



Ferroelectric memories

Asif Khan

School of Electrical and Computer Engineering

School of Materials Science and Engineering

Georgia Institute of Technology

akhan40@gatech.edu

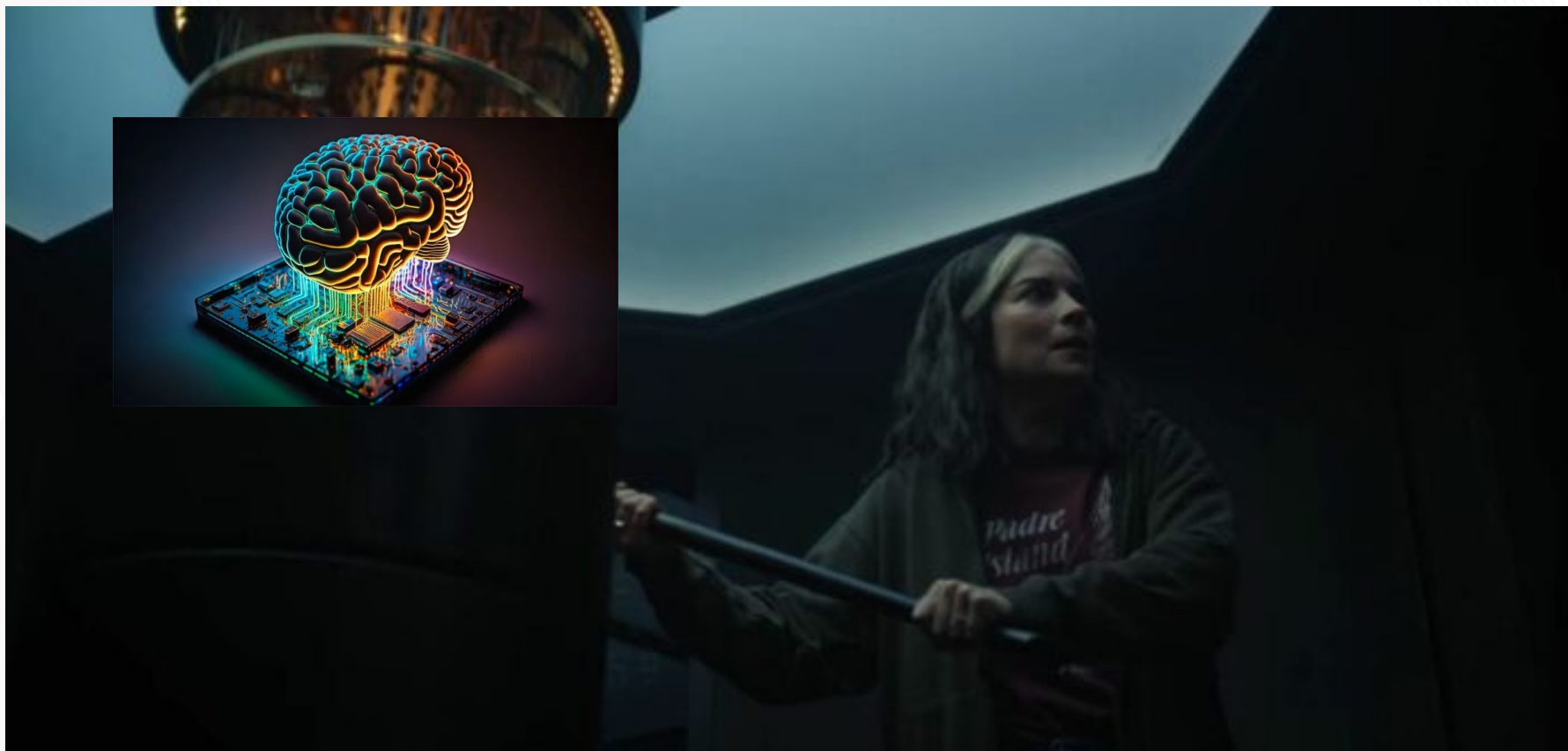
NVMTS

imec, Belgium

August 31, 2023









midtown

ATLANTA



Our team



Nujhat Tasneem
Graduate Student



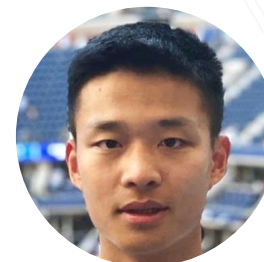
Prasanna Ravindran
Graduate Student



Nashrah Afroze
Graduate Student



Chinsung Park
Graduate Student



Jiayi Chen
Graduate Student



Dr. Hang Chen
Staff member



Priyanka G R
Graduate Student



Henna Mian
Graduate Student



Zekai Wang
Undergraduate student



Dr. Dipjyoti Das
Post-doctoral scholar



Dr. Mengkun Tian
Staff member



Dr. Sarah Lombardo
TEL



Dr. Zheng Wang
Micron



Anthony Gaskell
TSMC

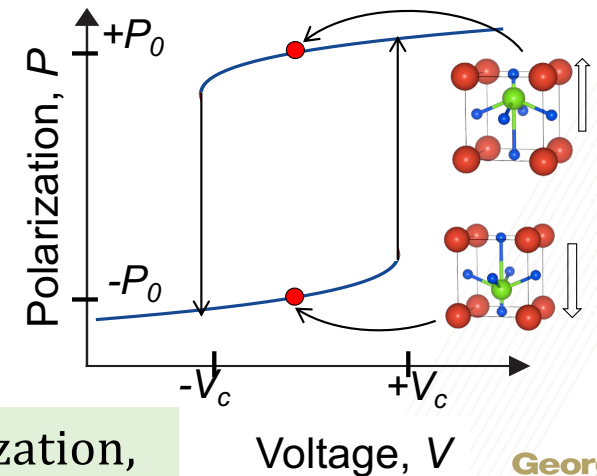
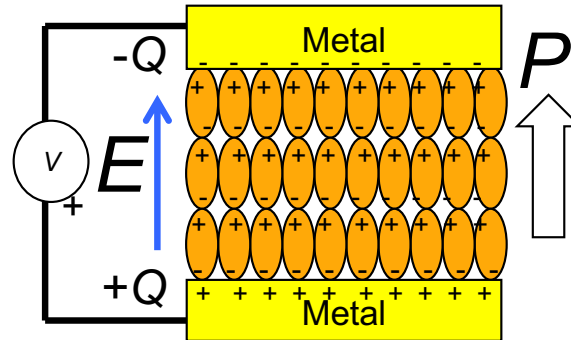
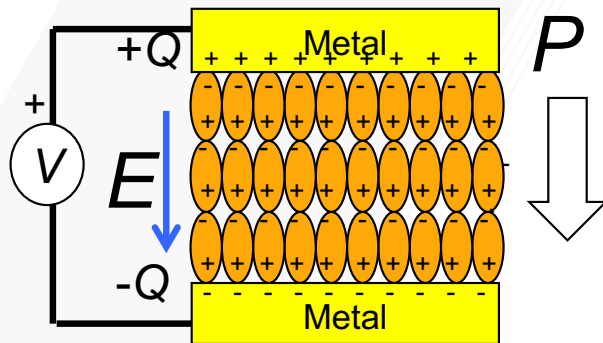
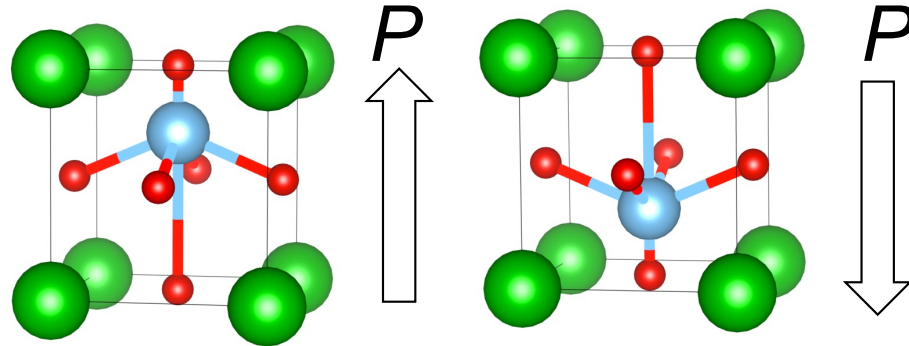
Current

Graduated

Ferroelectricity

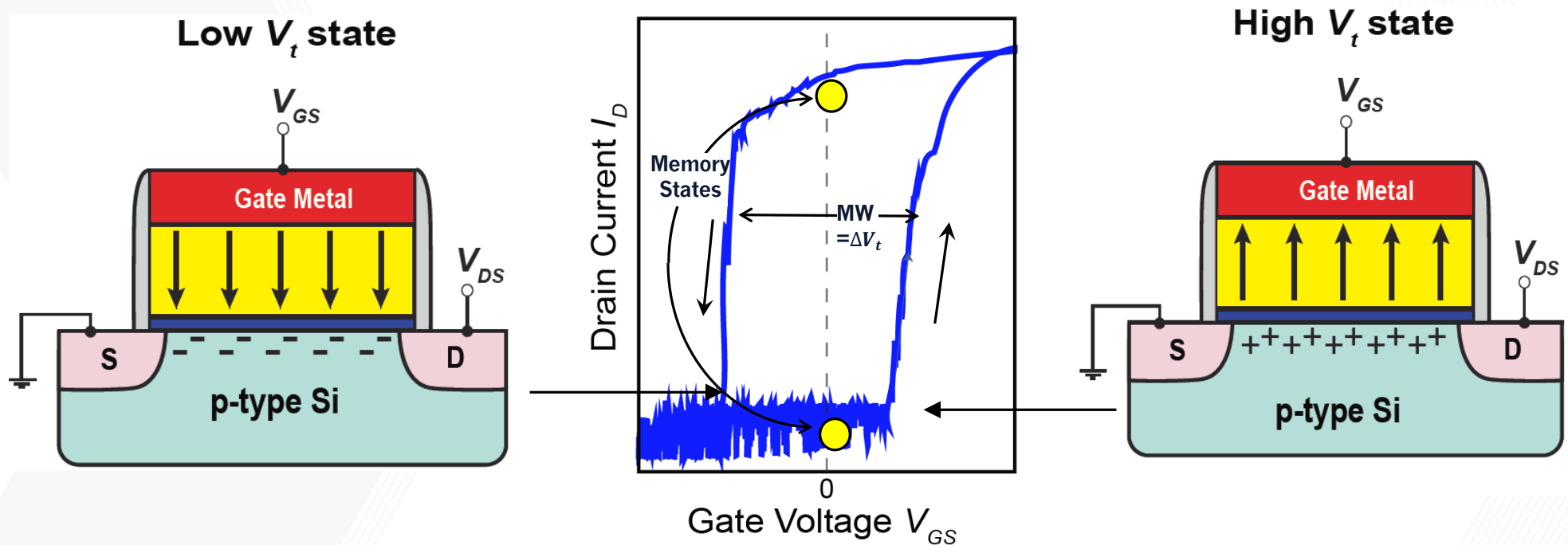
Classical Ferroelectric
 PbTiO_3 , BaTiO_3 etc.

Emerging CMOS compatible
Ferroelectrics:
Doped HfO_2



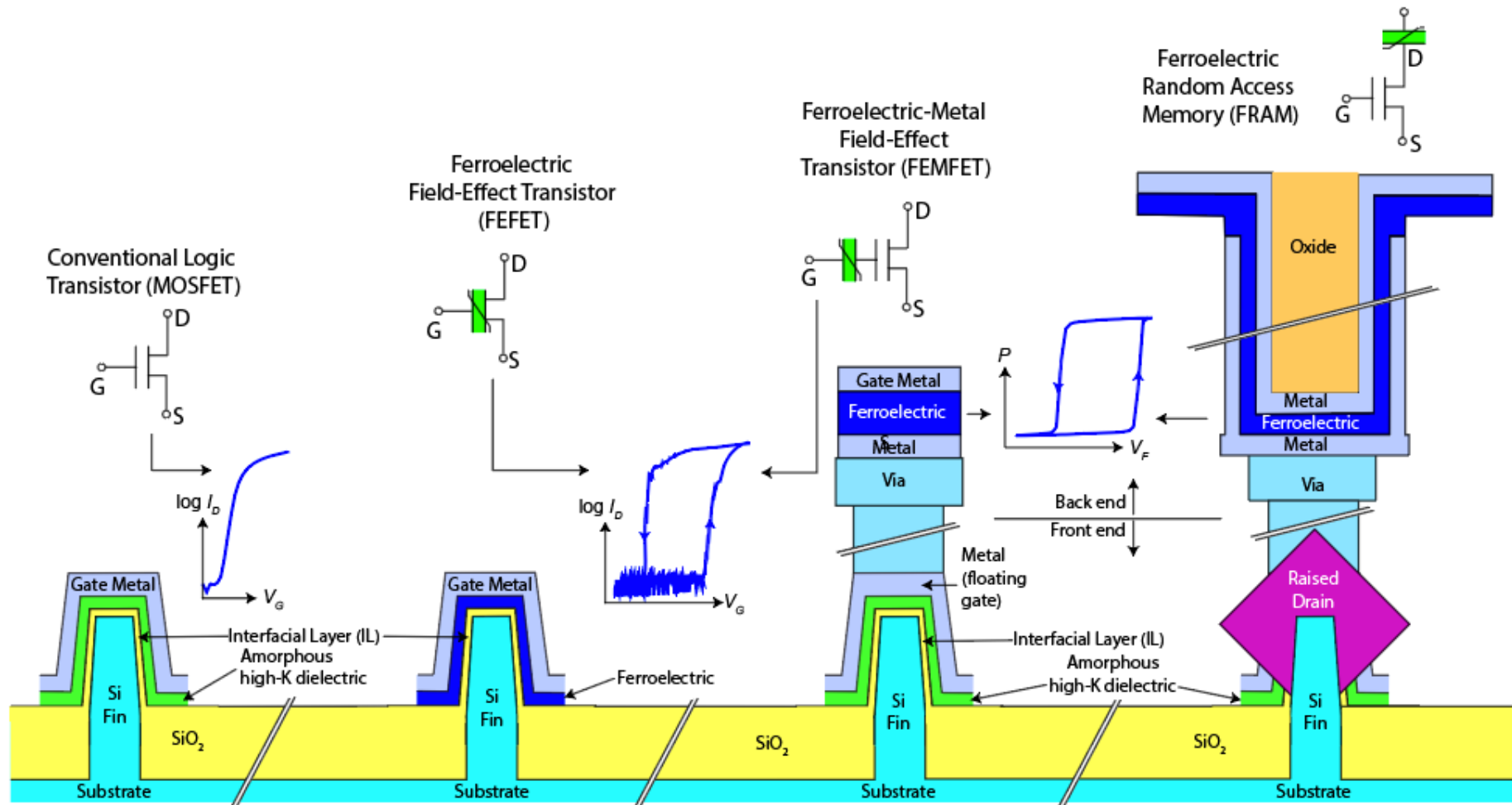
A ferroelectric is an insulator with a spontaneous polarization, which can be switched by an above coercive voltage .

Ferroelectric field-effect transistors (FEFETs)



FEFET is a FET wherein the threshold voltage gets shifted by the direction and magnitude of the “remnant” polarization.

Ferroelectric devices (1 of 2)

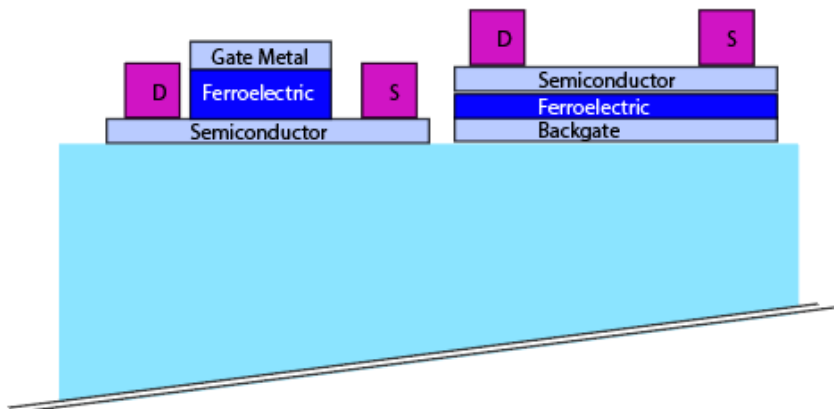


Khan, Keshavarzi, Datta. "The future of ferroelectric field-effect transistor technology." *Nature Electronics* 3.10 (2020): 588-597.

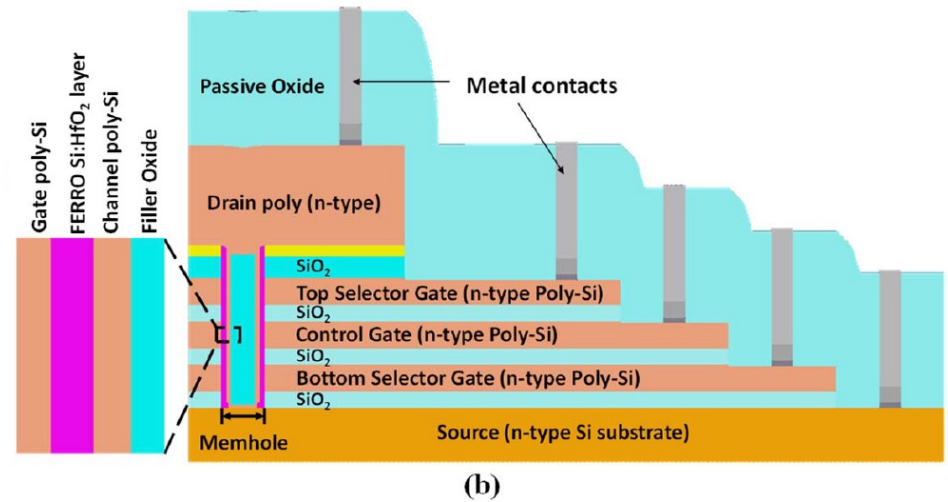
Ferroelectric devices (2 of 2)

BEOL FEFET

Ferroelectric
Field-Effect Transistor
(FEFET)



Vertical FEFET for NAND Storage



Khan, Keshavarzi, Datta. "The future of ferroelectric field-effect transistor technology." *Nature Electronics* 3.10 (2020): 588-597.

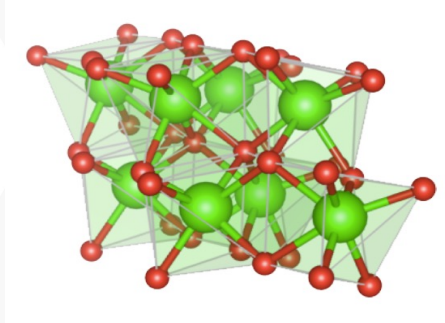
FEFET as an embedded memory

Metrics	Mainstream embedded memory					Embedded ferroelectric memory			
	eSRAM	eDRAM ⁷⁰	eFlash (FG)	eFlash (SG MONOS) ⁴²	eFlash (SONOS) ⁴¹	FEFET (hafnia based, MFIS structure)	FEFET (hafnia based, MFMIS structure)	FRAM (hafnia based)	FRAM (perovskite based) ⁶⁷
Cell size	120-150F ²	40F ²	40-60F ²	40-50F ²	50-60F ²	10-30F ²	10-30F ²	30-40F ²	50-60F ²
Cell structure	6T	1T1C	1.5T	1.5T	2T	1T	1T1FE, 1T	1T1FE, 2T2FE	1T1FE, 2T2FE
Non-volatile	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Multi-bit operation	No	No	Yes	Yes	Yes	Yes	Yes	No	No
Non-destructive read	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No
Status	Av.	Dev.	Av.	Dev.	Dev.	Res.	Res.	Res.	Av.
Advanced node demonstration	7 nm FinFET	22 nm FinFET	40 nm	16 nm FinFET	28 nm HKMG	22 nm FDSOI	N/A	N/A	130 nm
Write voltage	<1 V	<1 V	~12 V	~12 V	~5 V	1.5-4 V	~1.5 V	1-3 V	1.5 V
Write energy	~1 fJ	~1 pJ	~100 pJ	~100 pJ	1-10 pJ	1-10 fJ	1-10 fJ	~100 fJ	~1 pJ
Standby power	High	Medium	Low	Low	Low	Low	Low	Low	Low
Write speed	<1 ns	>10 ns	~100 ns	<100 ns	~100 ns	1-10 ns	1-10 ns	1-10 ns	1 μ s
Read speed	<1 ns	>10 ns	~10 ns	<10 ns	~10 ns	1-10 ns	1-10 ns	1-25 ns	50-100 ns
Endurance	>10 ¹⁶	>10 ¹⁶	~10 ⁴	~10 ⁵	~10 ⁶	10 ⁵ -10 ⁹	>10 ¹⁰	>10 ¹²	>10 ¹⁴

Khan, Keshavarzi, Datta. "The future of ferroelectric field-effect transistor technology." *Nature Electronics* 3.10 (2020): 588-597.

Ferroelectric field-effect transistors (FEFETs)

Ferroelectric Oxide



Properties of
Ferroelectric oxides

Non-volatility and
hysteresis

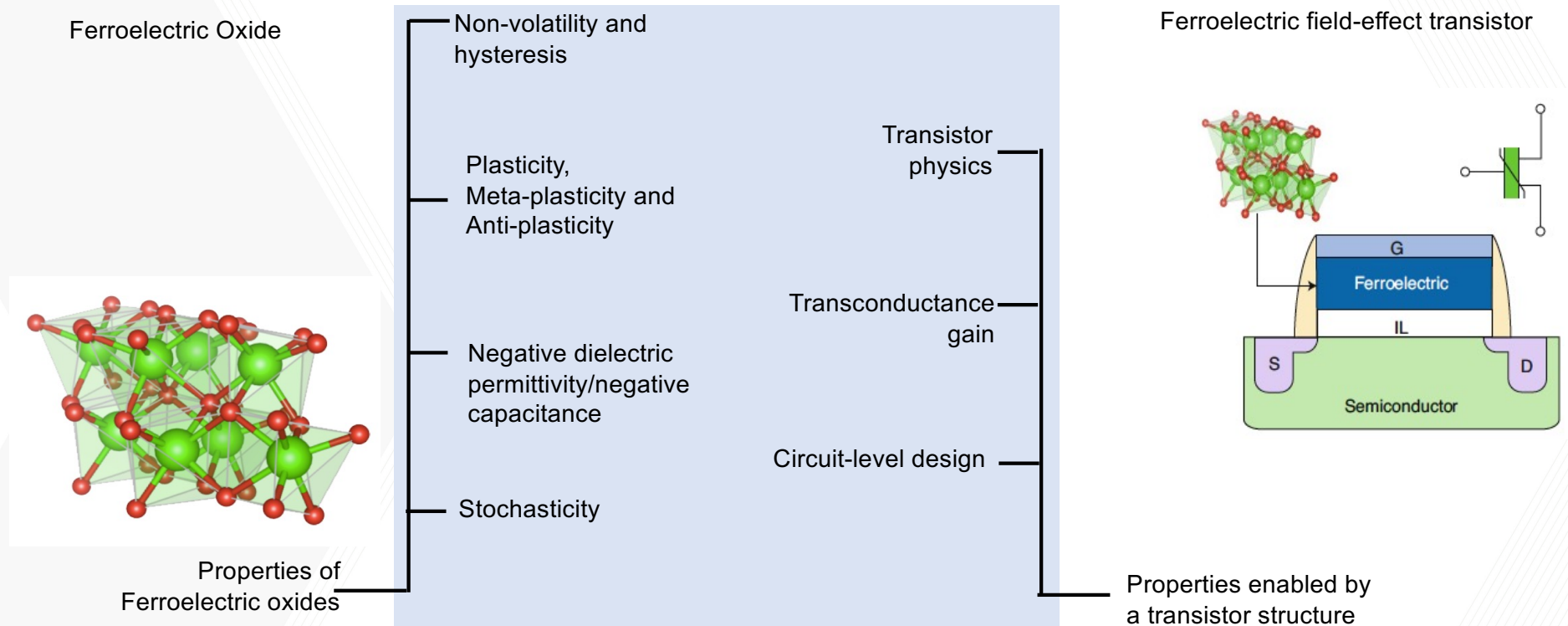
Plasticity,
Meta-plasticity and
Anti-plasticity

Negative dielectric
permittivity/negative
capacitance

Stochasticity

Khan, Keshavarzi, Datta. "The future of ferroelectric field-effect transistor technology." *Nature Electronics* 3.10 (2020): 588-597.

Ferroelectric field-effect transistors (FEFETs)

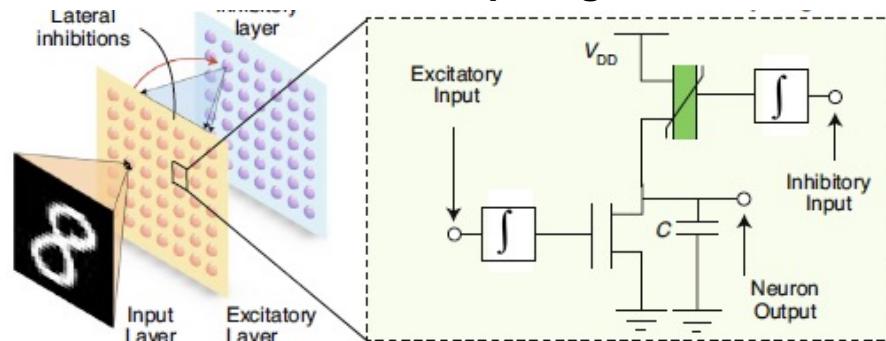


Ferroelectric FET is one of most versatile transistor technologies – ever conceived.

Khan, Keshavarzi, Datta. "The future of ferroelectric field-effect transistor technology." *Nature Electronics* 3.10 (2020): 588-597.

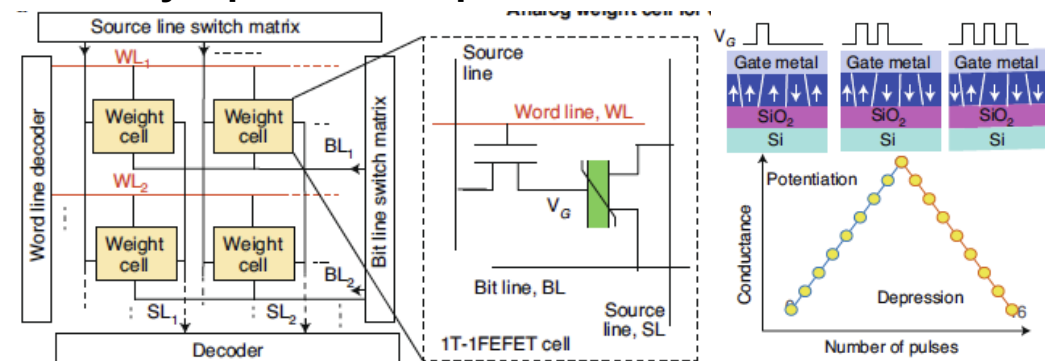
Ferroelectric FET Applications

Ferroelectric neurons for spiking neural networks



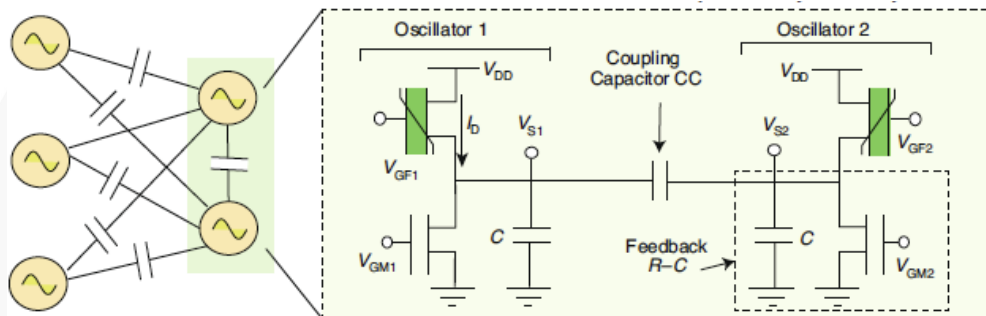
Wang et al. Int. Electron Dev. Meeting (IEDM) 2018.

FE synapses for deep neural network accelerators



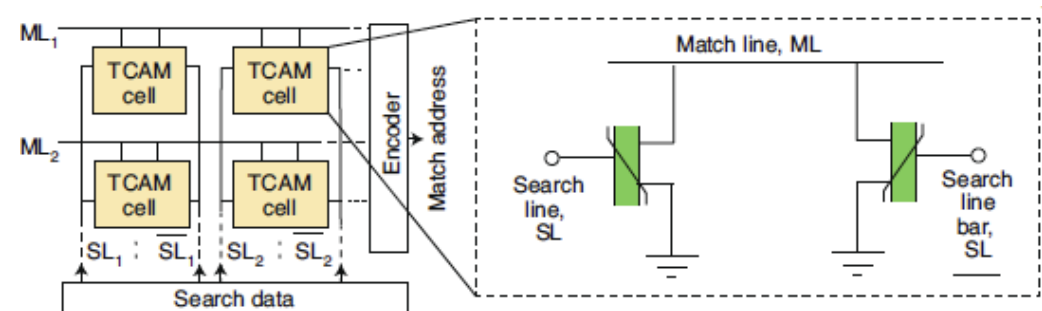
Aabrar et al. VLSI Symp. 2022.

Ferroelectric oscillators for time dynamical systems



Z. Wang et al. EDL 2017

Ferroelectric content addressable memory (CAM)



Tan et al. IEEE EDL

Khan, Keshavarzi, Datta. "The future of ferroelectric field-effect transistor technology." *Nature Electronics* 3.10 (2020): 588-597.

Progress in FEFET technology

1

Write voltage
and Memory Window

2

Read/Write
Speed

3

Device-to-device
variation

4

Reliability and endurance

Specs

<1.5 V write voltage
>0.5 V memory window

<10 ns write speed
<10 ns read-after-write delay

$\Delta V_{t,3\sigma} = 20\text{-}50\text{ mV}$
(7 nm node)

>10¹² cycles

Progress in FEFET technology

1

Write voltage
and Memory Window

2

Read/Write
Speed

3

Device-to-device
variation

4

Reliability and endurance

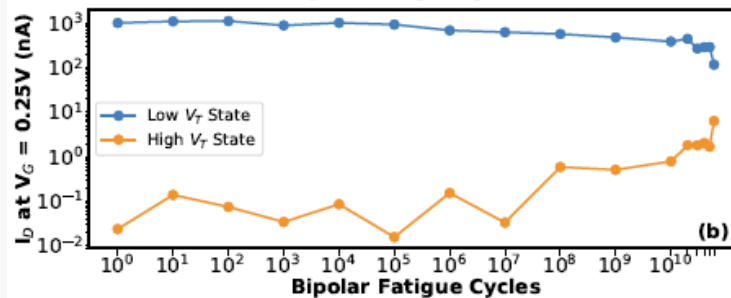
Specs

<1.5 V write voltage
>0.5 V memory window

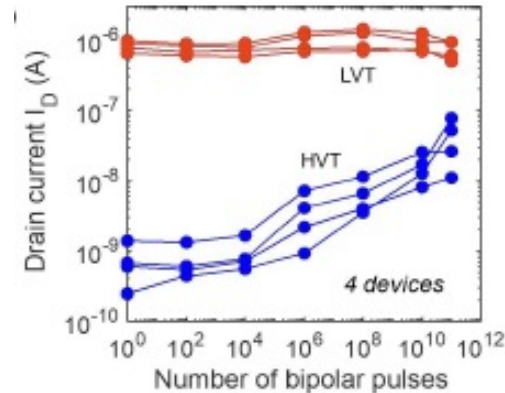
<10 ns write speed
<10 ns read-after-write delay

$\Delta V_{t,3\sigma} = 20\text{-}50\text{ mV}$
(7 nm node)

> 10^{12} cycles

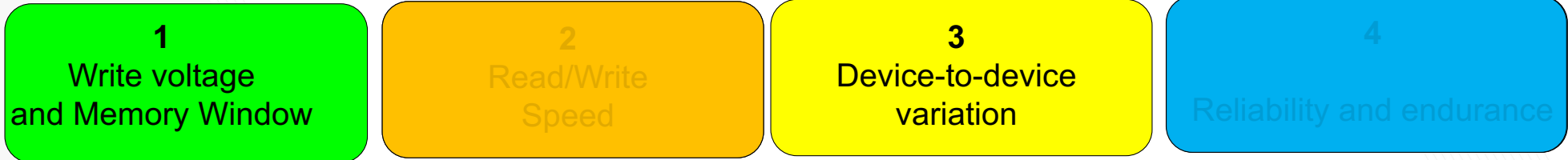


Tan et al. IEEE EDL 42, 994 (2021).



Dutta et al. IEEE EDL 43, 383 (2022).

Progress in FEFET technology



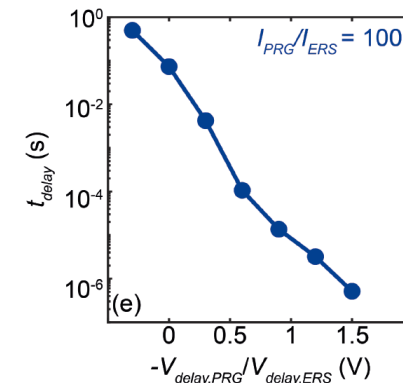
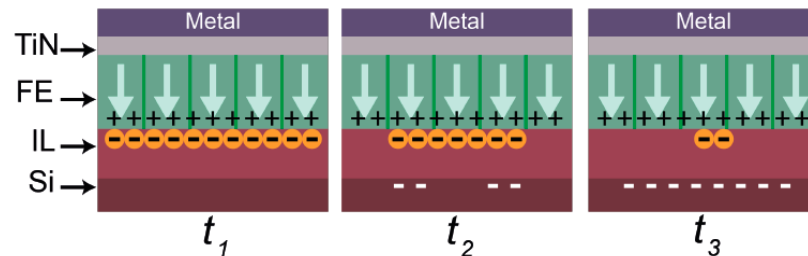
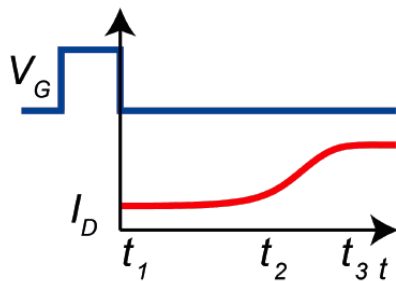
Specs

<1.5 V write voltage
>0.5 V memory window

<10 ns write speed
<10 ns read-after-write delay

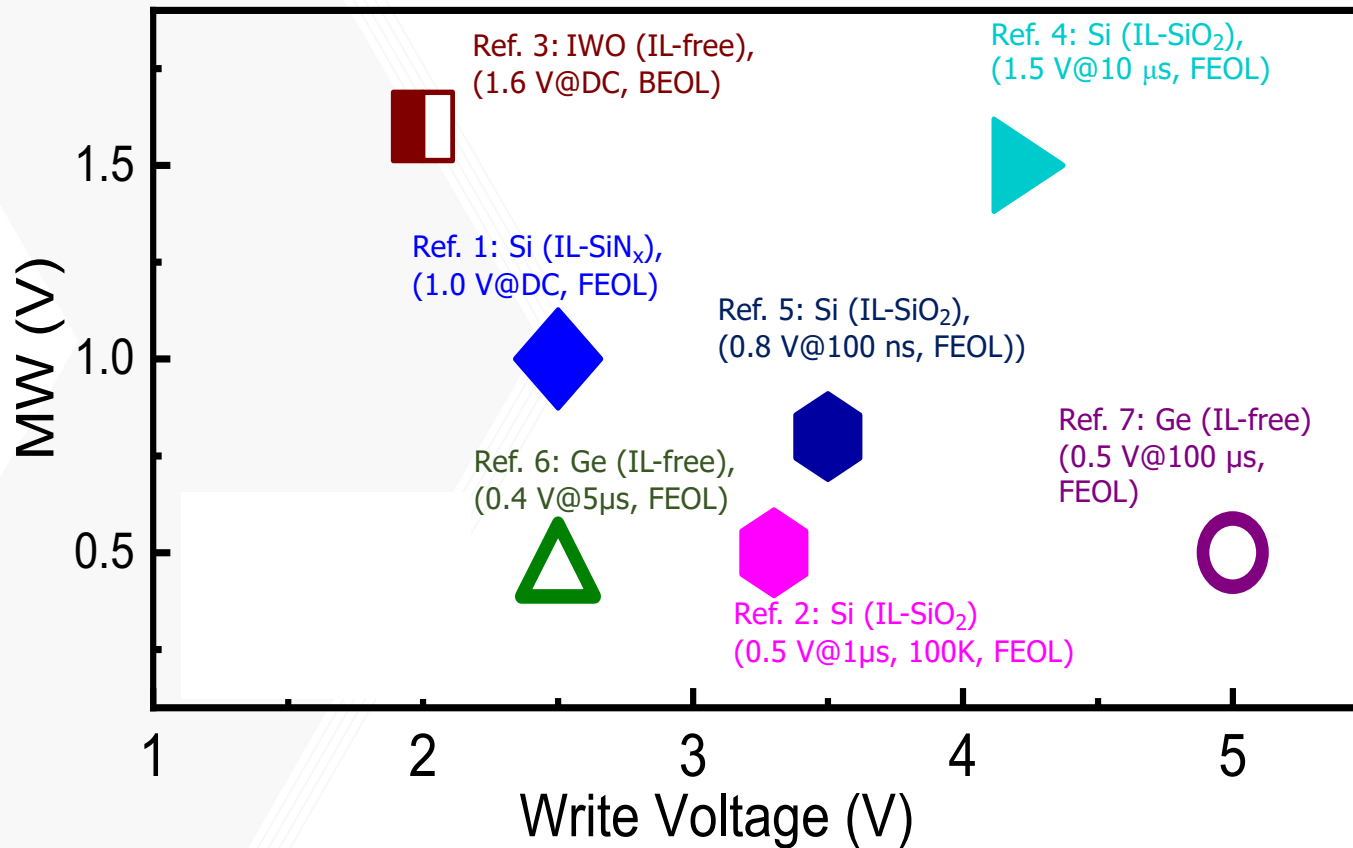
$\Delta V_{t,3\sigma} = 20\text{-}50\text{ mV}$
(7 nm node)

> 10^{12} cycles



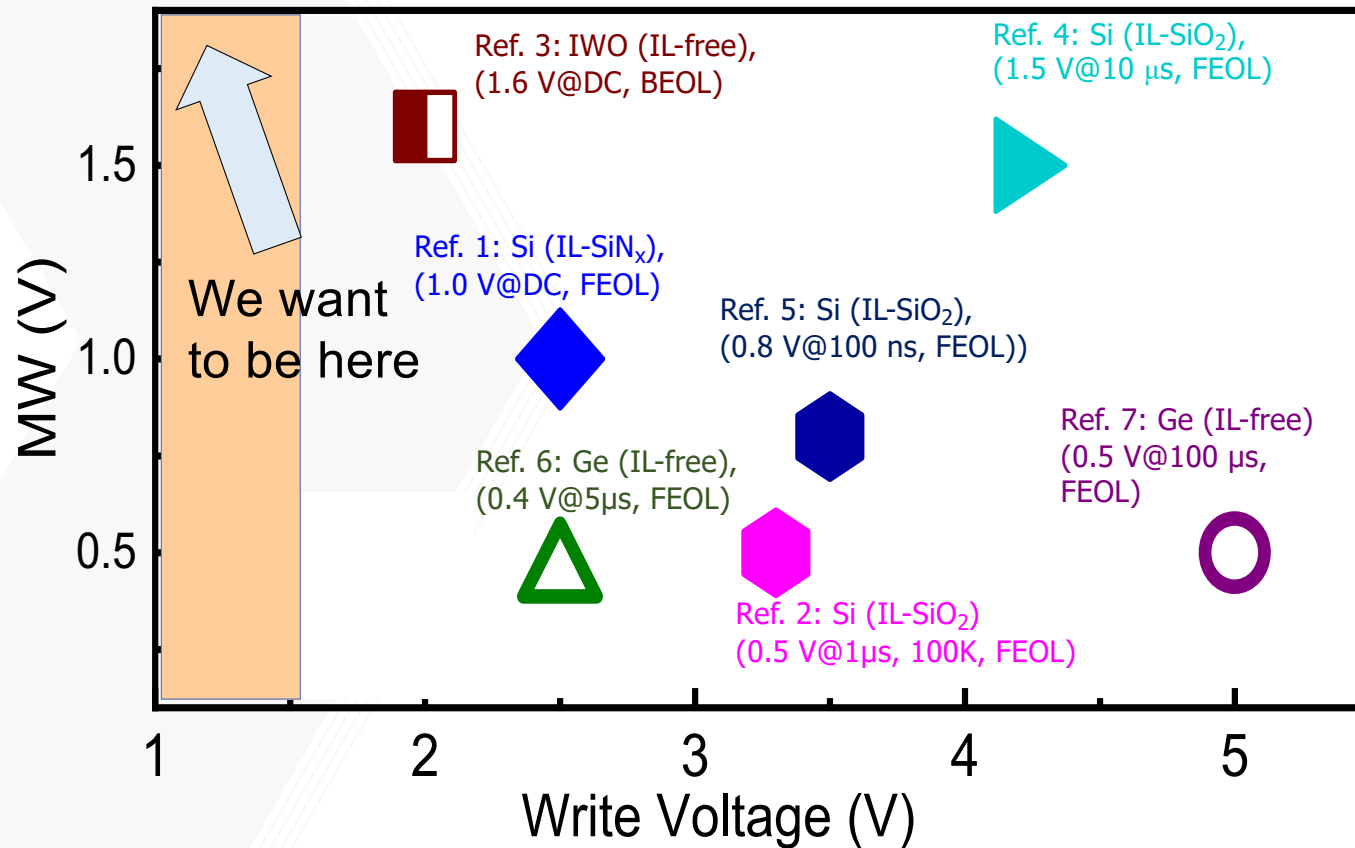
Wang, Z., Tasneem, N., Hur, J., Chen, H., Yu, S., Chern, W., & Khan, A. (2021, December). Standby bias improvement of read after write delay in ferroelectric field effect transistors. In *2021 IEEE International Electron Devices Meeting (IEDM)* (pp. 19-3). IEEE.

Benchmarking Memory Window v. Write Voltage Tradeoff



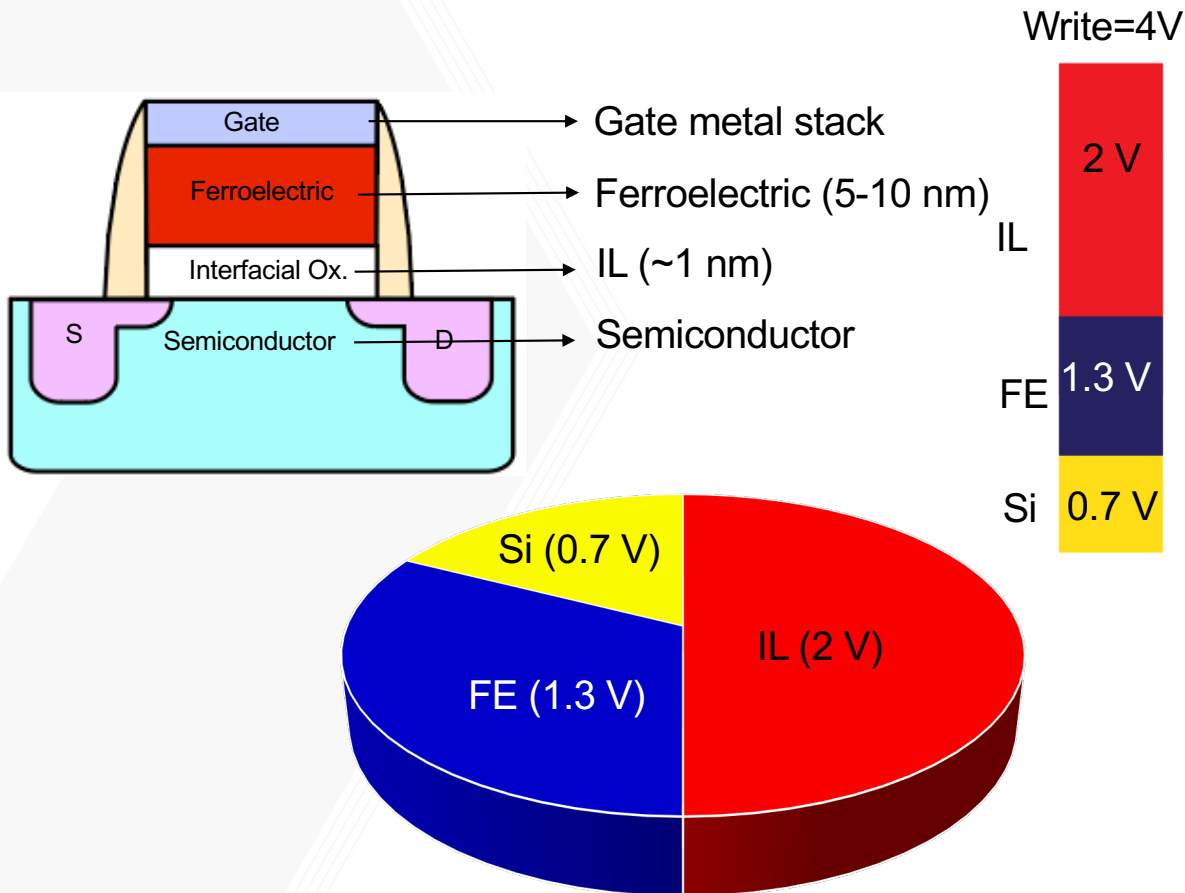
- [1] Tan *et al.*, *IEEE EDL*, 42, 994, (2021).
- [2] Tan *et al.*, *2020 IEEE Symposium on VLSI Technology* (2020).
- [3] Dutta *et al.*, *IEEE EDL*, 43, 382 (2022).
- [4] Dünkel *et al.*, *IEDM* (2017).
- [5] Nguyen *et al.*, *IEEE EDL*, 42, 1295, (2021).
- [6] Liu *et al.*, *IEEE EDL*, 40, 1419, (2019).
- [7] Zacharaki *et al.*, *ACS Appl. Electron. Mater.*, 4, (2022).

Benchmarking Memory Window v. Write Voltage Tradeoff

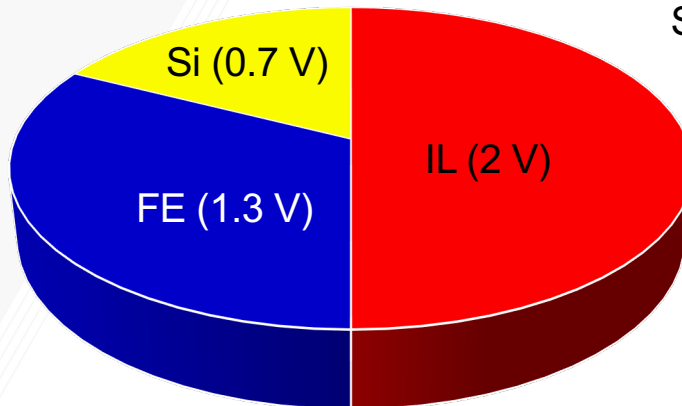
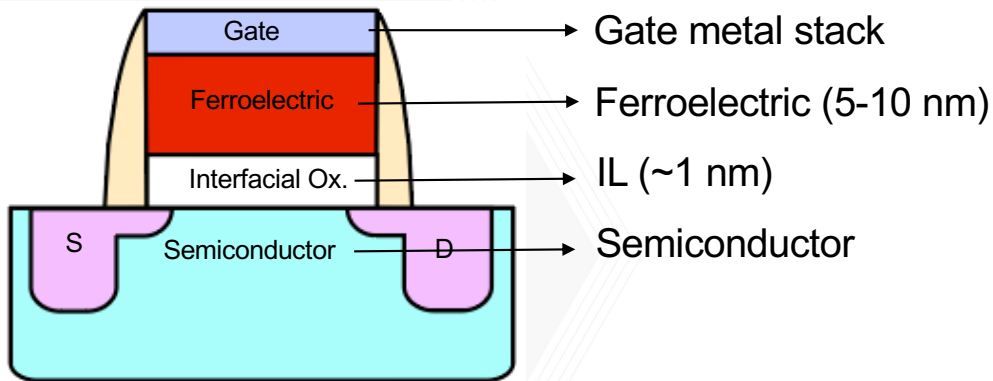


- [1] Tan *et al.*, *IEEE EDL*, 42, 994, (2021).
- [2] Tan *et al.*, *2020 IEEE Symposium on VLSI Technology* (2020).
- [3] Dutta *et al.*, *IEEE EDL*, 43, 382 (2022).
- [4] Dünkler *et al.*, *IEDM* (2017).
- [5] Nguyen *et al.*, *IEEE EDL*, 42, 1295, (2021).
- [6] Liu *et al.*, *IEEE EDL*, 40, 1419, (2019).
- [7] Zacharaki *et al.*, *ACS Appl. Electron. Mater.*, 4, (2022).

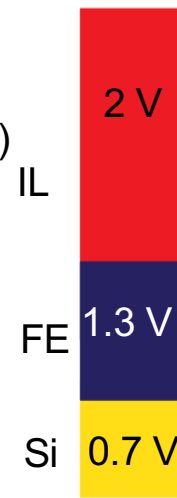
Write voltage vs. memory window trade-off



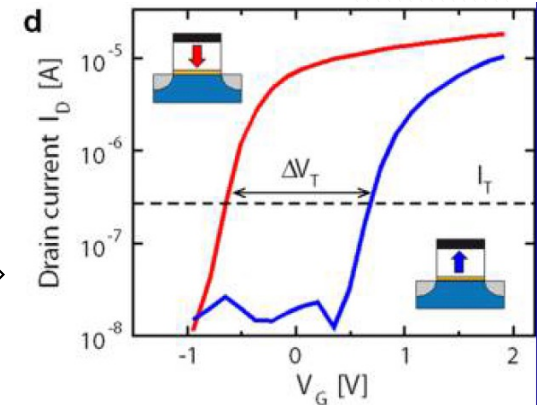
Write voltage vs. memory window trade-off



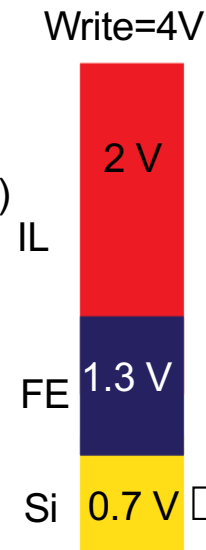
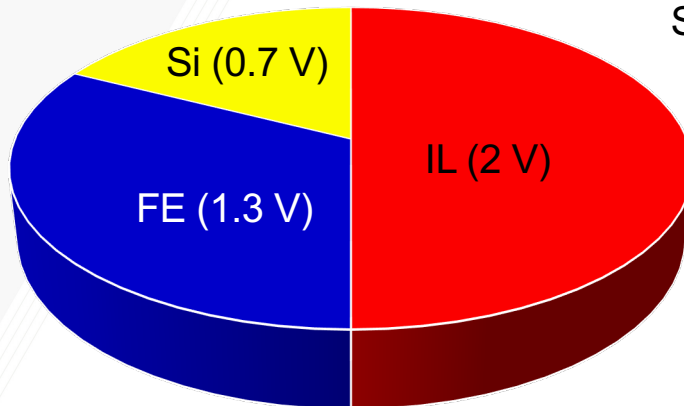
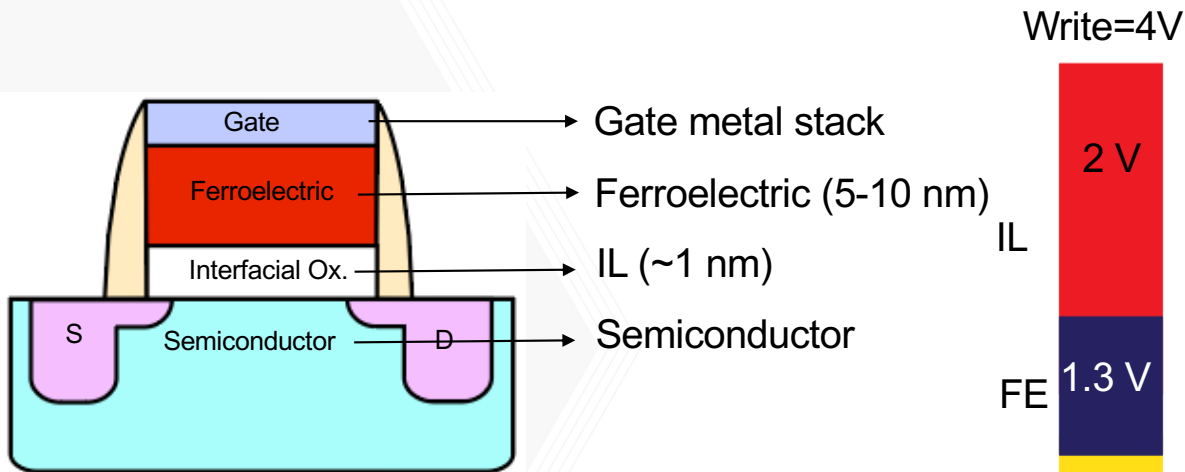
Write=4V



$$V_c \approx \sim 70\% \text{ of } V_{FE}$$
$$MW_{\max} = 2V_c$$

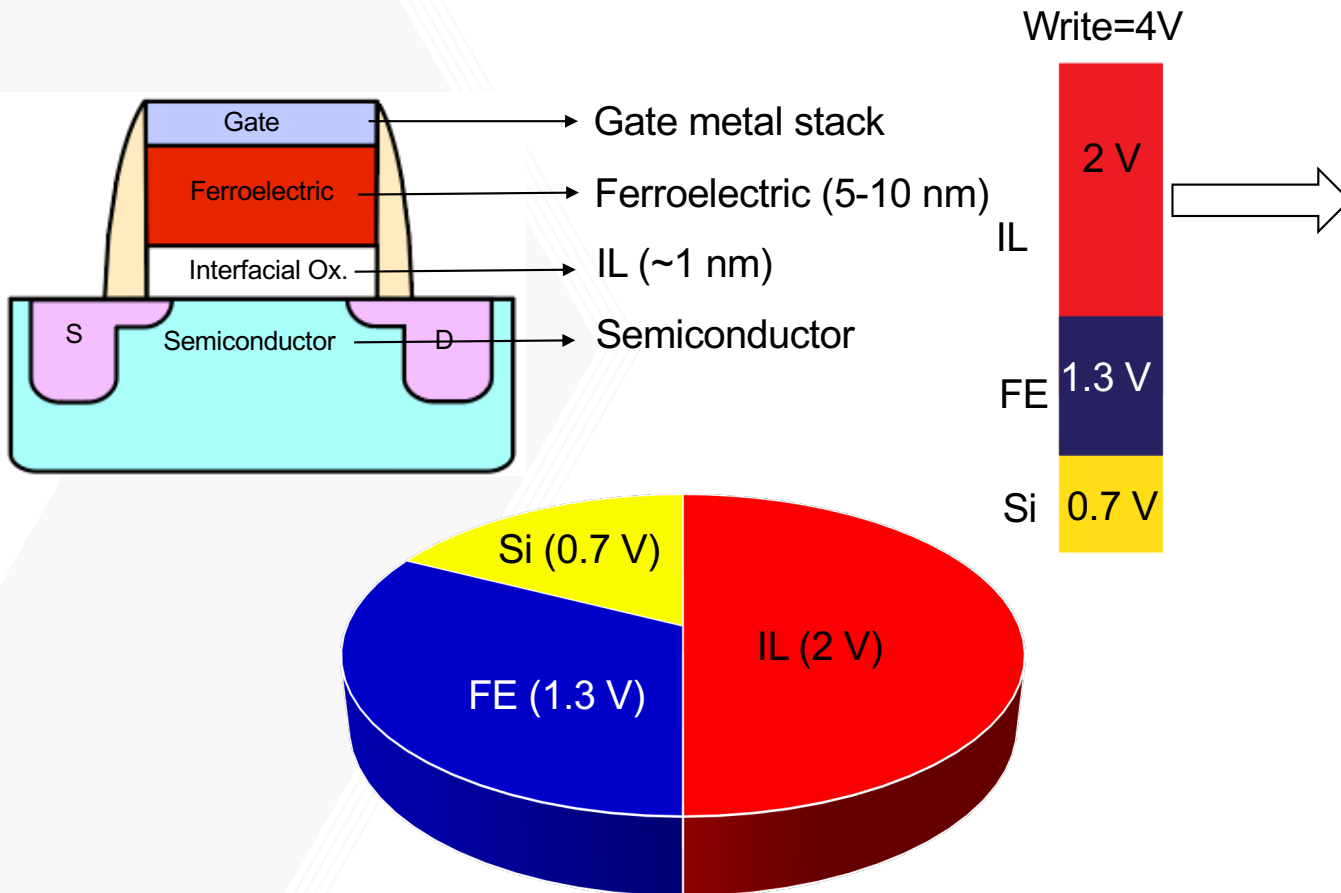


Write voltage vs. memory window trade-off



Changing the band-gap of the semiconductor By changing the channel material from Si to SiGe or Ge.

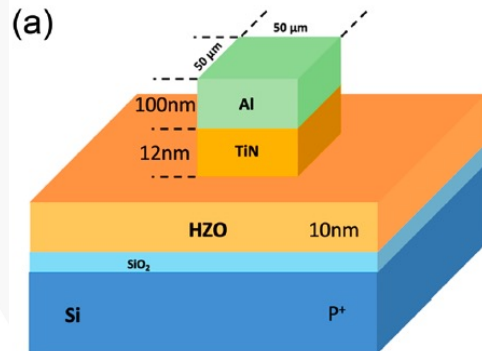
Write voltage vs. memory window trade-off



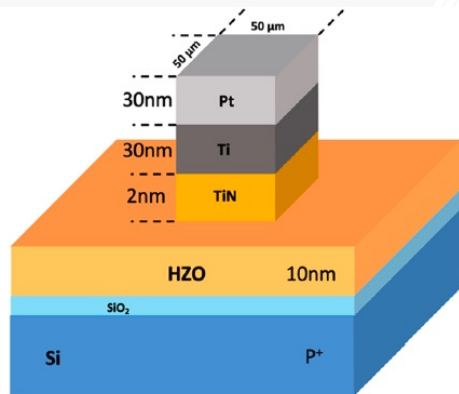
Reducing the thickness of the IL or increasing the K of the IL.

Reliability degradation is a concern.

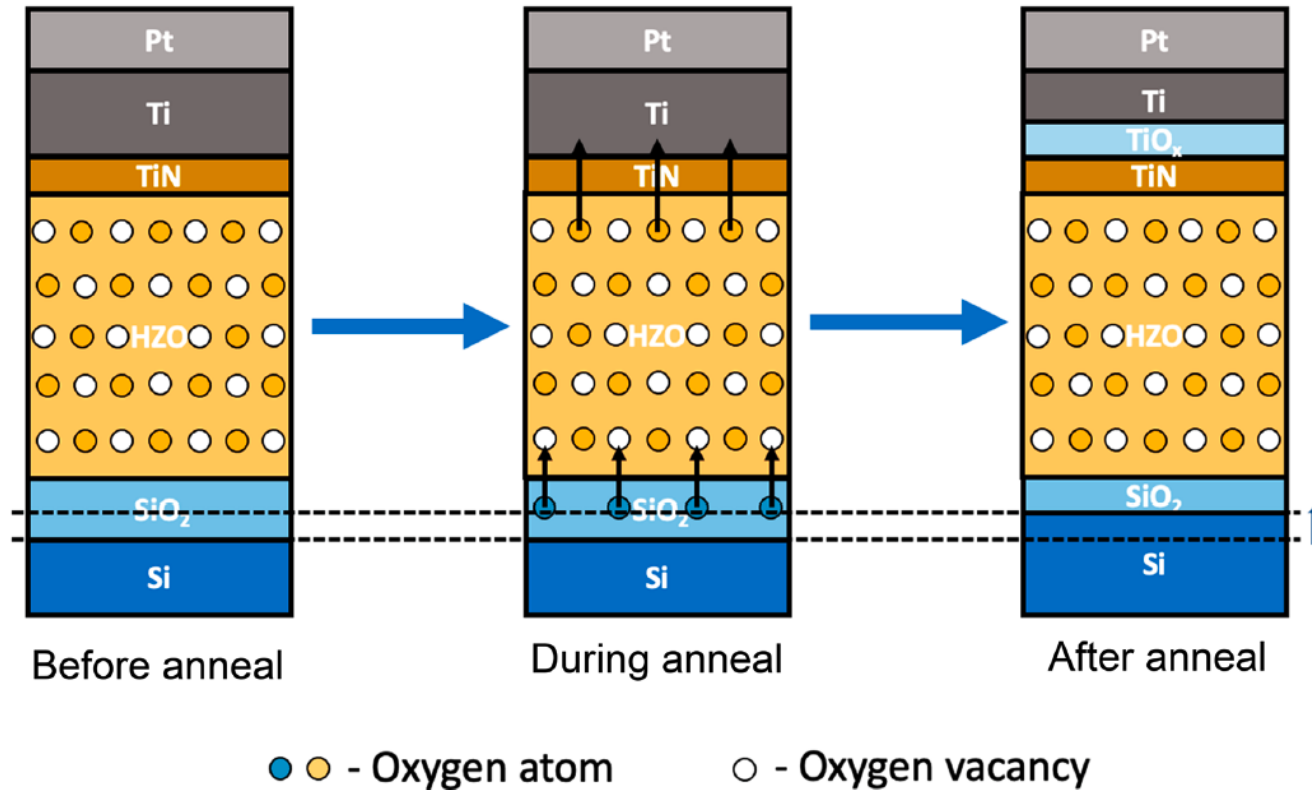
Remote oxygen scavenging to reduce IL thickness



Non-Scavenging

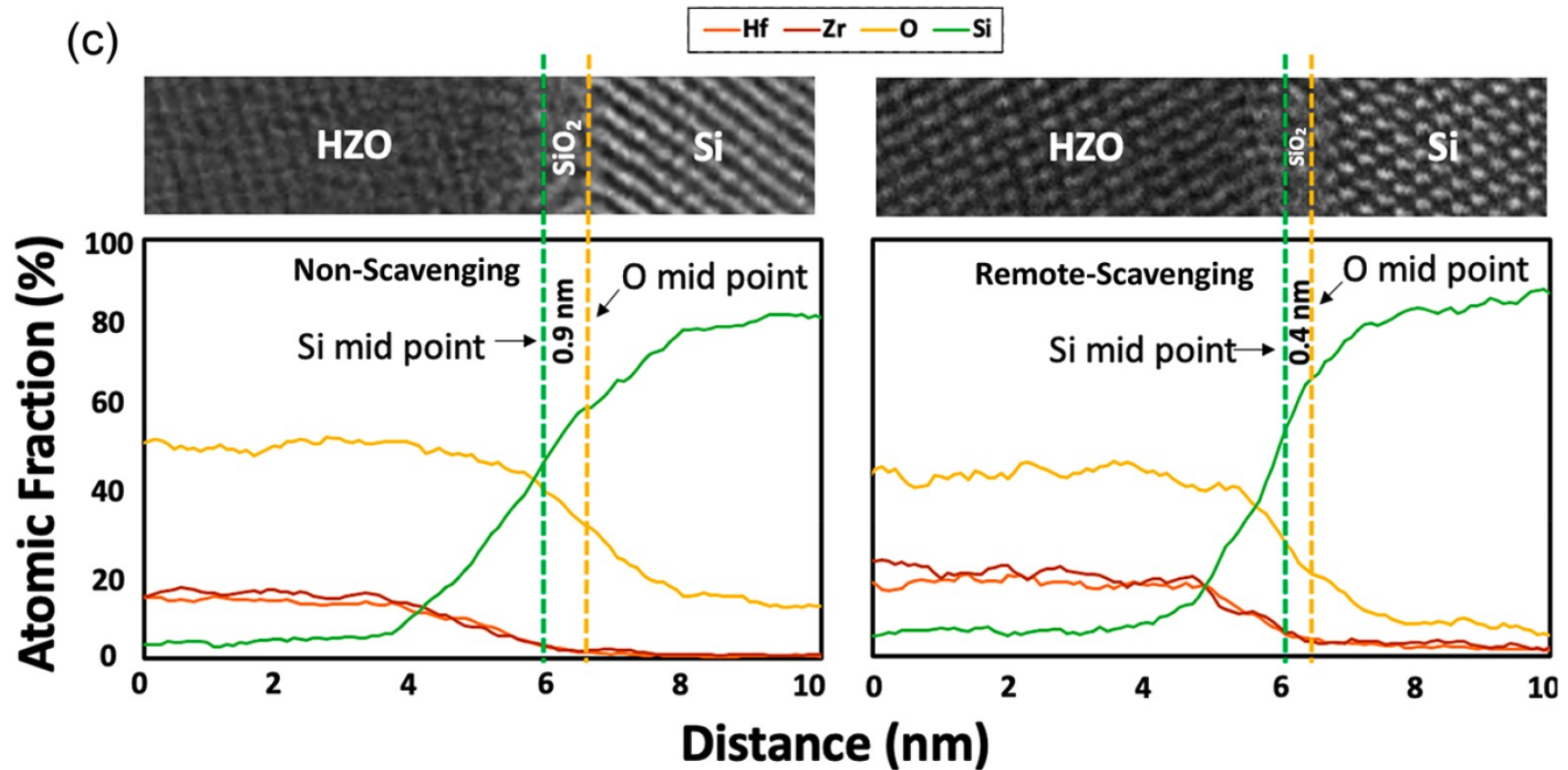


Remote-Scavenging



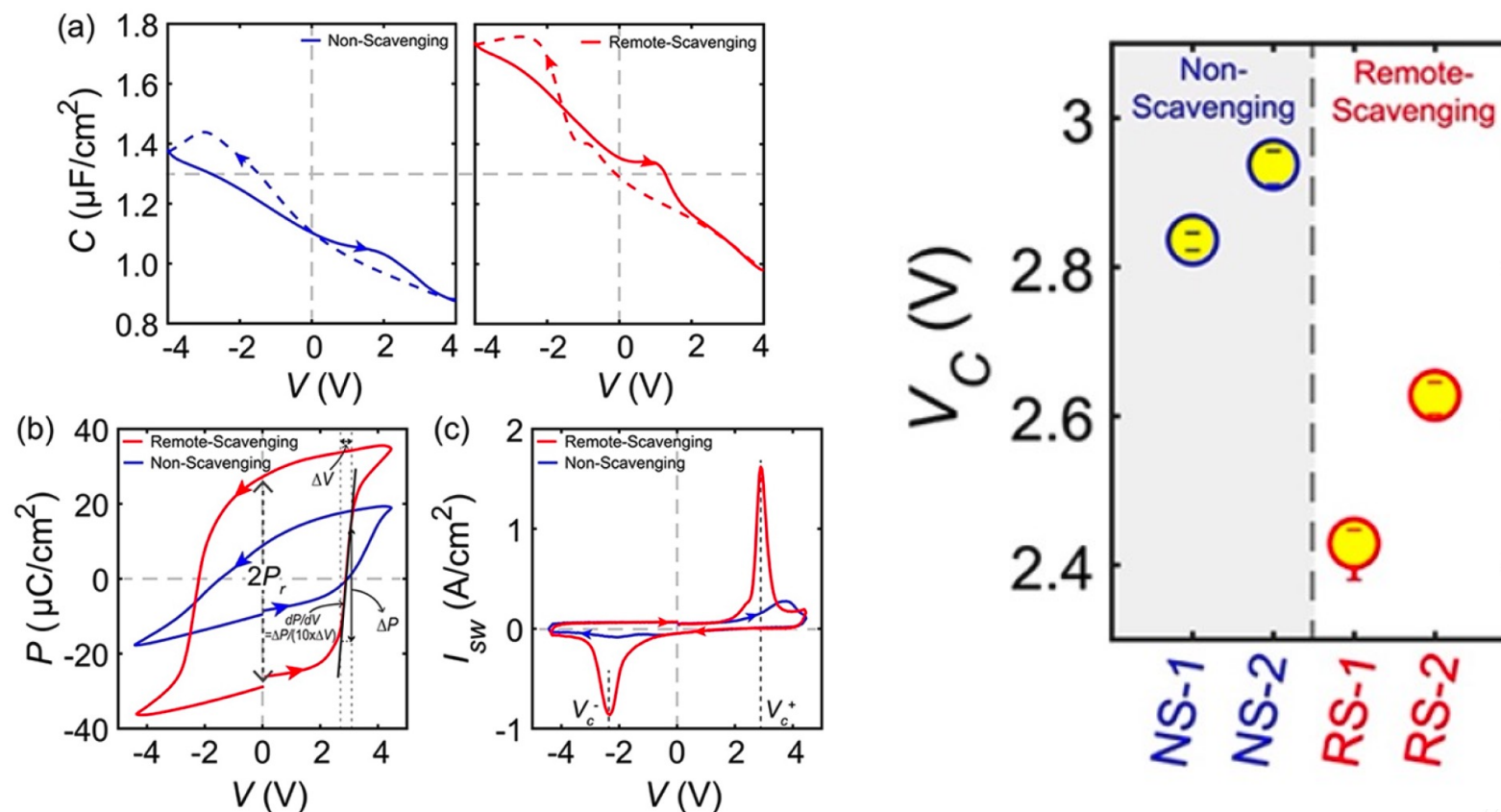
Tasneem et al. "Remote Oxygen Scavenging of the Interfacial Oxide Layer in Ferroelectric Hafnium–Zirconium Oxide-Based Metal–Oxide–Semiconductor Structures", ACS Appl. Mater. Interfaces 2022, 14, 43897–43906

Remote oxygen scavenging to reduce IL thickness



Tasneem et al. "Remote Oxygen Scavenging of the Interfacial Oxide Layer in Ferroelectric Hafnium–Zirconium Oxide-Based Metal–Oxide–Semiconductor Structures", *ACS Appl. Mater. Interfaces* 2022, 14, 43897–43906

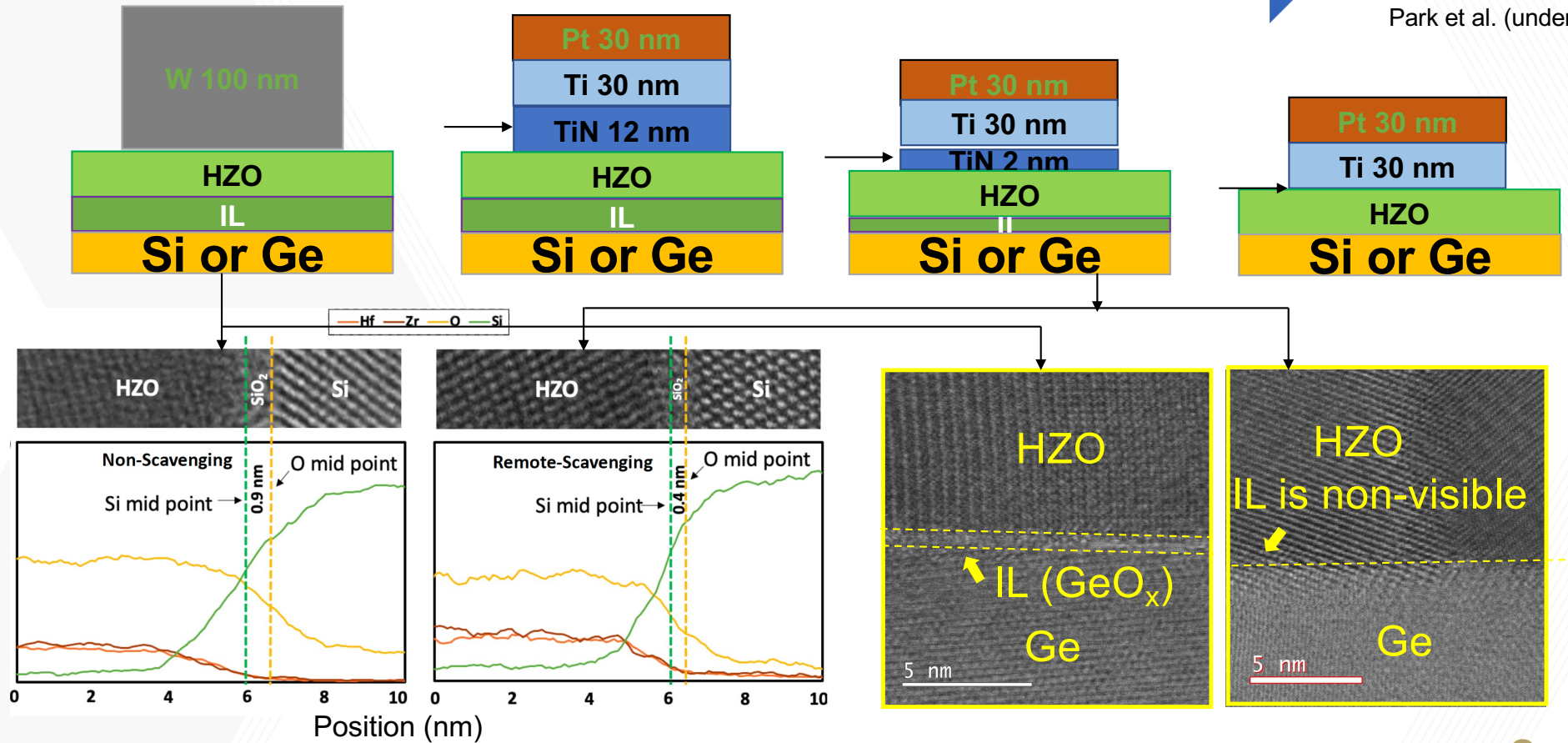
Remote oxygen scavenging to reduce IL thickness



Tasneem et al. "Remote Oxygen Scavenging of the Interfacial Oxide Layer in Ferroelectric Hafnium–Zirconium Oxide-Based Metal–Oxide–Semiconductor Structures", *ACS Appl. Mater. Interfaces* 2022, 14, 43897–43906

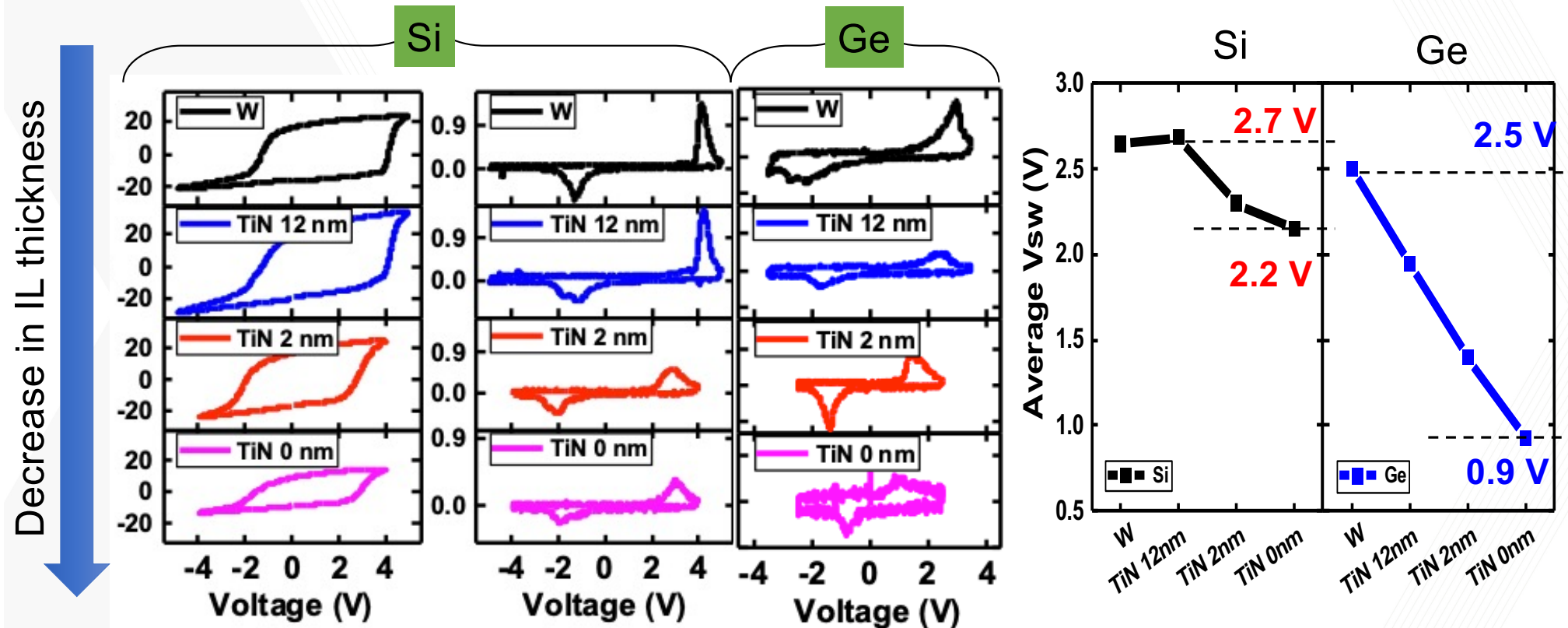
Decrease in IL thickness

Park et al. (under review)



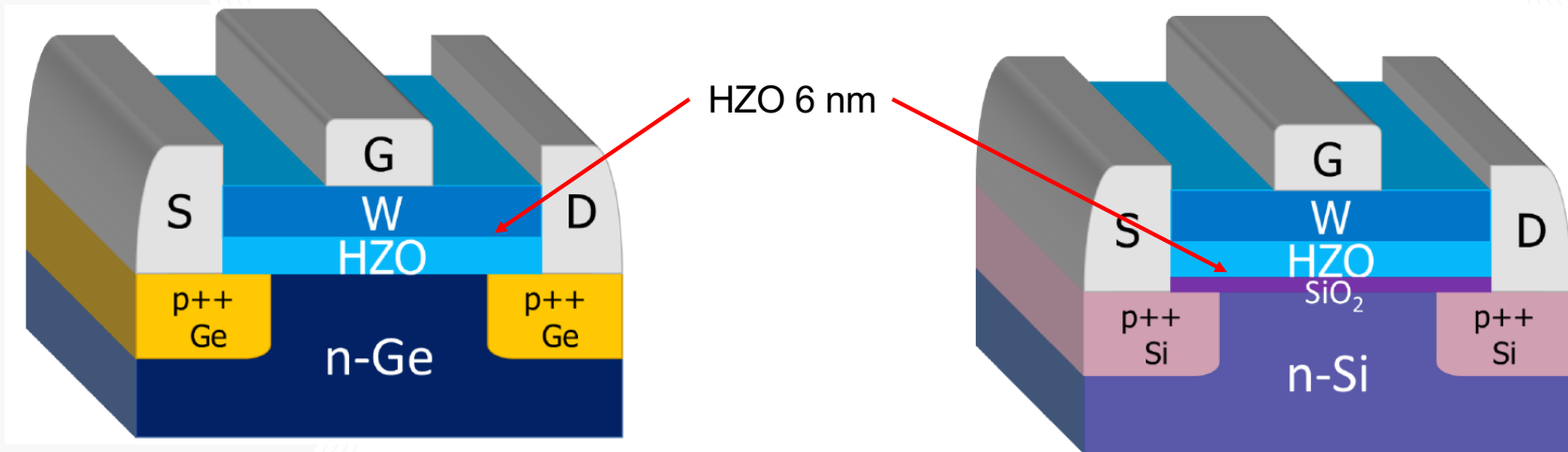
Remote oxygen scavenging can result in controllable IL thickness.

The effect of the IL thickness on V_c



Dramatic reduction in coercive voltage is observed in Ge platform with the change of the gate metal stack.

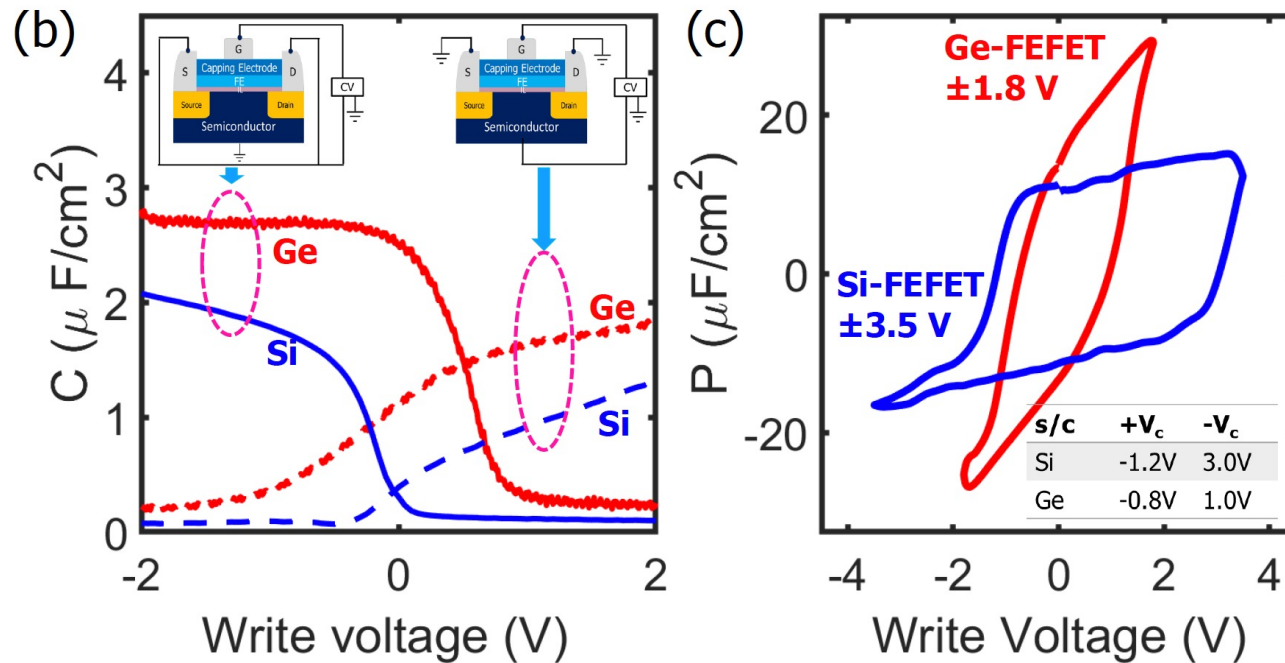
Ge-channel FEFETs with record-low write voltages



Si and Ge-channel FEFETs fabricated with the same 6 nm HZO layers, under similar process and fabrication conditions.

Das, Dipjyoti, et al. "A Ge-Channel Ferroelectric Field Effect Transistor with Logic-Compatible Write Voltage." *IEEE Electron Device Letters* (2022).

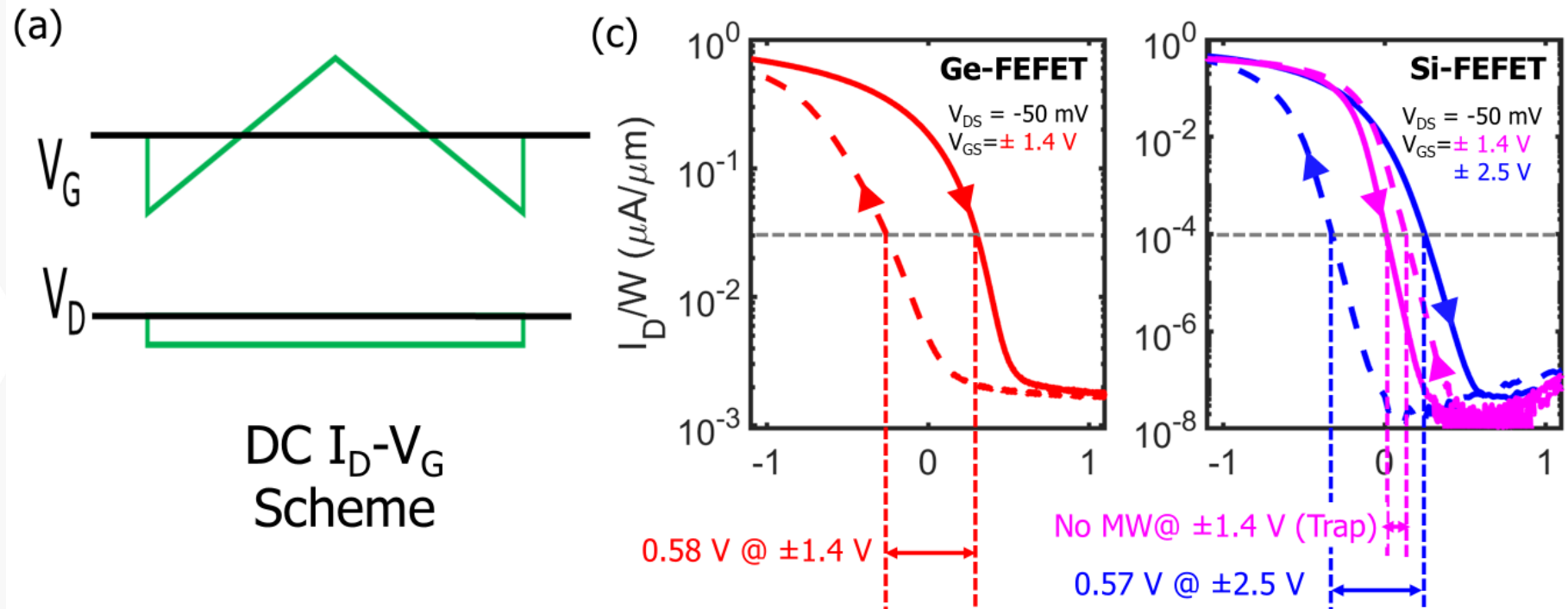
Ge-channel FEFETs with record-low write voltages



Significant increase on the on-capacitance and reduction in coercive voltage in Ge-channel FEFET.

Das, Dipjyoti, et al. "A Ge-Channel Ferroelectric Field Effect Transistor with Logic-Compatible Write Voltage." *IEEE Electron Device Letters* (2022).

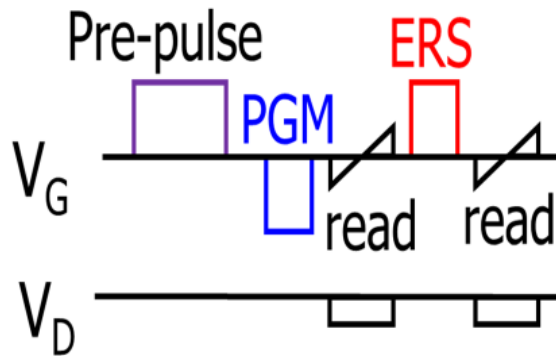
DC I_D - V_G characteristics



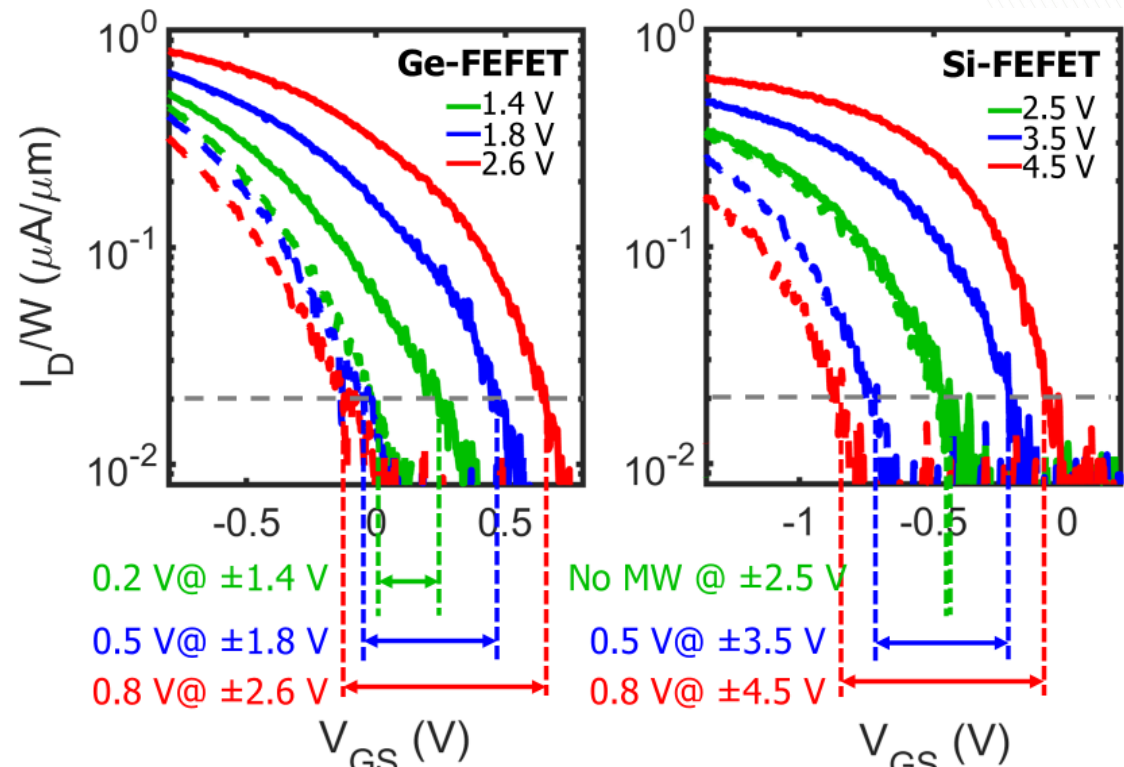
Significant reduction in the write voltage for iso-memory MW condition in Ge-FEFET.

Das, Dipjyoti, et al. "A Ge-Channel Ferroelectric Field Effect Transistor with Logic-Compatible Write Voltage." *IEEE Electron Device Letters* (2022).

Pulsed I_D - V_G characteristics



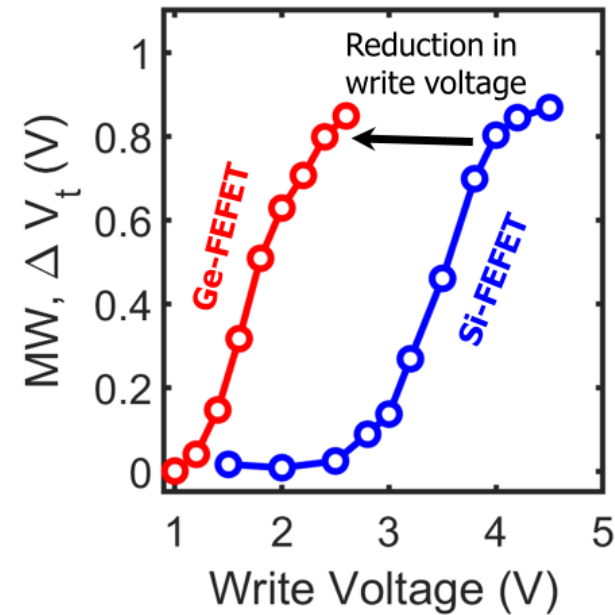
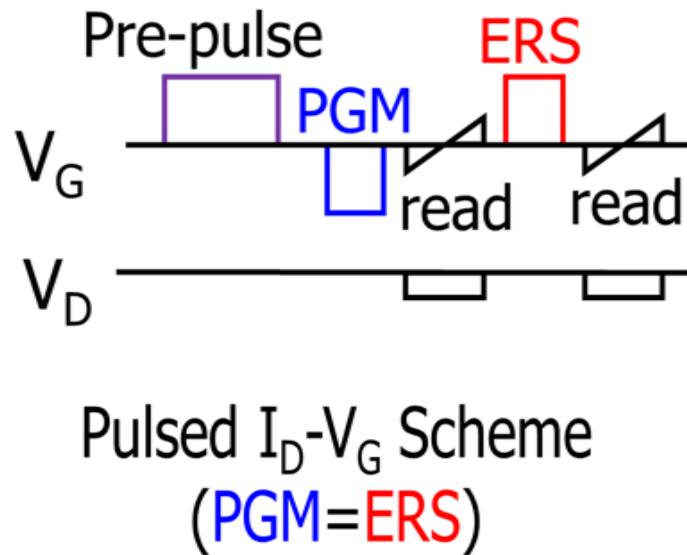
Pulsed I_D - V_G Scheme



Significant reduction in the write voltage for iso-memory MW condition in Ge-FEFET.

Das, Dipjyoti, et al. "A Ge-Channel Ferroelectric Field Effect Transistor with Logic-Compatible Write Voltage." *IEEE Electron Device Letters* (2022).

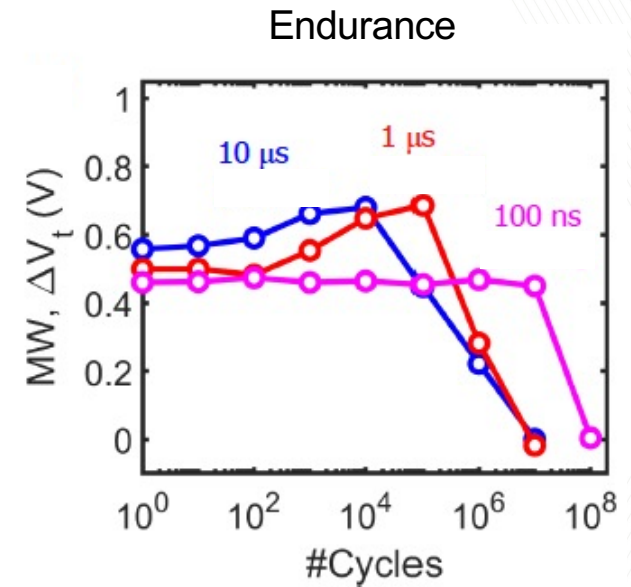
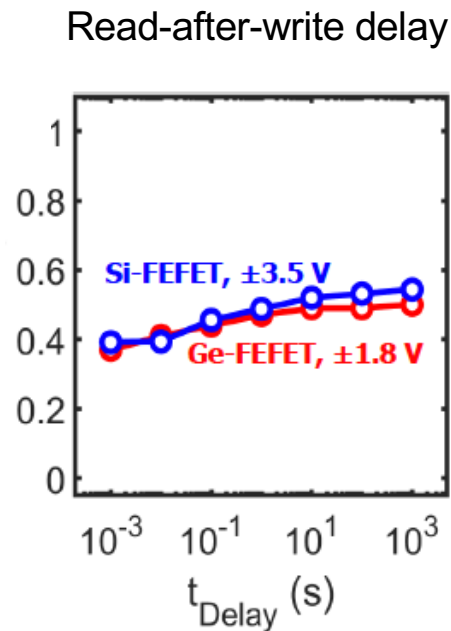
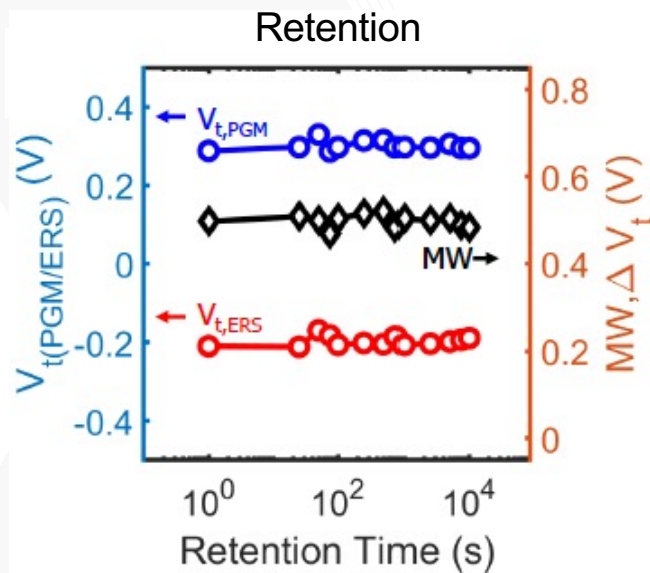
Pulsed I_D - V_G characteristics



Significant reduction in the write voltage for iso-memory MW condition in Ge-FEFET.

Das, Dipjyoti, et al. "A Ge-Channel Ferroelectric Field Effect Transistor with Logic-Compatible Write Voltage." *IEEE Electron Device Letters* (2022).

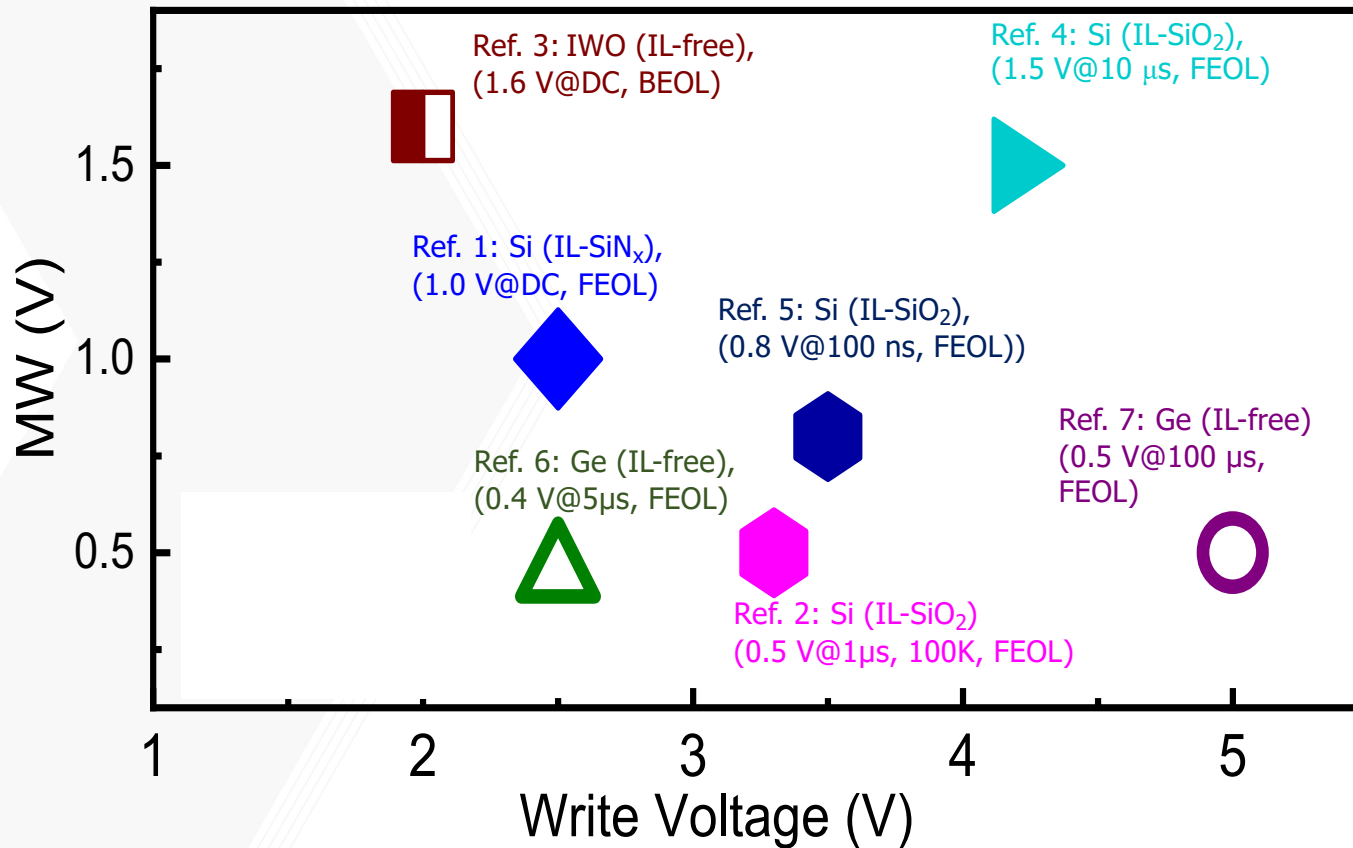
Retention, endurance and read-after-write delay



The Ge-FEFET show write endurance of 107 cycles, excellent data retention and immediate read-after-write capability.

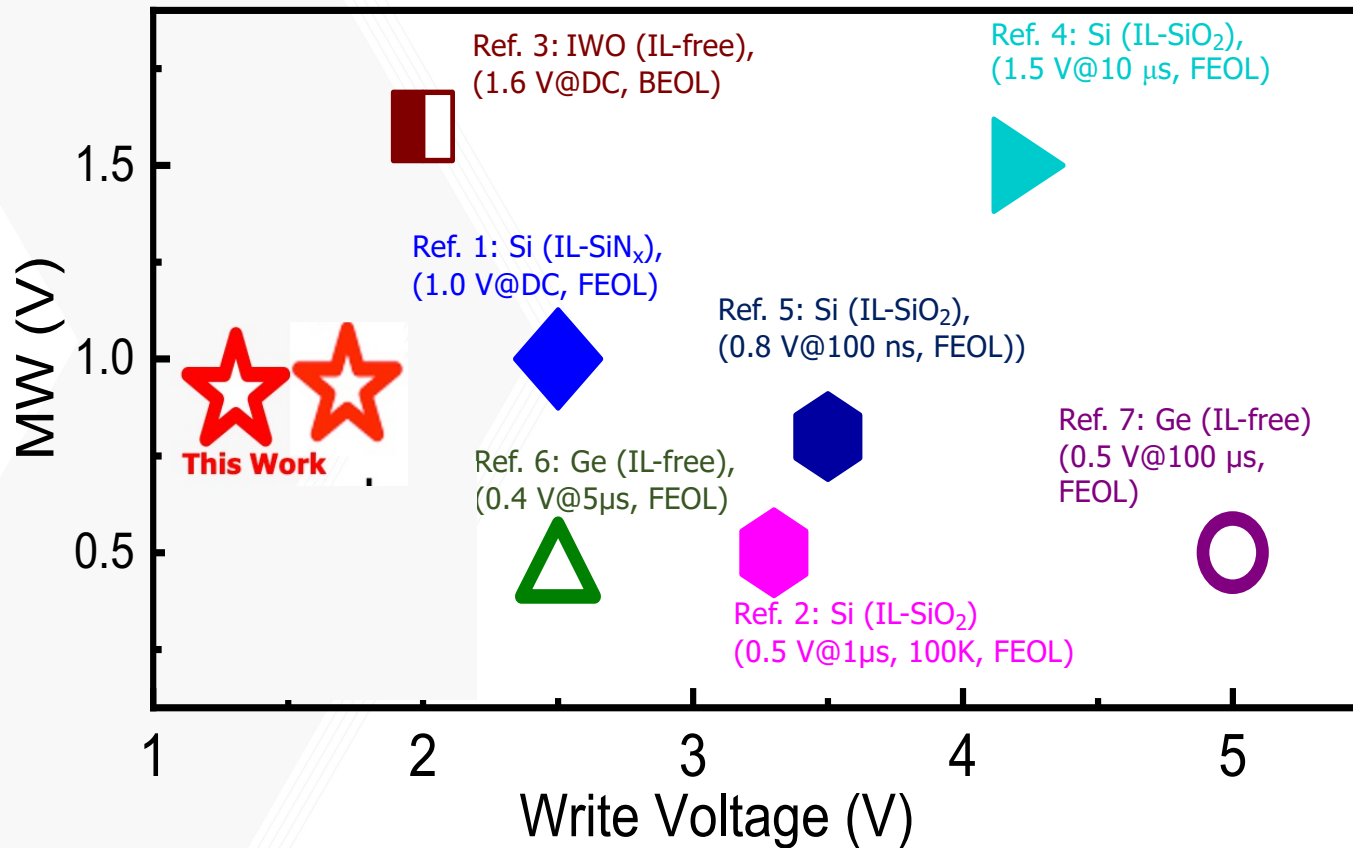
Das, Dipjyoti, et al. "A Ge-Channel Ferroelectric Field Effect Transistor with Logic-Compatible Write Voltage." *IEEE Electron Device Letters* (2022).

Benchmarking Memory Window v. Write Voltage Tradeoff



- [1] Tan *et al.*, *IEEE EDL*, 42, 994, (2021).
- [2] Tan *et al.*, *2020 IEEE Symposium on VLSI Technology* (2020).
- [3] Dutta *et al.*, *IEEE EDL*, 43, 382 (2022).
- [4] Dünkler *et al.*, *IEDM* (2017).
- [5] Nguyen *et al.*, *IEEE EDL*, 42, 1295, (2021).
- [6] Liu *et al.*, *IEEE EDL*, 40, 1419, (2019).
- [7] Zacharaki *et al.*, *ACS Appl. Electron. Mater.*, 4, (2022).

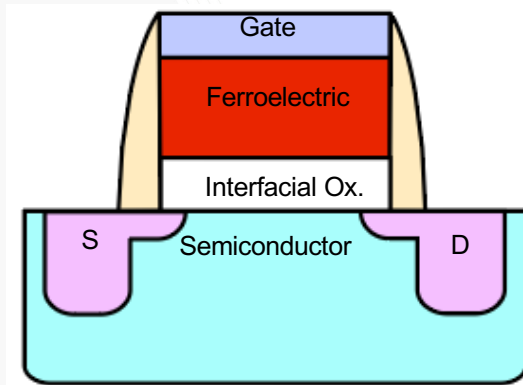
Benchmarking Memory Window v. Write Voltage Tradeoff



Das, Dipjyoti, et al. "A Ge-Channel Ferroelectric Field Effect Transistor with Logic-Compatible Write Voltage." *IEEE Electron Device Letters* (2022).

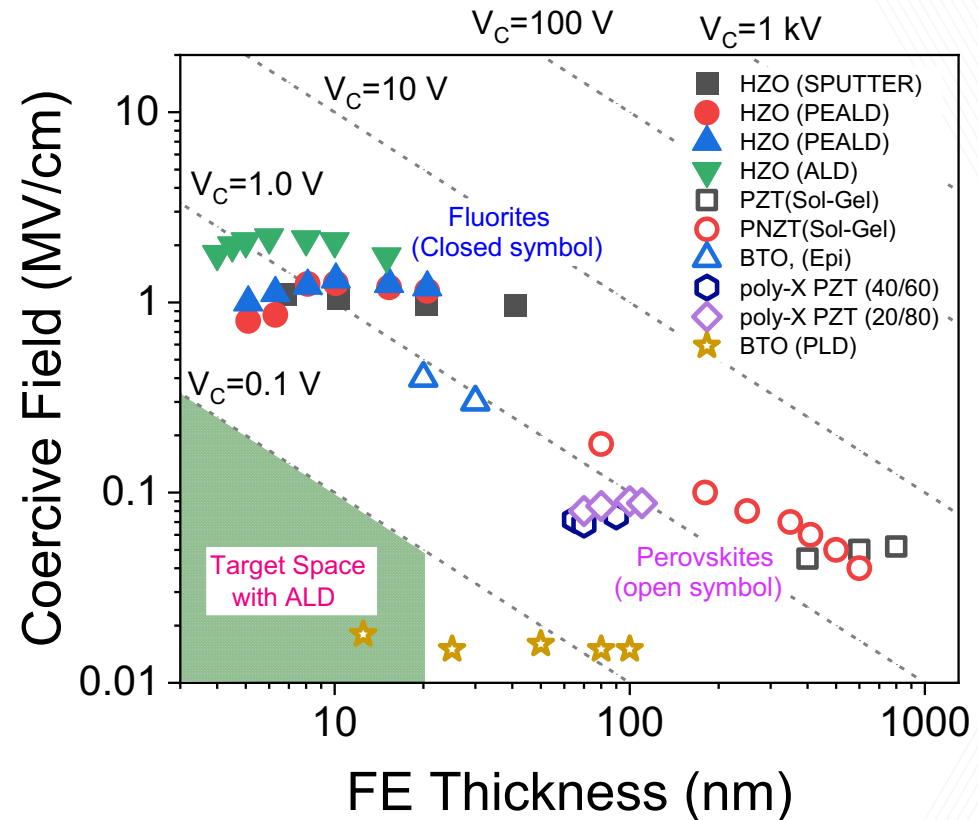
- [1] Tan *et al.*, *IEEE EDL*, 42, 994, (2021).
- [2] Tan *et al.*, *2020 IEEE Symposium on VLSI Technology* (2020).
- [3] Dutta *et al.*, *IEEE EDL*, 43, 382 (2022).
- [4] D unkel *et al.*, *IEDM* (2017).
- [5] Nguyen *et al.*, *IEEE EDL*, 42, 1295, (2021).
- [6] Liu *et al.*, *IEEE EDL*, 40, 1419, (2019).
- [7] Zacharaki *et al.*, *ACS Appl. Electron. Mater.*, 4, (2022).

Towards 0.5 V Ferroelectric Memories



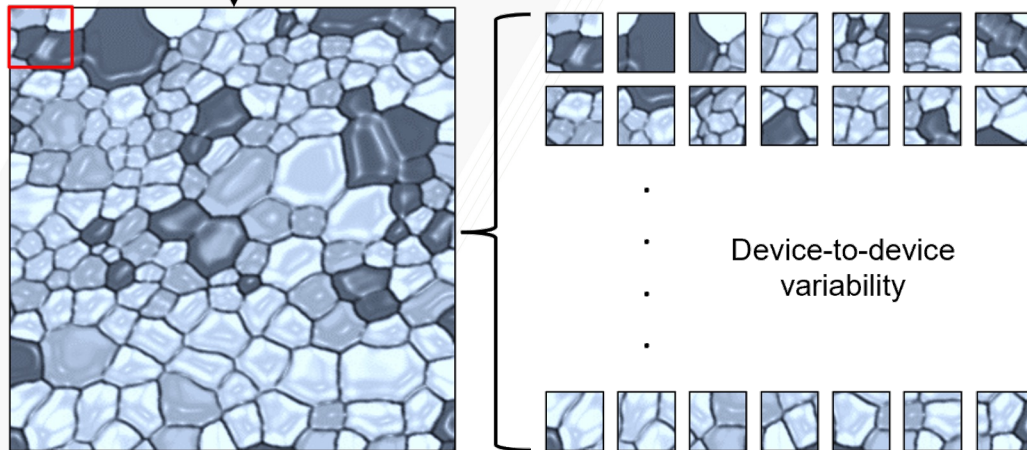
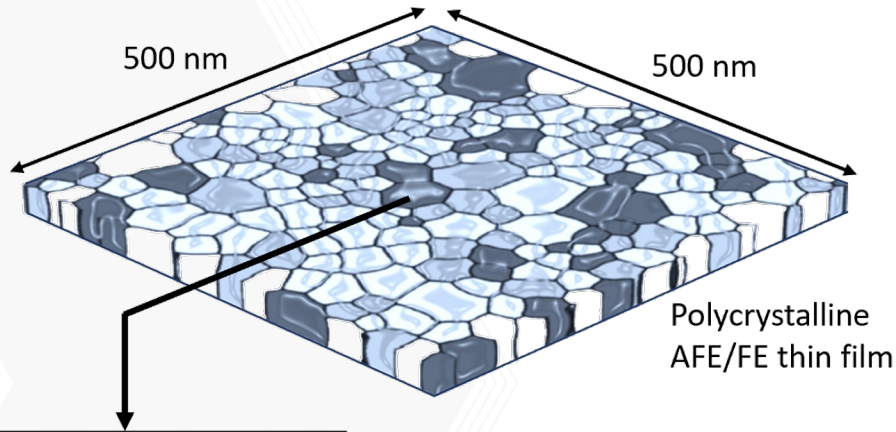
Classical Ferroelectrics:
 BaTiO_3 etc.

Emerging CMOS compatible
Ferroelectrics:
Doped HfO_2



Is there a case for classical ferroelectric oxides such as BaTiO_3 for emerging memory applications?

Microstructure in FEFETs



1.
Phase
(o-, m-, t-)

3.
Sub-grain features (domain
walls, interphase boundaries)

2.
Grain size &
orientation

Device-to-device variability

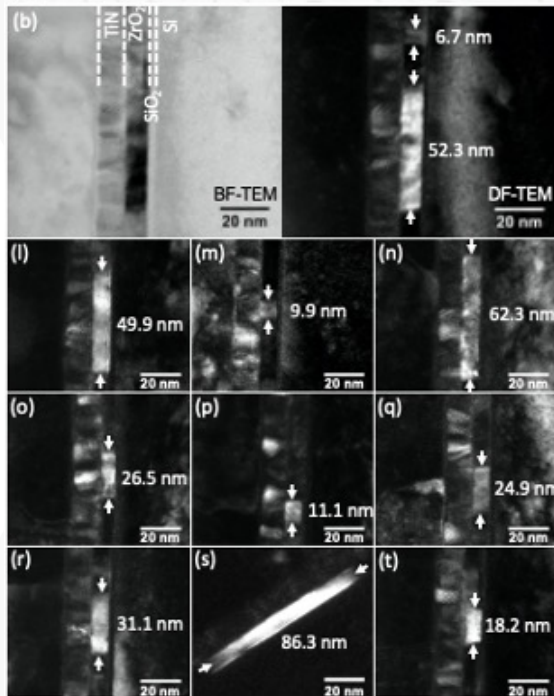
- Applied field causes changes in microstructure
 - Enables multi-level NVM
 - Poses challenges for (VLSI)

4.
Irreversible change of grain
structure electric field cycling

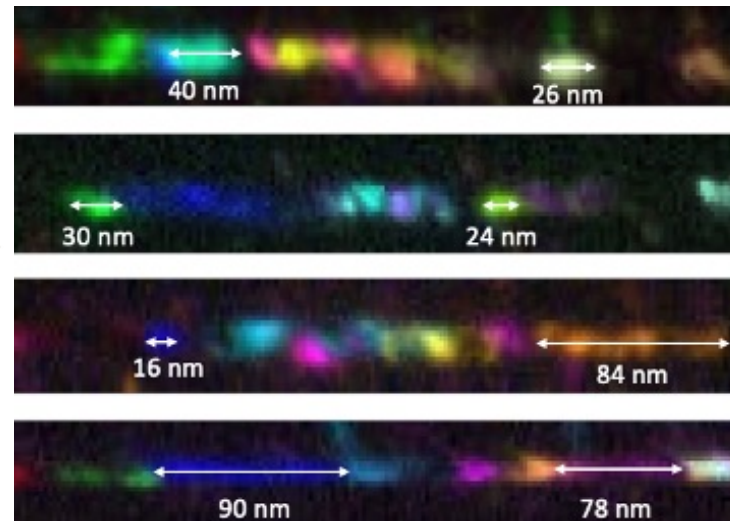
Cycle-to-cycle variability

Quantification of microstructure

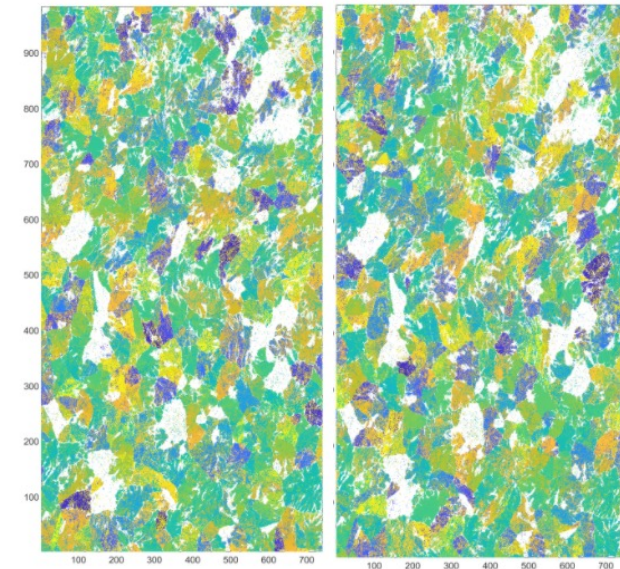
Dark field TEM



Nano-Beam Electron
Diffraction
(NBED)

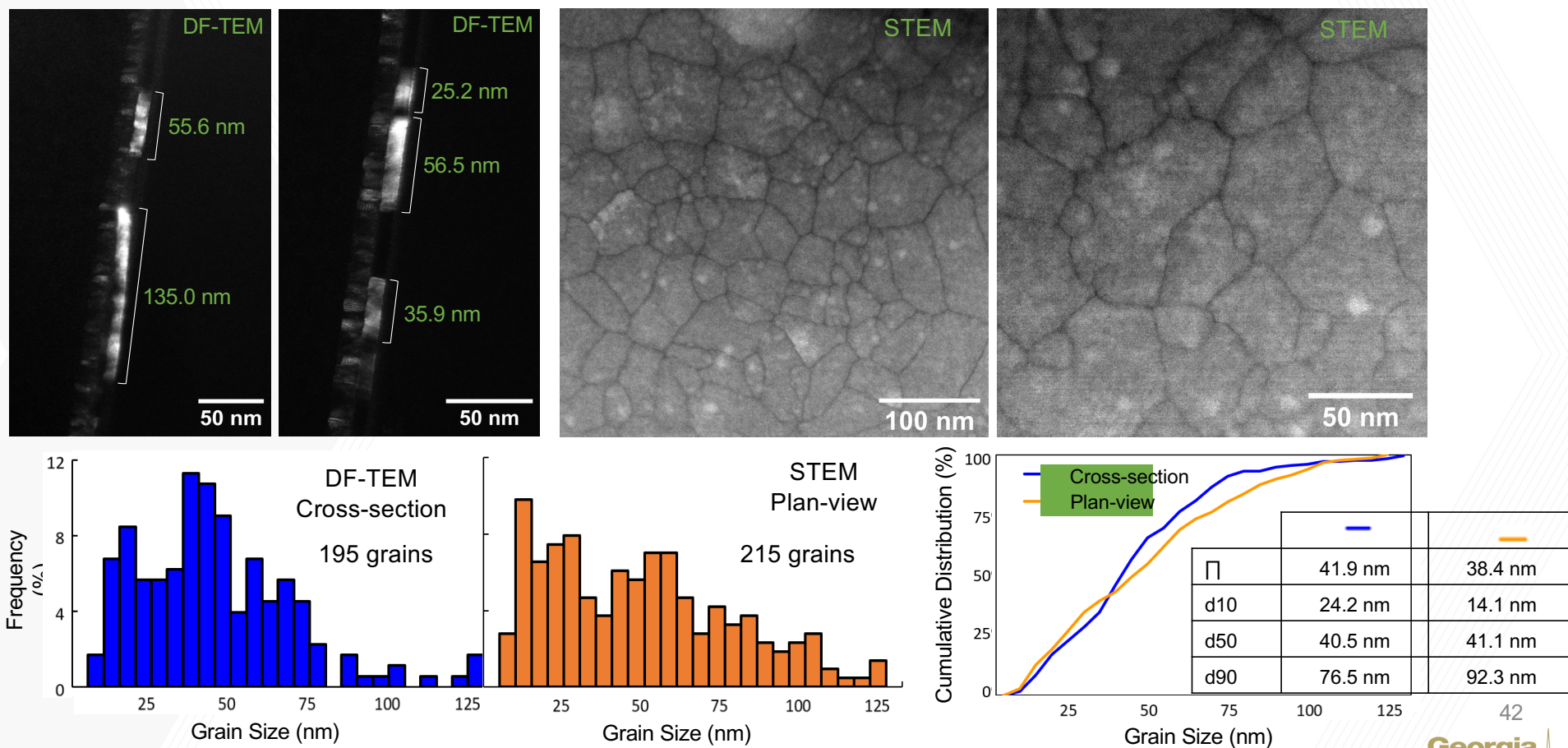


Transmission Kikuchi
Diffraction (TKD)



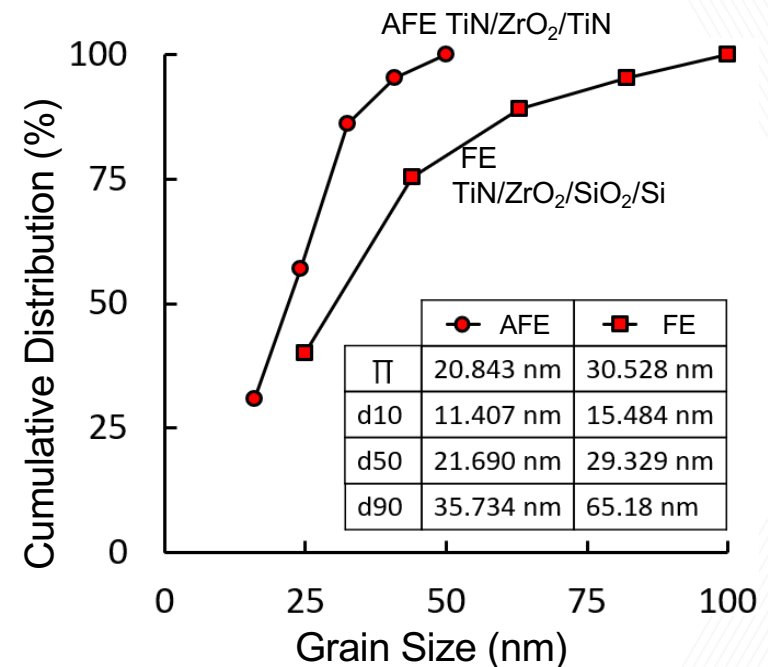
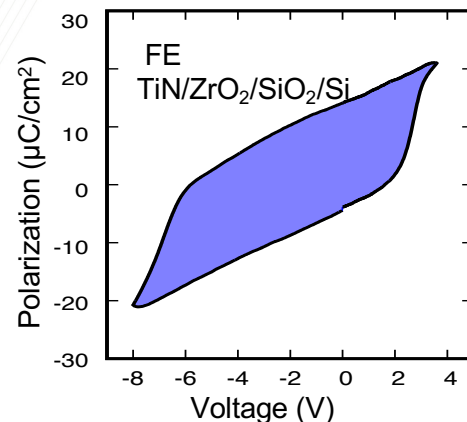
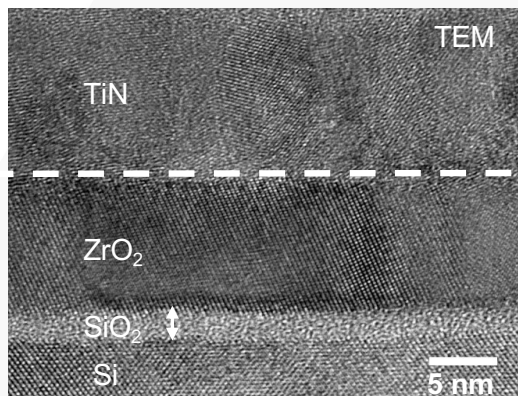
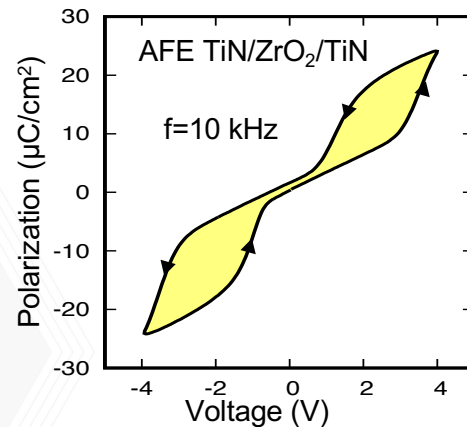
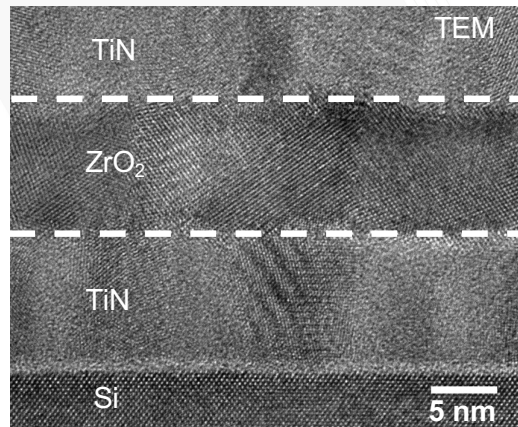
Lombardo, S. F., et al. "Local epitaxial-like templating effects and grain size distribution in atomic layer deposited $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$ thin film ferroelectric capacitors." *Applied Physics Letters* 119.9 (2021): 092901.

Quantification of microstructure



Chae, K., Lombardo, S. F., Tasneem, N., Tian, M., Kumarasubramanian, H., Hur, J., ... & Khan, A. I. (2022). Local Epitaxial Templating Effects in Ferroelectric and Antiferroelectric ZrO₂. *ACS Applied Materials & Interfaces*, 14(32), 36771-36780.

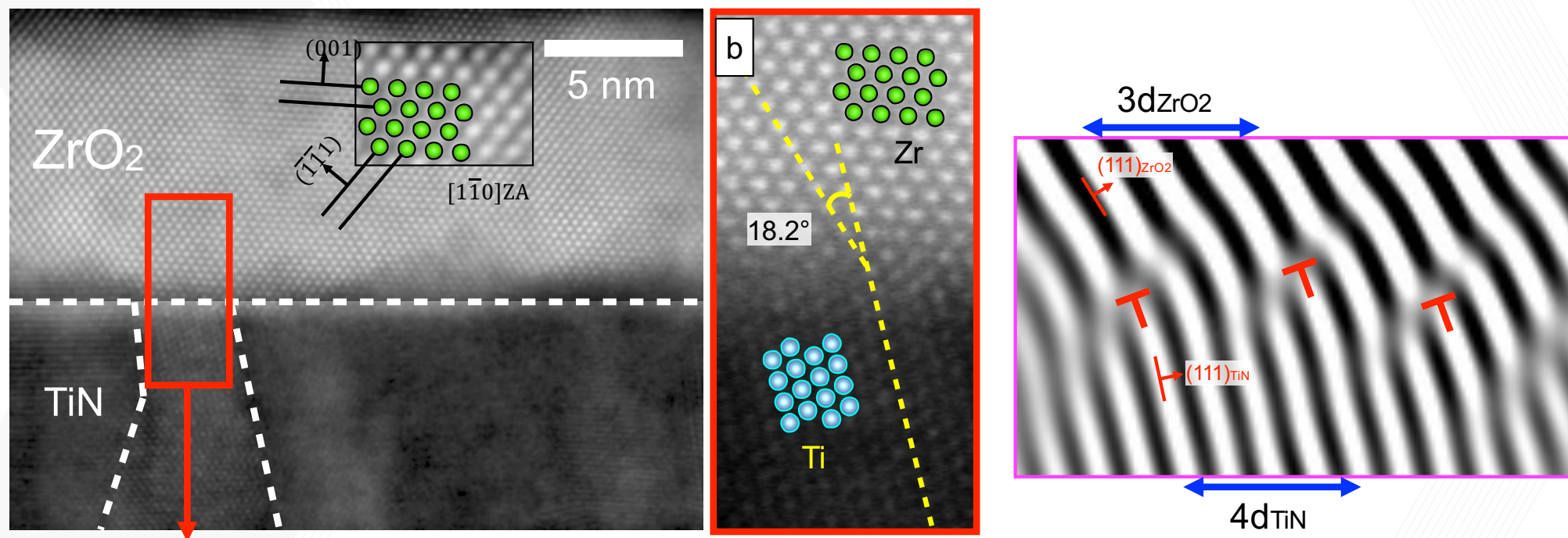
Microstructural origin of AFE and FE in ZrO₂



Smaller grain size favored by Tetragonal phase over FE Orthorhombic phase

Chae, K., Lombardo, S. F., Tasneem, N., Tian, M., Kumarasubramanian, H., Hur, J., ... & Khan, A. I. (2022). Local Epitaxial Templating Effects in Ferroelectric and Antiferroelectric ZrO₂. *ACS Applied Materials & Interfaces*, 14(32), 36771-36780.

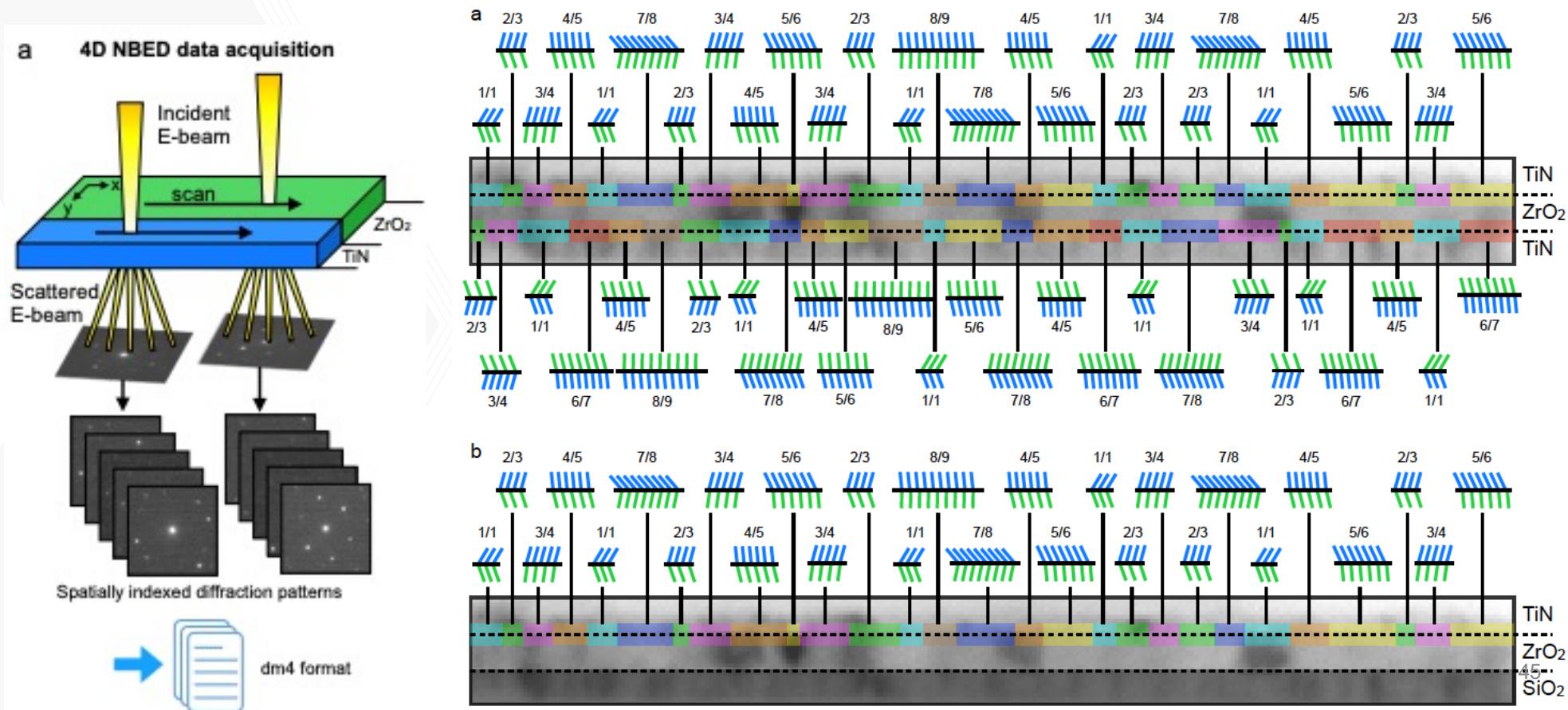
Epitaxial-like templating: Near coincidence site epitaxy



Orientations in TiN and ZrO₂ are often correlated.

Chae, K., Lombardo, S. F., Tasneem, N., Tian, M., Kumarasubramanian, H., Hur, J., ... & Khan, A. I. (2022). Local Epitaxial Templating Effects in Ferroelectric and Antiferroelectric ZrO₂. *ACS Applied Materials & Interfaces*, 14(32), 36771-36780.

Epitaxial-like templating: Near coincidence site epitaxy

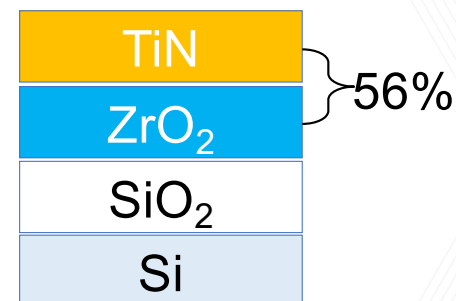
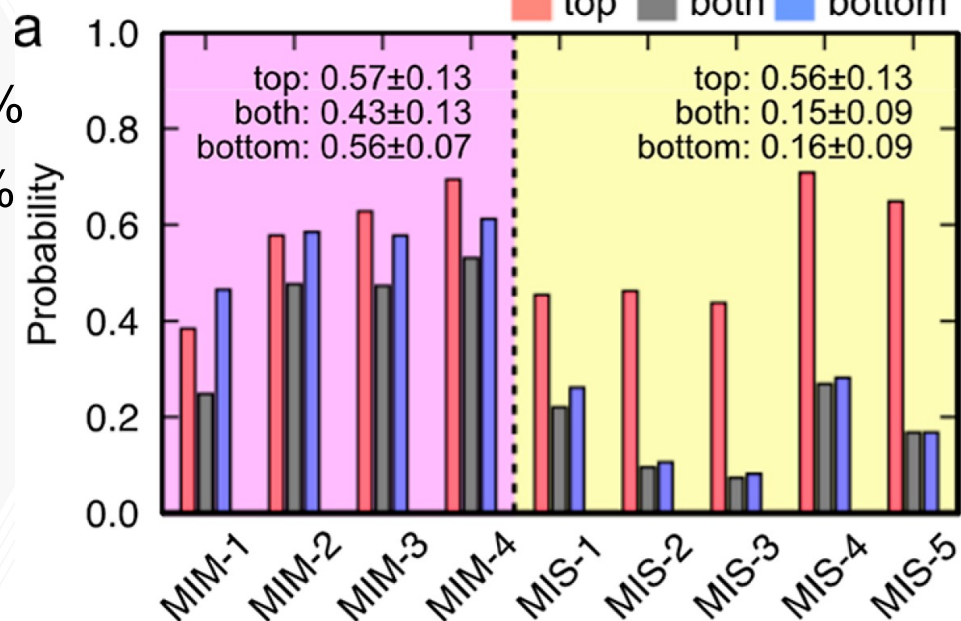


Chae, K., Lombardo, S. F., Tasneem, N., Tian, M., Kumarasubramanian, H., Hur, J., ... & Khan, A. I. (2022). Local Epitaxial Templating Effects in Ferroelectric and Antiferroelectric ZrO₂. *ACS Applied Materials & Interfaces*, 14(32), 36771-36780.

Statistical Epitaxy Analysis via Automated NBED

MIM

MOS



Chae, K., Lombardo, S. F., Tasneem, N., Tian, M., Kumarasubramanian, H., Hur, J., ... & Khan, A. I. (2022). Local Epitaxial Templating Effects in Ferroelectric and Antiferroelectric ZrO₂. *ACS Applied Materials & Interfaces*, 14(32), 36771-36780.

Machine Learning Assisted Predictive TCAD Modeling (from Metrology to Device Metrics)

Ferro polarization map (from TKD data from SEM/TEM)

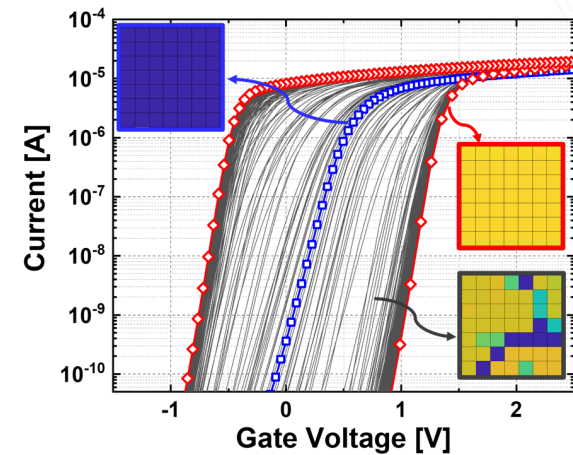
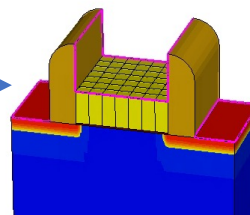
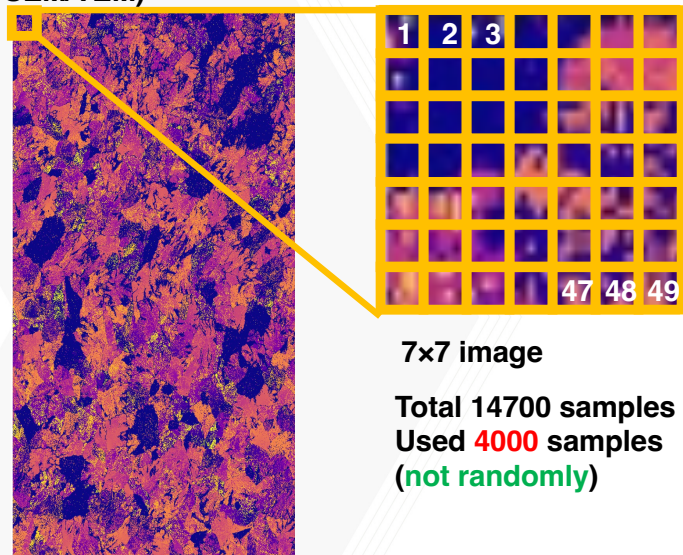


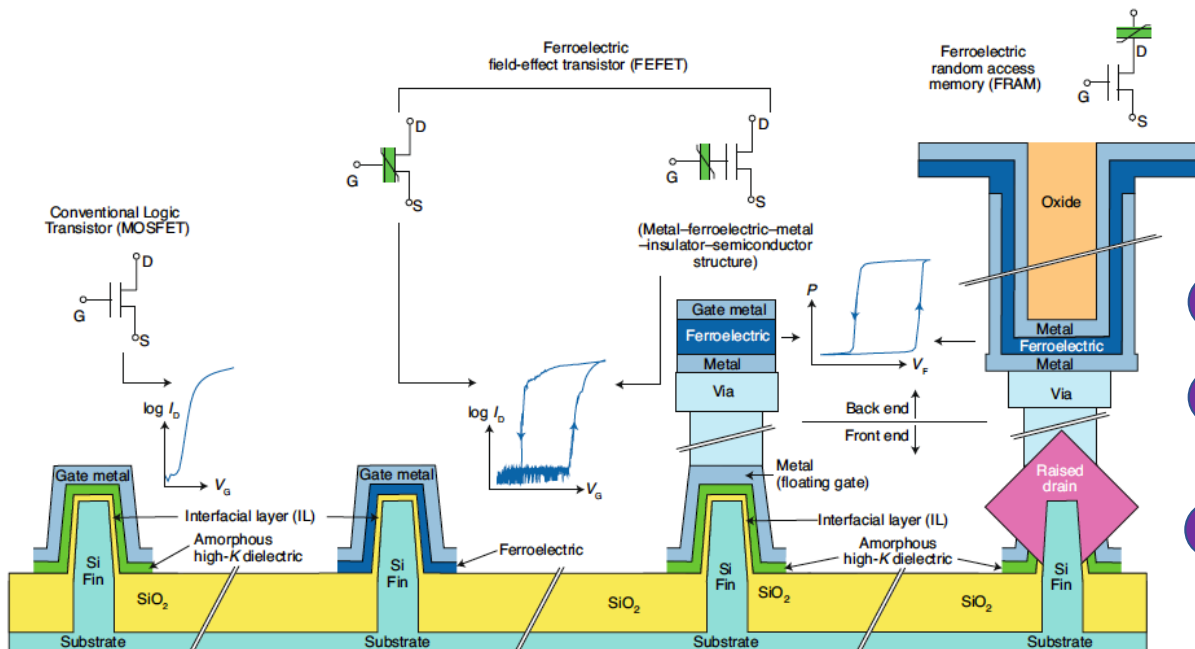
TABLE II. Average, 3-sigma and percentage of prediction error

	TCAD	ML-based prediction		
	μ	μ	3σ	Error
HVT [V]	1.05	1.05	0.08	1.2%
LVT [V]	-0.53	-0.53	0.07	2.0%
I_{on} [μA]	6.68	6.68	1.01	2.1%
SS [mV/dec]	94.52	94.48	9.0	1.6%

G. Choe, P. V. Ravindran, A. Lu, J. Hur, M. Lederer, A. Reck, S. Lombardo, N. Afroze, J. Kacher, A. I. Khan, S. Yu, "Machine learning assisted statistical variation analysis of ferroelectric transistors: from experimental metrology to predictive modeling," IEEE Symposium on VLSI Technology and Circuits (VLSI) 2022.

The era of ferroelectronics

The next wave of exponential growth of the semiconductor industry depends on how well the electronic hardware can support the explosion of data-centric computing.



Ferroelectric technology will be a key component because of

- 1 Performance
- 2 Energy and area efficiency
- 3 Logic and memory functionalities

Thank you





midtown

ATLANTA

