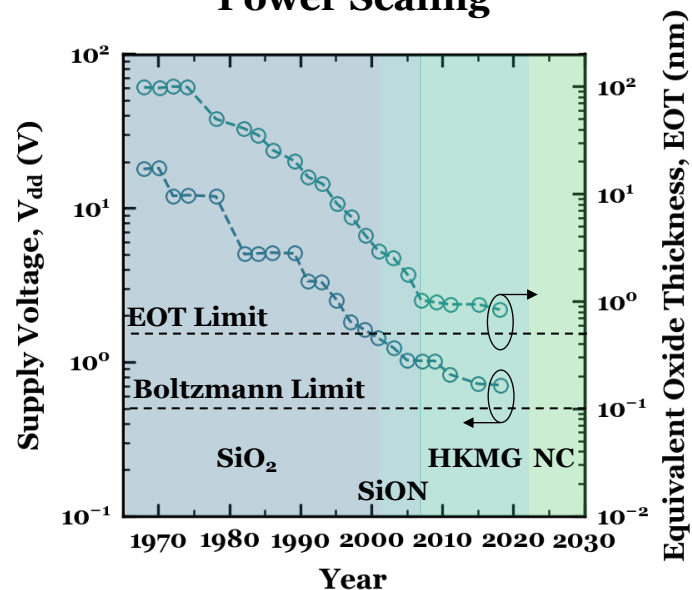
ES Jung. Creating the Future with Silicon.
Adv. Mater. Technol. 2200867 (2023).



More Moore: Logic Transistors
From High- κ to Negative- κ Gate Dielectrics

Negative Capacitance for Computing | Materials Design Considerations

Power Scaling



Hoffmann *et al.* *APL Mater.* 9, 020902 (2021)

$\text{SiO}_2 \rightarrow \text{High-}\kappa \text{ HfO}_2 \rightarrow \text{Neg.-}\kappa \text{ HfO}_2\text{-ZrO}_2?$

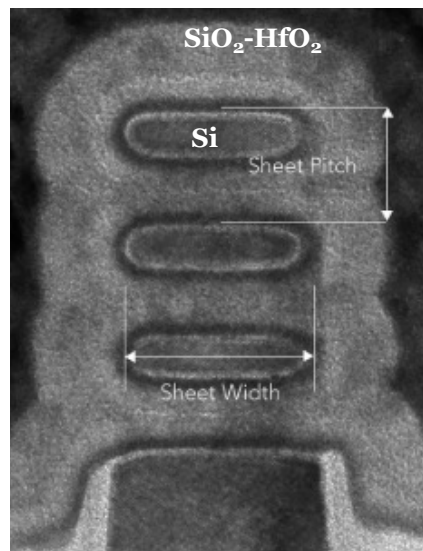
Equivalent Oxide Thickness

$$EOT = t_{\text{SiO}_2} + \frac{\epsilon_{\text{SiO}_2}}{\epsilon_{\text{HK}}} t_{\text{HK}} \rightarrow \text{Can this be negative?}$$

Transistor Scaling

Lower EOT $\rightarrow$ Low Power Operation

Size Scaling



Samsung GAA FET

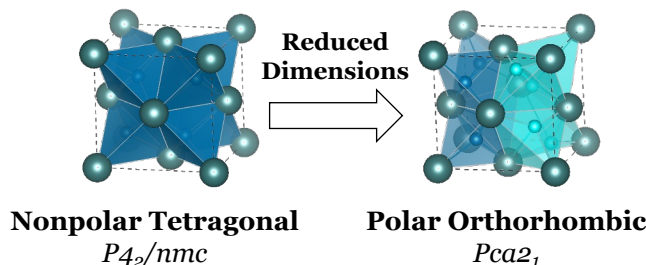
Advanced transistors
No room for the gate oxide!
< 1.5 nm

Materials Challenge
Ferroelectricity vanishes
< 2 nm!

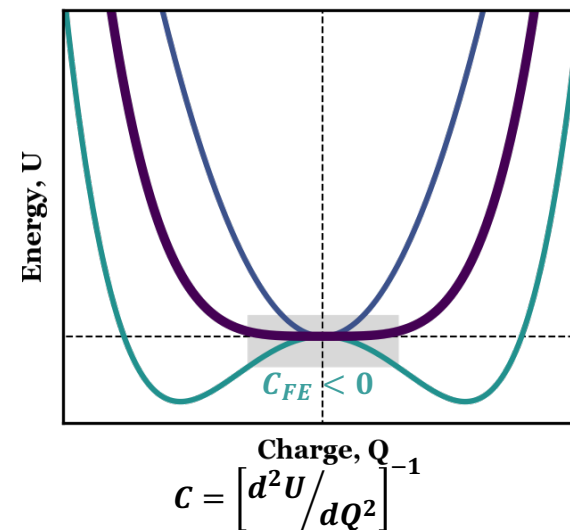
Breakthrough 1

Stabilized ultrathin ferroelectricity in HfO_2 & ZrO_2 on Si, today's high- κ dielectrics

[HfO_2] Cheema *et al.* Enhanced ferroelectricity in ultrathin films on silicon. *Nature* (2020).
[ZrO_2] Cheema *et al.* Emergent ferroelectricity in sub-nanometer films on silicon. *Science* (2022).



Ferroelectricity Not Enough



Landau Model of Ferroelectric

$$U = \alpha P^2 + \beta P^4 + \gamma P^6$$

Conventional Insulator

$$U = Q^2/2C$$

Ferroelectric + Dielectric

Total system stable @ $Q=0$

$$\frac{1}{C_{\text{Total}}} = \frac{1}{C_{\text{DE}}} - \frac{1}{|C_{\text{FE}}|}$$

$$C_{\text{Total}} = \frac{|C_{\text{FE}}|C_{\text{DE}}}{|C_{\text{FE}}| - C_{\text{DE}}} > C_{\text{DE}}$$

if $|C_{\text{FE}}| > C_{\text{DE}}$

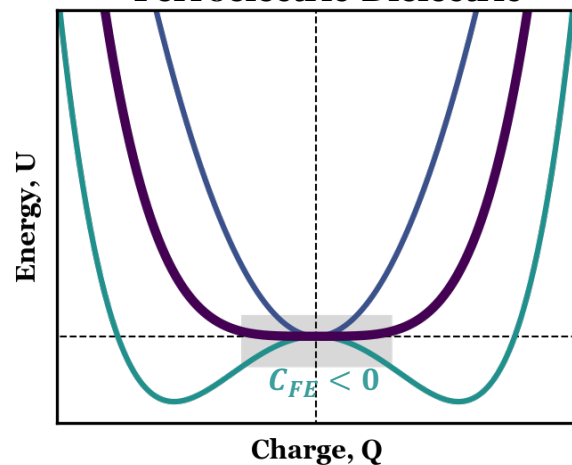
Metal
Dielectric
Ferroelectric
Metal

How can we manipulate ferroelectricity in $\text{HfO}_2\text{-ZrO}_2$ to stabilize the Negative Capacitance effect?

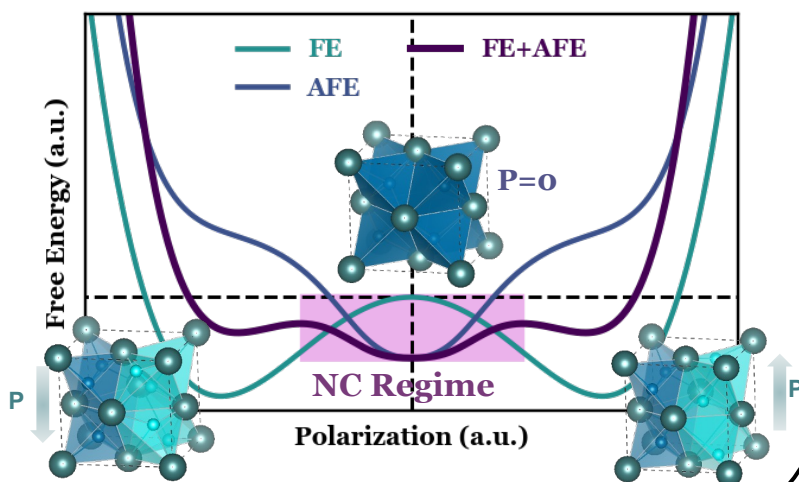
Negative Capacitance for Computing | Atomic-Scale Design

Energy Landscape Picture

Ferroelectric-Dielectric

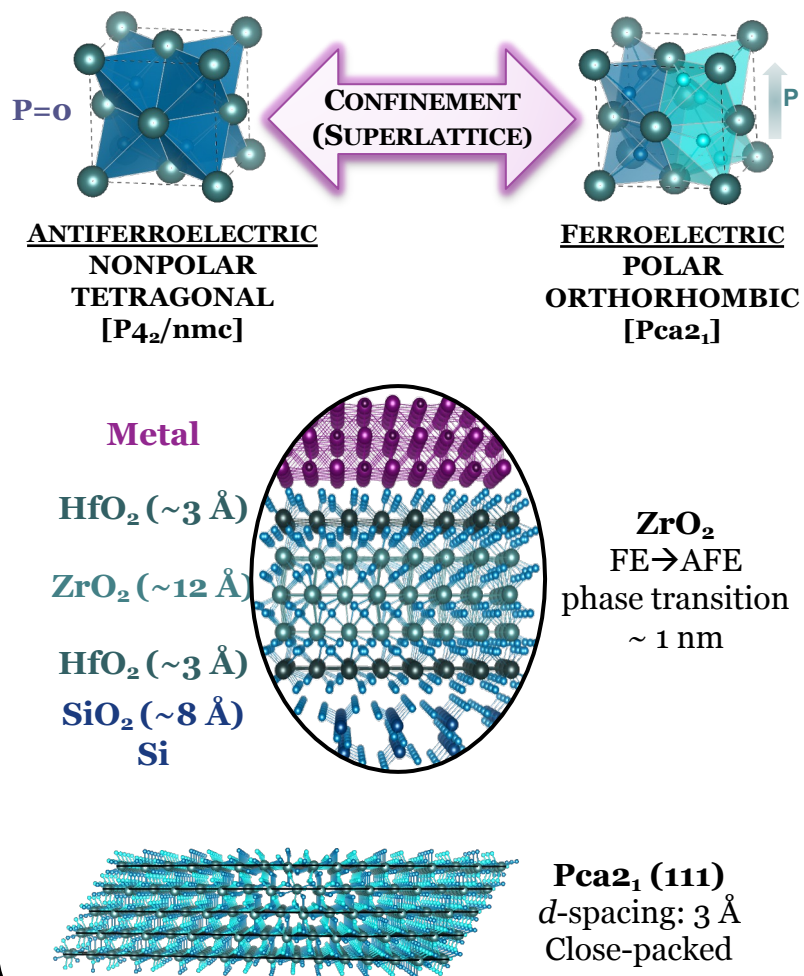


Ferroelectric-Antiferroelectric



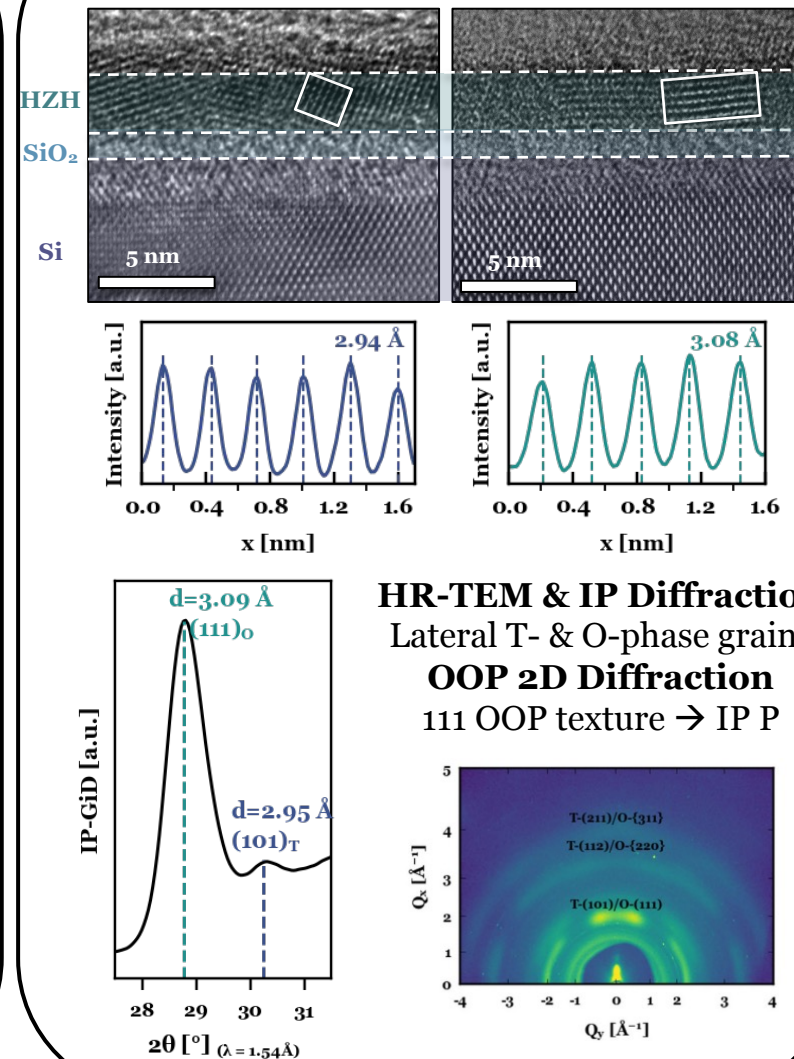
Dielectric vs. Antiferroelectric
Similar negative capacitance stabilization

Phase Competition



Superlattice Structure
Helps stabilize AFE-FE ferroic phase boundary

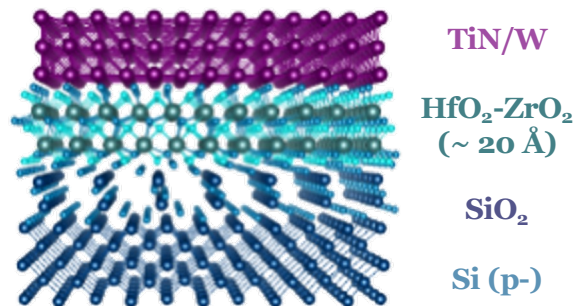
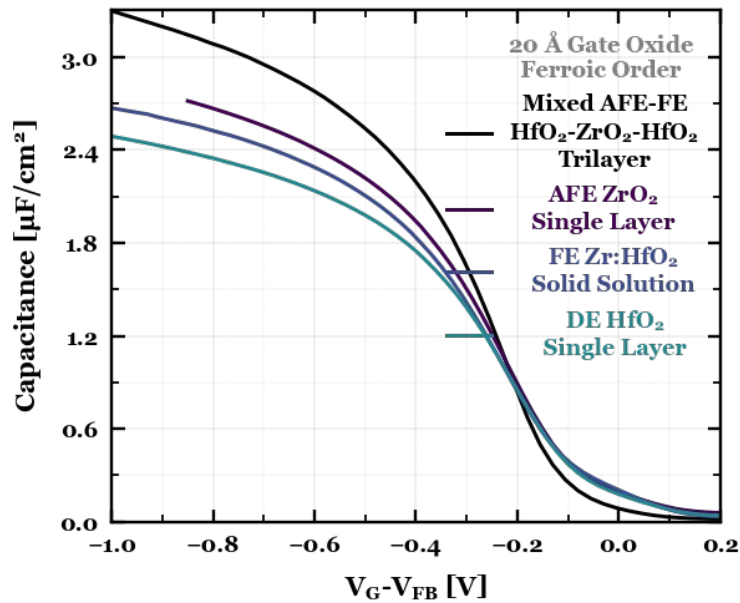
FE-AFE Phase Co-Existence



Co-existing ground states
Laterally-arranged FE-AFE domains

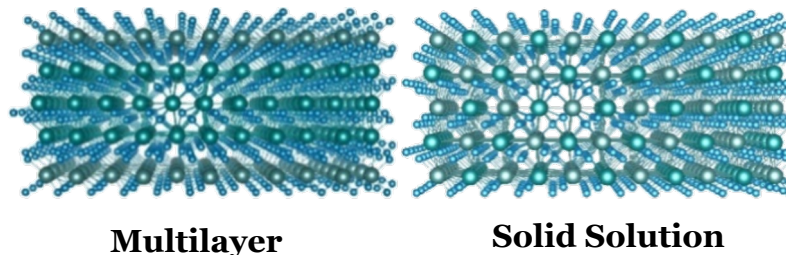
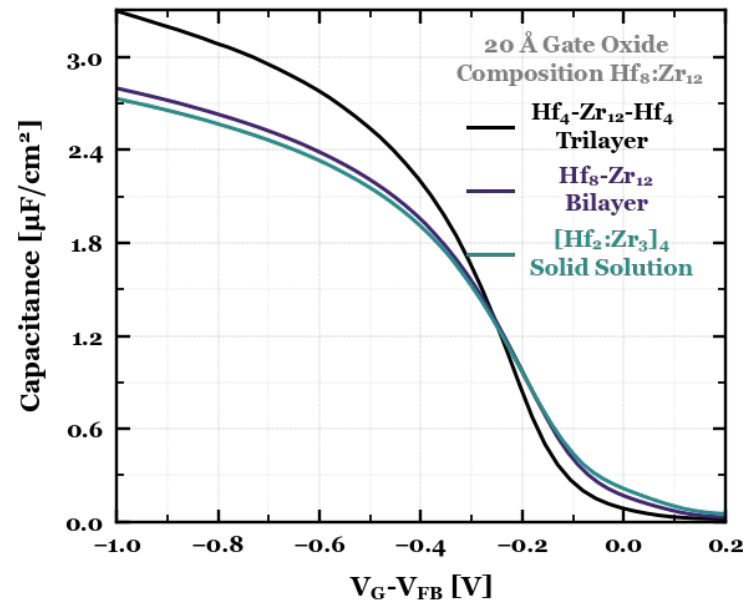
Negative Capacitance for Computing | Competing Ferroic Ground States

Ferroic Dependence



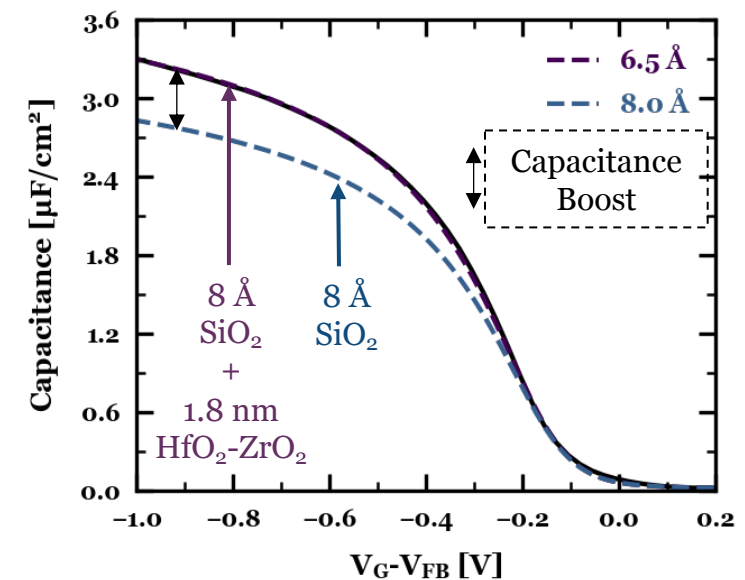
Importance of Mixed FE-AFE Order
Better for NC effect than FE or AFE order

Stacking Dependence



Importance of Layer Stacking
Rather than volume fraction of components

Capacitance Boost



Equivalent Oxide Thickness

$$EOT = t_{\text{SiO}_2} + \frac{\epsilon_{\text{SiO}_2}}{\epsilon_{\text{HK}}} t_{\text{HK}}$$

< 8 Å 8 Å < 0 Å via NC

1st Unambiguous Demo of Capacitance Boost
→ **Steady-State NC (negative- κ dielectric)**
→ **Not due to polarization switching**

[Transient NC] Khan *et al. Nat. Mater.* 14, 182–186 (2015)
[Microscopic Static NC] Yadav *et al. Nature* 565, 468–471 (2019)
[Macroscopic Static NC] Cheema *et al. Nature* 604, 65 (2022)

Capacitance enhancement over SiO₂
Benefit of Negative Capacitance

Negative Capacitance for Computing | Comparison to the Semiconductor Industry

Electrical Thickness (EOT) Scaling

THIS WORK NC GATE OXIDE

HKMG GATE STACK

CONVENTIONAL INTERLAYER SCAVENGING

Gate

Gate

Gate

HZH 18Å

HfO₂ 18Å

HfO₂ 18Å

SiO₂ 8Å

SiO₂ 8Å

SiO₂

EOT=6.5Å

EOT=9.5Å

EOT<9.5Å

- Leakage
- Mobility
- Reliability Maintained

- Leakage
- Mobility
- Reliability Degraded

This Work
Cheema et al. Nature
604, 65–71 (2022)

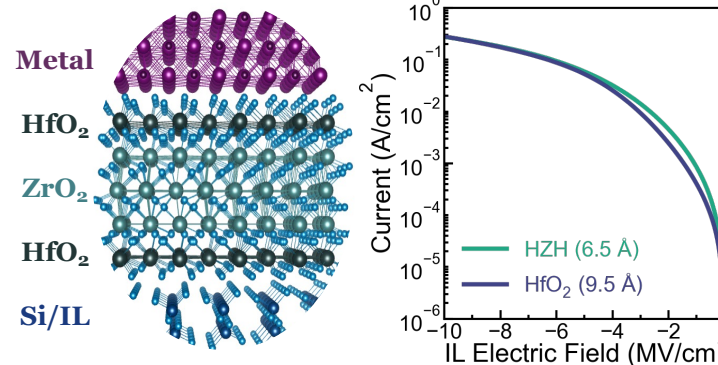
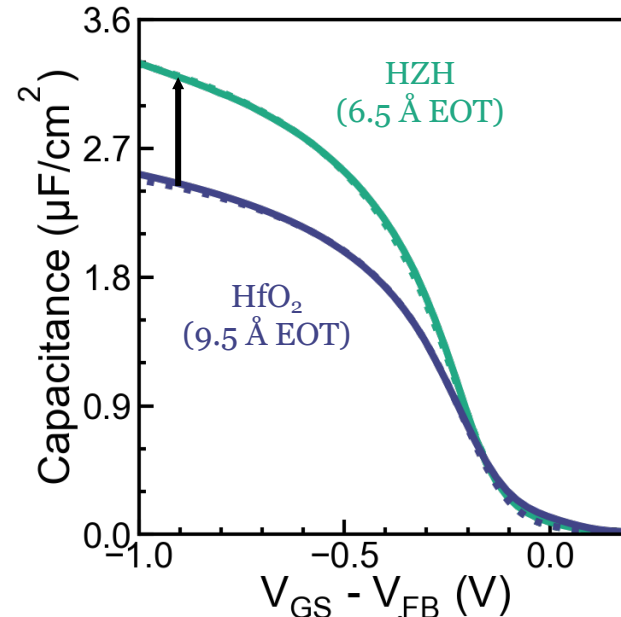
IBM, Intel, imec
T Ando et al. Materials
5, 478–500 (2012)

Equivalent Oxide Thickness

$$EOT = t_{SiO_2} + \frac{\epsilon_{SiO_2}}{\epsilon_{HK}} t_{HK}$$

< 8 Å 8 Å < 0 Å via NC

Standard high-κ vs. negative-κ



Metal

HfO₂

ZrO₂

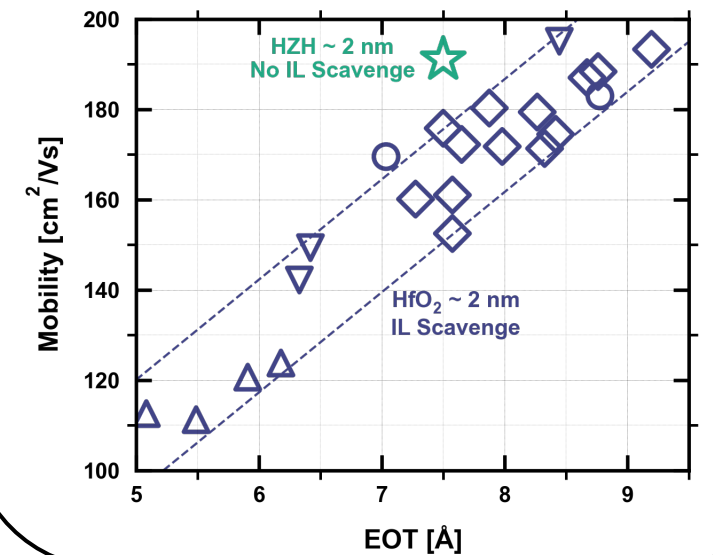
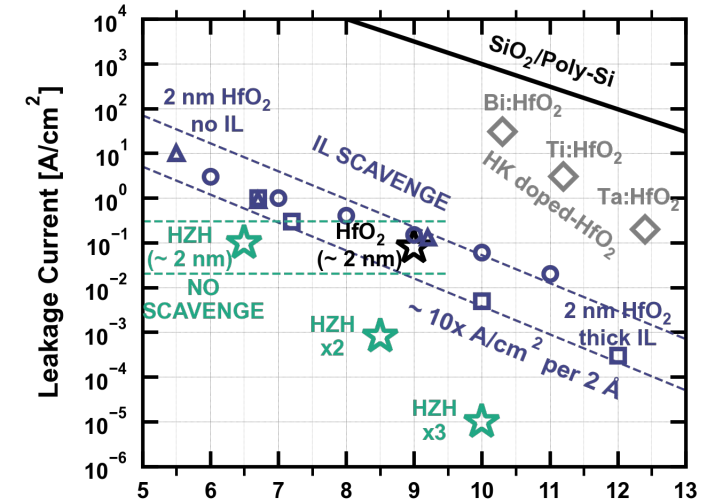
HfO₂

Si/IL

[HZH] Cheema et al. Ultrathin ferroic superlattice for advanced transistors.
Nature 604, 65 (2022)

[HZH] Cheema et al. Ultrathin ferroic superlattice for advanced transistors.
Nature 604, 65 (2022)

Standard high-κ vs. negative-κ



[HZH] Cheema et al. Ultrathin ferroic superlattice for advanced transistors.
Nature 604, 65 (2022)

Electric Thickness Scaling
Reduce EOT without reducing thickness

Boost in Capacitance
No Leakage Degradation (same tunnel barrier)

Leakage & Mobility Maintained
No Interlayer Removal

Negative Capacitance for Computing | Comparison to the Semiconductor Industry

Electrical Thickness (EOT) Scaling

THIS WORK NC GATE OXIDE

HKMG GATE STACK

CONVENTIONAL INTERLAYER SCAVENGING

Gate

Gate

Gate

HZH 18Å

HfO₂ 18Å

HfO₂ 18Å

SiO₂ 8Å

SiO₂ 8Å

SiO₂

EOT=6.5Å

EOT=9.5Å

EOT<9.5Å

- Leakage
- Mobility
- Reliability Maintained

- Leakage
- Mobility
- Reliability Degraded

This Work
Cheema *et al. Nature*
604, 65–71 (2022)

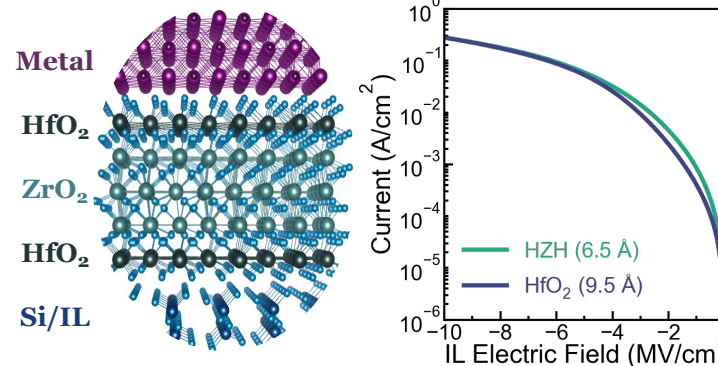
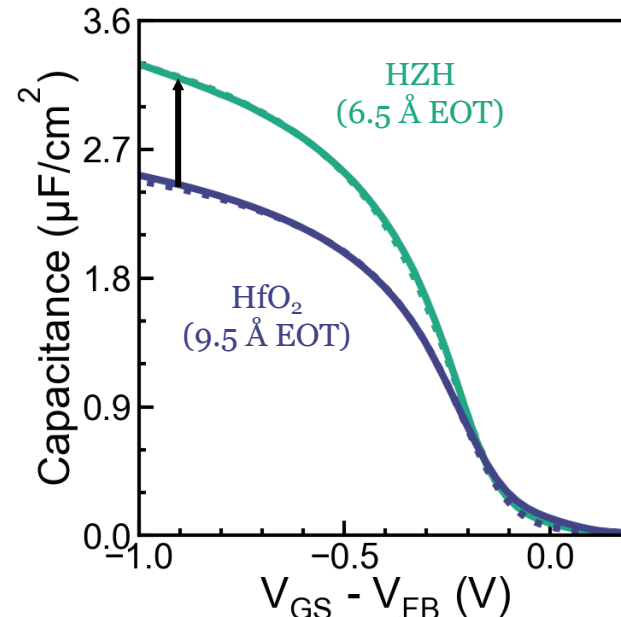
IBM, Intel, imec
T Ando *et al. Materials*
5, 478–500 (2012)

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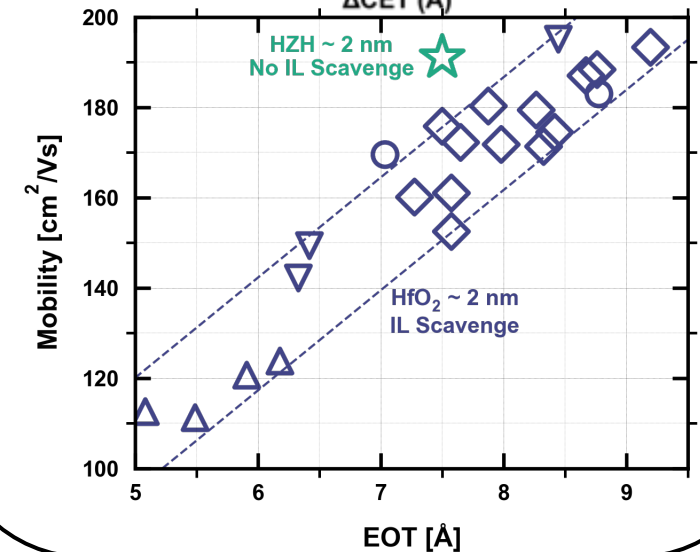
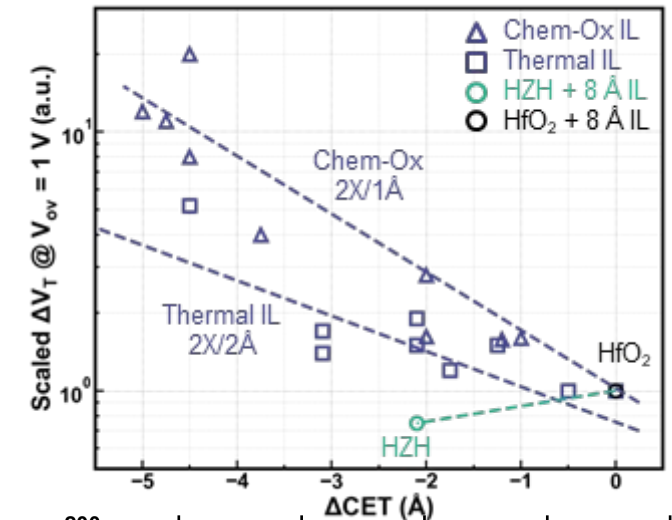
Standard high-κ vs. negative-κ



[HZH] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors.
Nature 604, 65 (2022)

[HZH] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors.
Nature 604, 65 (2022)

Standard high-κ vs. negative-κ



[HZH] On the PBTI Reliability of Low EOT Negative Capacitance 1.8 nm HfO ZrO₂ Superlattice Gate Stack on L_g=90nm nFETs. *VLSI* (2022)

Electric Thickness Scaling

Reduce EOT without reducing thickness

Boost in Capacitance

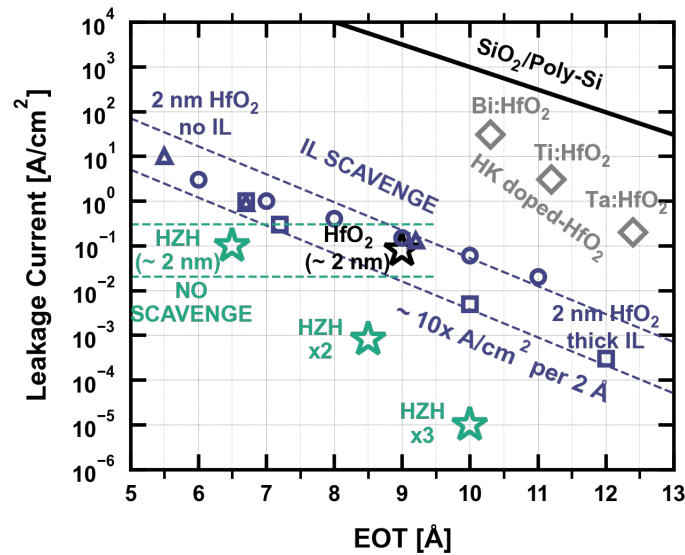
No Leakage Degradation (same tunnel barrier)

Reliability Maintained

No Interlayer Removal

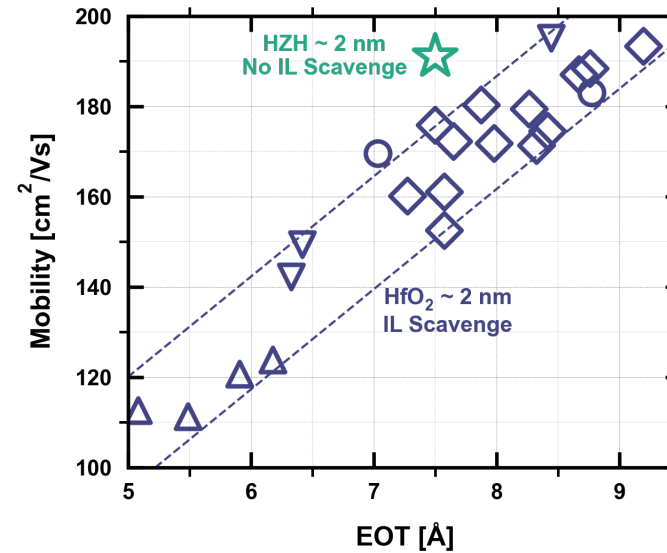
Negative Capacitance for Computing | Comparison to the Semiconductor Industry

Gate Leakage - EOT



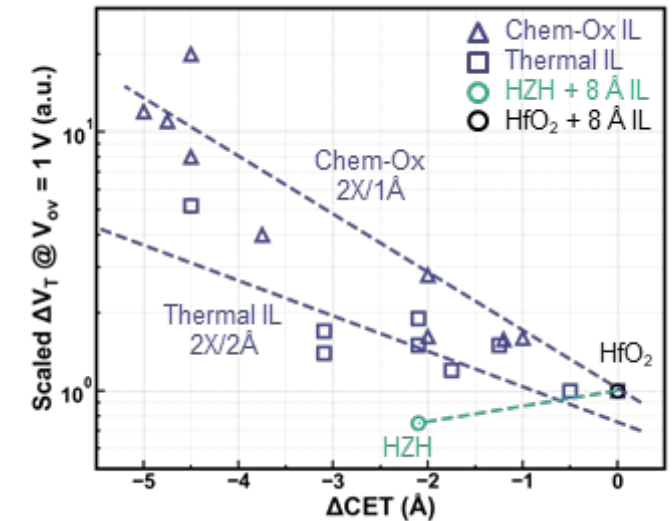
[HZH] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors. *Nature* 604, 65 (2022)

Mobility EOT



[HZH] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors. *Nature* 604, 65 (2022)

PBTI Reliability - EOT



[HZH] On the PBTI Reliability of Low EOT Negative Capacitance 1.8 nm HfO ZrO₂ Superlattice Gate Stack on L_g=90nm nFETs. *VLSI* (2022)

Boost in capacitance without transport penalty
Opposite trend that is observed in conventional HKMG stacks

Negative Capacitance for Computing | Robust to High-T Anneal

Electrical Thickness (EOT) Scaling

THIS WORK NC GATE OXIDE

HKMG GATE STACK

CONVENTIONAL INTERLAYER SCAVENGING

Gate

Gate

Gate

HZH 18Å

HfO₂ 18Å

HfO₂ 18Å

SiO₂ 8Å

SiO₂ 8Å

SiO₂

EOT=6.5Å

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EOT<9.5Å

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- Mobility
- Reliability Maintained

- Leakage
- Mobility
- Reliability Degraded

This Work
Cheema et al. Nature
604, 65–71 (2022)

IBM, Intel, imec
T Ando et al. Materials
5, 478–500 (2012)

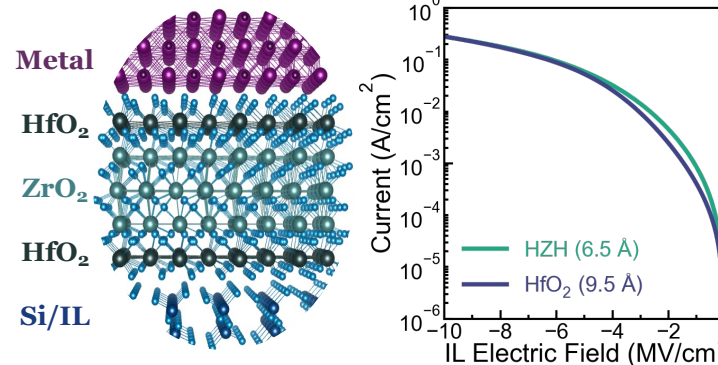
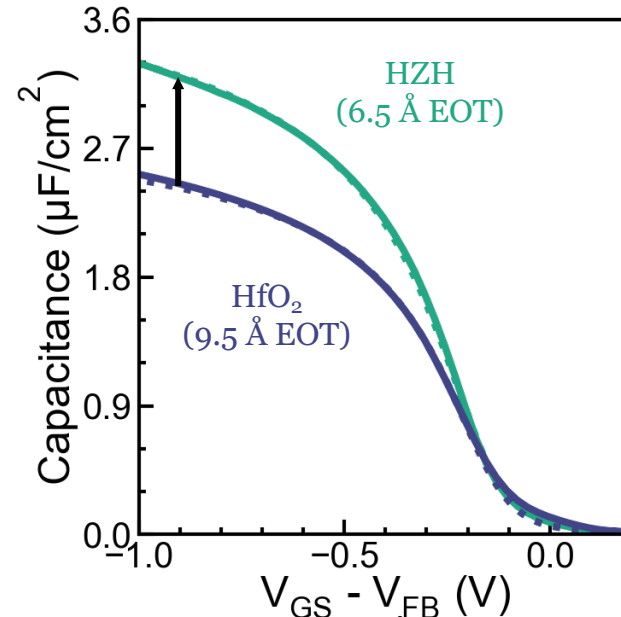
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[HfO₂-ZrO₂] Cheema et al. Ultrathin ferroic superlattice for advanced transistors. Nature 604, 65 (2022)

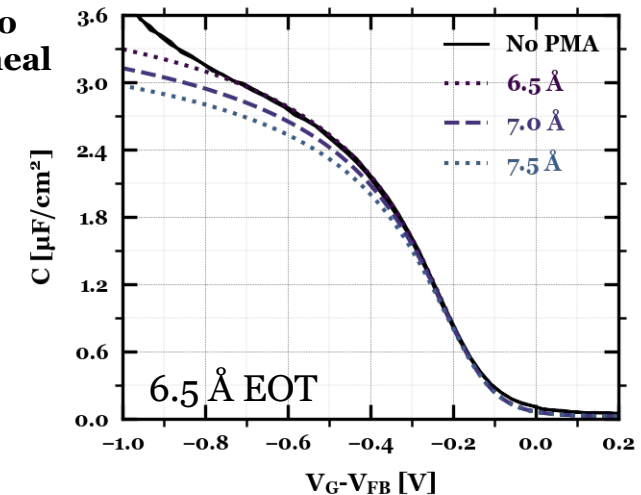
Standard high-κ vs. negative-κ



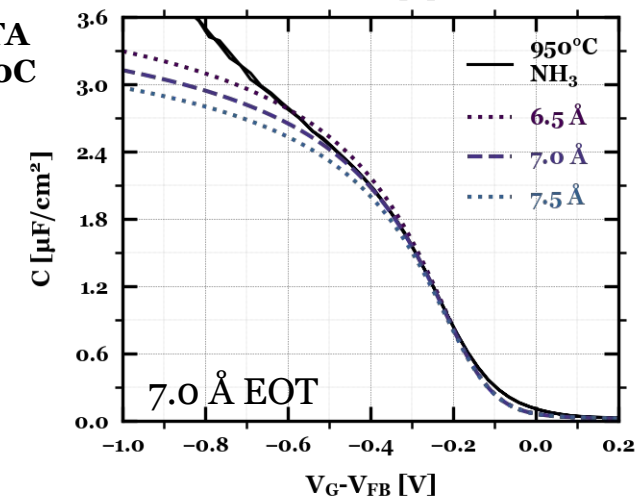
[HfO₂-ZrO₂] Cheema et al. Ultrathin ferroic superlattice for advanced transistors. Nature 604, 65 (2022)

High-T Spike Anneal

No Anneal



RTA 950C



[HfO₂-ZrO₂] Cheema et al. Thermal stability of negative capacitance ultrathin ferroic gate stack. In prep.

Electric Thickness Scaling
Reduce EOT without reducing thickness

Boost in Capacitance
No Leakage Degradation (same tunnel barrier)

Low EOT robust to high-T anneal
Thin ALD TiN + a-Si process

Negative Capacitance for Computing | Robust to RF & Cryogenic T

Electrical Thickness (EOT) Scaling

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CONVENTIONAL INTERLAYER SCAVENGING

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- Mobility
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- Mobility
- Reliability Degraded

This Work
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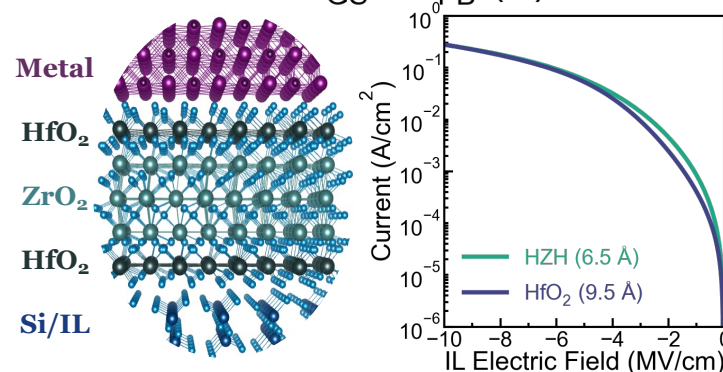
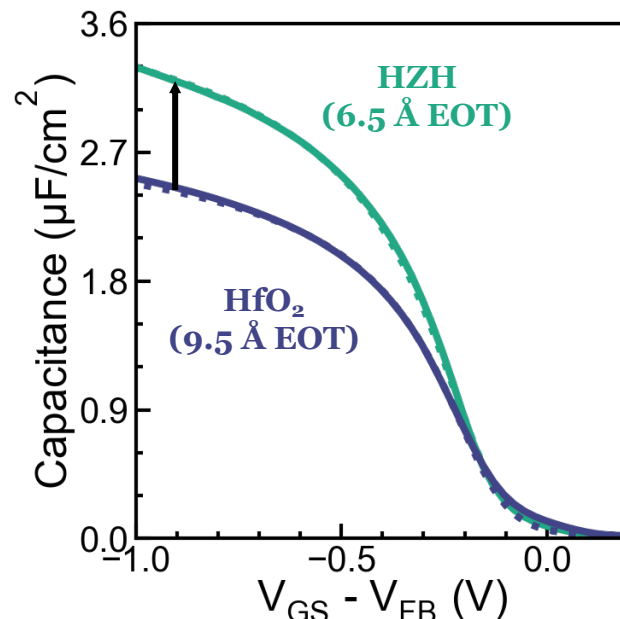
IBM, Intel, imec
T Ando *et al. Materials*
5, 478–500 (2012)

Equivalent Oxide Thickness

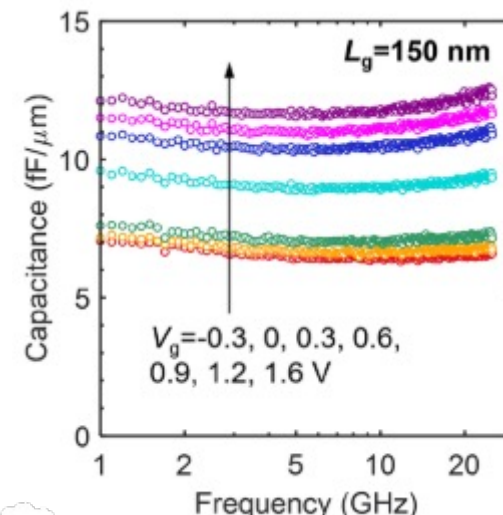
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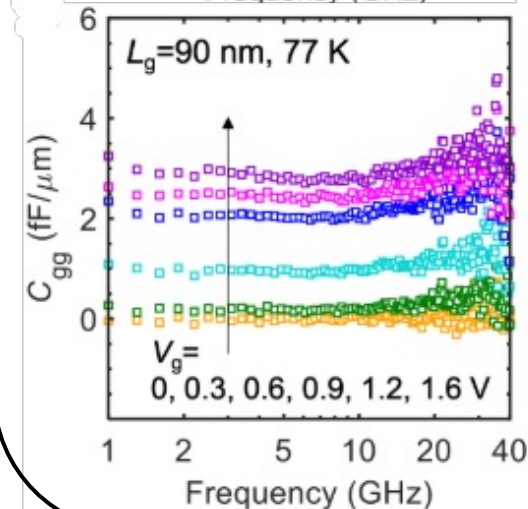
Standard high-κ vs. negative-κ



High Frequency & Low Temperature



RF
Enhanced capacitance persists beyond 20 GHz, no frequency dispersion



Cryo
Enhanced capacitance persists to 77 K, no frequency dispersion

[HZH] Cheema *et al. Ultrathin ferroic superlattice for advanced transistors. Nature* 604, 65 (2022)

[HZH] Cheema *et al. Ultrathin ferroic superlattice for advanced transistors. Nature* 604, 65 (2022)

[HZH] Enhancement in Capacitance and Transconductance with HfO₂-ZrO₂ Superlattice Gate Stack for Energy-efficient Cryo-CMOS. *IEDM* (2022)

Electric Thickness Scaling

Reduce EOT without reducing thickness

Boost in Capacitance

No Leakage Degradation (same tunnel barrier)

High frequency

No speed limits to NC Capacitance Boost

Negative Capacitance for Computing | Comparison to the Semiconductor Industry

Electrical Thickness (EOT) Scaling

THIS WORK NC GATE OXIDE

HKMG GATE STACK

CONVENTIONAL INTERLAYER SCAVENGING

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This Work
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604, 65–71 (2022)

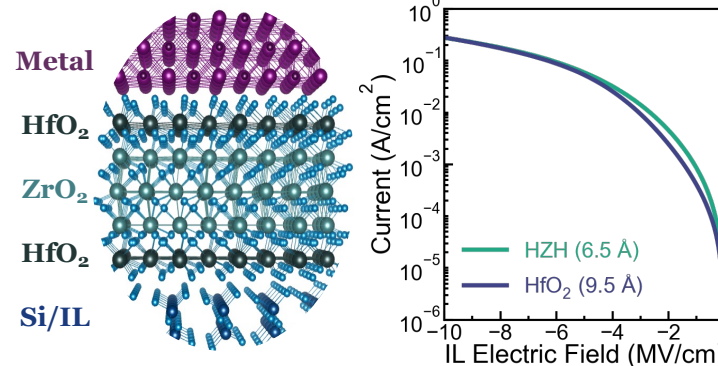
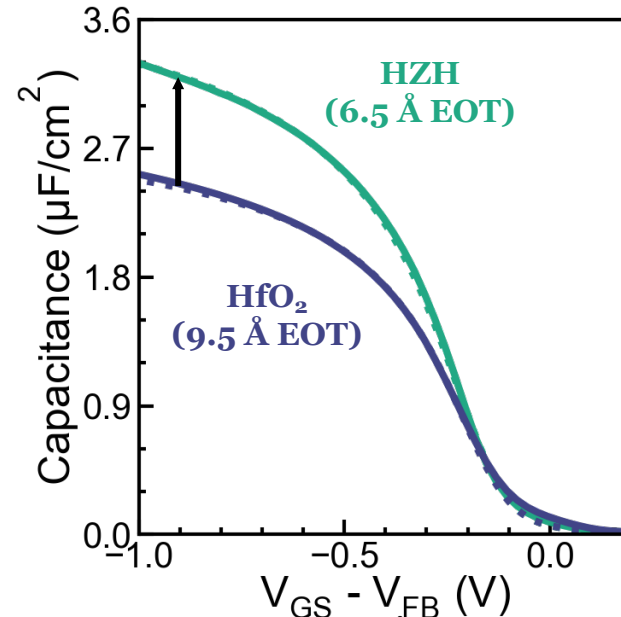
IBM, Intel, imec
T Ando *et al. Materials*
5, 478–500 (2012)

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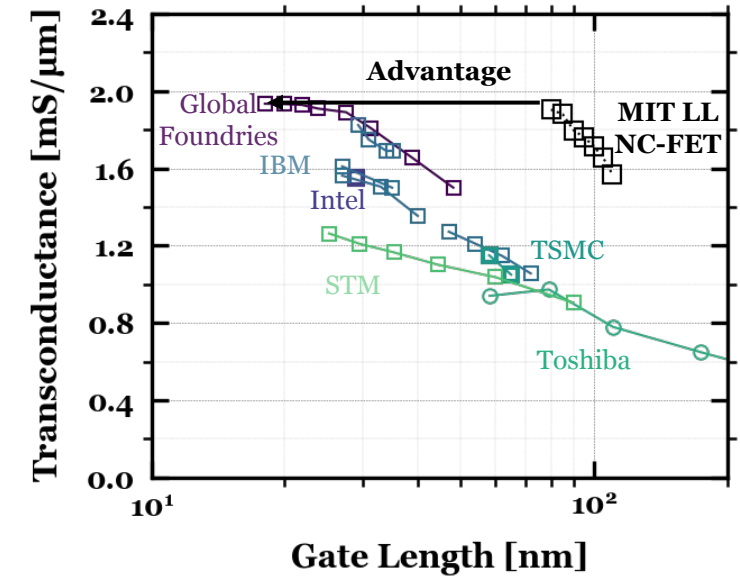
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< 8 Å 8 Å < 0 Å via NC

Standard high-κ vs. negative-κ



MIT Lincoln Lab NC-FETs



NC Transconductance Boost

Increased capacitance without degraded velocity

$$g_m \propto C \cdot v$$

**NC HZH gate oxide integrated into
US Defense Foundry R&D Transistors**

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

[HZH] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors.
Nature 604, 65 (2022)

[HZH] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors.
Nature 604, 65 (2022)

[HZH] Shanker*, Cheema* *et al.* CMOS Demonstration of Negative Capacitance HfO₂-ZrO₂
Superlattice Gate Stack.. *IEDM* (2022)

Electric Thickness Scaling

Reduce EOT without reducing thickness

Boost in Capacitance

No Leakage Degradation (same tunnel barrier)

Lab to Fab

Neg.-κ dielectric translated to foundry

Negative Capacitance for Computing | Comparison to the Semiconductor Industry

Electrical Thickness (EOT) Scaling

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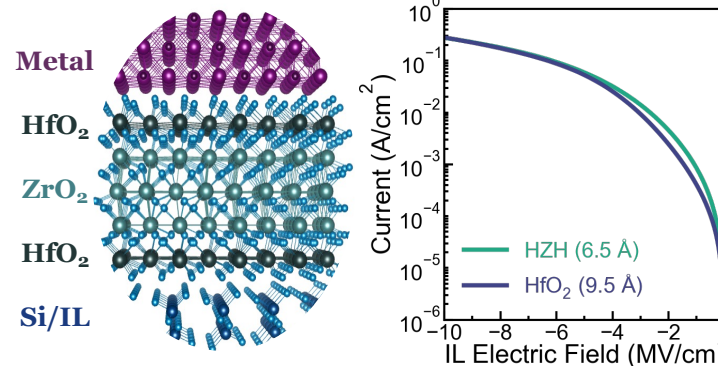
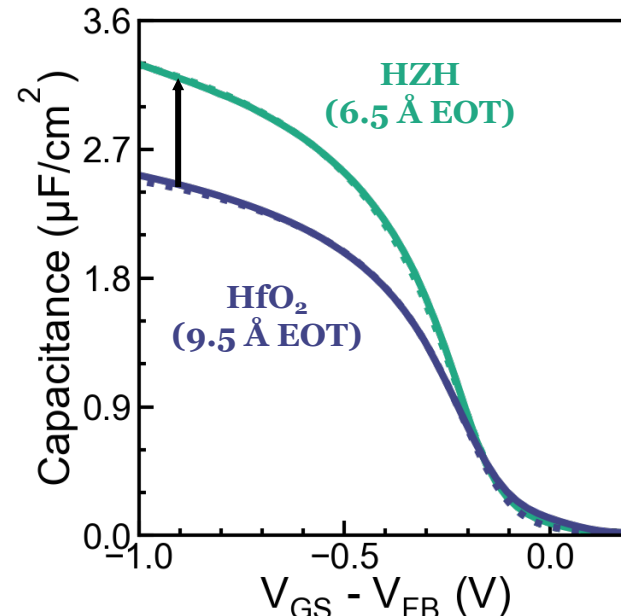
IBM, Intel, imec
T Ando *et al. Materials*
5, 478–500 (2012)

Equivalent Oxide Thickness

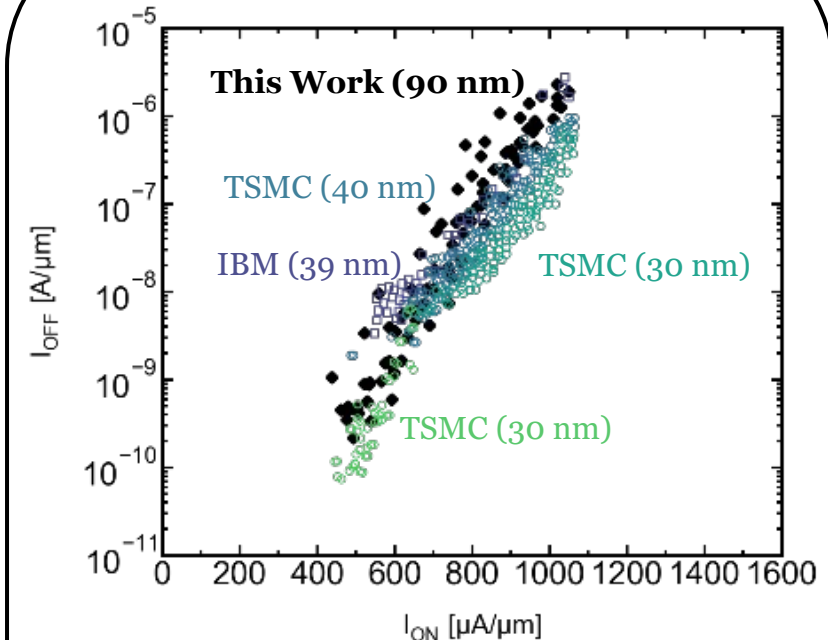
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Standard high-κ vs. negative-κ



MIT Lincoln Lab NC-FETs



NC Current Boost

Increased C (Q) without degraded mobility

$$I_D(V_D) \propto Q_{inv} \cdot \mu \cdot V_D$$

NC HZH gate oxide integrated into
US Defense Foundry R&D Transistors

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Superlattice Gate Stack.. *IEDM* (2022)

Electric Thickness Scaling

Reduce EOT without reducing thickness

Boost in Capacitance

No Leakage Degradation (same tunnel barrier)

Lab to Fab

Neg.-κ dielectric translated to foundry

Negative Capacitance for Computing | Comparison to the Semiconductor Industry

Electrical Thickness (EOT) Scaling

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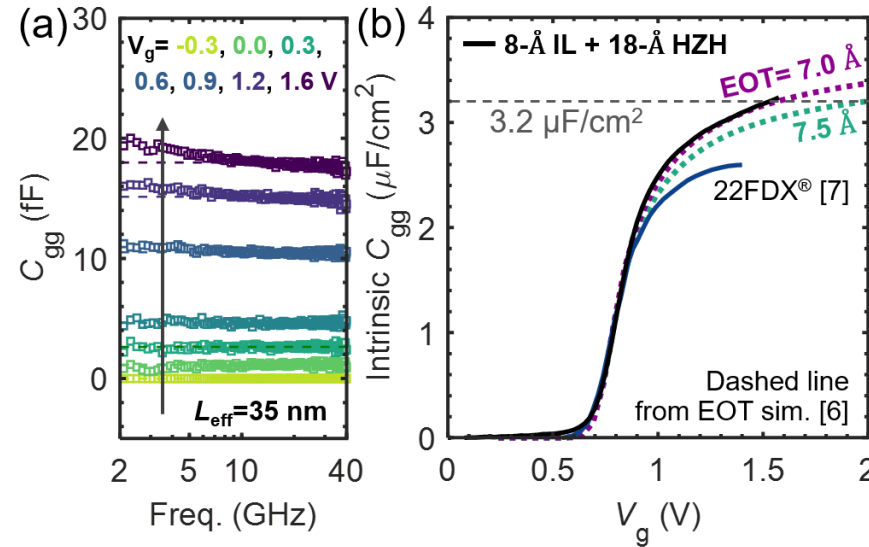
8 Å

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[HfO₂-ZrO₂] Cheema et al. Ultrathin ferroic superlattice for advanced transistors. *Nature* 604, 65 (2022)

Electric Thickness Scaling
Reduce EOT without reducing thickness

30 nm SOI NC-FET (UC Berkeley)

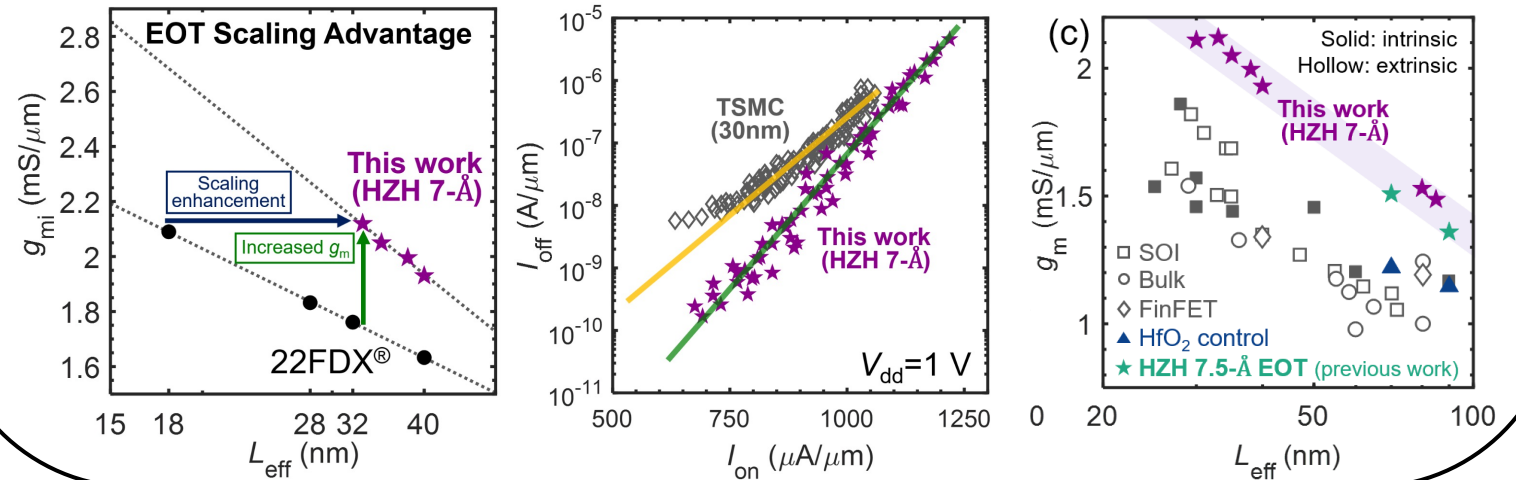


Capacitance Boost Maintained
minimal C_{gg} dispersion to 40 GHz

Significant Scaling Enhancement
vs. GF 22 FDX

Improved Ion/Ioff Performance
vs. TSMC planar-SOI technology

Record gm
NC C_{gg} boost w/o velocity degradation



[HZH] Record Transconductance in $L_{eff} \sim 30$ nm ETSOI nFETs Using Low EOT Negative Capacitance HfO₂-ZrO₂ Superlattice Gate Stack. *VLSI* (2023)

Performance boost from NC gate stack more pronounced in shorter-Lg FETs
How many node enhancements are possible in more advanced transistor geometries?

Negative Capacitance for Computing | Subthreshold Swing

Electrical Thickness (EOT) Scaling

THIS WORK NC GATE OXIDE

HKMG GATE STACK

CONVENTIONAL INTERLAYER SCAVENGING

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This Work
Cheema et al. *Nature*
604, 65–71 (2022)

IBM, Intel, imec
T Ando et al. *Materials*
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Electric Thickness Scaling
Reduce EOT without reducing thickness

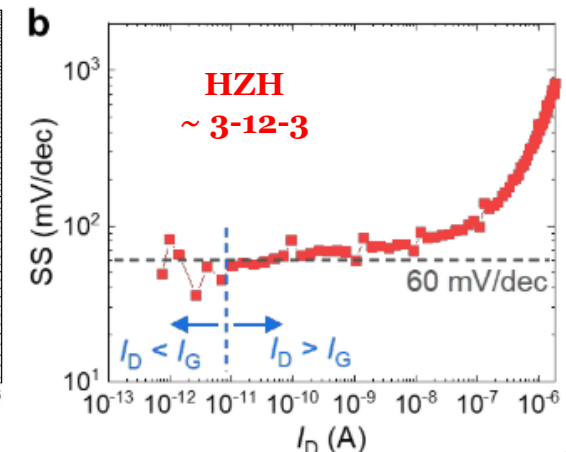
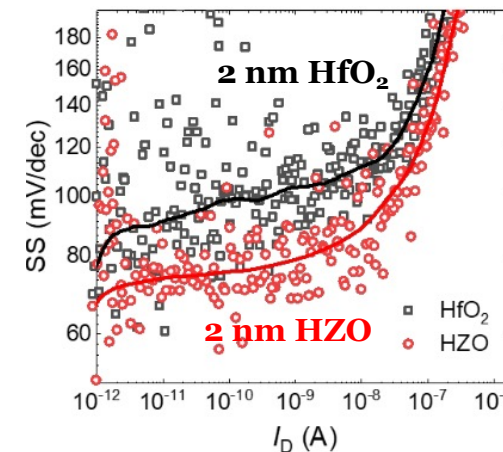
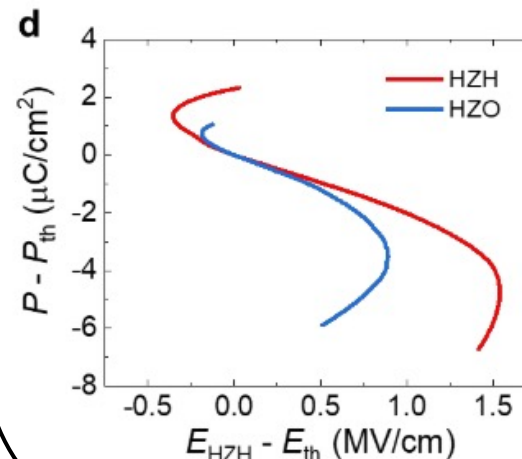
Samsung Electronics NC FinFET

nature electronics

Negative differential capacitance in ultrathin ferroelectric hafnia

Nature Electronics 6, 390–397 (2023)

Sanghyun Jo^{1,6}, Hyangsook Lee^{1,6}, Duk-Hyun Choe¹, Jung-Hwa Kim¹, Yun Seong Lee¹, Owoong Kwon², Seunggeol Nam¹, Yoonsang Park¹, Kihong Kim¹, Byeong Gyu Chae¹, Sangwook Kim¹, Seunghun Kang², Taehwan Moon¹, Hagyoul Bae^{1,3}, Jung Yeon Won¹, Dong-Jin Yun¹, Myoungcho Jeong¹, Hyun Hwi Lee^{1,4}, Yeonchoo Cho¹, Kwang-Hee Lee¹, Hyun Jae Lee¹, Sangjun Lee¹, Kab-Jin Nam⁵, Dongjin Jung⁵, Bong Jin Kuh⁵, Daewon Ha⁵, Yongsung Kim¹, Seongjun Park⁵, Yunseok Kim², Eunha Lee¹ & Jinseong Heo¹



S Jo, H Lee, D-H Choe [...] E Lee, J Heo. Negative differential capacitance in ultrathin ferroelectric hafnia. *Nat. Electron.* 6, 390–397 (2023).

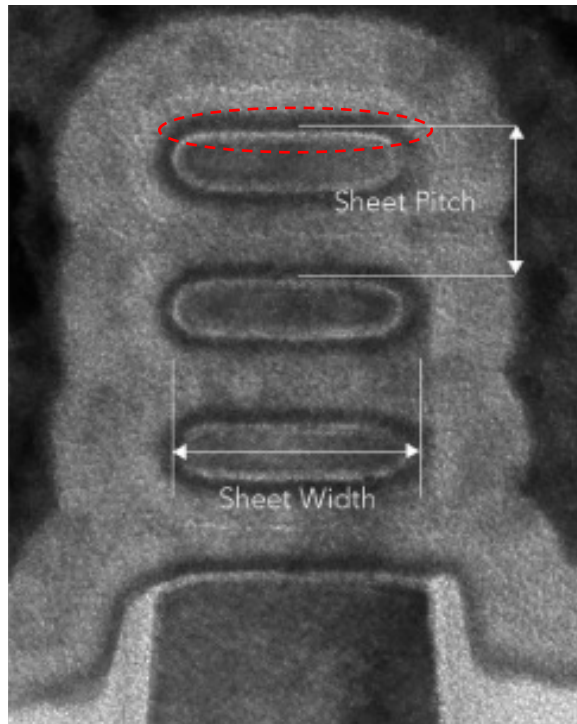
Negative Capacitance confirmed in HZH stack integrated into FinFET Technology
Enhanced NC effect compared to conventional HZO

Negative Capacitance for Computing | Scaling Down Thickness

Thickness Scaling

Next Generation Transistors

< 1.5 nm for gate oxide
(including SiO₂ interlayer)

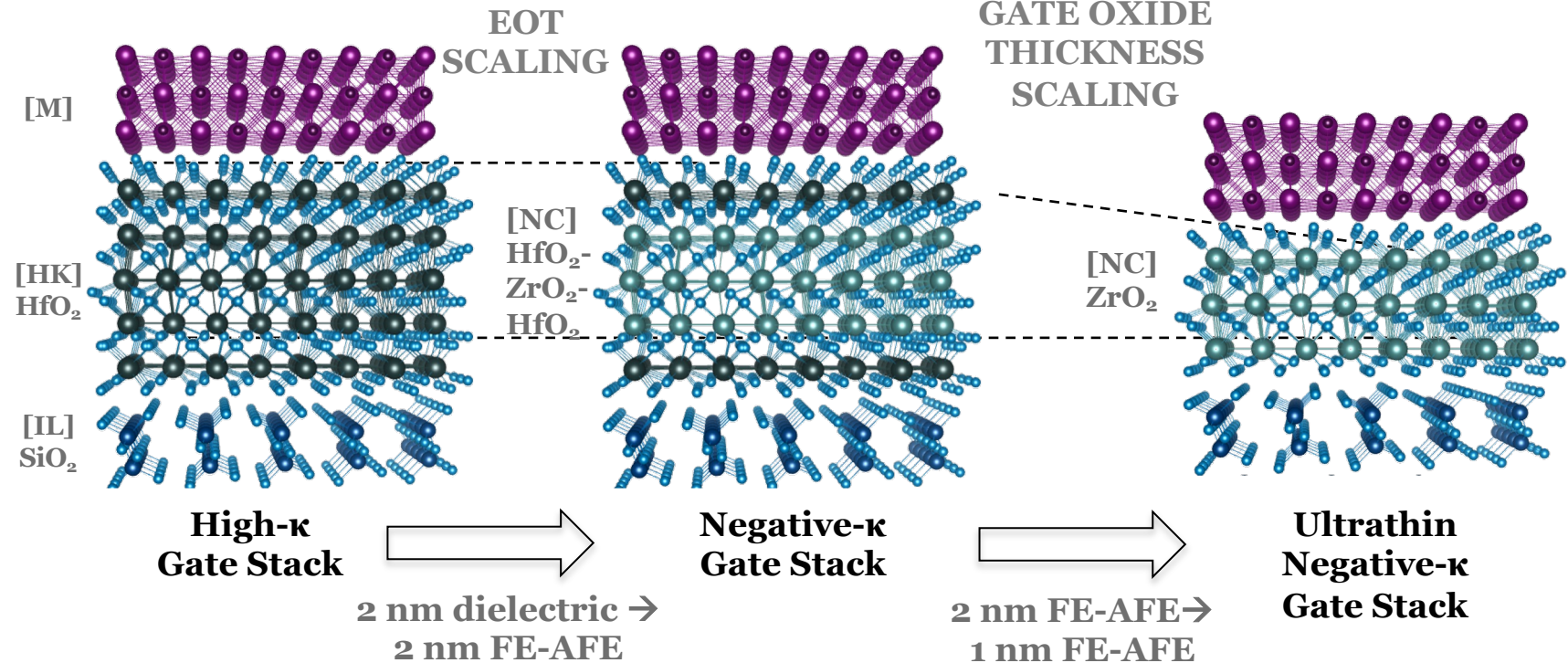


Nanosheet Logic Transistor
Samsung GAA FET

Power & Dimensionality Scaling

POWER SCALING
Ultralow EOT without
transport degradation

DIMENSIONAL SCALING
Ultrathin Ferroelectric
NC Gate Oxide



[HfO₂-ZrO₂] Cheema *et al.* Ultrathin HfO₂-ZrO₂ ferroic superlattice for advanced transistors. *Nature* 604, 65 (2022).

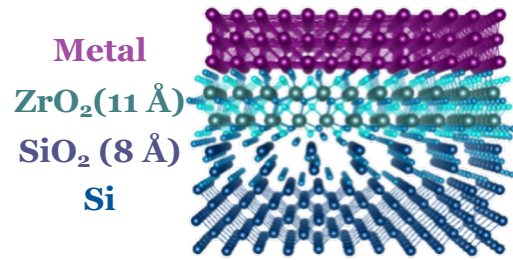
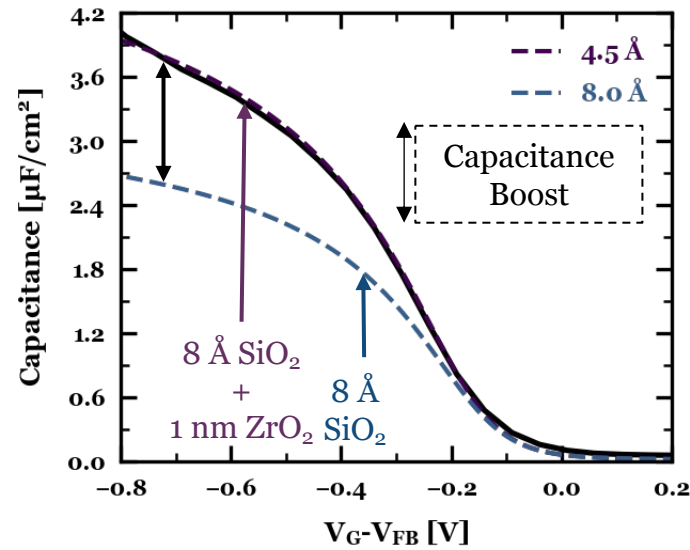
[ZrO₂] Cheema *et al.* Ultralow electrical thickness via one nanometer negative capacitance. (2024)

ZrO₂: Ideal Candidate for scaling down NC gate oxide thickness

Sub-nanometer thickness ferroelectricity & competing ferroelectric-antiferroelectric ground states

Negative Capacitance for Computing | Scaling Down Thickness

Thickness Scaling



Equivalent Oxide Thickness

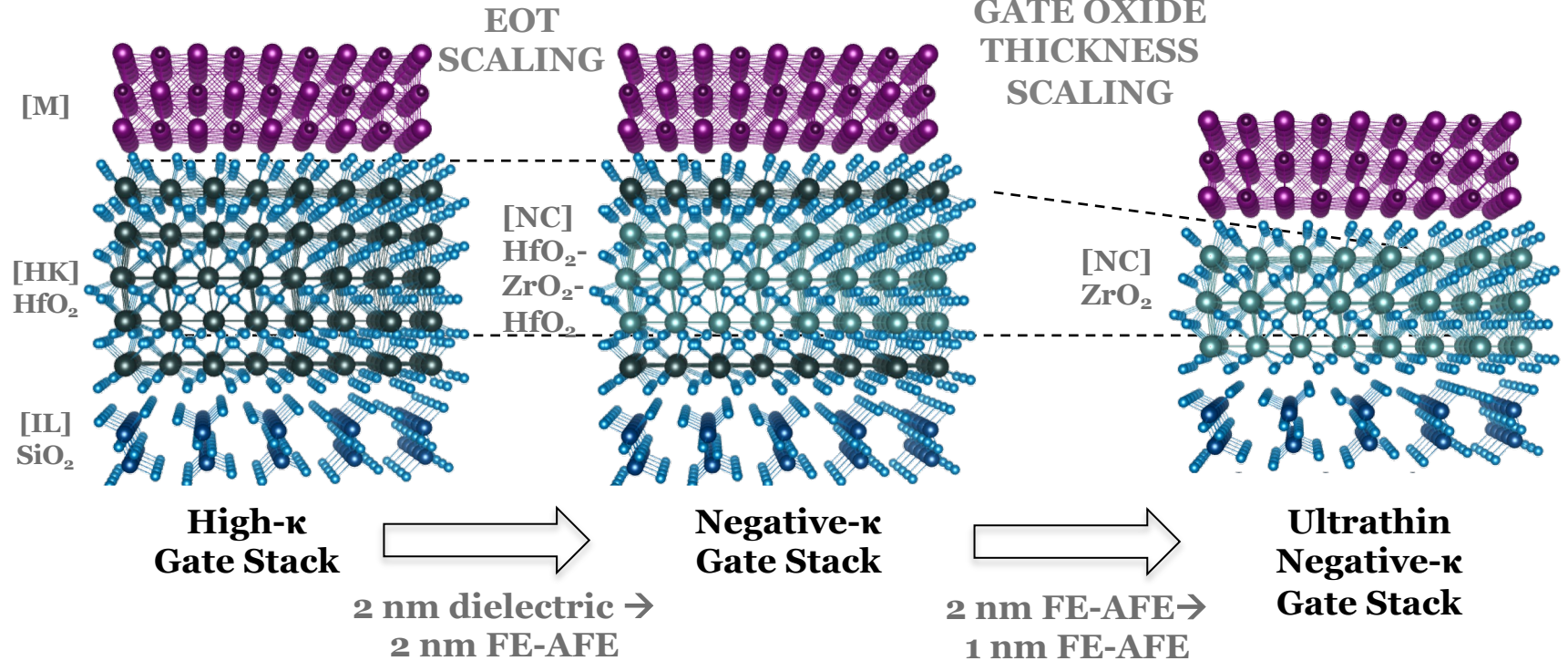
$$EOT = t_{SiO_2} + \frac{\epsilon_{SiO_2}}{\epsilon_{HK}} t_{HK}$$

$< 8 \text{ \AA}$ $8 \text{ \AA}$ $< 0 \text{ \AA}$ via NC

Power & Dimensionality Scaling

POWER SCALING
Ultralow EOT without transport degradation

DIMENSIONAL SCALING
Ultrathin Ferroelectric NC Gate Oxide



[HfO_2 - ZrO_2] Cheema *et al.* Ultrathin HfO_2 - ZrO_2 ferroic superlattice for advanced transistors. *Nature* 604, 65 (2022).

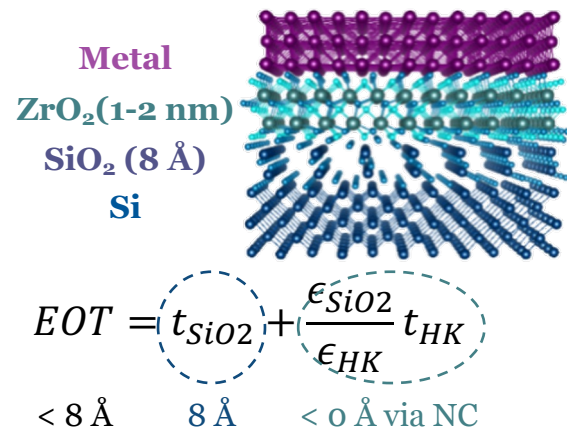
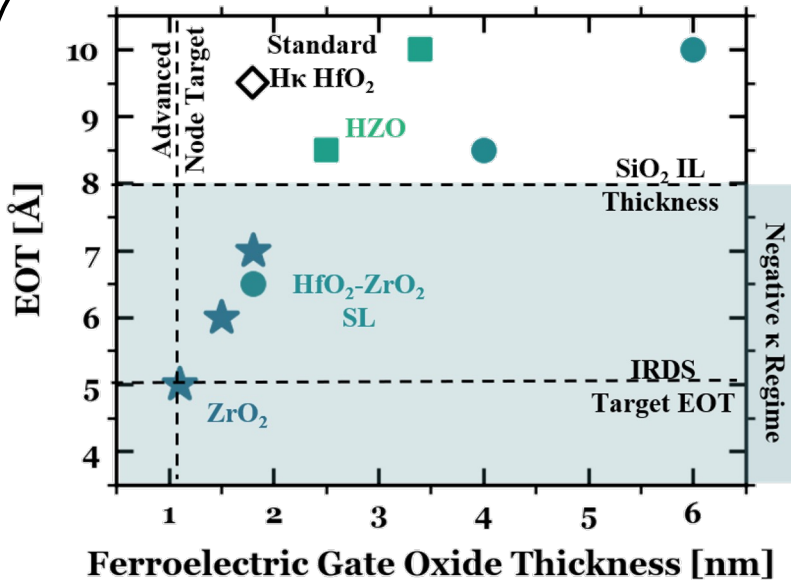
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Sub-nanometer thickness ferroelectricity & competing ferroelectric-antiferroelectric ground states

Negative Capacitance for Computing | Scaling Down Thickness

EOT-Thickness Scaling



Cheema *et al.* "Ultralow equivalent oxide thickness via one nanometer ferroelectric negative capacitance." *In preparation* (2023).

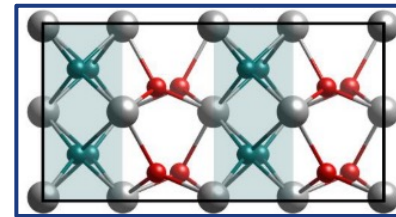
NC effect stronger with decreasing size
Like "negative" ferroelectric size effects

Domain Walls

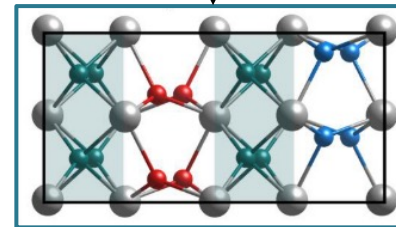
Unique nature of fluorite-structure FE
Zero (negative) DW formation energy (g_{44}) →
No cost (favored) for system to break into DWs

Polar Orthorhombic Pca2₁

$E = 0 \text{ meV/f.u.}$



Negative DW Energy



Antipolar Orthorhombic Pbca

$E = -12 \text{ meV/f.u.}$

Dipoles persist to half-unit cell widths

Lee *et al.* "Scale-free ferroelectricity induced by flat phonon bands in HfO₂." *Science* 369, 1343 (2020)

Negative domain wall energy
Enables NC effect to scale down

Microscopic Picture

LLK scaling law

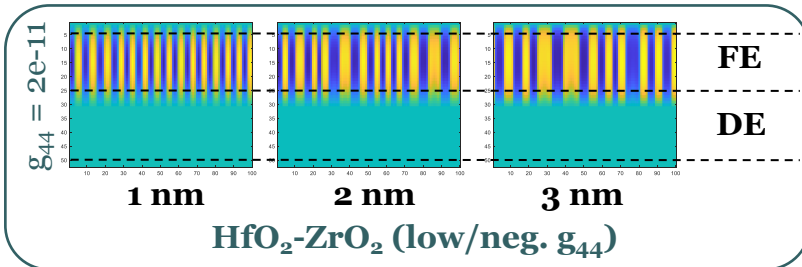
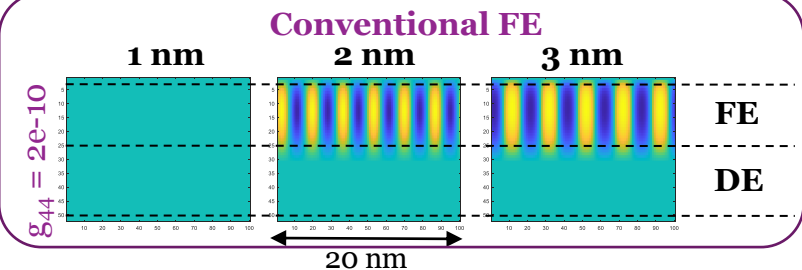
d : domain width

g_{44} : domain coupling constant

$$d \propto \sqrt{g_{44} t_{FE}}$$

↑ DW density (NC pockets) with ↓ FE thickness

Simplified 2D Electrostatic Model



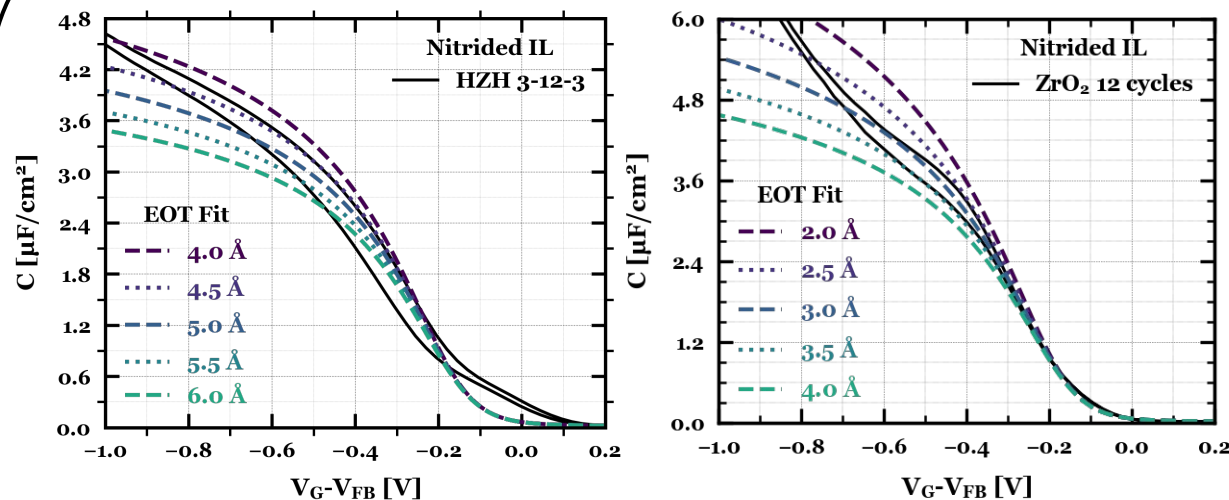
Synchrotron PEEM & Plan-view TEM
Narrower domains with ↓ ZrO₂ thickness

Cheema *et al.* "Ultralow equivalent oxide thickness via one nanometer ferroelectric negative capacitance." (2024)

Domain walls persist to ultrathin limit
Unique to HfO₂-ZrO₂ ferroelectric system

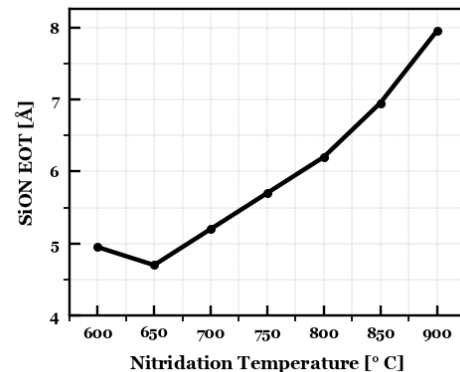
Negative Capacitance for Computing | Interlayer Engineering

Higher- κ SiON Interlayer



18 cycles HZH
on Chemical SiO_2 : ~ 6.5 Å EOT
on Thermal SiON : ~ 4.5 Å EOT

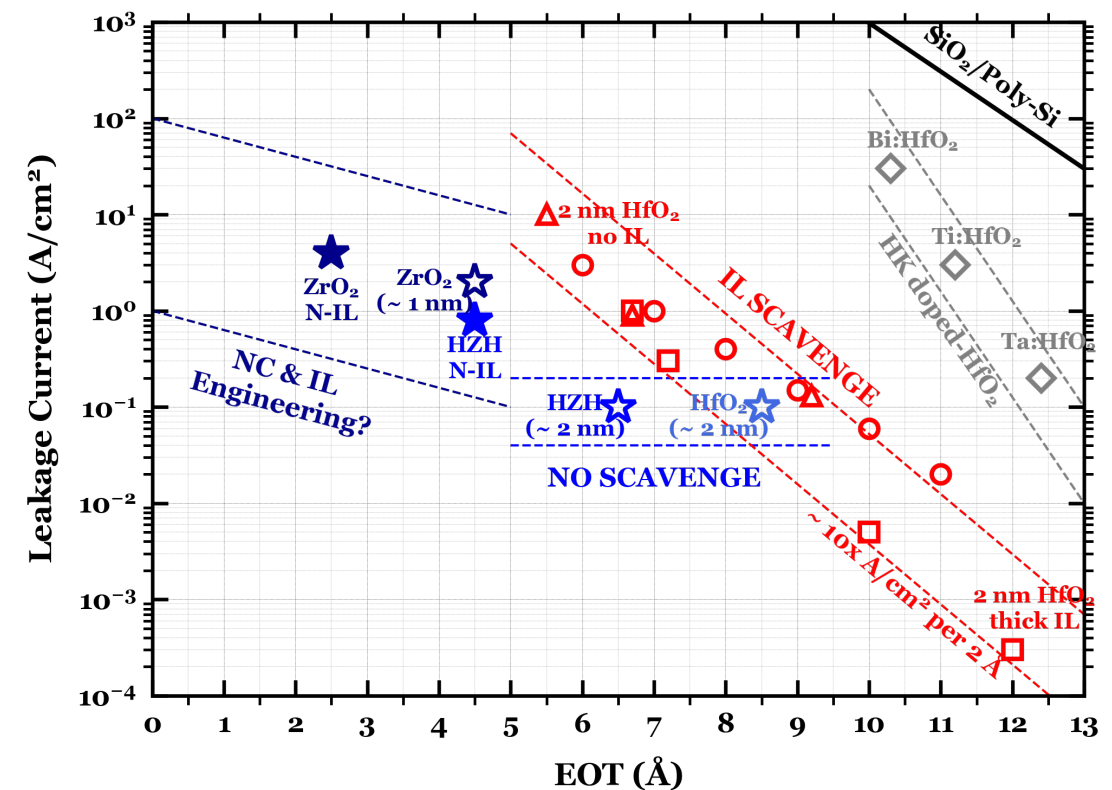
12 cycles ZrO_2
on Chemical SiO_2 : ~ 5.0 Å EOT
on Thermal SiON : ~ 2.5 Å EOT



Cheema *et al.* Unpublished.

NC Gate Stack + Higher- κ Interlayer
Gate stack maintains NC behavior on SiON IL

Extreme EOT Scaling



Intermediate EOTs possible as well
via controlled RTA temperature during nitridation process

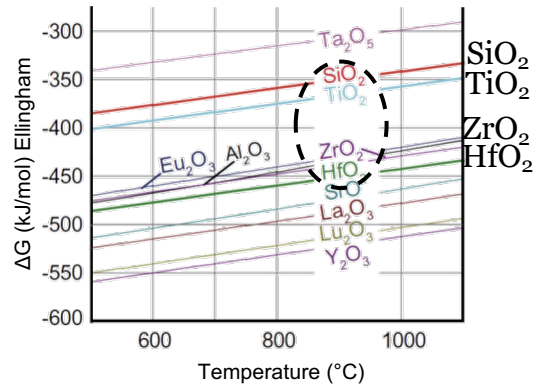
Cheema *et al.* Unpublished.

Sub-5 Å EOT Possible with NC Gate Stack & IL Engineering
Further examine performance in this unexplored EOT space

Negative Capacitance for Computing | Interlayer Engineering

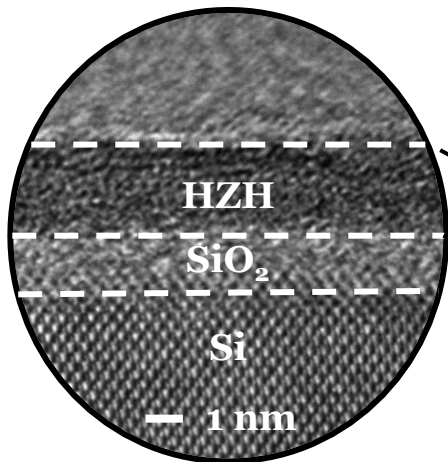
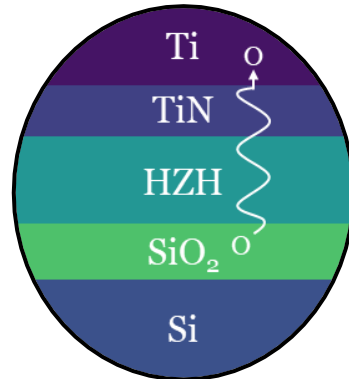
Atomic Layer “Deletion”

Ellingham Diagram

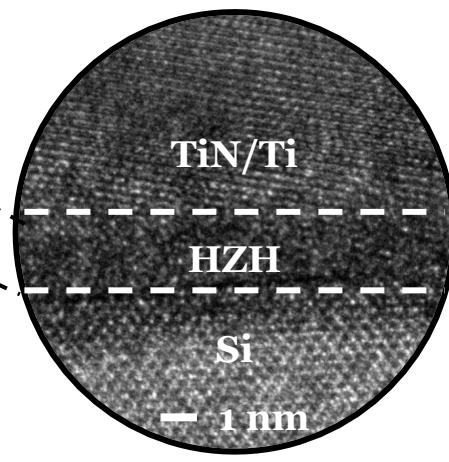


A Nichau *et al.* Microelectron. Eng. 109, 109–112 (2013).

Oxygen Diffusion



SiO₂ Interlayer Present

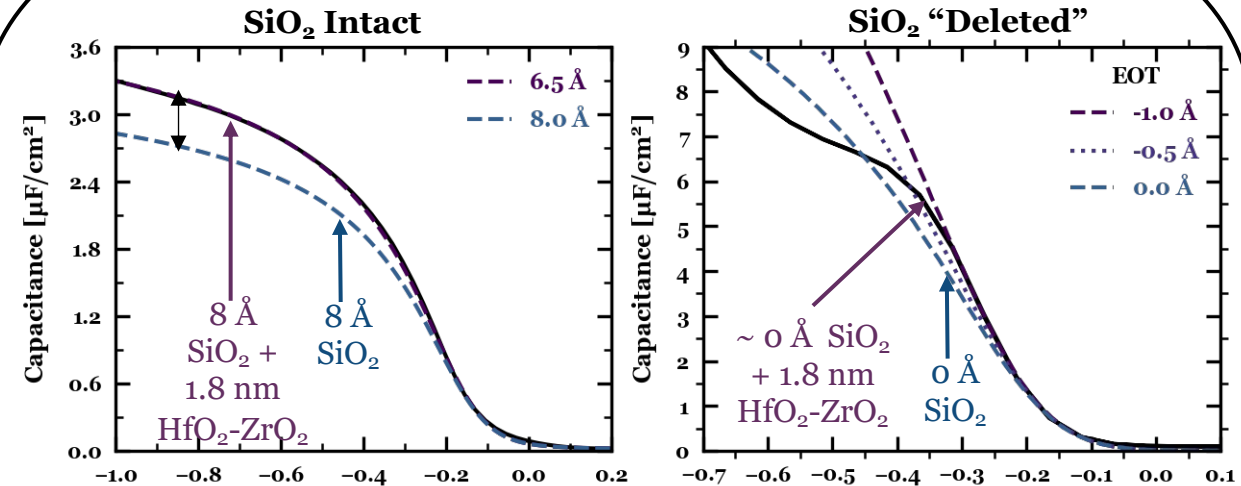


SiO₂ Interlayer “Deleted”

[HfO₂-ZrO₂] Cheema *et al.* Negative electrical thickness via negative capacitance. (2024)

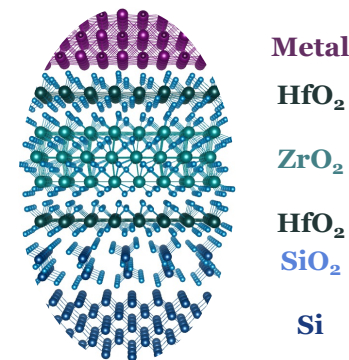
Reducing oxide interlayers remotely
Exploiting free energy of oxygen formation

MOS Capacitors



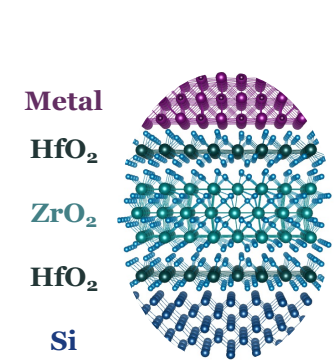
$$EOT = t_{SiO_2} + \frac{\epsilon_{SiO_2}}{\epsilon_{HK}} t_{HK}$$

< 8 Å 8 Å < 0 Å via NC



$$EOT = t_{SiO_2} + \frac{\epsilon_{SiO_2}}{\epsilon_{HK}} t_{HK}$$

< 0 Å 0 Å < 0 Å via NC



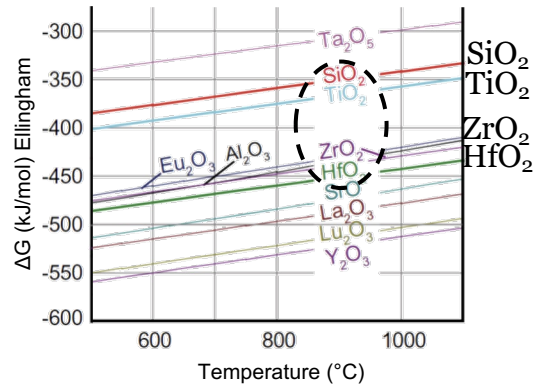
[HfO₂-ZrO₂] Cheema *et al.* Negative electrical thickness via negative capacitance. (2024)

Negative EOT possible!
Neg.-κ dielectric in direct contact with Si, not dielectric

Negative Capacitance for Computing | Interlayer Engineering

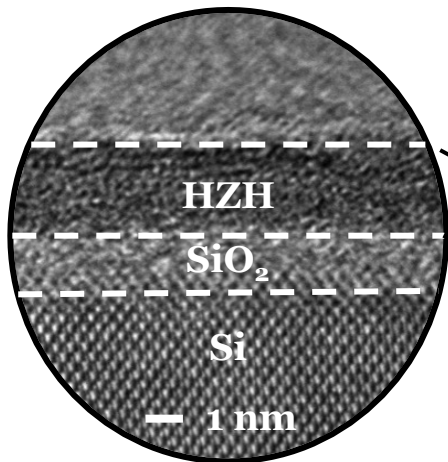
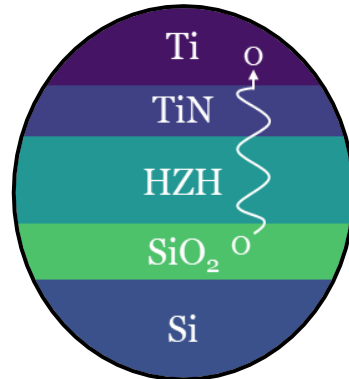
Atomic Layer “Deletion”

Ellingham Diagram

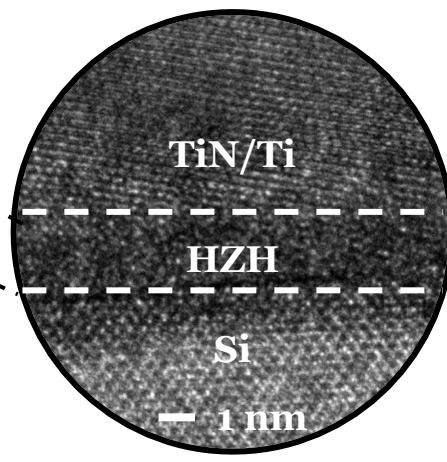


A Nichau *et al.* Microelectron. Eng. 109, 109–112 (2013).

Oxygen Diffusion



SiO₂ Interlayer Present

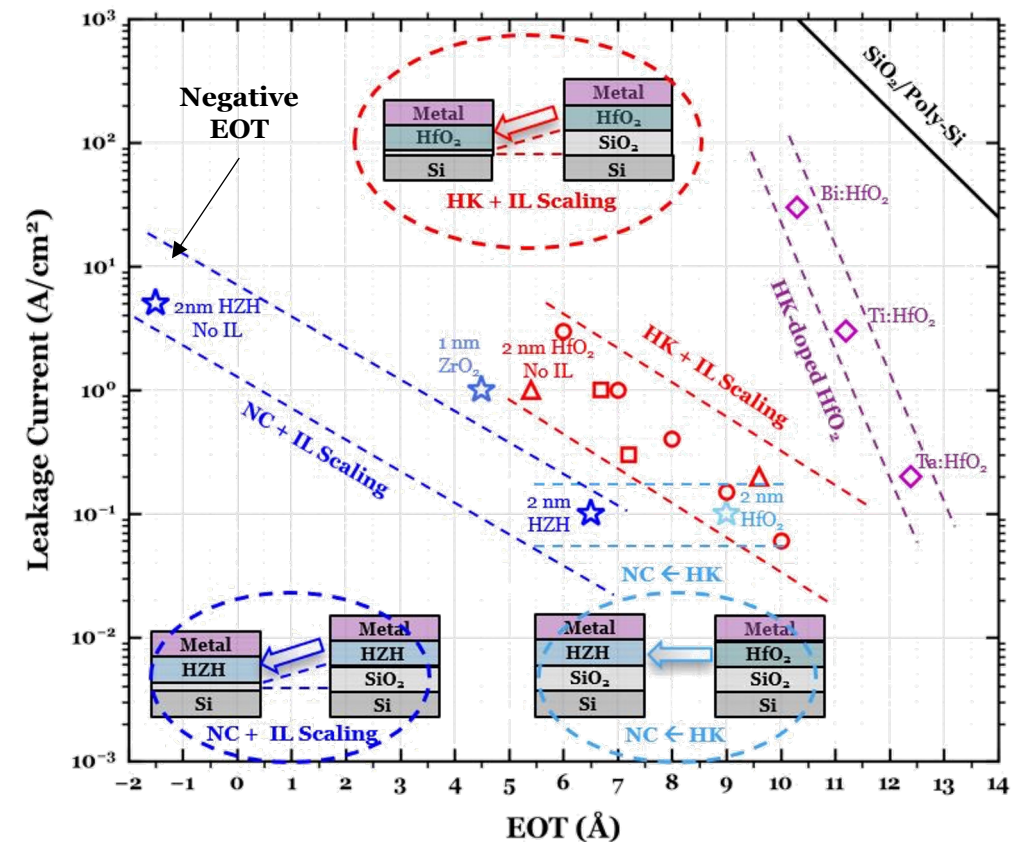


SiO₂ Interlayer “Deleted”

[HfO₂-ZrO₂] Cheema *et al.* Negative electrical thickness via negative capacitance. (2024)

Reducing oxide interlayers remotely
Exploiting free energy of oxygen formation

Negative Electrical Thickness



Intermediate EOTs (5 Å → -1 Å) possible as well
via partial scavenging (tune TiN barrier thickness & scavenging temperature)

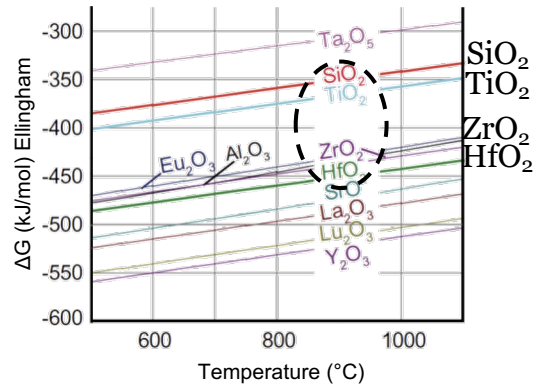
[HfO₂-ZrO₂] Cheema *et al.* Negative electrical thickness via negative capacitance. (2024)

Negative EOT
Further examine performance in this unexplored EOT space

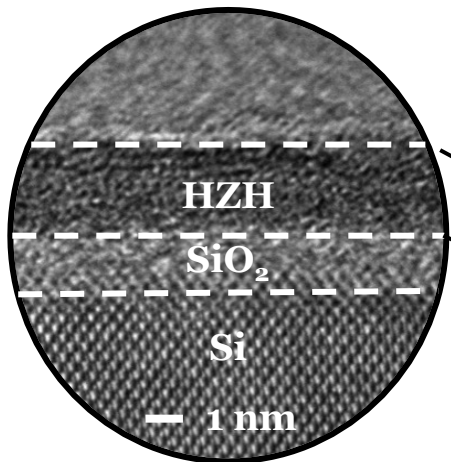
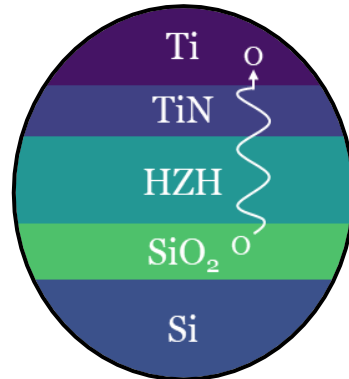
Negative Capacitance for Computing | Interlayer Engineering

Atomic Layer “Deletion”

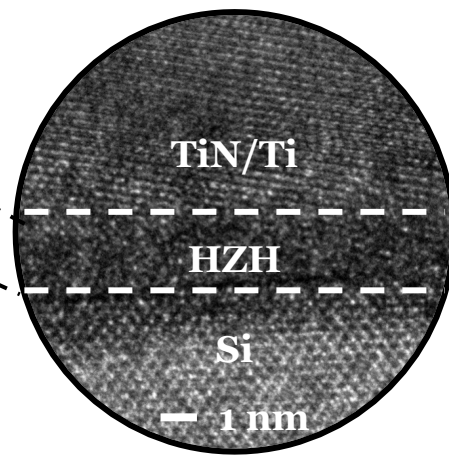
Ellingham Diagram



Oxygen Diffusion



SiO₂ Interlayer Present

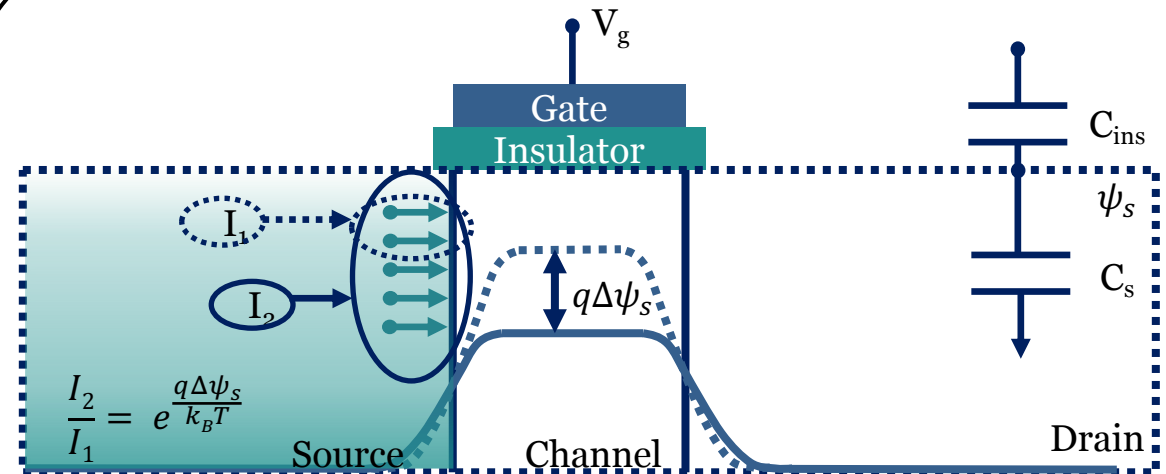


SiO₂ Interlayer “Deleted”

[HfO₂-ZrO₂] Cheema *et al.* Negative electrical thickness via negative capacitance. (2024)

Reducing oxide interlayers remotely
Exploiting free energy of oxygen formation

Overcoming Boltzmann’s Tyranny



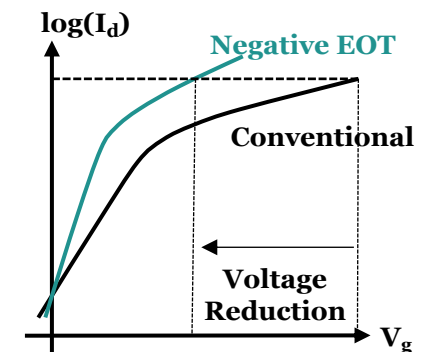
Subthreshold Swing (S)

$$S = \frac{\partial V_g}{\partial \log_{10} I_D} = \left(\frac{\partial V_g}{\partial \psi_s} \right) \left(\frac{\partial \psi_s}{\partial \log_{10} I_D} \right)$$

$$\frac{\partial \psi_s}{\partial \log_{10} I_D} = \frac{k_B T}{q} \ln(10) = 60 \frac{mV}{dec} @ 300 K$$

$$\frac{\partial V_g}{\partial \psi_s} = \frac{C_{ins} + C_s}{C_{ins}} = 1 + \frac{C_s}{C_{ins}}$$

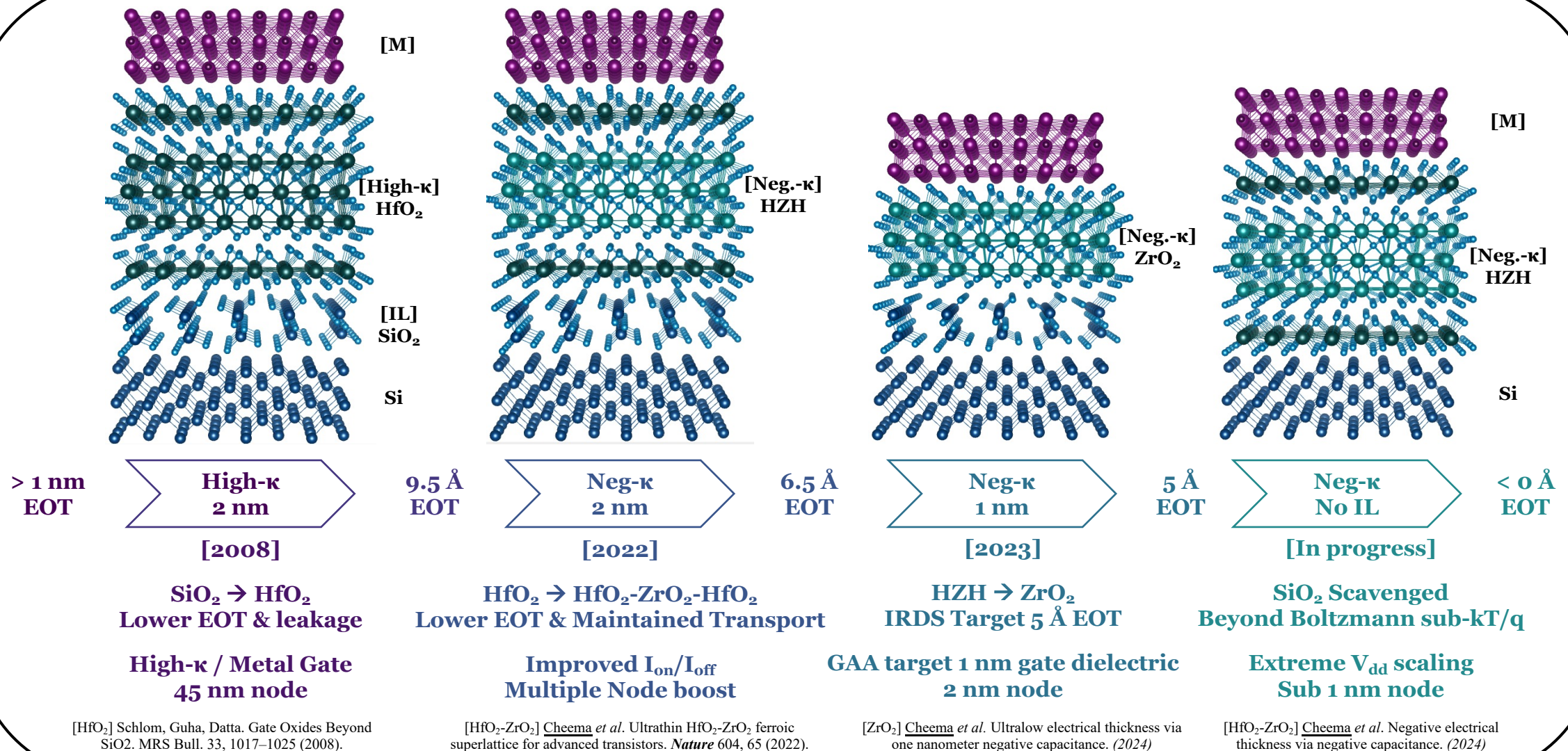
$$\frac{\partial V_g}{\partial \psi_s} < 1 \text{ if } C_{ins} < 0$$



Salahuddin & Datta. Negative Capacitance to Provide Voltage Amplification for Low Power Nanoscale Devices. *Nano Lett.* **8**, 405–410 (2008)

Negative EOT: Voltage amplification of Si surface potential
Can overcome fundamental thermodynamic limits

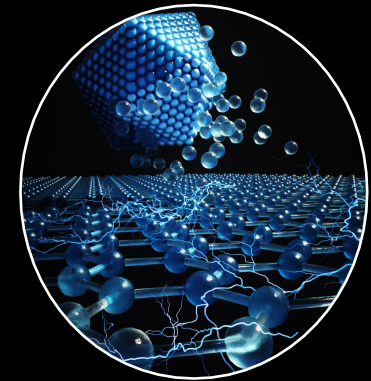
Negative Capacitance for Computing | EOT Scaling Roadmap



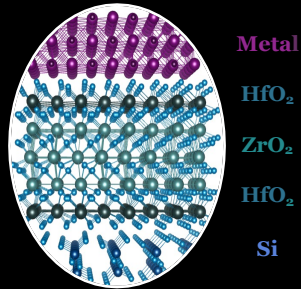
More Moore: From High- κ Dielectrics to Negative- κ Gate Ferroelectrics

Future Gate Stack Studies: In-situ plasma, annealing (laser, high-T), new ferroic origins, DW engineering, IL engineering
 Future NC Integration: FEOL nanosheet FETs, BEOL Oxide FETs

Ferroelectrics | A Novel Platform for Computing & Energy Technologies

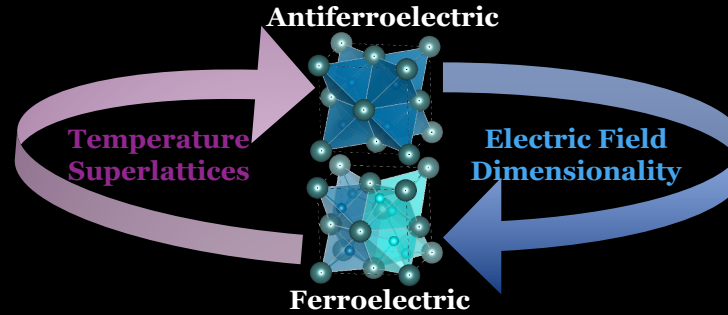


Atomic Layer
Synthesis

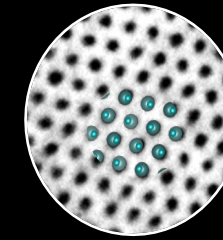


Stacking-dependent
Sub-Unit Cell Superlattices

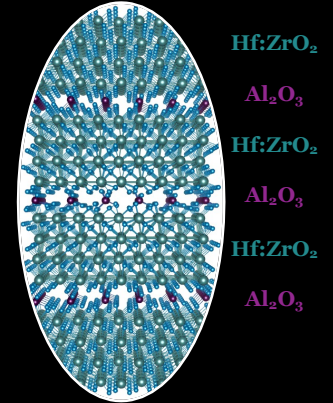
Ferroelectrics: Building Blocks
competing polar-nonpolar crystal structures
platform for emergent (negative) electronic phenomena



[HfO₂] Cheema *et al.* Enhanced ferroelectricity in ultrathin films grown directly on silicon. *Nature* (2020).
[ZrO₂] Cheema *et al.* Emergent ferroelectricity in sub-nanometer binary oxide films on silicon. *Science* (2022).

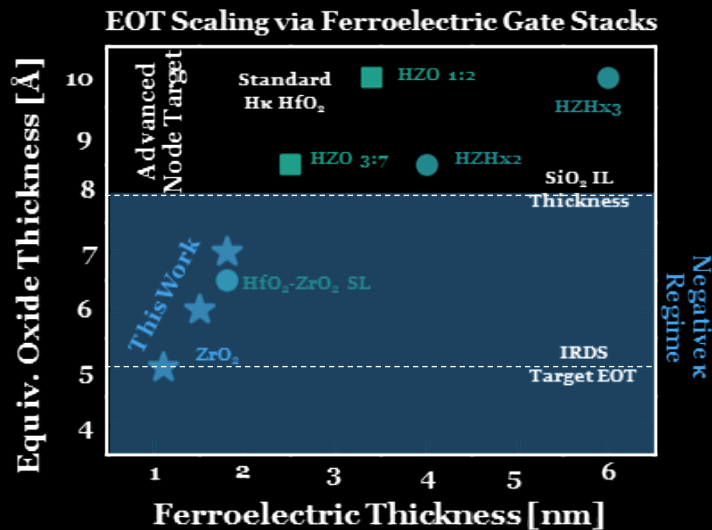


Crystal Symmetry
Manipulation



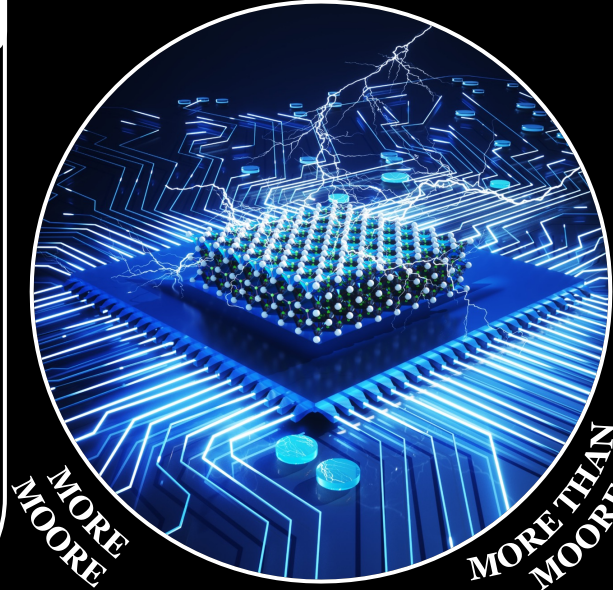
Crystalline-Amorphous
Superlattices

Ferroelectrics: New paradigm for Logic & Memory
high- κ dielectrics $\rightarrow$ negative- κ ferroelectrics
defective $\rightarrow$ collective switching



[HfO₂-ZrO₂] Cheema *et al.* Ultrathin ferroic superlattice for advanced transistors. *Nature* (2022).
[ZrO₂] Cheema *et al.* Ultralow electrical thickness via one nanometer negative capacitance. (2024)

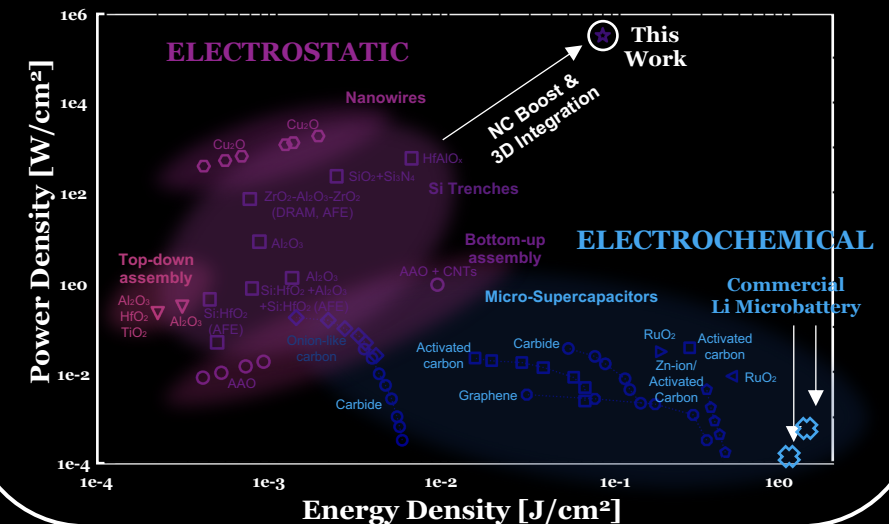
FERRO-ELECTRONICS



MORE
MOORE

MORE THAN
MOORE

Ferroelectrics: New paradigm for Energy Tech
electrochemical $\rightarrow$ electrostatic energy storage
thermoelectric $\rightarrow$ pyroelectric energy harvesting

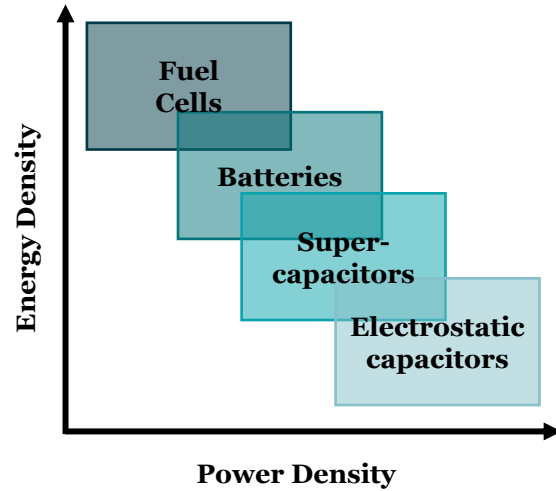


[ZrO₂-Al₂O₃] Cheema *et al.* Giant energy storage & power density neg. capacitance superlattices. *Nature* (2024)

Negative Capacitance for Energy Storage | Overcoming Traditional Trade-Offs

Energy Storage Considerations

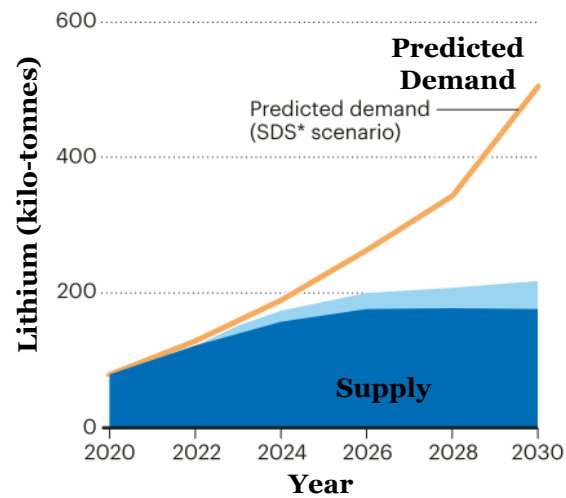
Energy Storage Landscape



Electrostatic storage:
Fast but low energy density
Promising for on-chip integration and miniaturization

Kyeremateng, Brousse, & Pech.
Microsupercapacitors as miniaturized energy-storage components for on-chip electronics.
Nature Nanotechnology 12, 7–15 (2017).

Lithium Supply Gap

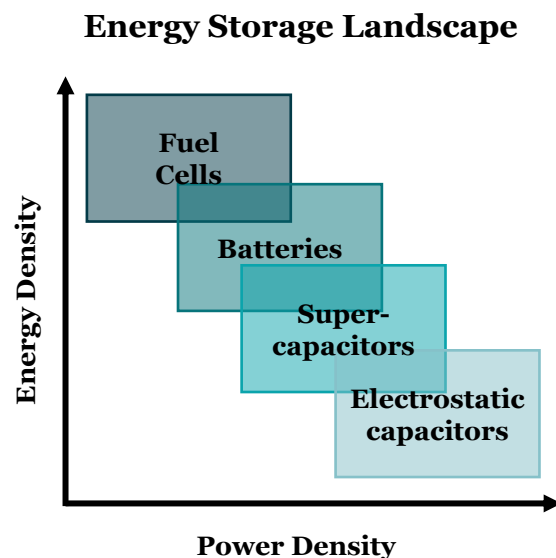


Electrochemical storage:
Sustainability & Lifecycle challenges
Global Li production not sufficient to meet trillion IoT demands

Haddad *et al.*
How to make lithium extraction cleaner, faster and cheaper.
Nature 616, 245–248 (2023).

Negative Capacitance for Energy Storage | Overcoming Traditional Trade-Offs

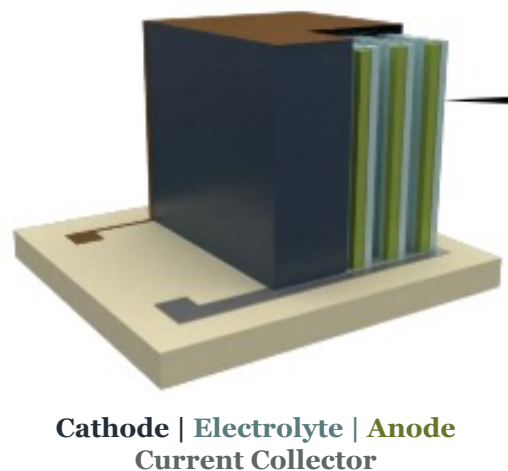
Energy Storage Considerations



Electrostatic storage:
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 Promising for on-chip integration and miniaturization

Kyeremateng, Brousse, & Pech.
 Microsupercapacitors as miniaturized energy-storage components for on-chip electronics.
Nature Nanotechnology 12, 7–15 (2017).

Miniaturization

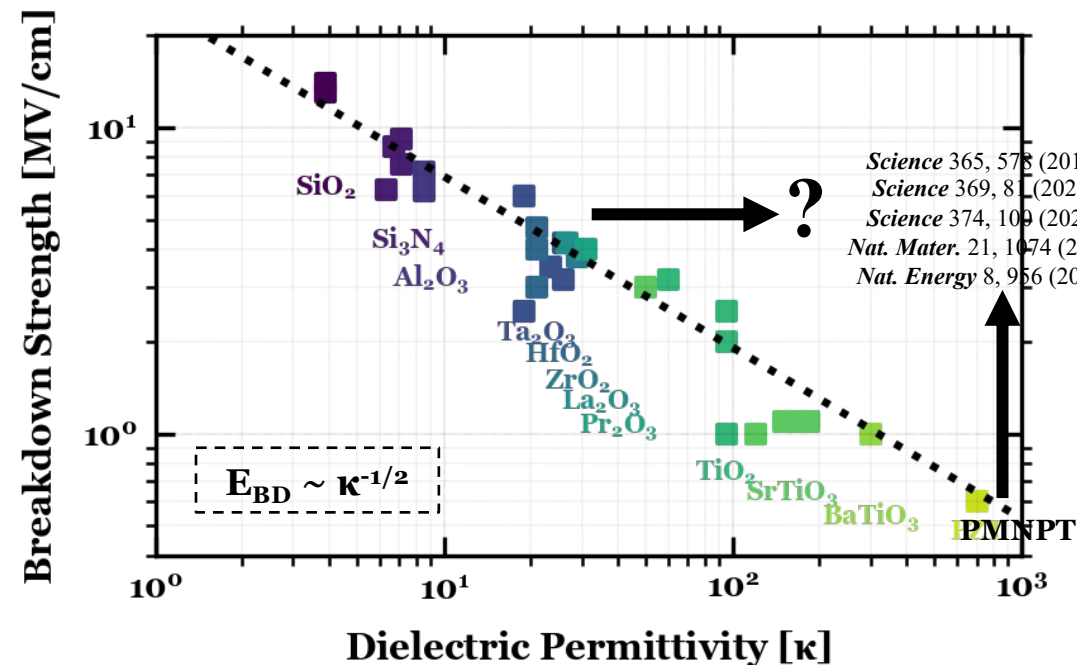


Electrochemical storage:
Size & Integration challenges
 Complex processes incompatible with on-chip integration & scaling

Zhu & Schmidt.
 Tiny robots and sensors need tiny batteries — here's how to do it.
Nature 589, 195–197 (2021).

Speed-Capacity (Energy Density – Power Density) Trade-Off
 How do we overcome this, specifically for miniaturized energy storage?

What's Limiting Electrostatic Energy Storage?



McPherson *et al.* Trends in the ultimate breakdown strength of high dielectric-constant materials.
IEEE Trans. Electron Devices 50, 1771–1778 (2003).

Electrostatic Energy Storage

$$U \sim \frac{1}{2} CV^2 \sim \frac{1}{2} \epsilon_0 \kappa E_{BD}^2$$

$$E_{BD} \sim \kappa^{-1/2}$$

Metal
Ferroelectric
Metal

Permittivity – Breakdown Trade-Off
 Empirical Trend in Dielectrics: No dielectric stands out

Solution: Negative Capacitance
 Increase κ while maintaining E_{BD}

Negative Capacitance for Energy Storage | 10 nm HfO₂-ZrO₂ Composition Series

HfO₂

ZrO₂

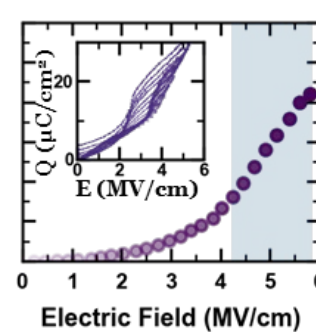
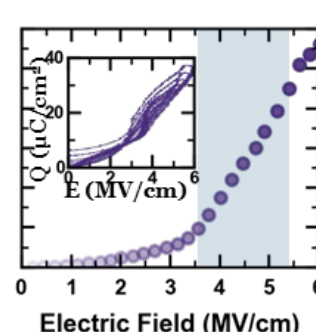
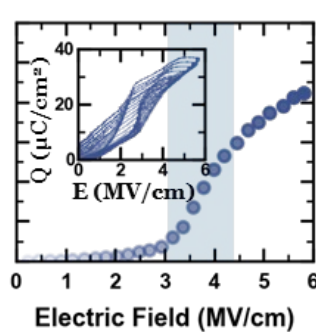
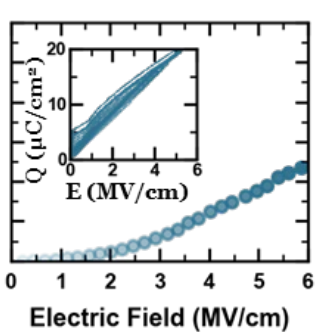
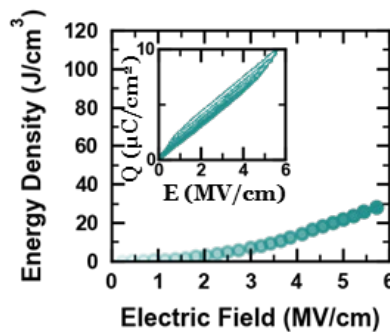
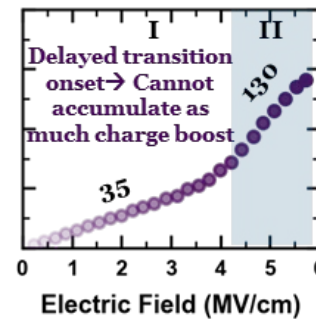
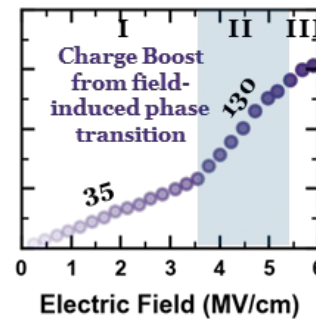
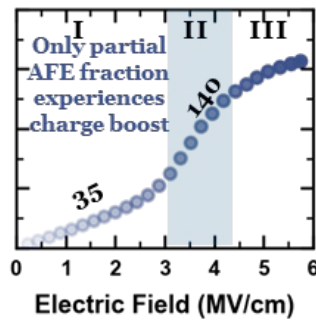
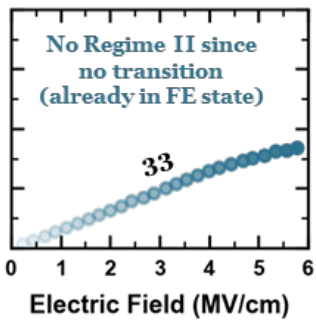
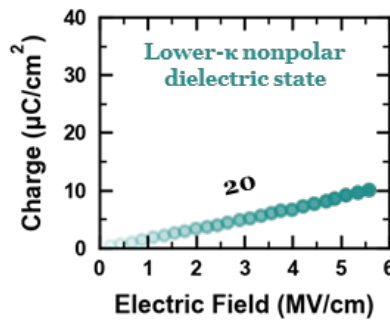
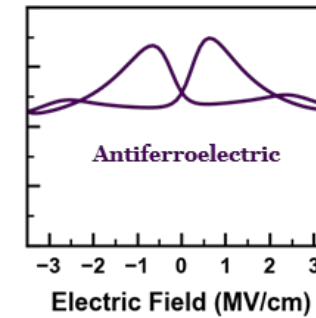
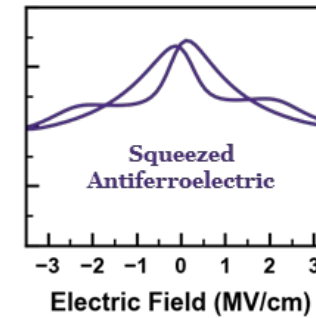
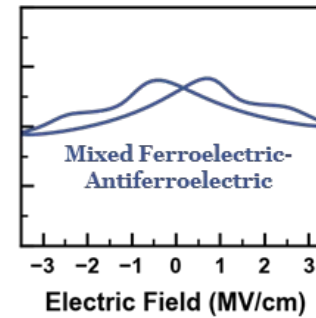
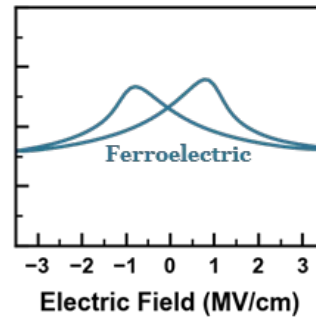
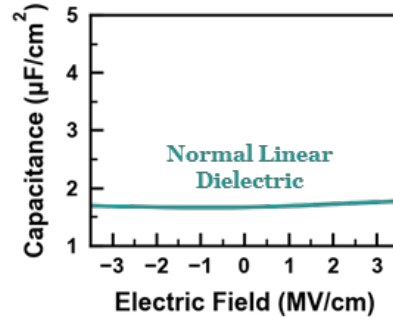
DIELECTRIC
Monoclinic (P2₁/c)

FERROELECTRIC
Orthorhombic (Pca2₁)

MIXED FERROIC
AFE-FE

ANTIFERROELECTRIC
Squeezed

ANTIFERROELECTRIC
Tetragonal (P4₂/nmc)

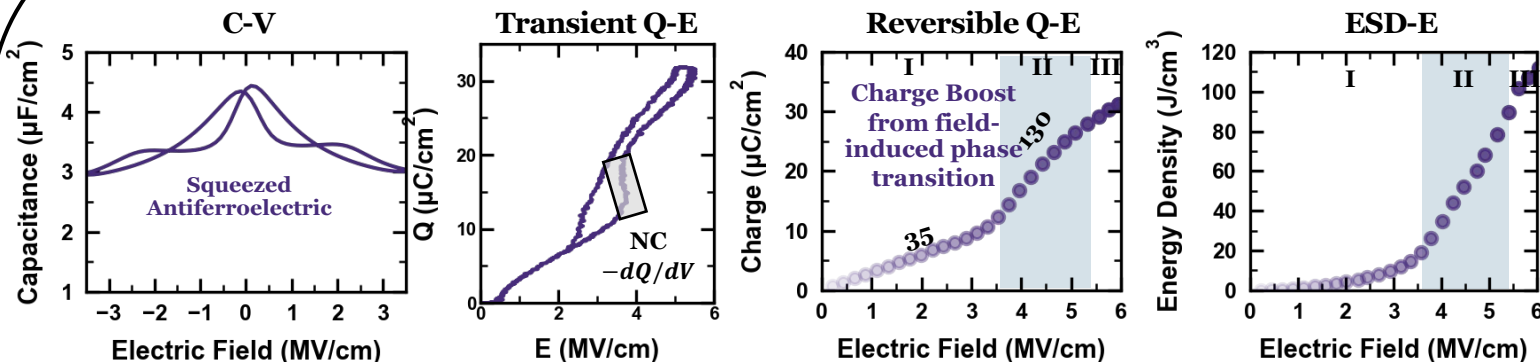


$$ESD = \frac{\int_0^{Q_{max}} V dQ}{A d}$$

Squeezed Antiferroelectric State Best for Energy Storage
What is going on in Regime II? Why better than mixed FE-AFE state?

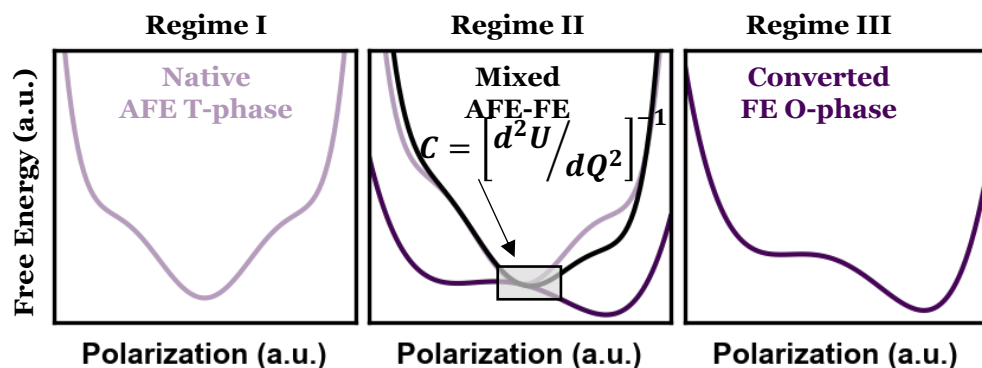
Negative Capacitance for Energy Storage | Overcoming Traditional Trade-Offs

Field-Dependent Evolution of 10 nm Antiferroelectric HZO

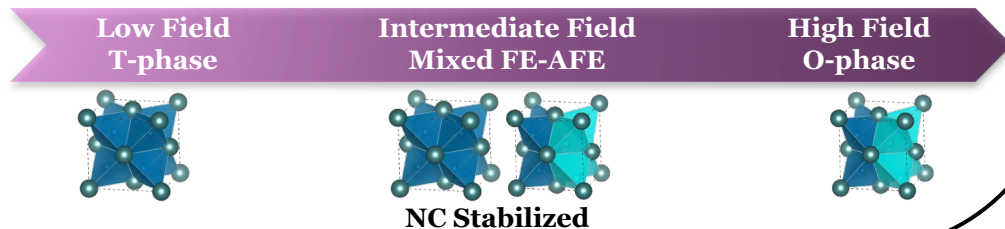


Previous work on NC stabilization via mixed FE-AFE phases

Cheema *et al.* "Ultrathin ferroic HfO₂-ZrO₂ superlattice gate stacks for advanced transistors." *Nature* 604 (2022).

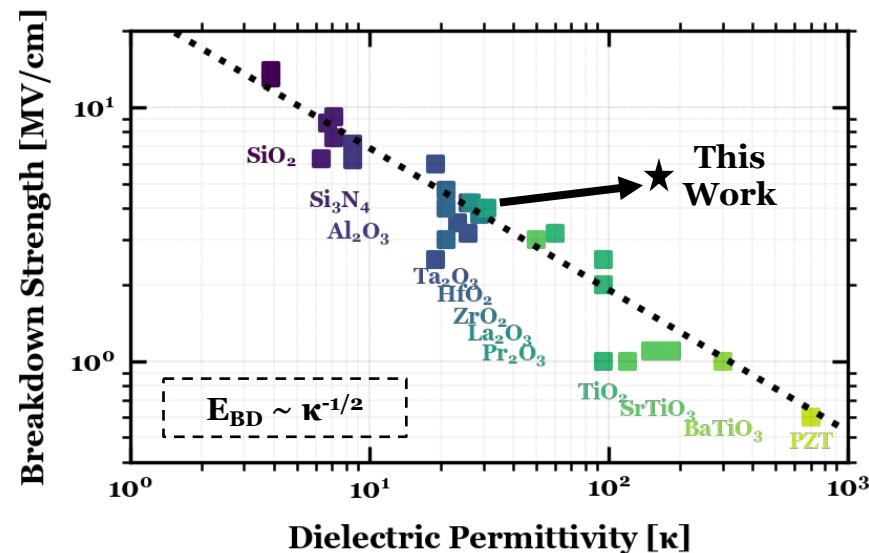


Antiferroelectric Energy Landscape Evolution



Negative Capacitance Stabilized During Ferroic Phase Transition
Transient NC as opposed to steady-state NC shown previously

Fundamental Trade-Off



Electrostatic Energy Storage

$$ESD \sim \frac{1}{2} CV^2 \sim \frac{1}{2} \epsilon_0 \kappa E_{BD}^2$$

$$E_{BD} \sim \kappa^{-1/2}$$



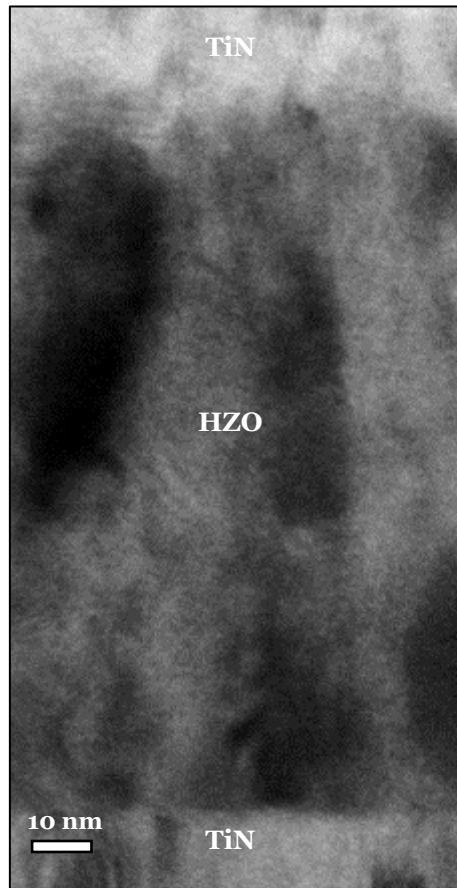
Permittivity – Breakdown Trade-Off
Empirical Trend in Dielectrics: No dielectric stands out

Solution: Negative Capacitance
Increase κ while maintaining E_{BD}

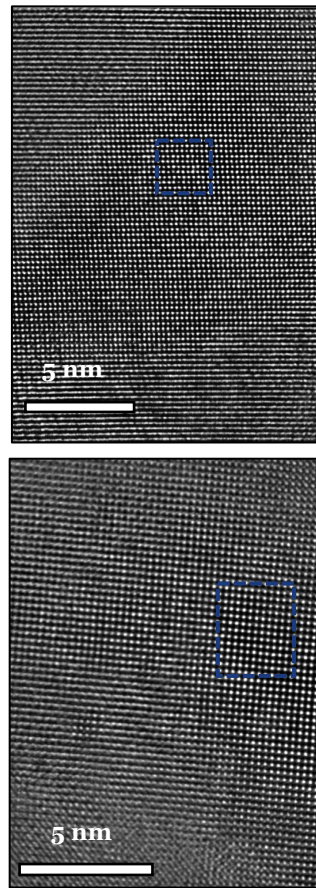
Negative Capacitance for Energy Storage | Scaling Up Antiferroelectricity

Continuous HZO Approach

Ultrathick HZO

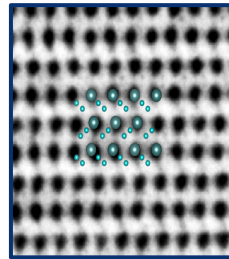


Zoom-In

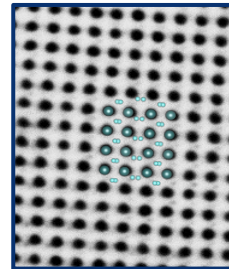


Polar
Orthorhombic

Inv Contrast
 $Pca2_1$
[100]



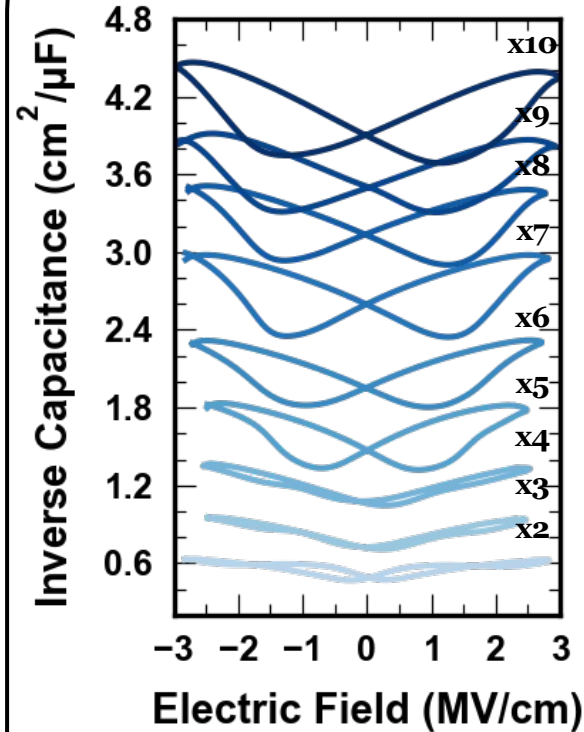
Inv Contrast
 $Pca2_1$
[001]



Courtesy: Shang-Lin Hsu (NCEM)

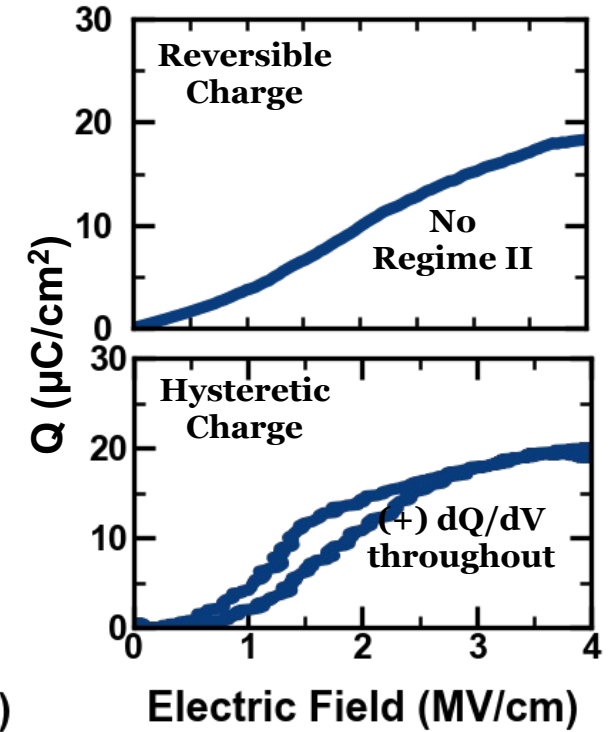
Continuous HZO Approach

HZO Thickness Series



AFE → FE Evolution

HZOx10 Continuous



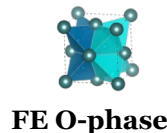
Regime II NC Boost Lost

$$U \sim CV^2$$

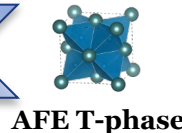
$$\sim \left[\frac{1}{t} \right] [t^2]$$

(Anti)Ferroelectric Thickness Scaling

Degraded
NC Charge Boost
Permittivity
Breakdown

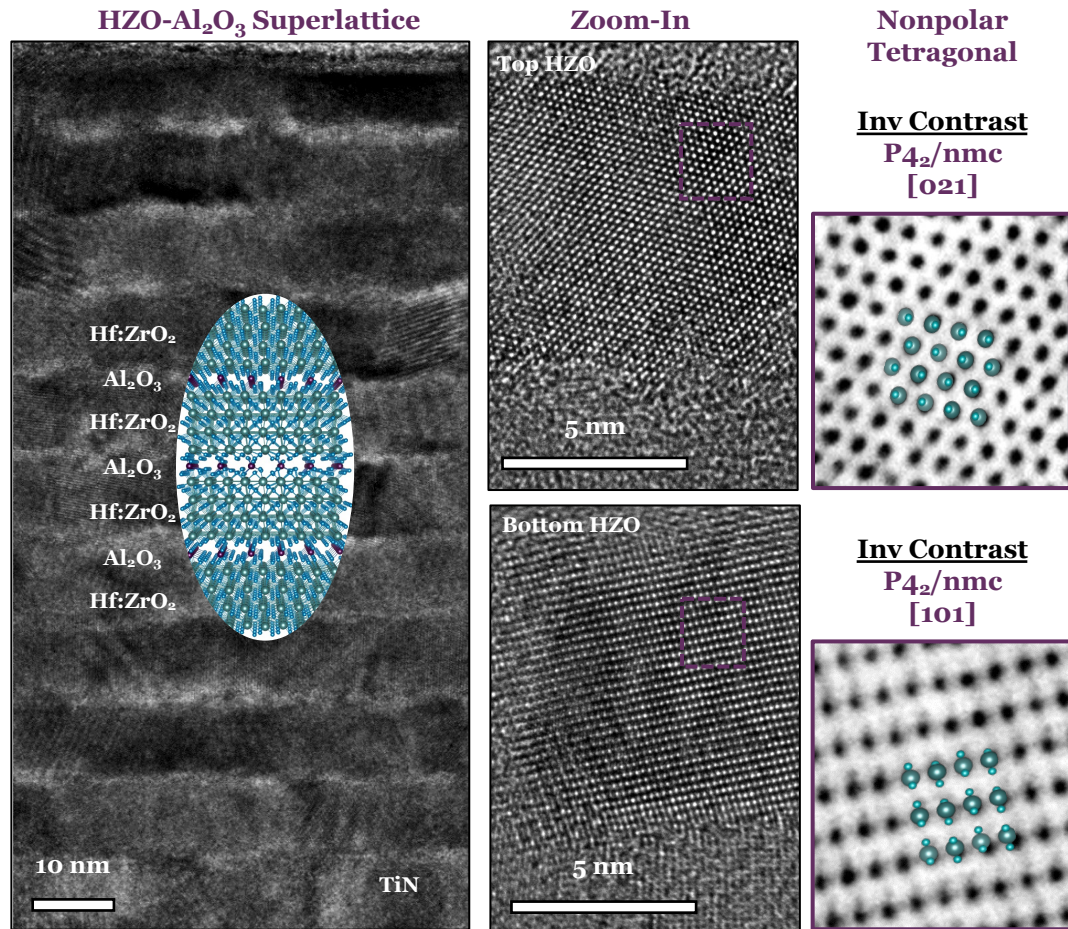


Continuous
Approach

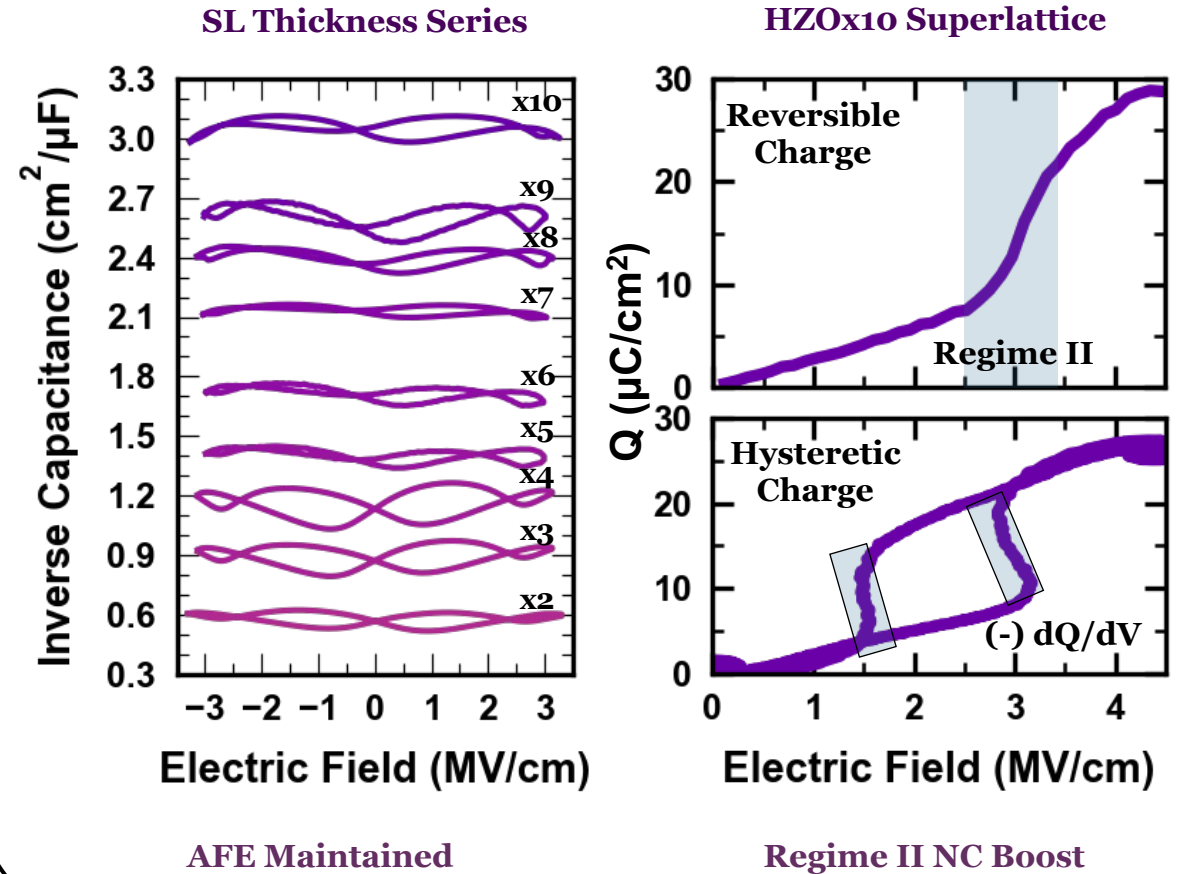


Negative Capacitance for Energy Storage | Scaling Up Antiferroelectricity

HZO-Al₂O₃ Superlattice Approach



HZO-Al₂O₃ Superlattice Approach

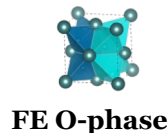


$$U \sim CV^2$$

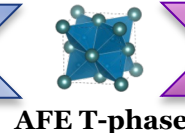
$$\sim \left[\frac{1}{t} \right] [t^2]$$

(Anti)Ferroelectric Thickness Scaling

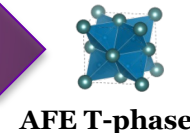
Degraded
NC Charge Boost
Permittivity
Breakdown



Continuous
Approach



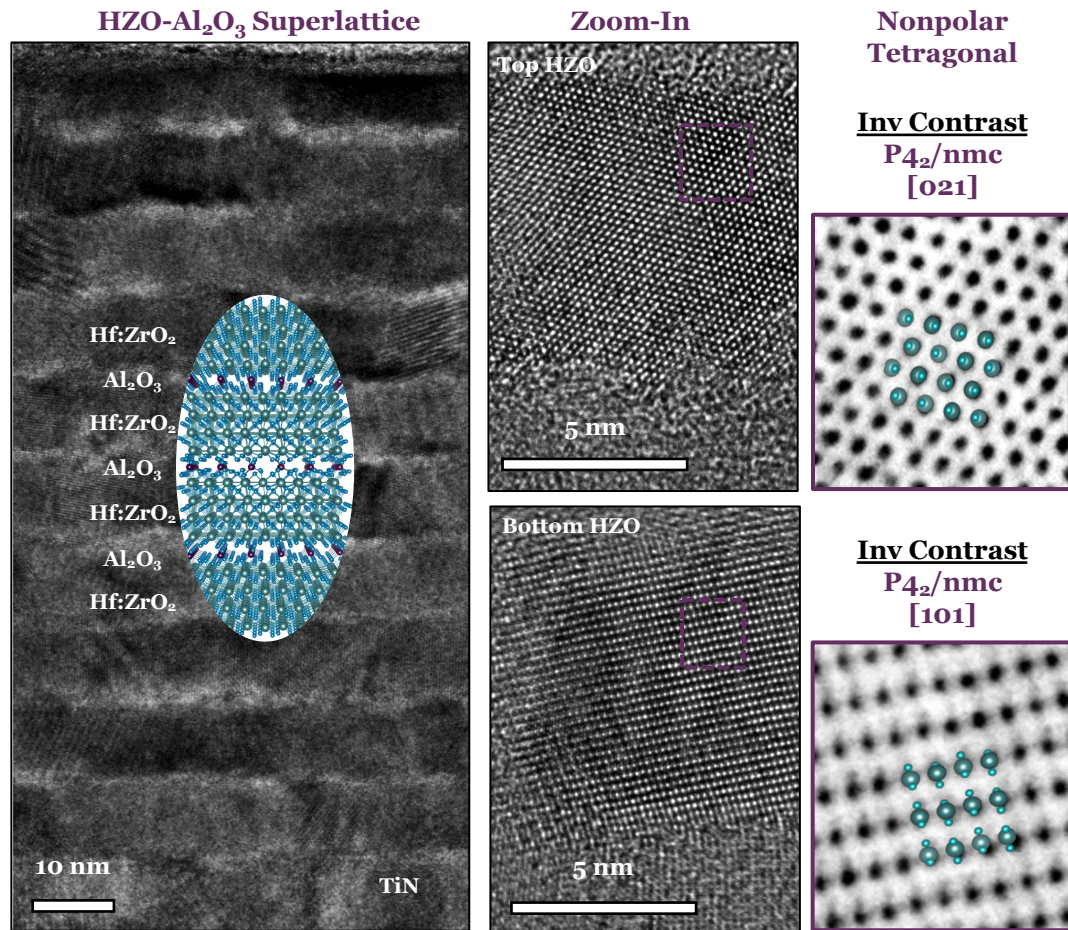
Superlattice
Approach



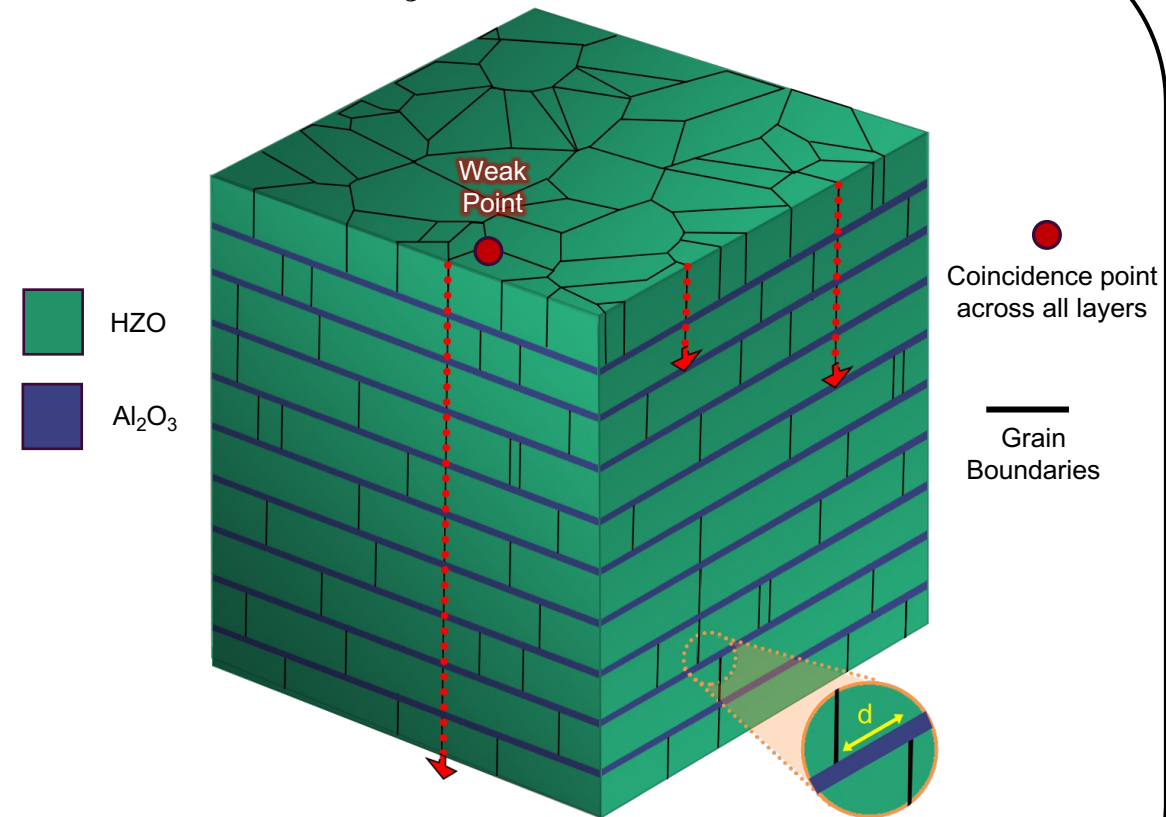
Maintained
NC Charge Boost
Permittivity
Breakdown

Negative Capacitance for Energy Storage | Scaling Up Antiferroelectricity

HZO-Al₂O₃ Superlattice Approach



HZO-Al₂O₃ Superlattice Approach



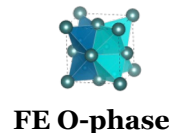
Breakdown Maintained
Weak Breakdown Path: Grain boundaries coincide across all layers

$$U \sim CV^2$$

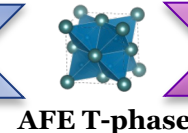
$$\sim \left[\frac{1}{t} \right] [t^2]$$

(Anti)Ferroelectric Thickness Scaling

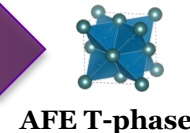
Degraded
NC Charge Boost
Permittivity
Breakdown



Continuous
Approach



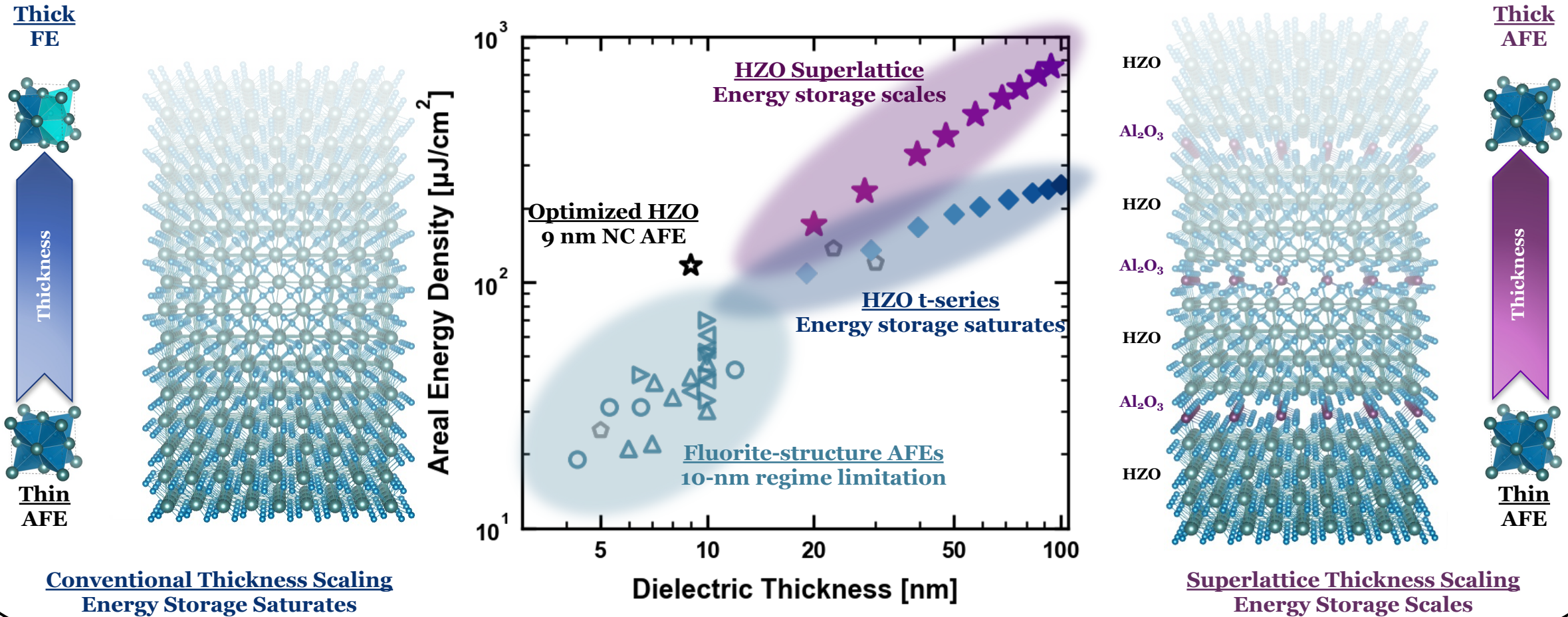
Superlattice
Approach



Maintained
NC Charge Boost
Permittivity
Breakdown

Negative Capacitance for Energy Storage | Scaling Up Antiferroelectricity

Benchmark of Energy Storage Capacitors

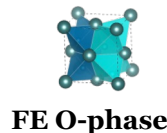


$$U \sim CV^2$$

$$\sim \left[\frac{1}{t} \right] [t^2]$$

(Anti)Ferroelectric Thickness Scaling

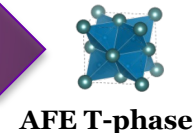
Degraded
NC Charge Boost
Permittivity
Breakdown



Continuous
Approach



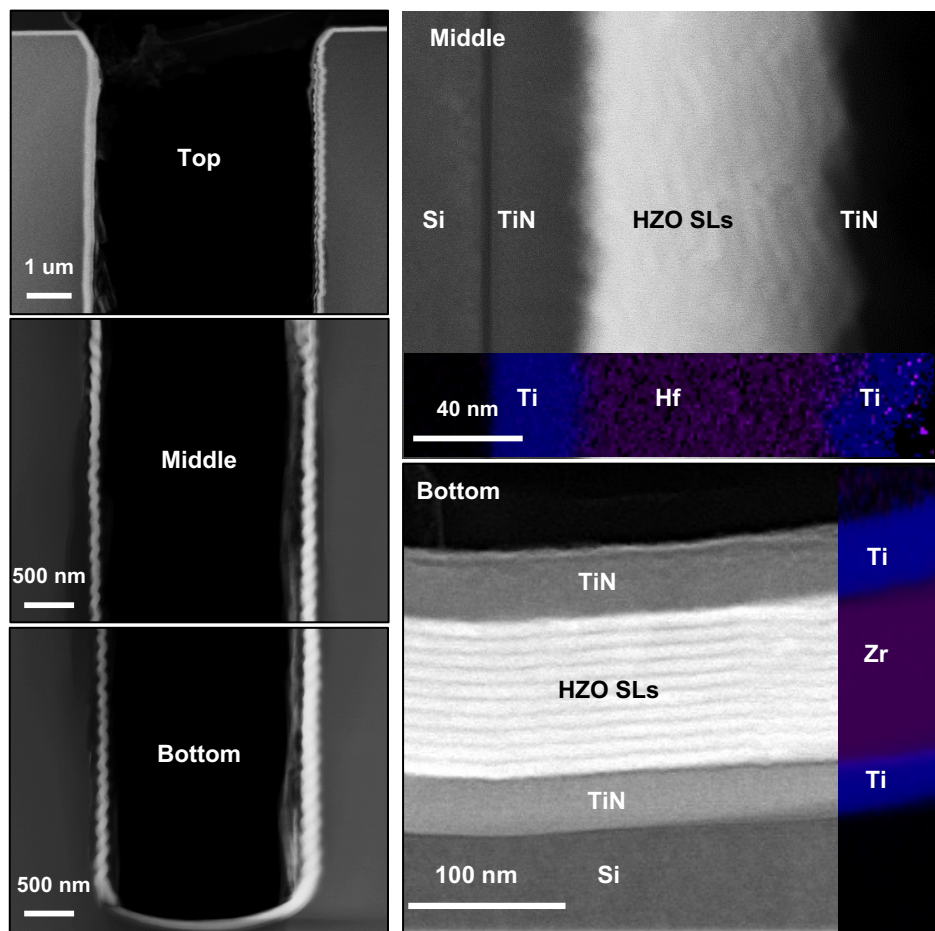
Superlattice
Approach



Maintained
NC Charge Boost
Permittivity
Breakdown

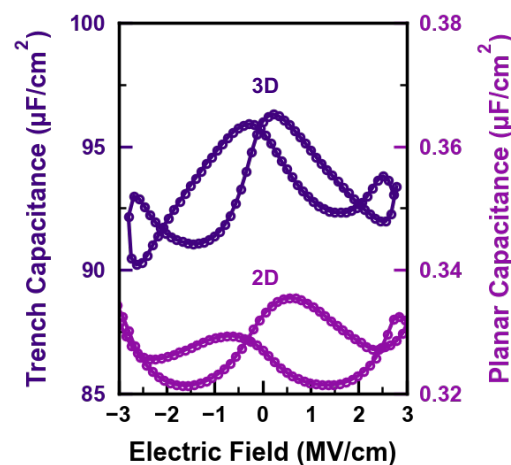
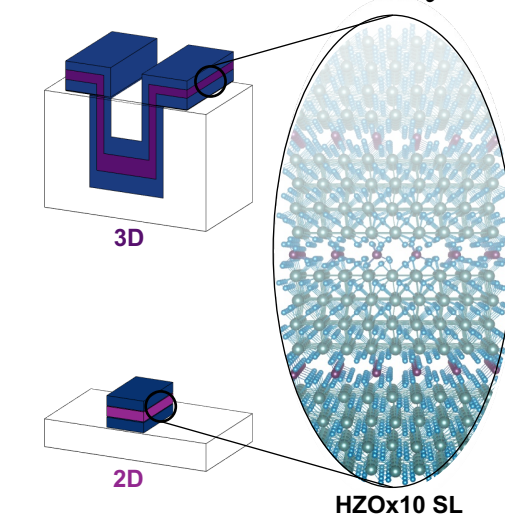
Negative Capacitance for Energy Storage | Scaling Up Antiferroelectricity [3D]

3D Trench Capacitor

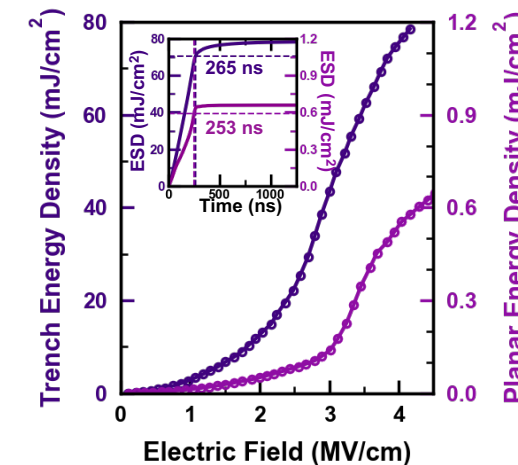
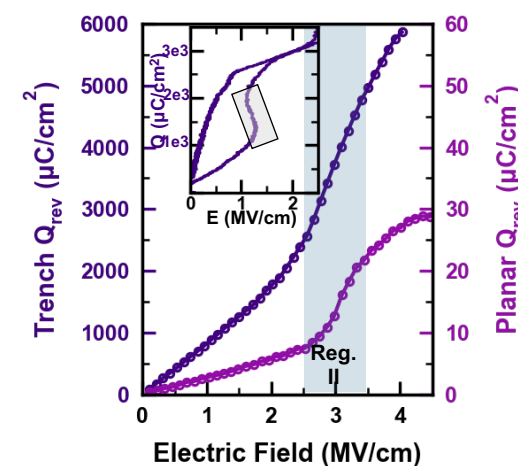


Courtesy: MIT Lincoln Laboratory

Antiferroelectricity



Negative Capacitance



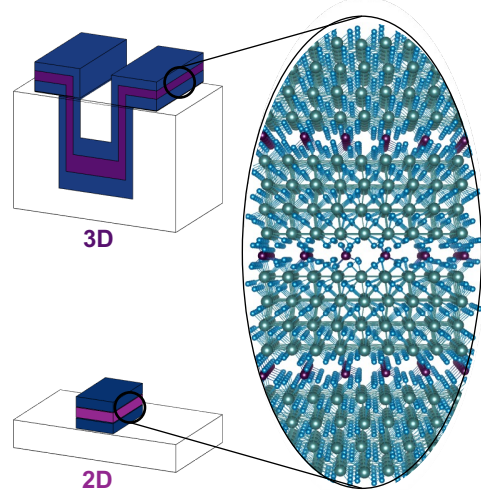
Conformal ALD Coverage
Superlattice Structure Maintained

Antiferroelectricity Maintained
> 200x boost in capacitance

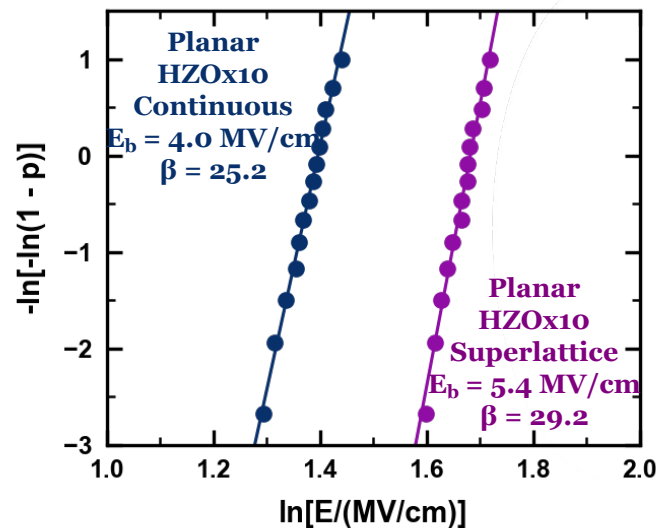
Negative Capacitance Maintained
> 100x boost in energy storage

Negative Capacitance for Energy Storage | Reliability

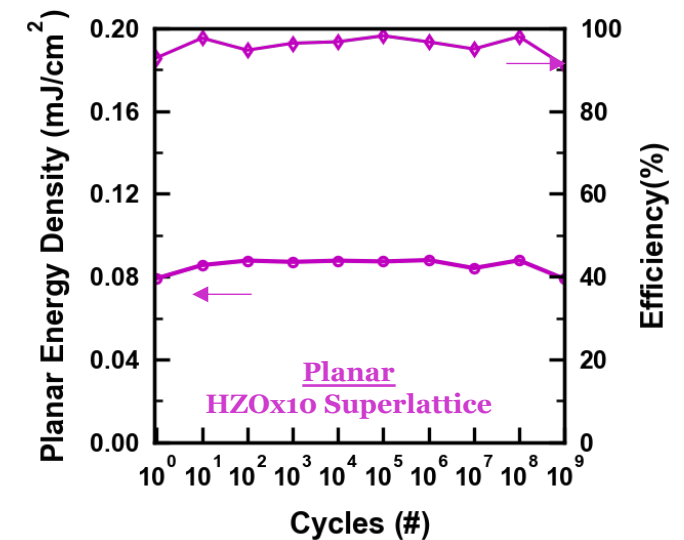
3D Trench Capacitor



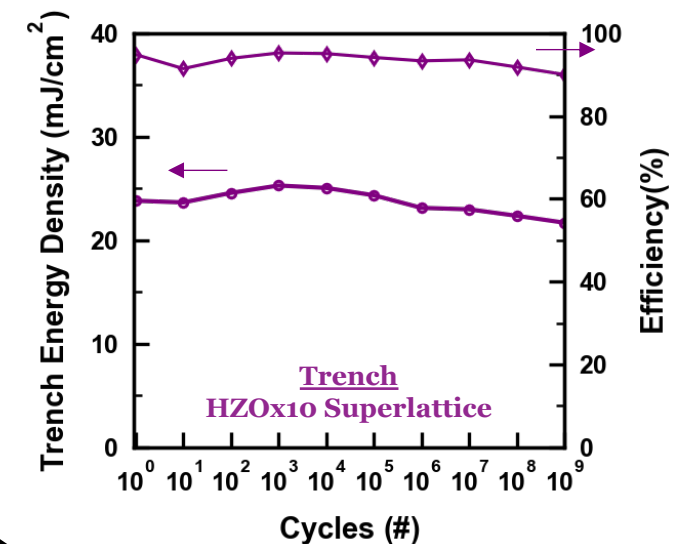
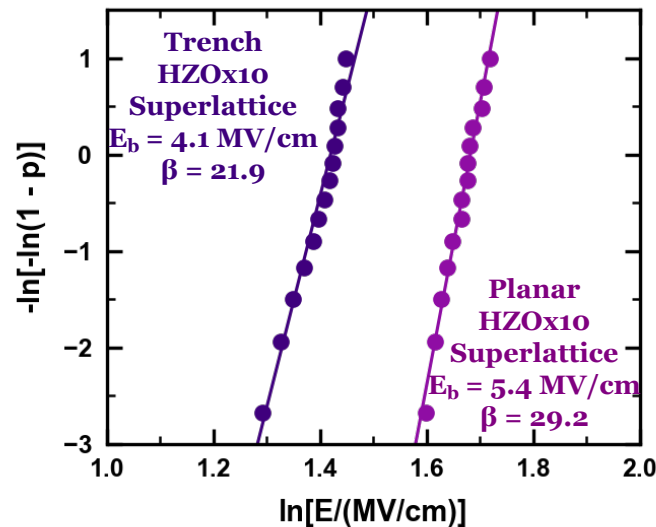
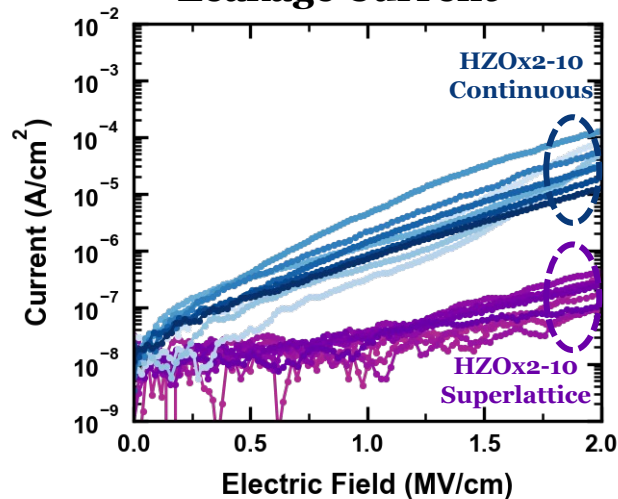
Breakdown Field



Endurance Cycling



Leakage Current



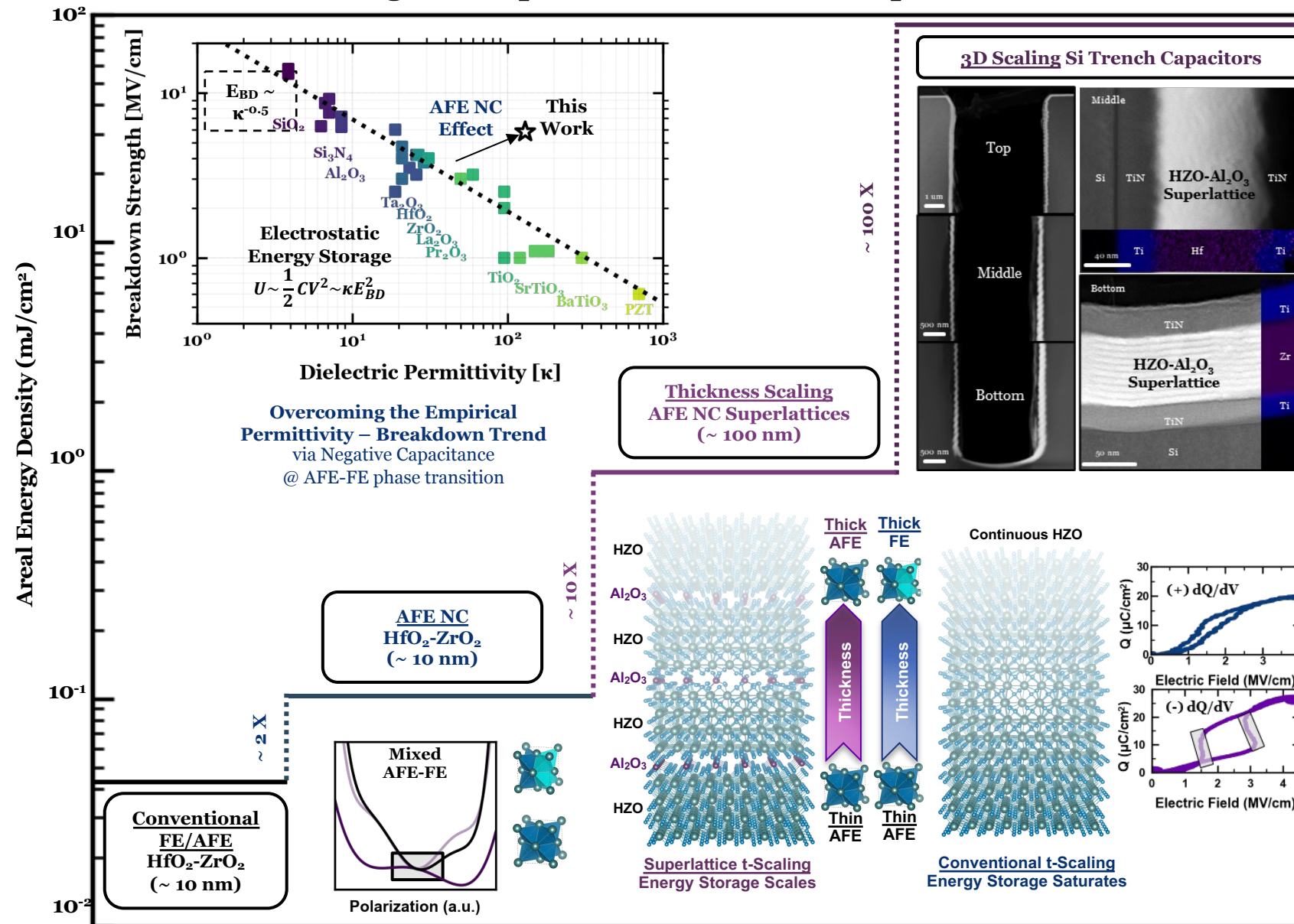
Superlattice vs. Continuous HZO
Superlattice: 2-3 orders lower leakage current

Superlattice: 1.5 MV/cm larger E_{bd}
Trench: 1.5 MV/cm lower E_{bd}

Planar: $1e9/1e8/1e6$ @ 2.5/3.0/3.5 MV/cm
Trench: $> 1e9/1e6$ @ 2.5/3.0 MV/cm

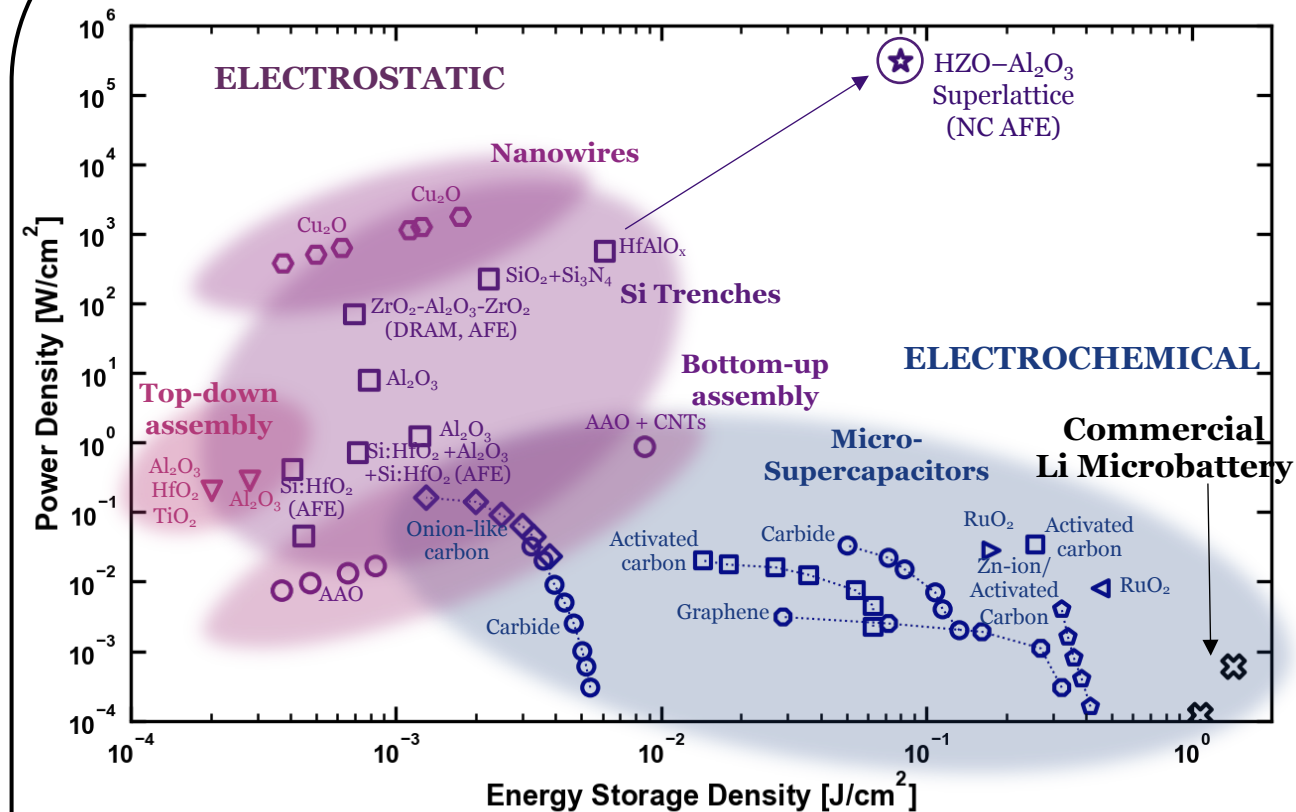
Negative Capacitance for Energy Storage | Summary

Negative Capacitance Micro-Ultra-Capacitors

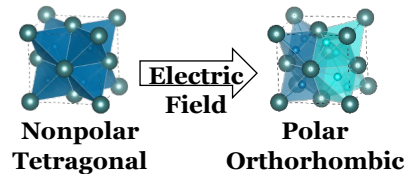


Negative Capacitance for Energy Storage | Outlook

Miniaturized Energy Storage: Benchmarks



**Nonpolar-Polar
Field-induced phase transition
Exploiting Negative Capacitance**



Miniaturized Energy Storage: On-Chip Technological Considerations

	Electrochemical Micro-Battery	Electrochemical Micro-Supercap	Electrostatic This Work
Energy Density	> 1 J/cm²	10-500 mJ/cm ²	80 mJ/cm ²
Power Density	~1 mW/cm ²	10-100 mW/cm ²	300 kW/cm²
Lifetime Cycles	1e1-1e3 cycles	1e3-1e6 cycles	1e6-1e9 cycles
High Voltage	✗	✗	✓
On-Chip Integration	✗	✗	✓
Safety Hazards	☠	☠	✓
Materials Sustainability	👎	👎	👍

Kyeremateng, Brousse, & Pech. Microsupercapacitors as miniaturized energy-storage components for on-chip electronics. *Nat. Nanotechnol.* 12 (2017).

Janek & Zeier. Challenges in speeding up solid-state battery development. *Nat. Energy* 8, (2023).

From Electrochemical to Electrostatic Supercapacitors

A New Paradigm for Energy Storage

Overcomes the traditional speed-capacity (power-energy density) trade-off

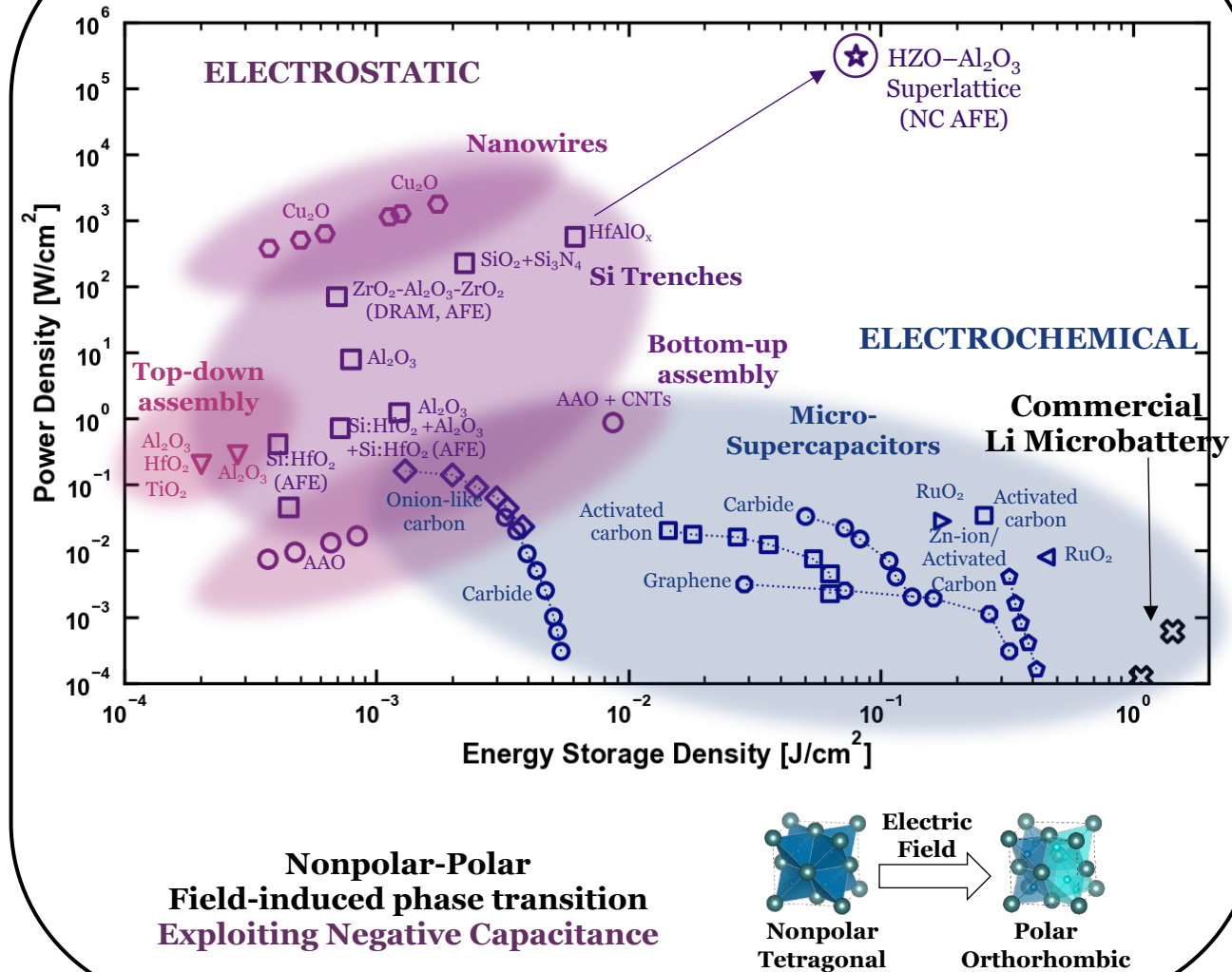
Solid State Micro-Batteries: Challenges Remain

Long-Term Reliability, Materials Sustainability, etc.

Electrostatic Microcapacitors: Address key issues

Ferroelectronics for Energy Technology | Energy Storage & Harvesting

Outlook: Energy Storage via Antiferroelectricity



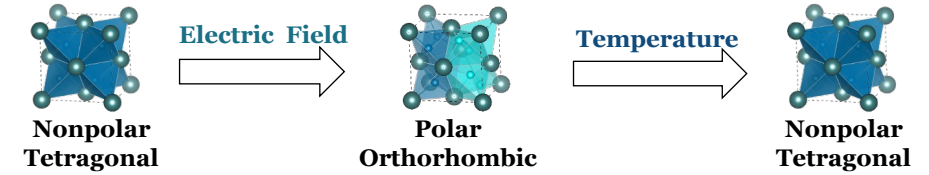
From Electrochemical to Electrostatic Supercapacitors

A New Paradigm for Energy Storage

Overcomes the traditional speed-capacity (power-energy density) trade-off

Outlook: Energy Harvesting via Pyroelectricity

Phase Transition Engineering

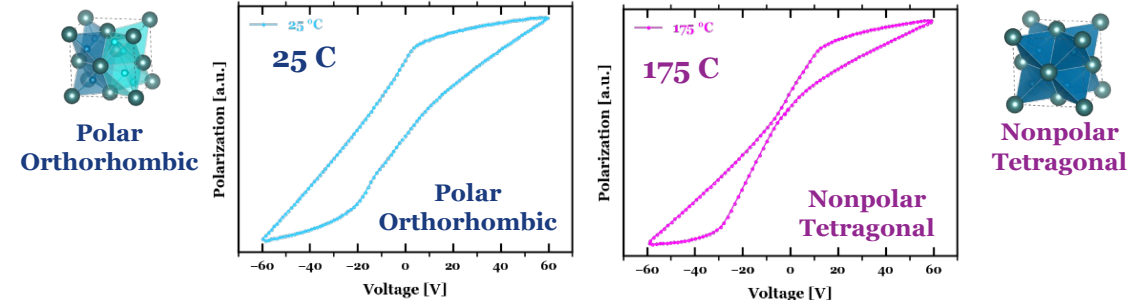


Energy Storage
Nonpolar-Polar
E-driven transition
Negative Capacitance

Cheema et al. Nature (2024)

Energy Harvesting
Polar-Nonpolar
T-driven transition
Negative Piezoelectricity

Cheema et al. Science (2022)



phase transition near on-chip temperatures

Cheema et al. Science 376, 648-652 (2022)

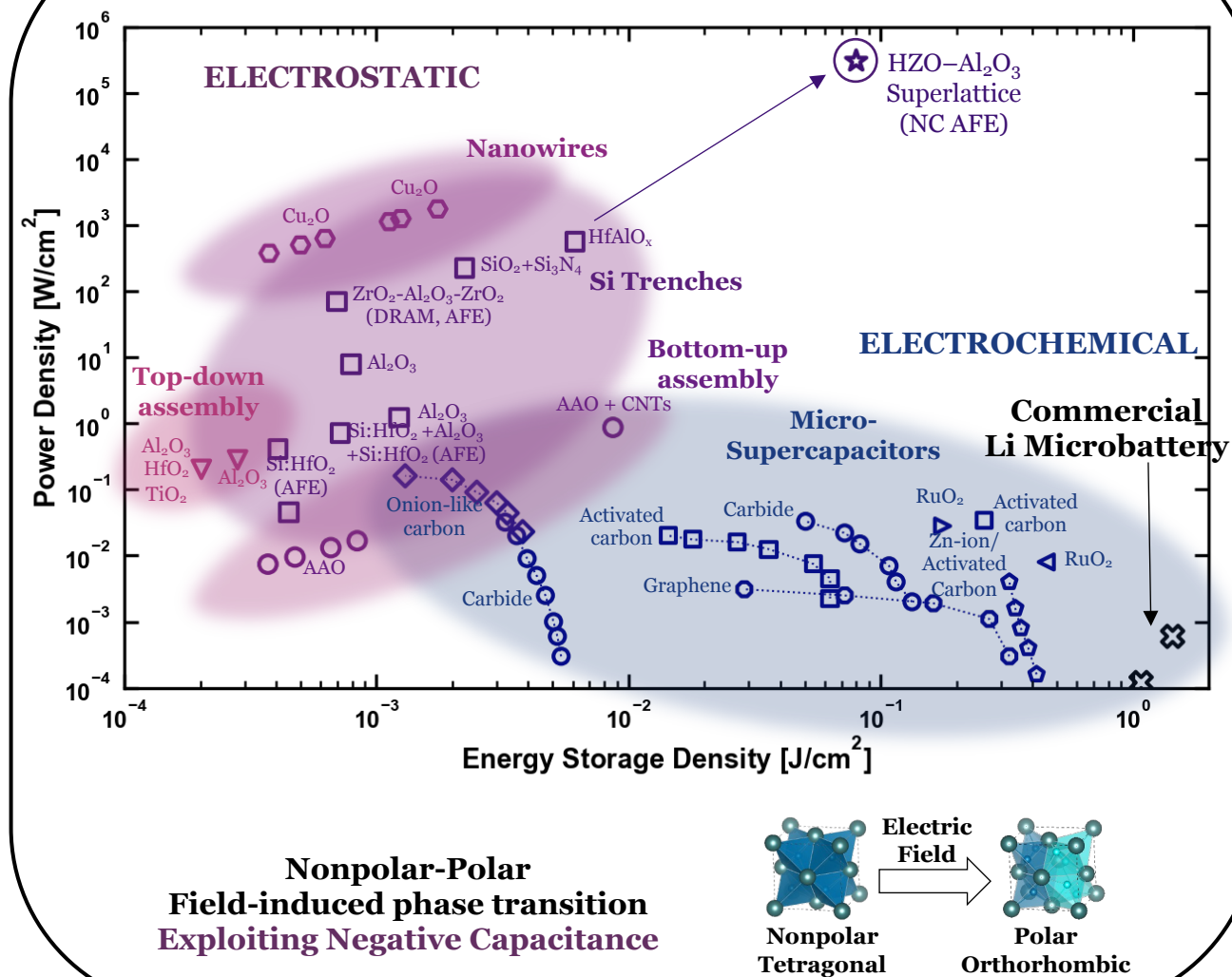
From Thermoelectrics to Pyroelectrics

A New Paradigm for Electrothermal Energy Harvesting

Overcomes the electrical-thermal conductivity trade-off

Ferroelectronics for Energy Technology | Energy Storage & Harvesting

Outlook: Energy Storage via Antiferroelectricity

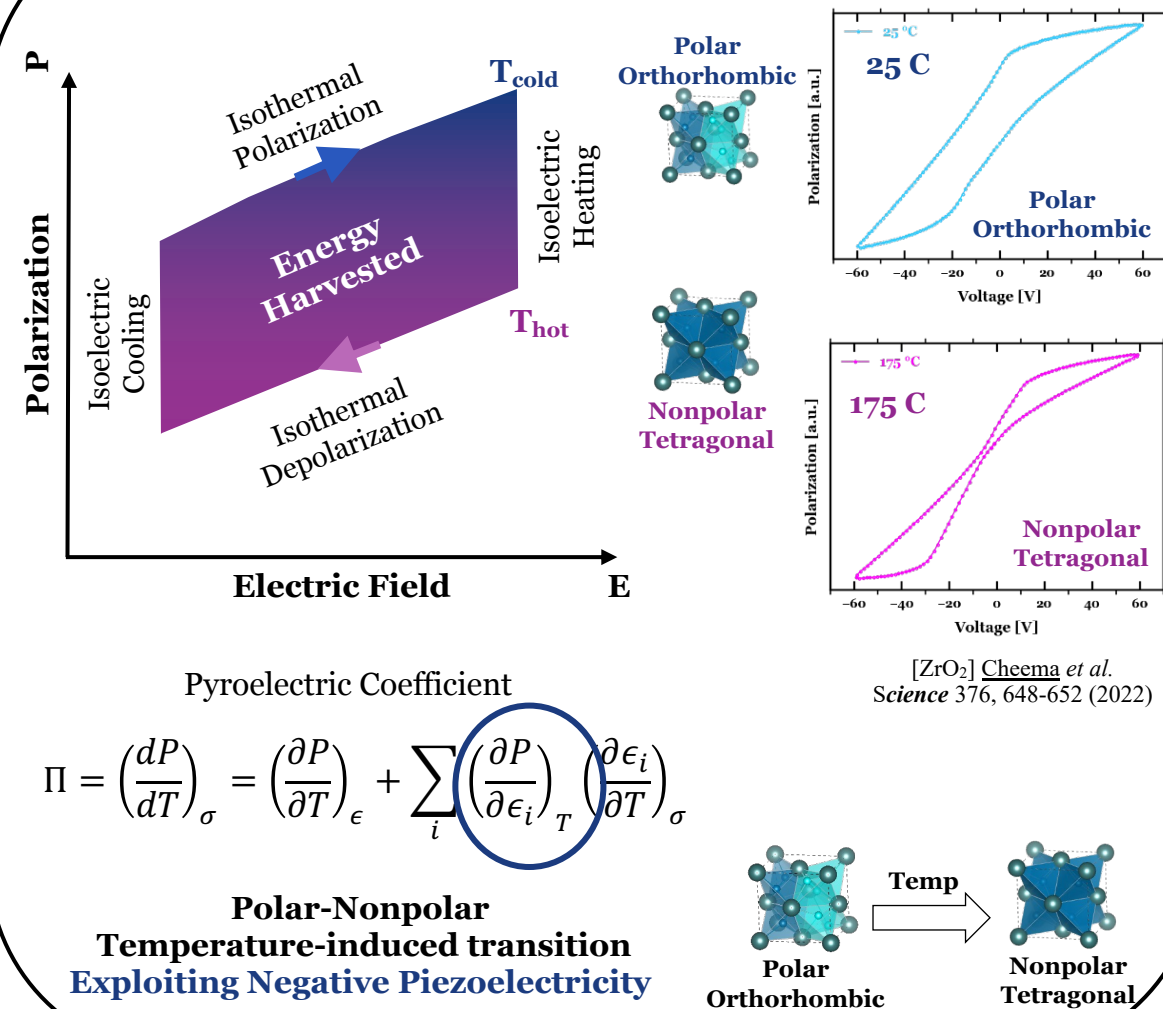


From Electrochemical to Electrostatic Supercapacitors

A New Paradigm for Energy Storage

Overcomes the traditional speed-capacity (power-energy density) trade-off

Outlook: Energy Harvesting via Pyroelectricity



From Thermoelectrics to Pyroelectrics

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