Single-domain Switching Dynamics in BEOL Nanoscale Ferroelectric Field-effect Transistors

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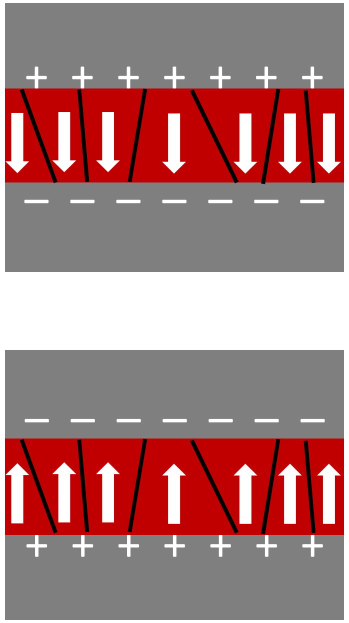
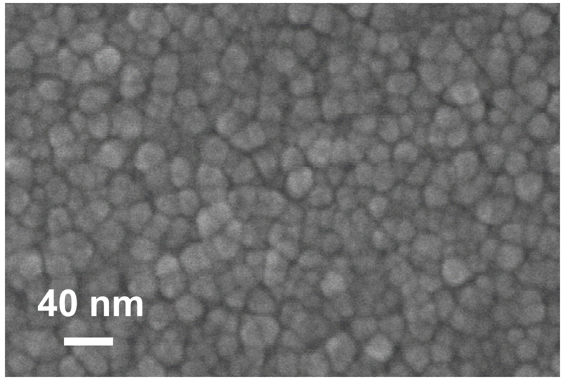
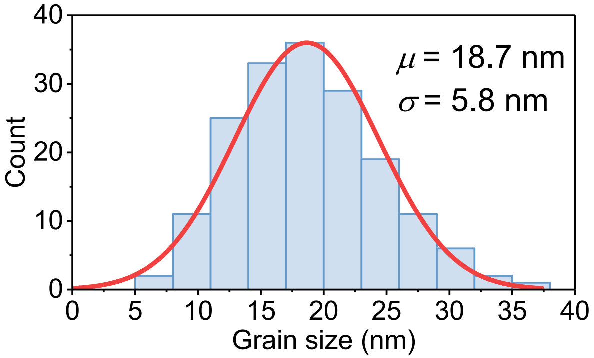
Sponsorship: SRC & Intel

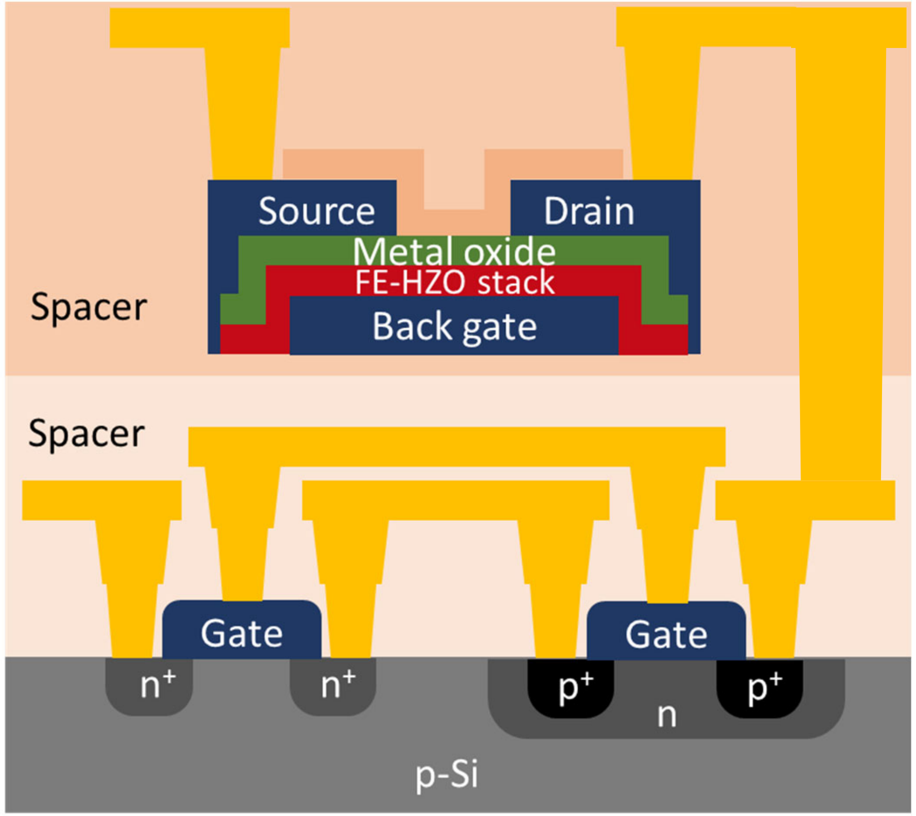
Studying domain dynamics in nanoscale BEOL FE-FETs

Ferroelectric (FE) $Hf_xZr_{1-x}O$ (HZO)







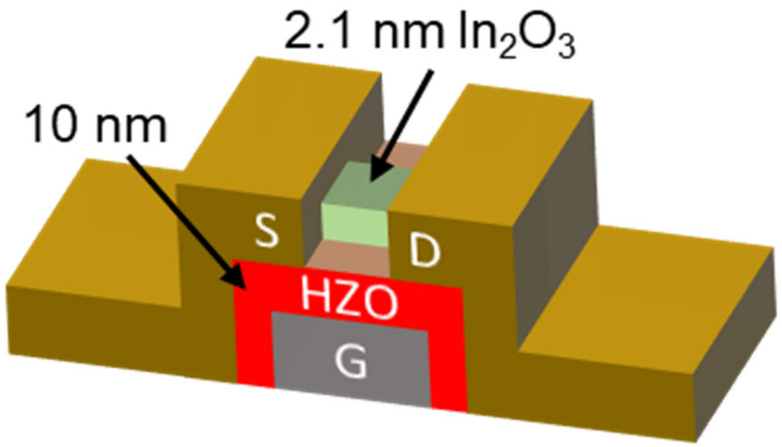


Polycrystalline → Multiple FE domains

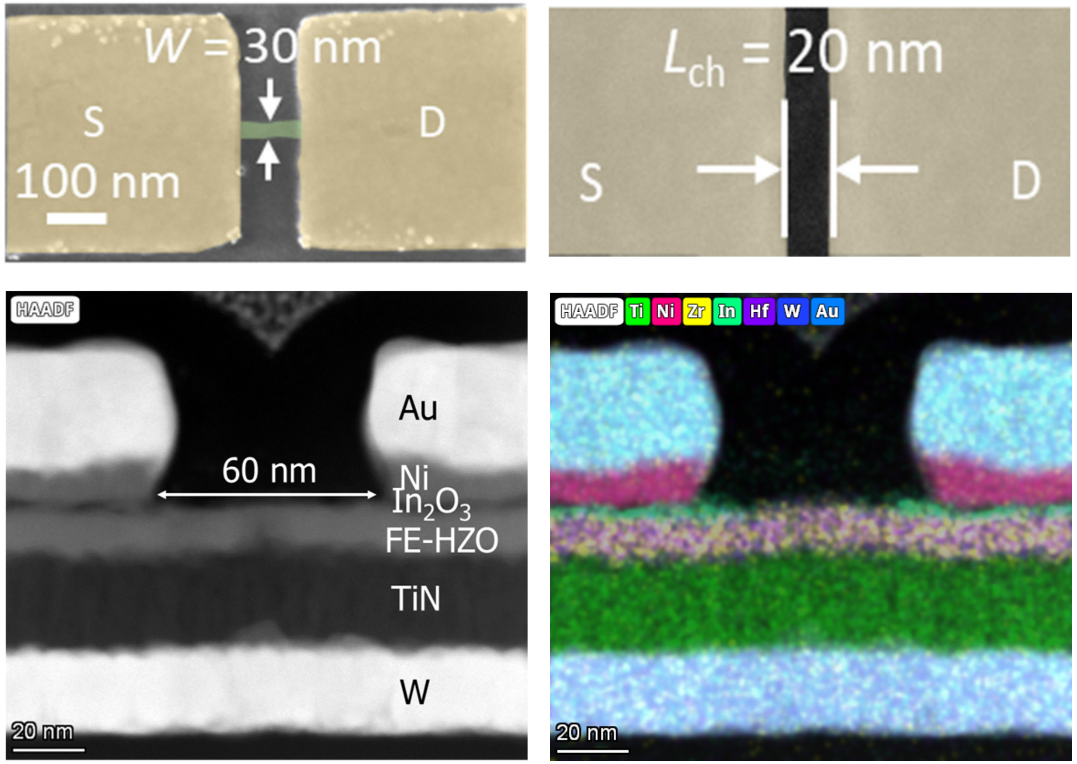
BEOL oxide-channel FE-FETs:
Monolithic 3D integration

Our focus: nanoscale oxide-channel FE-FETs down to single domain

Fabrication of nanoscale In_2O_3-channel FE-FETs



- Key features:
  - PEALD In_2O_3 channel
  - W/TiN back gate
  - MFS intrinsic region

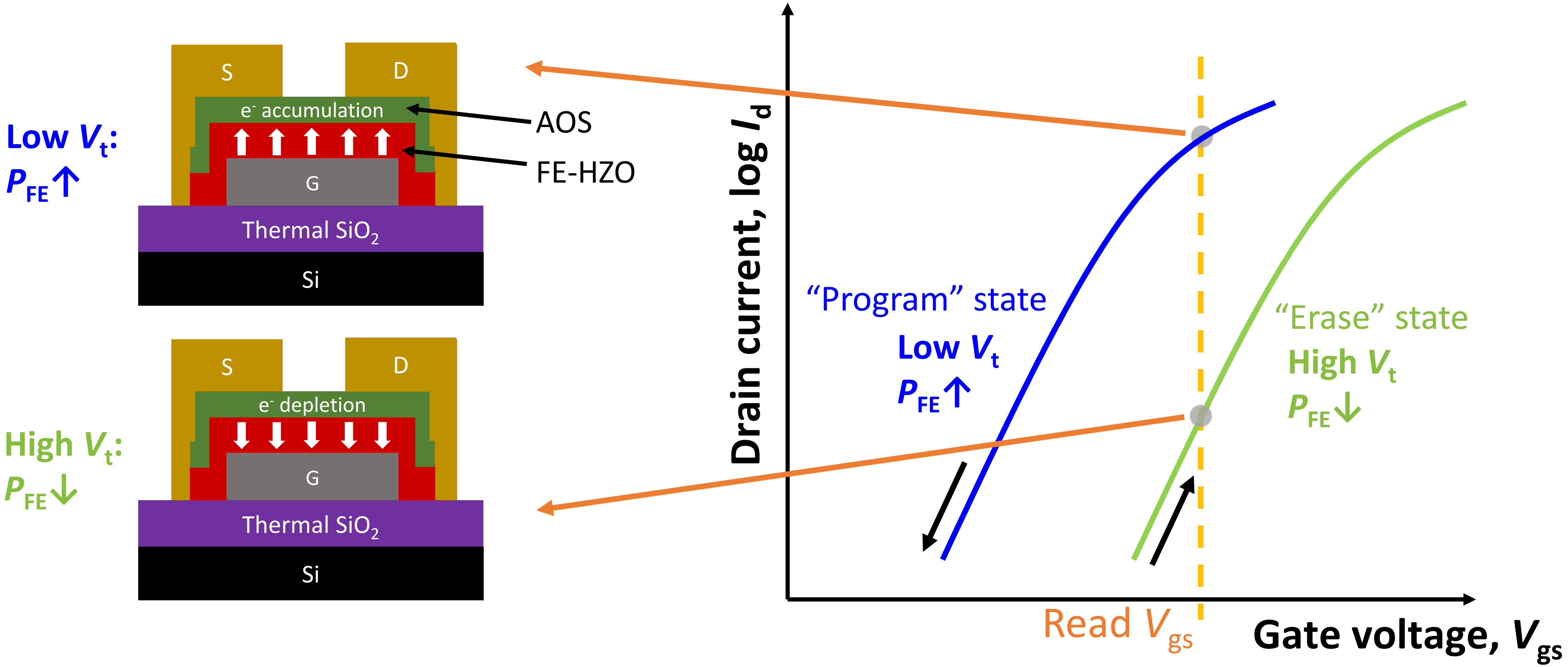


STEM by Zhenjing Liu in Frances Ross's group at MIT

- CMOS-compatible thermal budget (T_{max} = 400 °C)
- W/L_{ch} down to 30/20 nm

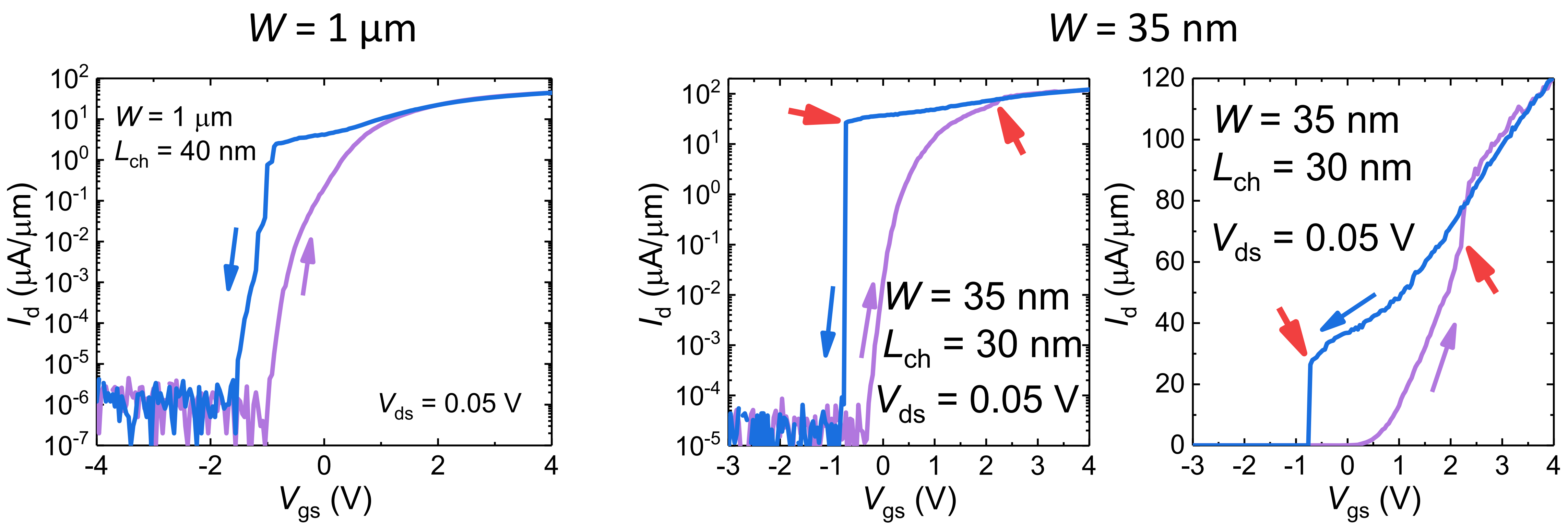
Shao, *IEDM* 2024

Memory behavior of oxide-channel FE-FETs



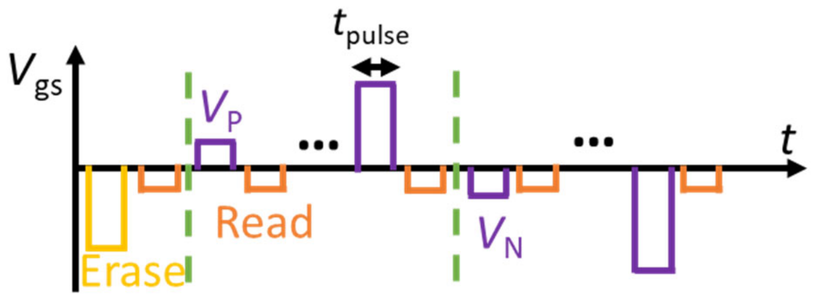
- Two V_T states with complete FE polarization switching

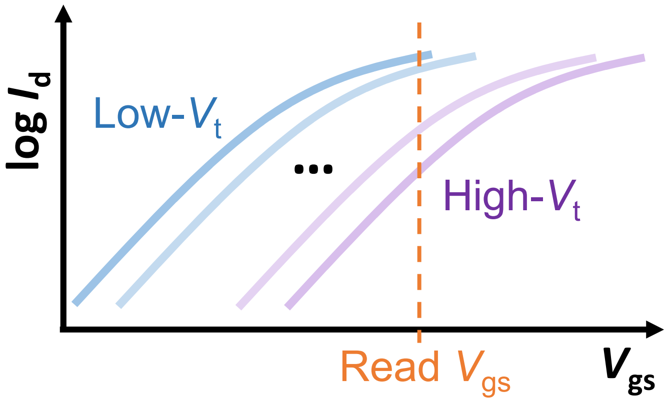
Memory characteristics

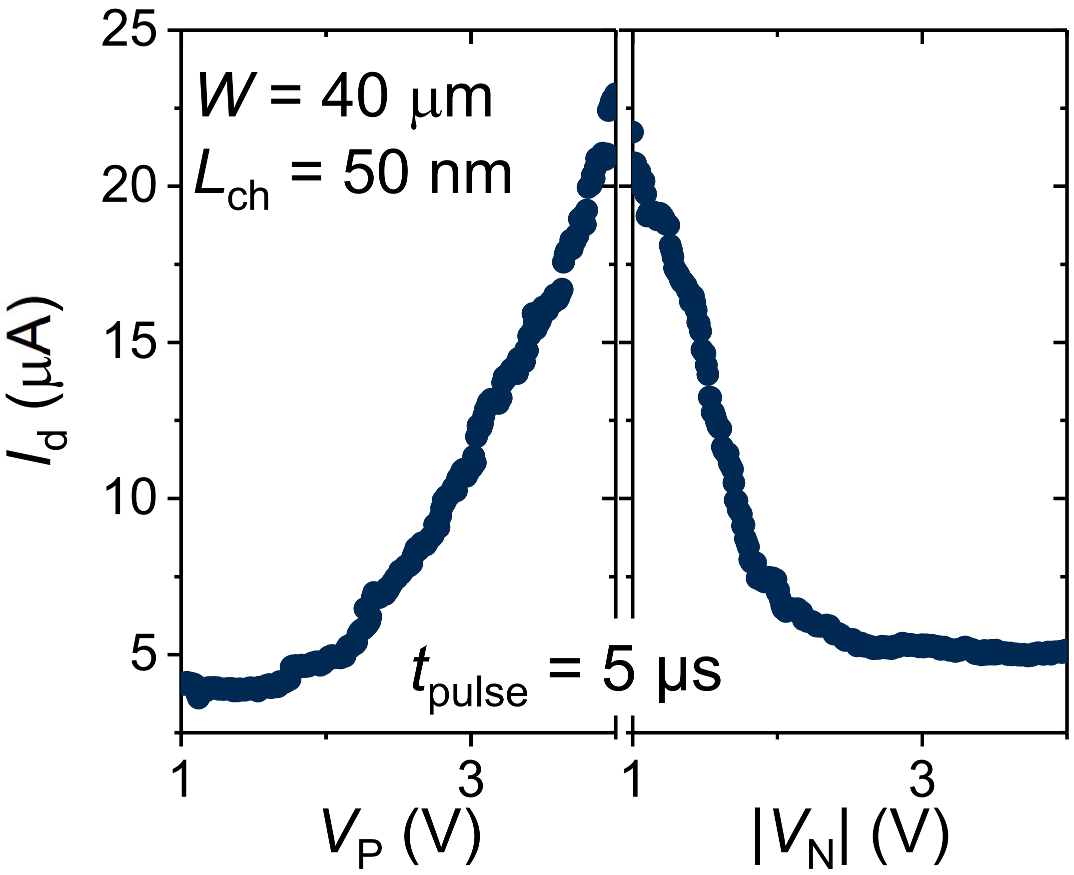


- Prominent FE memory behavior
- Signature of abrupt FE switching in nanoscale devices

Wide FE-FETs: gradual conductance switching

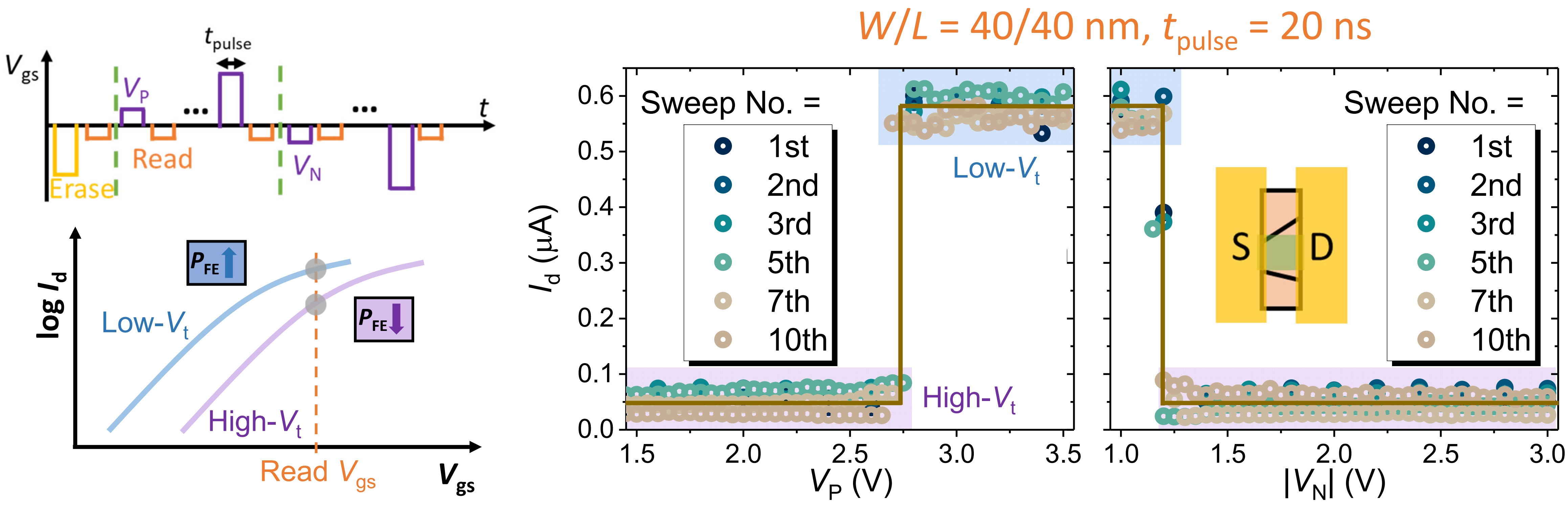






- A large FE domain ensemble with a statistical distribution of domain activation field (E_a)

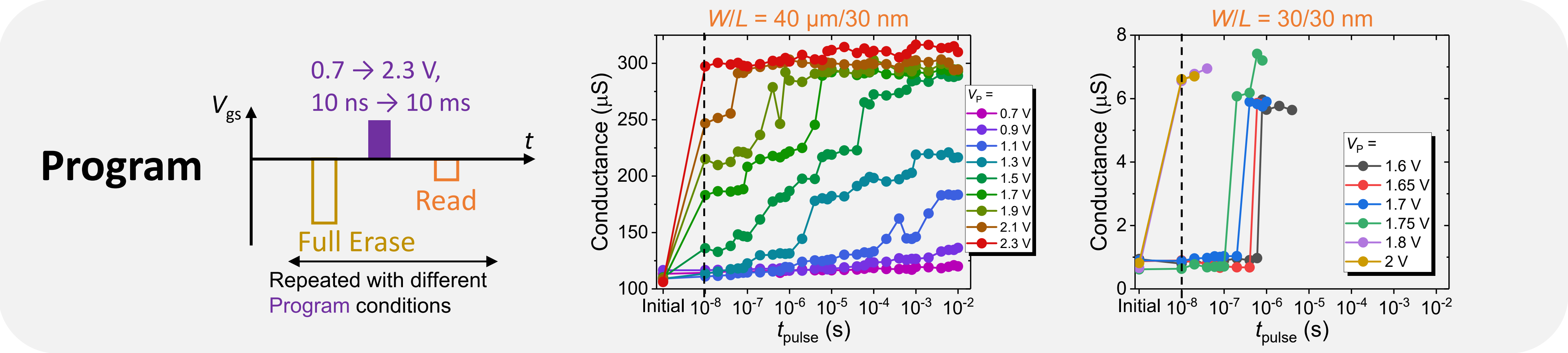
Nanoscale FE-FETs: single-domain switching



- Fast switching with 20 ns pulse width
- Reproducible two-level conductance switching → single FE domain

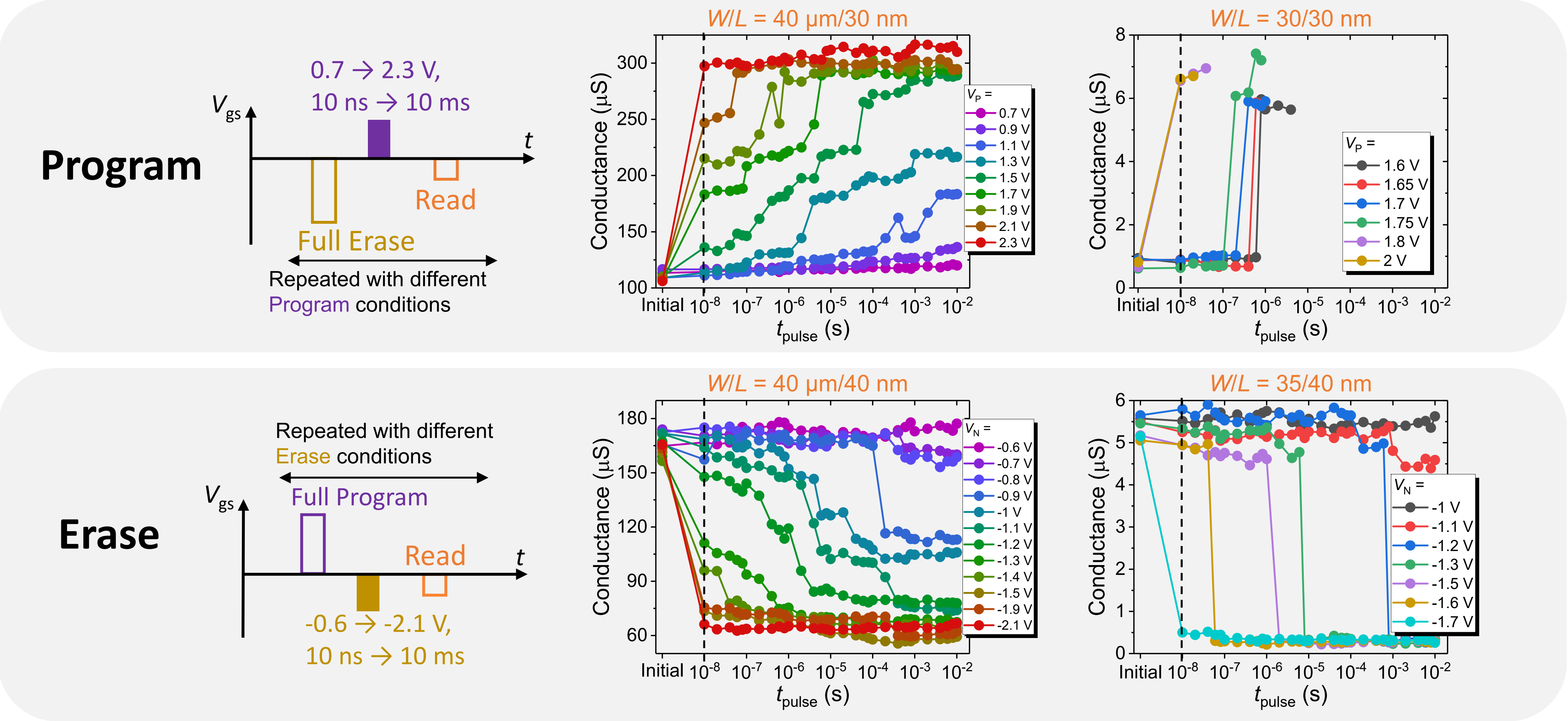
Shao, *IEDM* 2024

Fast and low-voltage FE domain switching



- Pulse amplitude ↑: FE switching speed ↑↑
- At 10 ns (instrumentation limit), V_P < 1.8 V for domain switching

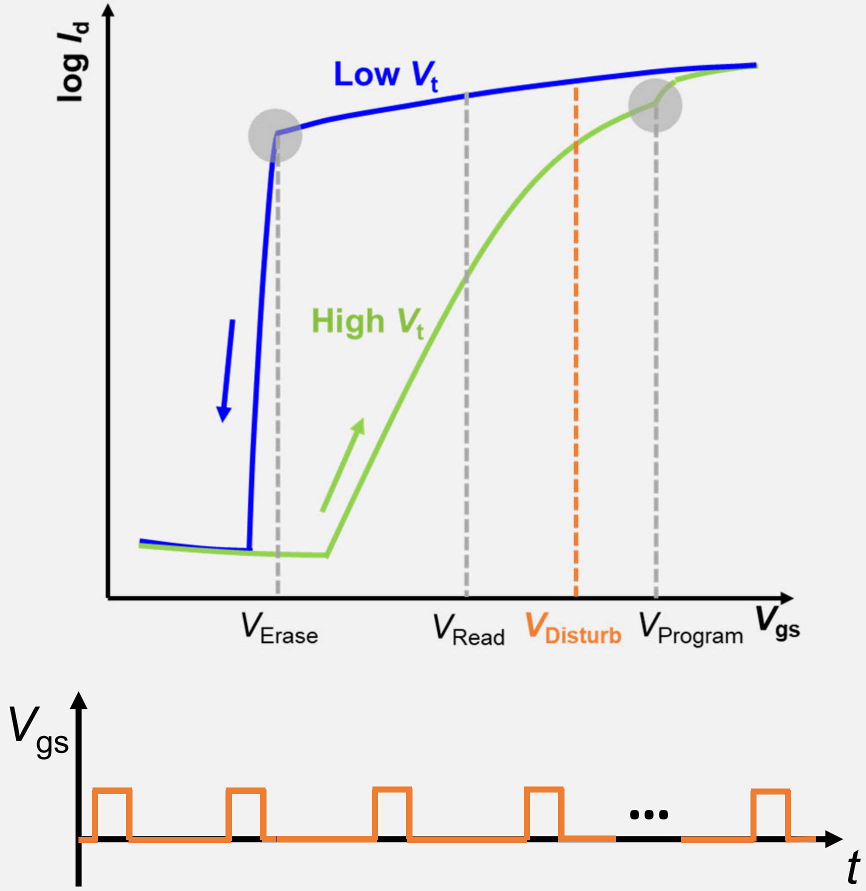
Fast and low-voltage FE domain switching



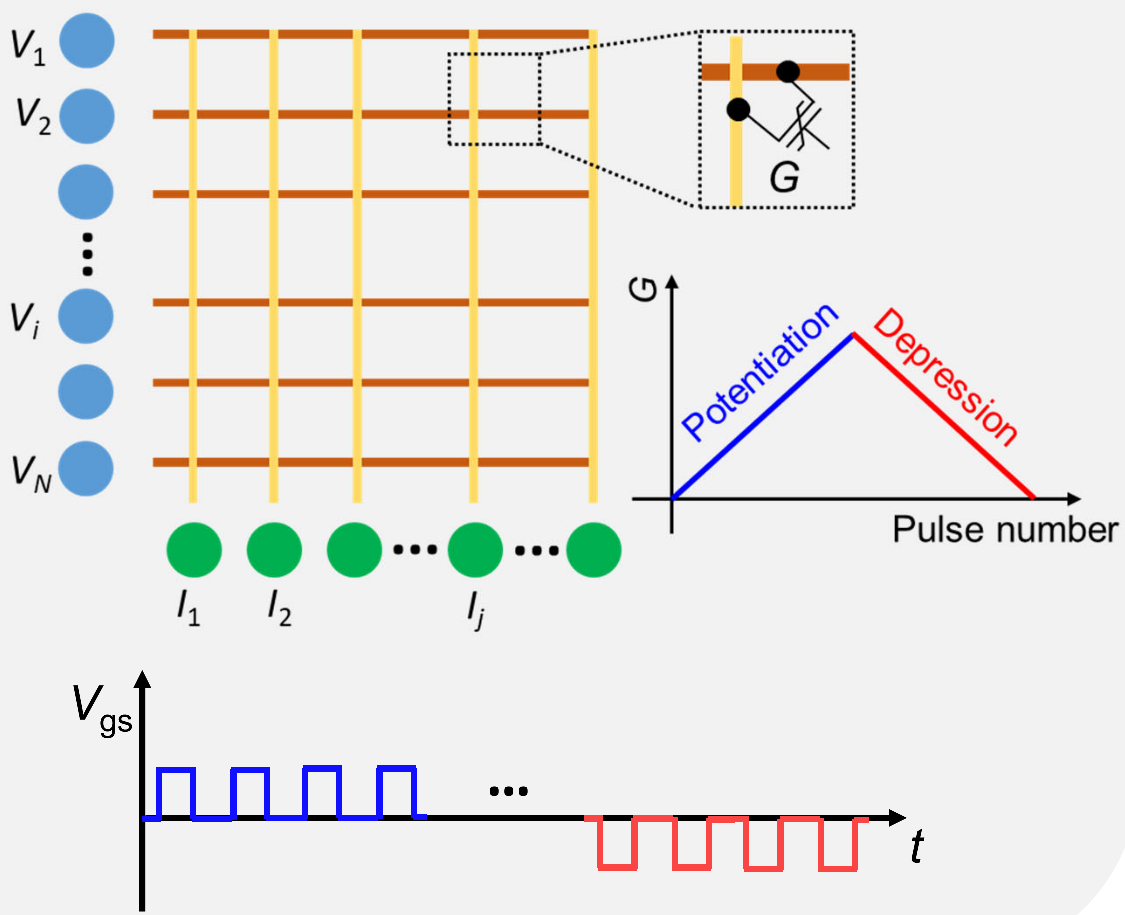
- Pulse amplitude ↑: FE switching speed ↑↑
- At 10 ns (instrumentation limit), V_P < 1.8 V and $|V_N|$ < 1.7 V for domain switching

Characterization of FE switching under a pulse train

NVM: read/write disturb

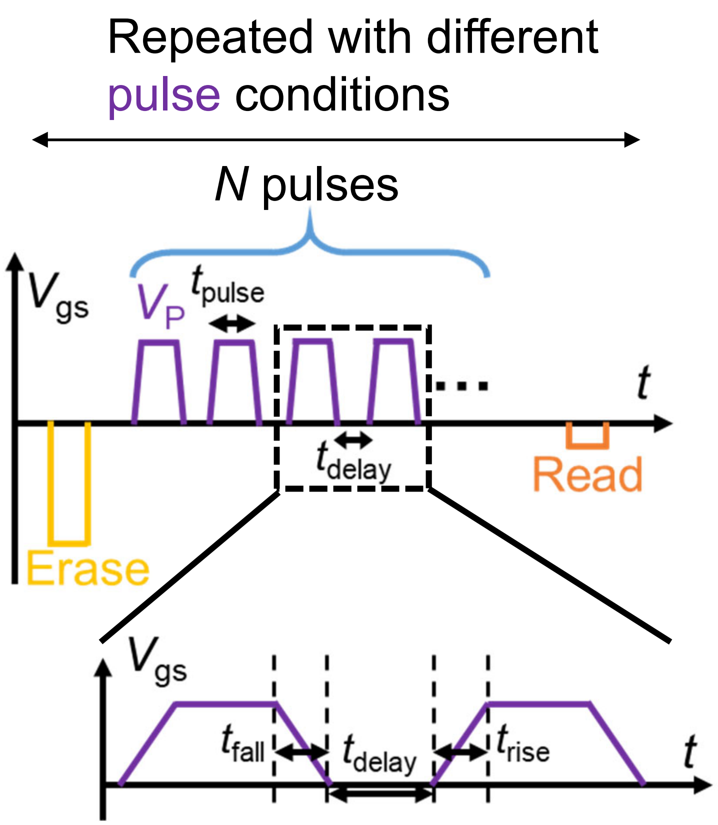


Analog compute-in-memory

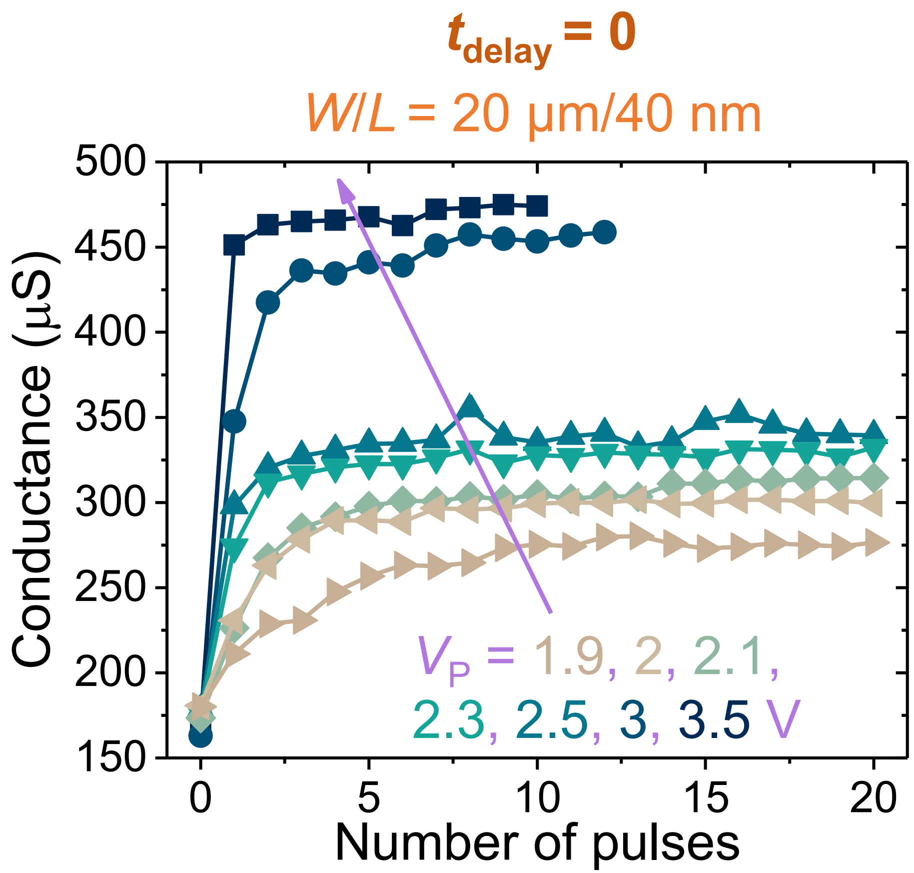


- FE switching behavior under a pulse train with identical amplitude?

Polarization *accumulation* in a domain ensemble



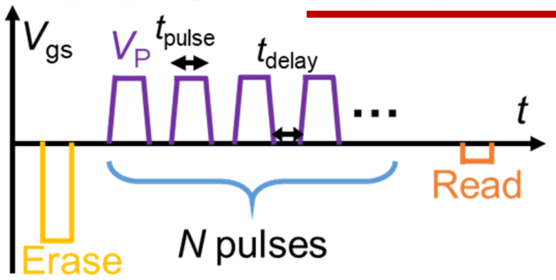
t_{pulse} = 20 ns; t_{fall} = t_{rise} = 8 ns



Note: Independent measurement for each point, which starts from the full Erase state

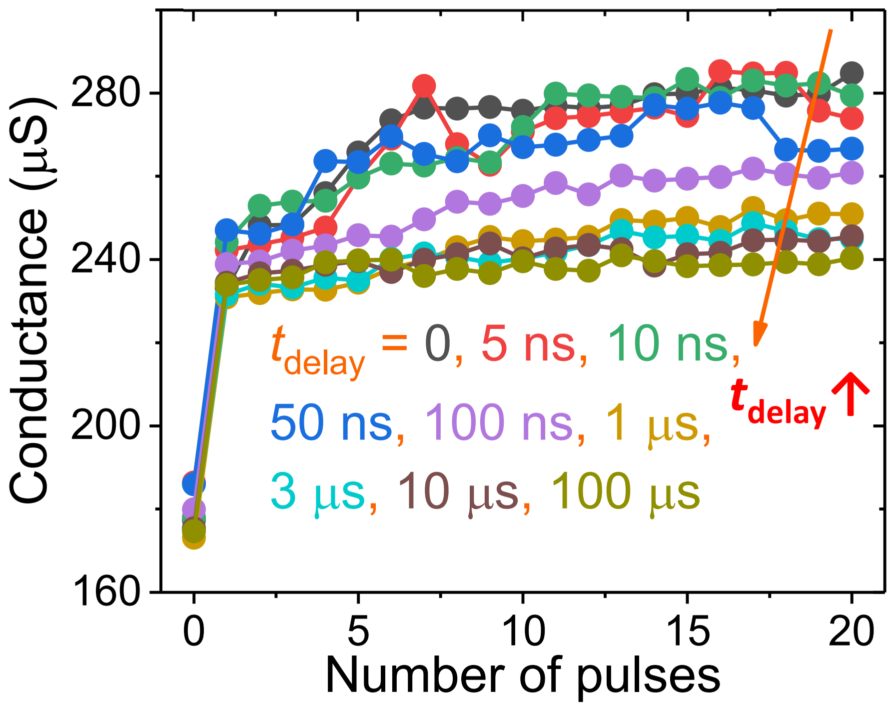
- For fixed V_P: $N \uparrow \Rightarrow G \uparrow$, but saturates
- For fixed N: $V_P \uparrow \Rightarrow G \uparrow$

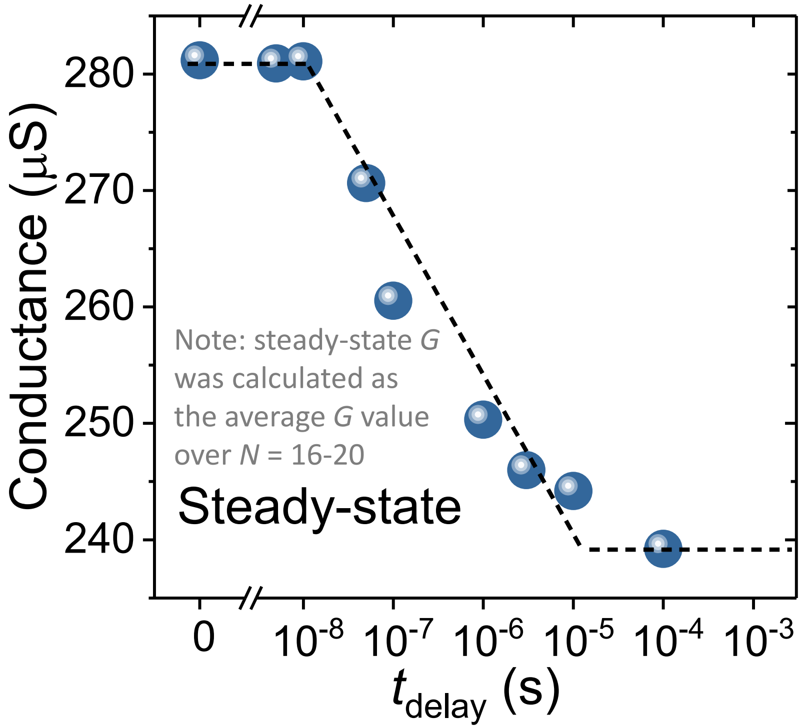
Polarization *relaxation* in a domain ensemble

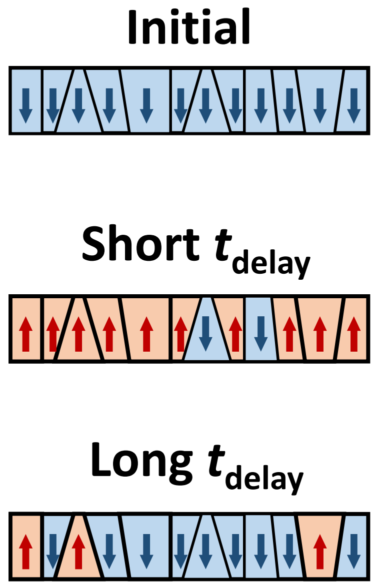


t_{pulse} = 20 ns; V_P = 2 V

W/L = 20 µm/40 nm





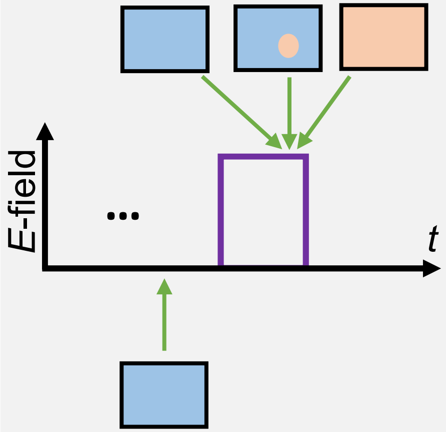


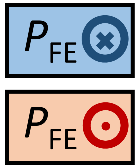
See also:
Alessandri, *TED* 2019

- In steady state, t_{delay}↑ ➡ G↓, but saturates at very short or very long t_{delay}
- Polarization relaxation when t_{delay} ∈ [~10 ns, ~10 µs] in a domain ensemble

Possible physics of polarization switching?

Nucleation-limited switching (NLS) model

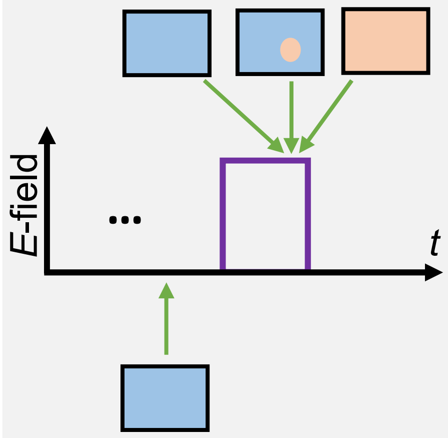




NLS assumes near-instant domain expansion after seed nucleation

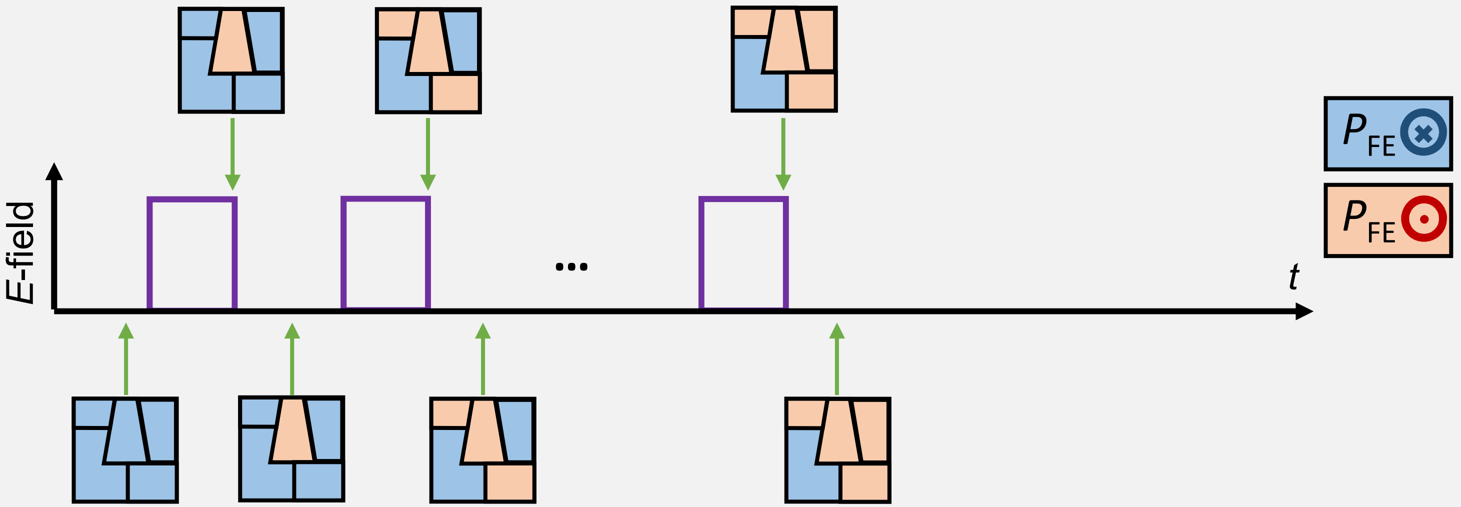
Physics based on the nucleation-limited switching model?

NLS model



NLS assumes near-instant domain expansion after seed nucleation

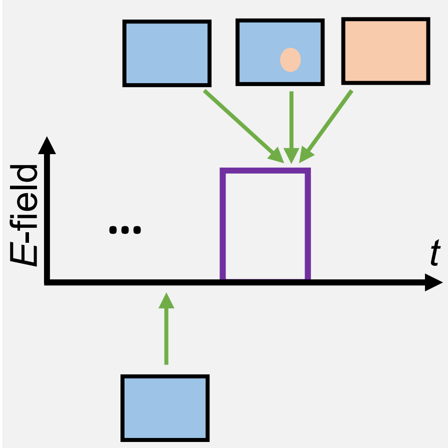
Short t_{delay}



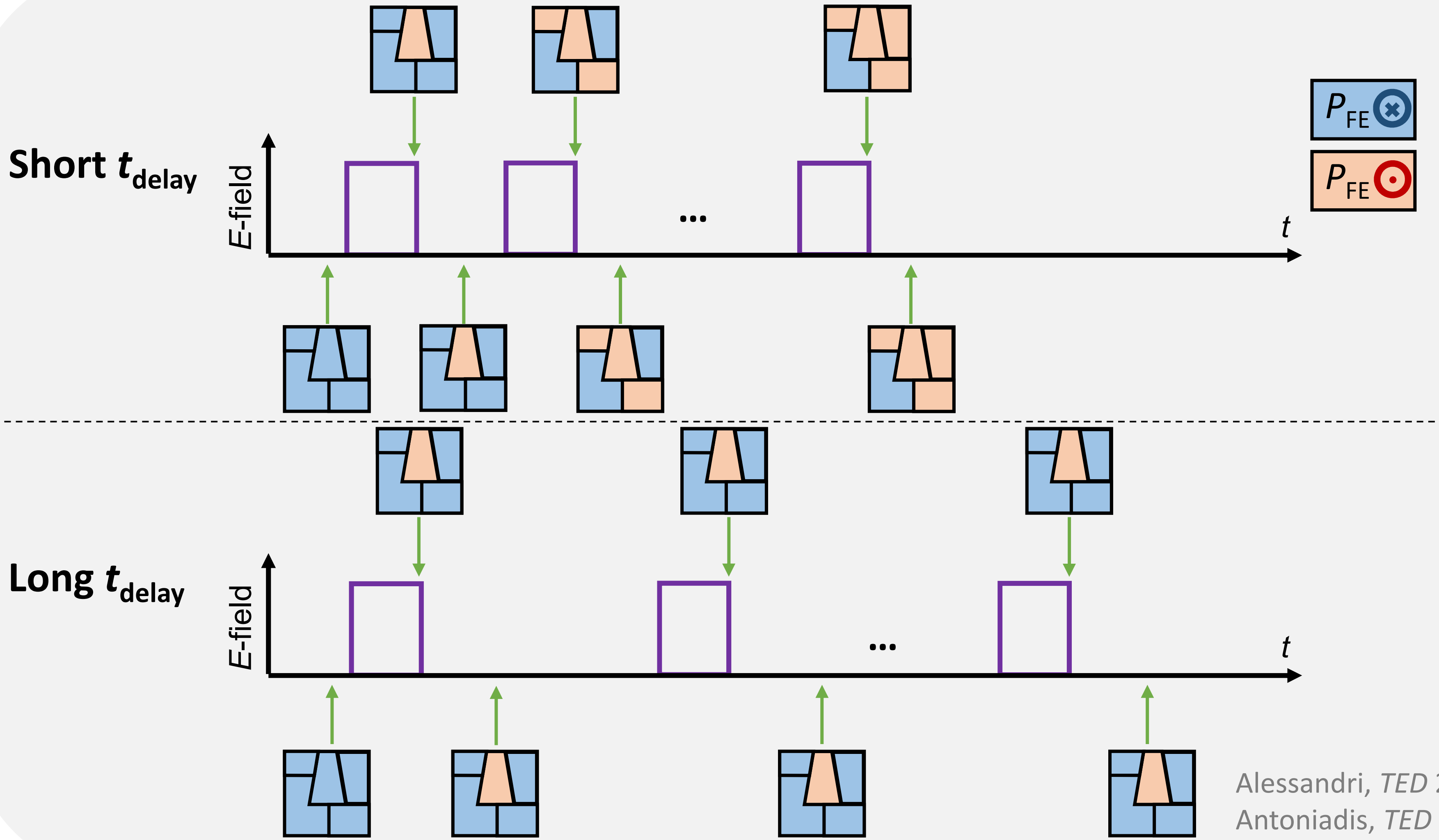
Alessandri, *TED* 2019
Antoniadis, *TED* 2022

- Short gap in E-field: incubation of nucleation little affected

Physics based on the nucleation-limited switching model?



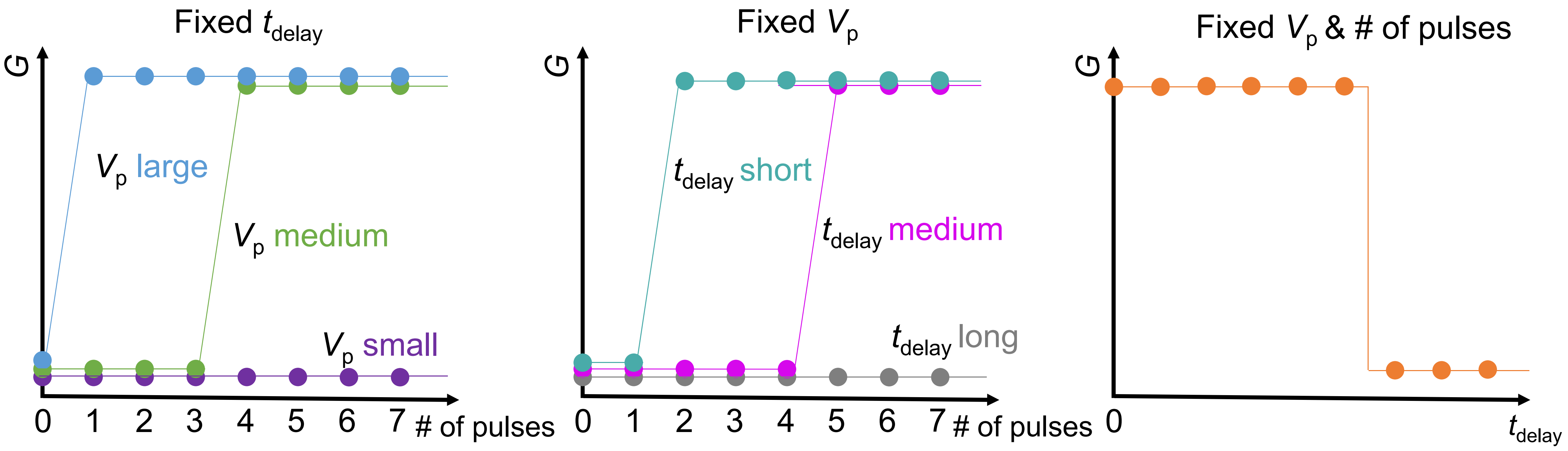
NLS assumes near-instant domain expansion after seed nucleation



Alessandri, *TED* 2019
Antoniadis, *TED* 2022

- Long gap in E-field: incubation of nucleation quenched

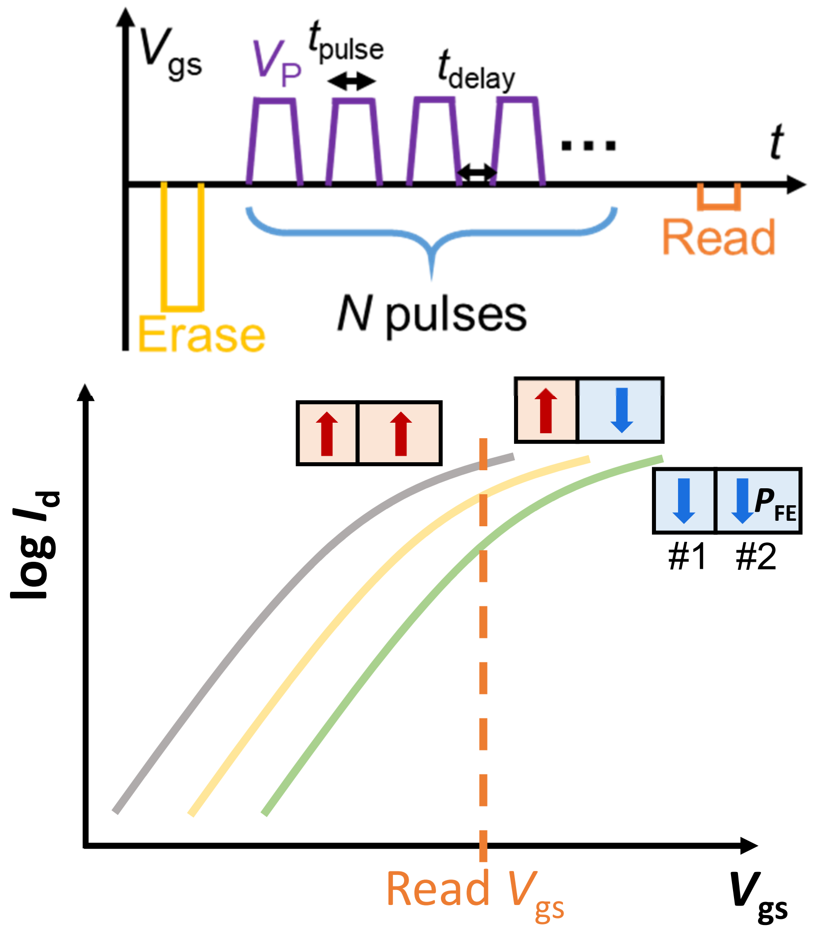
Expected single domain switching behavior

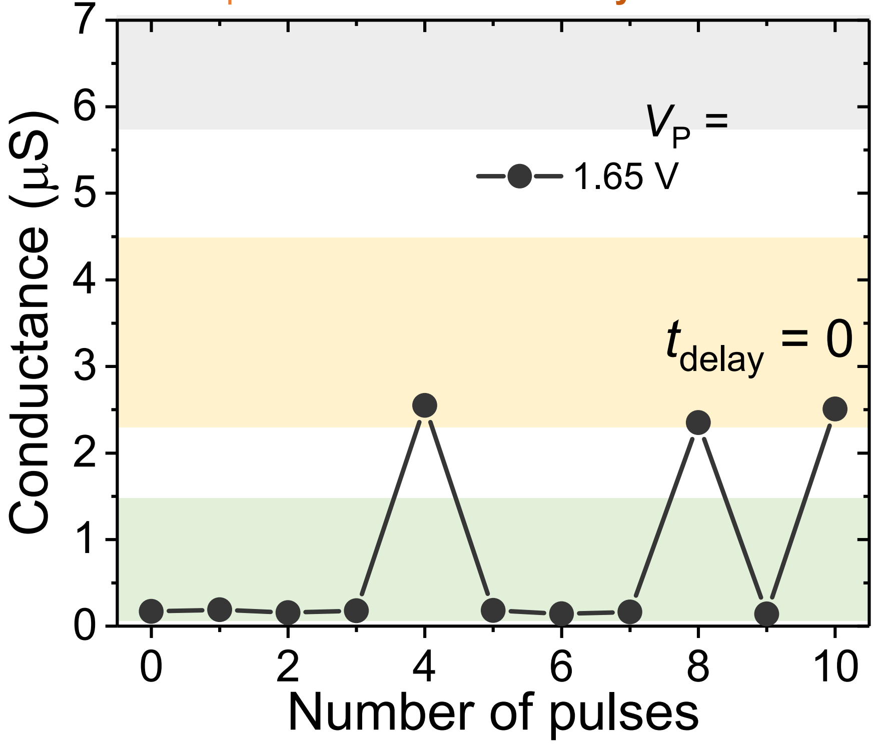


Note: Intentionally shifted *G* levels with different data point colors for clarity

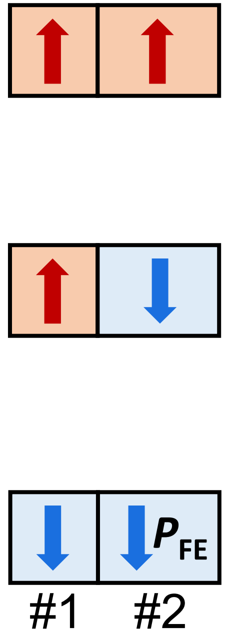
- Sharp transition in a single domain?
  - As V_p decreases below a threshold
  - As t_{delay} increases above a threshold

Single-domain polarization accumulation



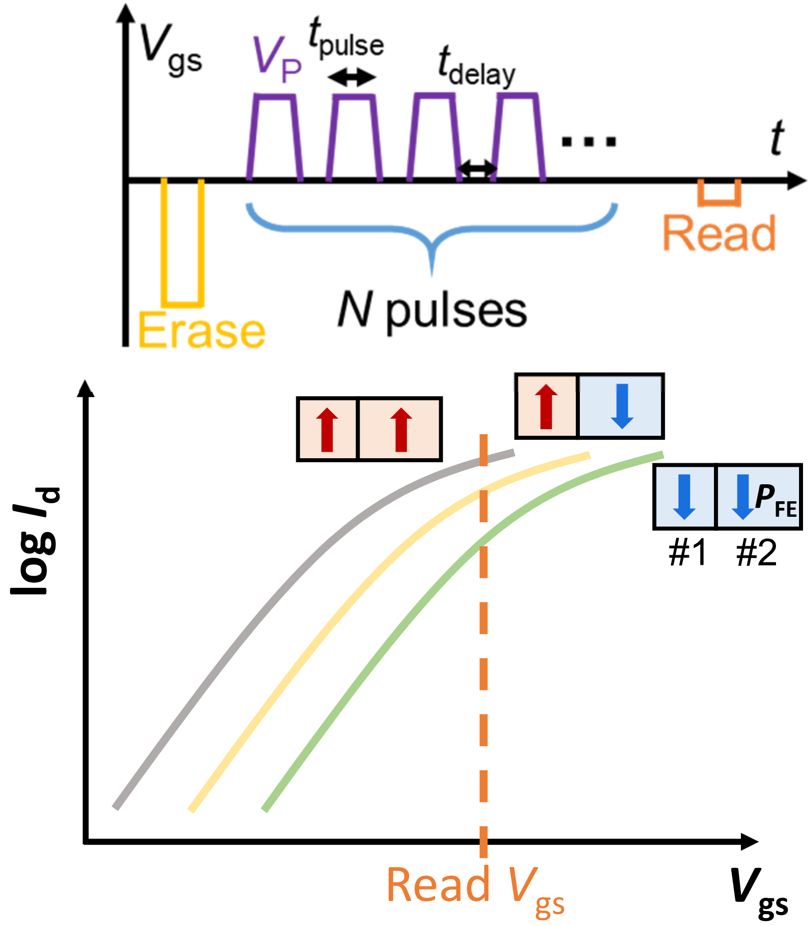


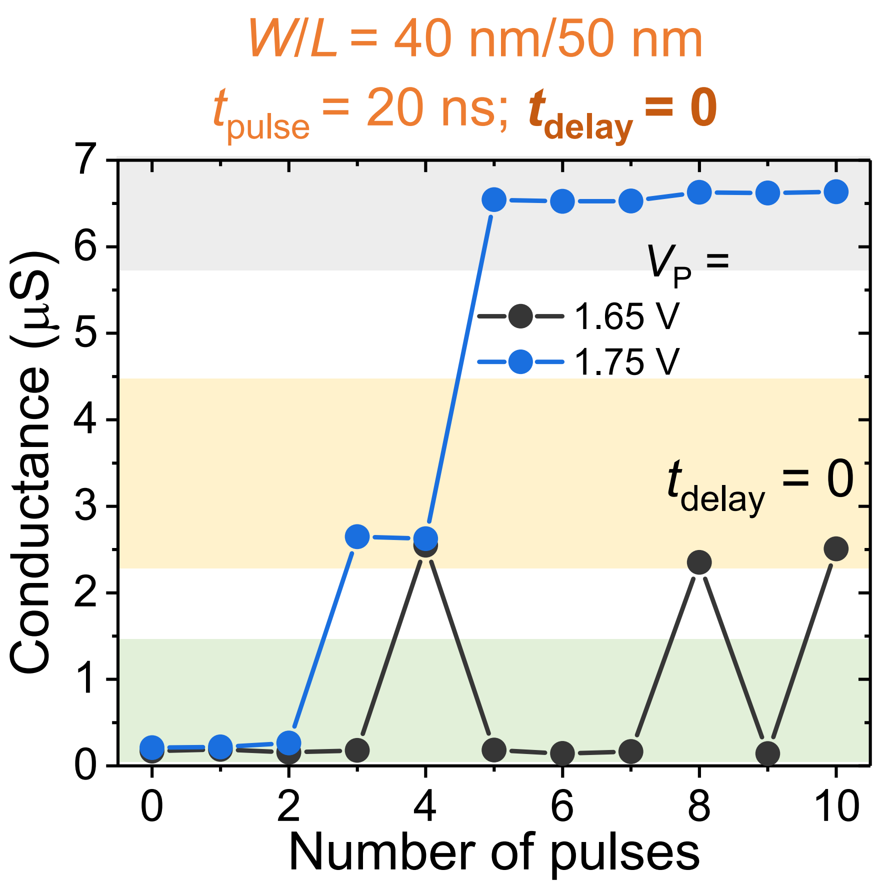
Two FE domains in action



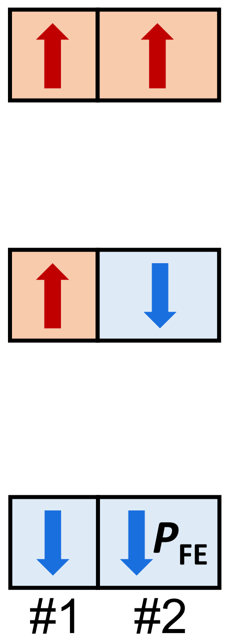
- Domain #1 (low E_a) shows stochasticity in polarization accumulation

Single-domain polarization accumulation



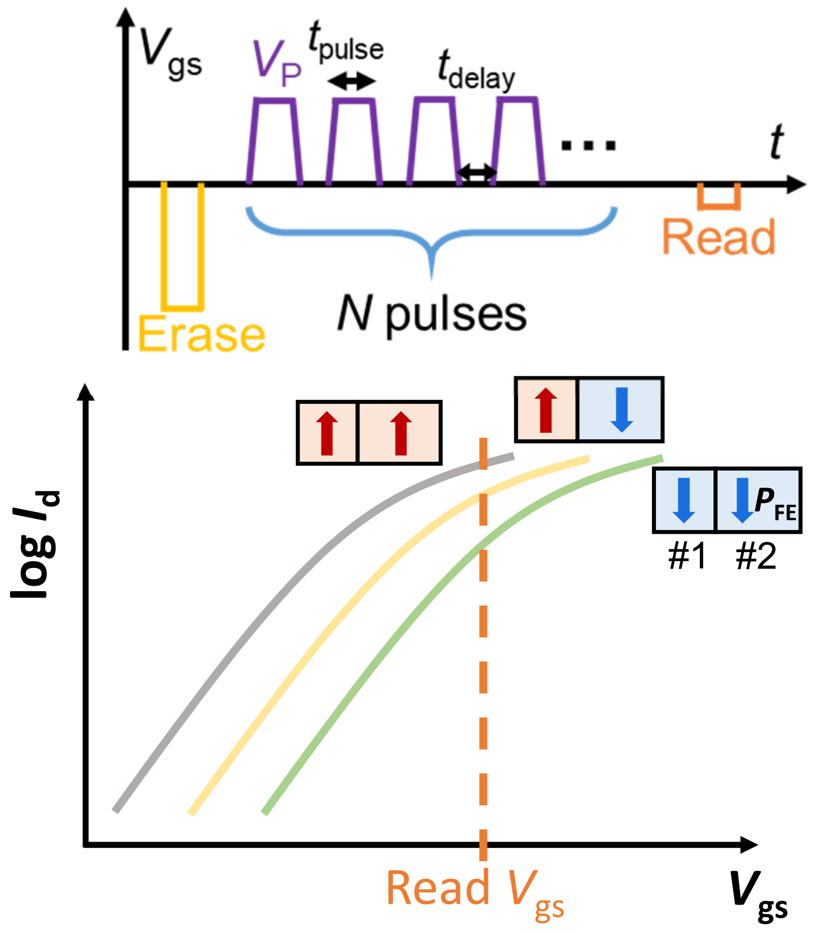


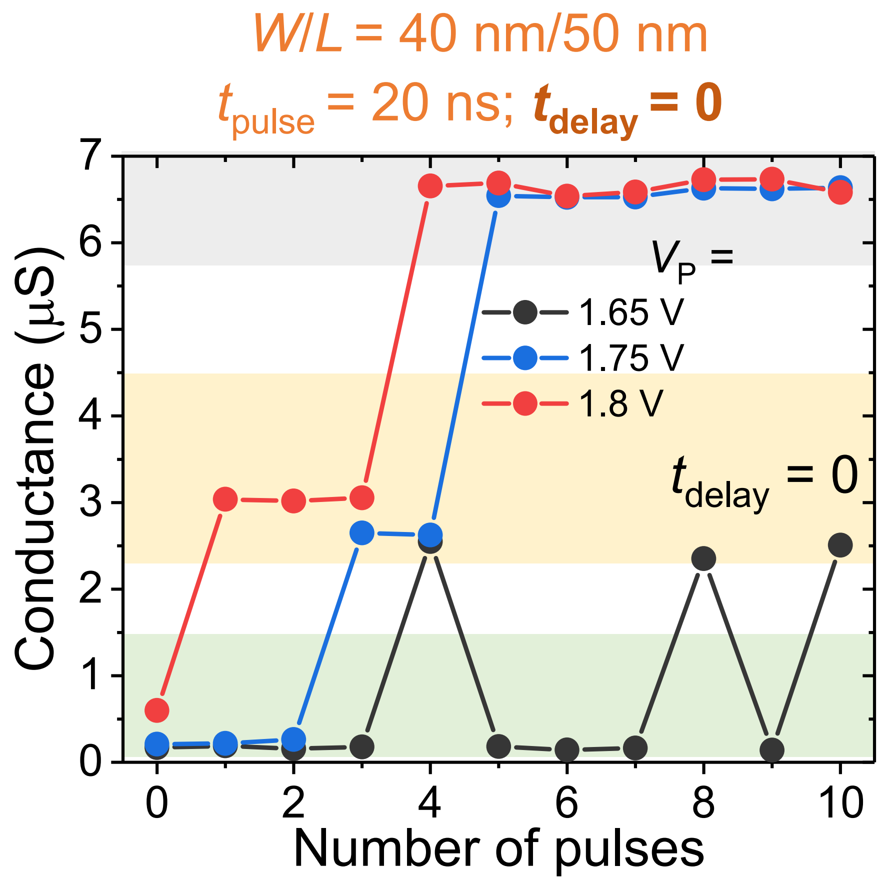
Two FE domains in action



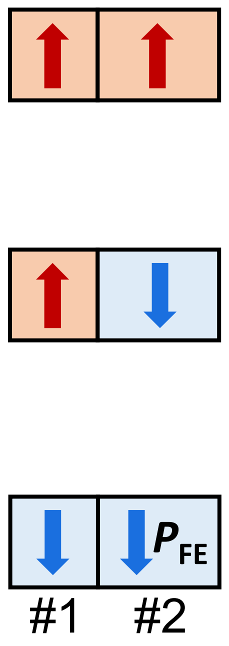
- Domain #2 (high E_a) starts to switch at 1.75 V

Single-domain polarization accumulation



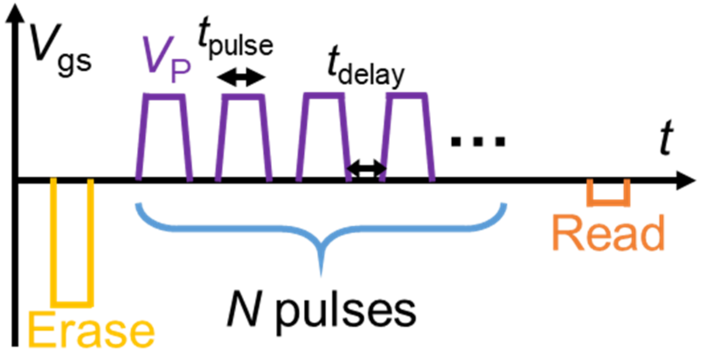


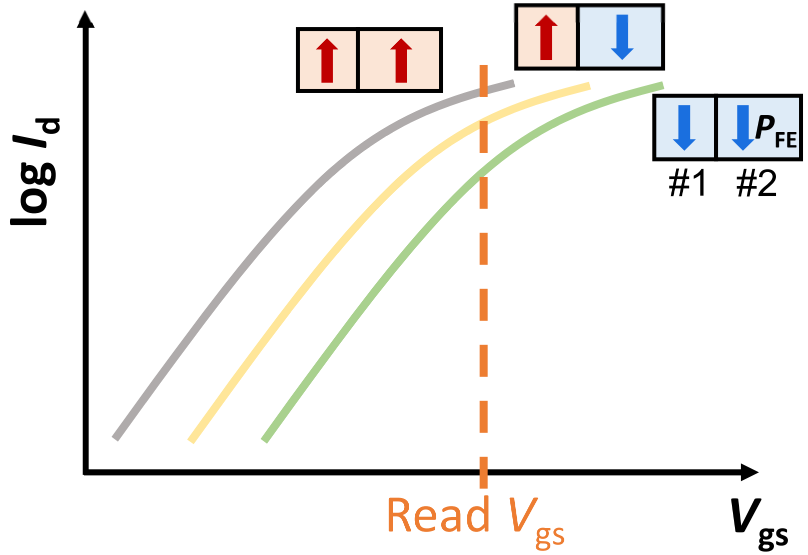
Two FE domains in action

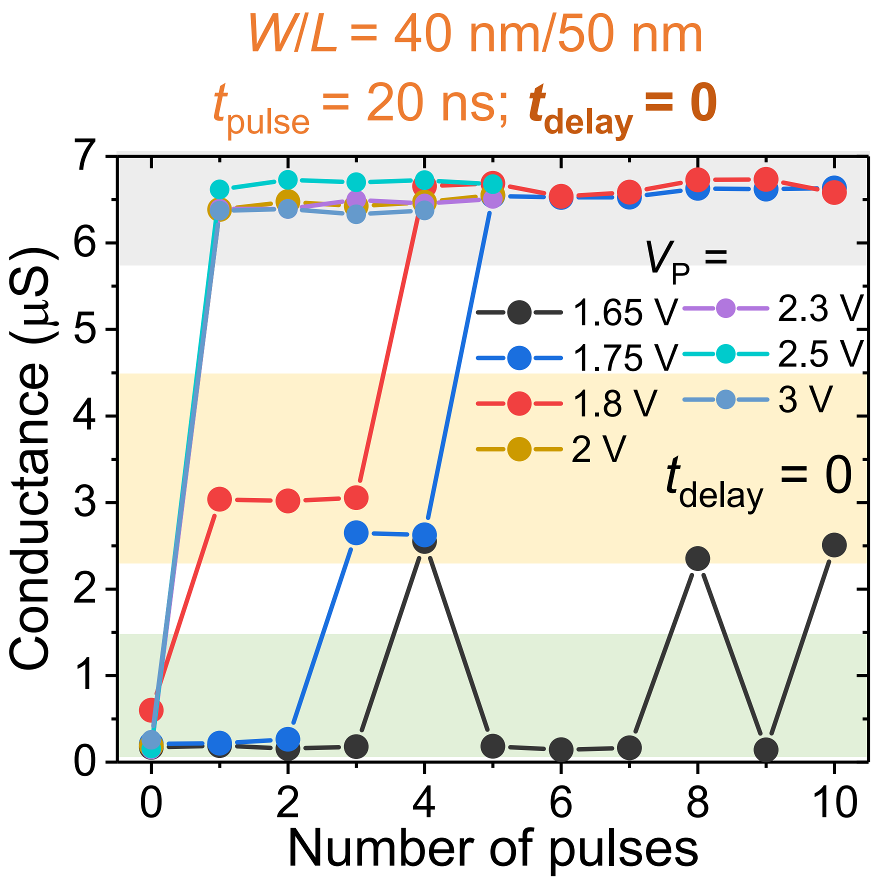


- Both domains switch at fewer pulses when V_P increases

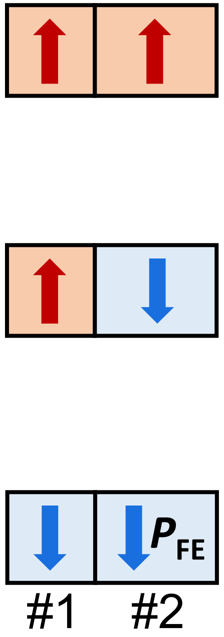
Single-domain polarization accumulation







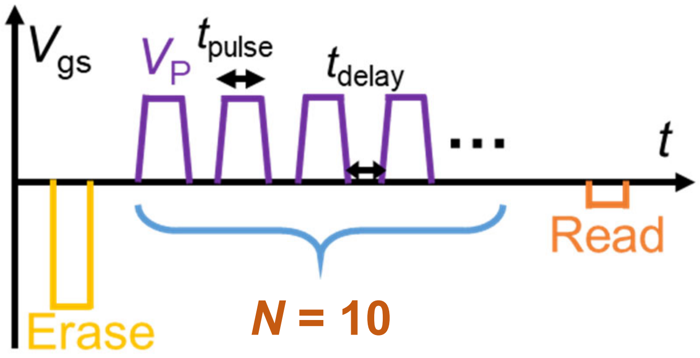
Two FE domains in action



- Both domains are switched with a single pulse at ≥ 2 V
- At 1.8 V, domain #1 is always switched with a single pulse

Deterministic single-domain polarization switching

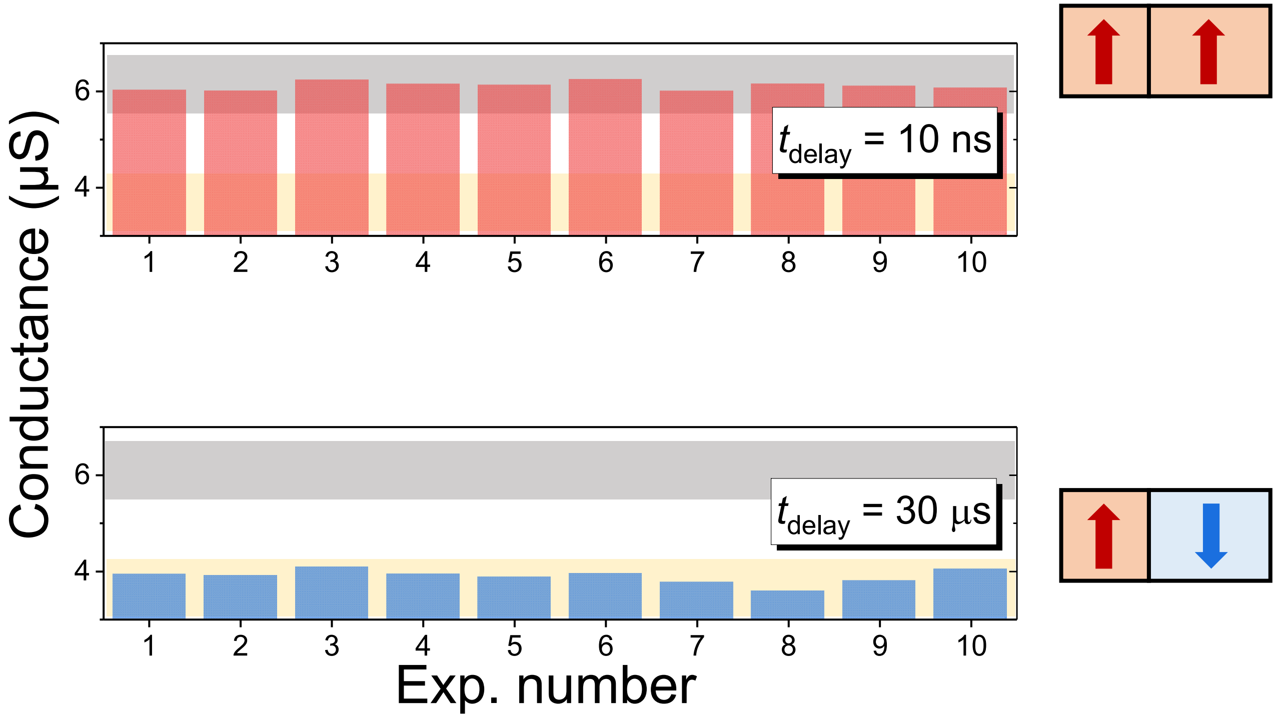
- One polarization switching experiment:



- For each t_{delay} group, we carry out ≥10 identical experiments

W/L = 40 nm/50 nm

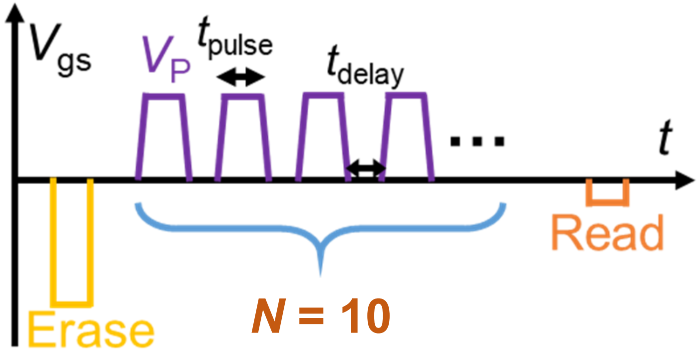
t_{pulse} = 20 ns; V_P = 1.8 V; N = 10



- Deterministic switching of domain #2 at very short or very long t_{delay}

Stochastic single-domain polarization switching

- One polarization switching experiment:



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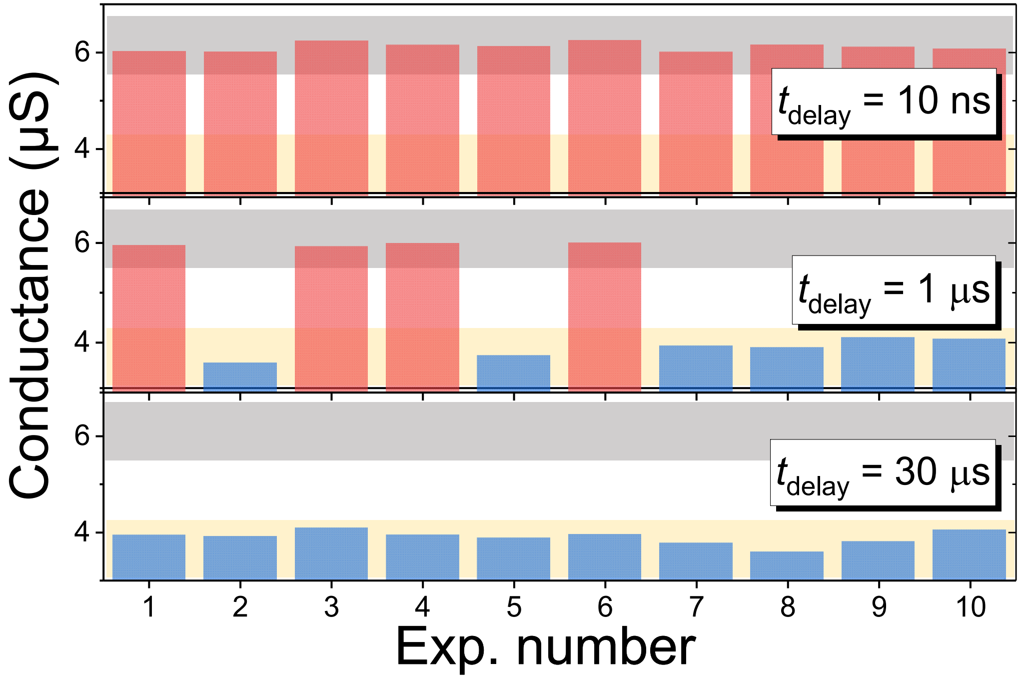


S_p =

1

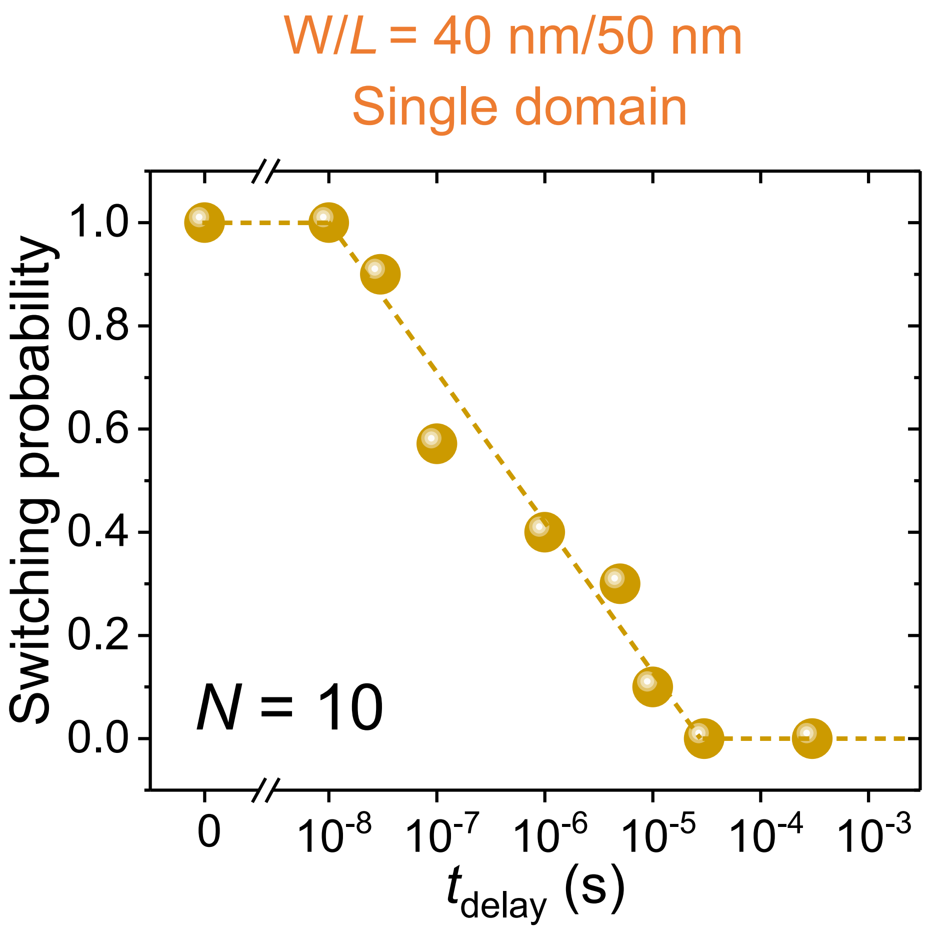
0.4

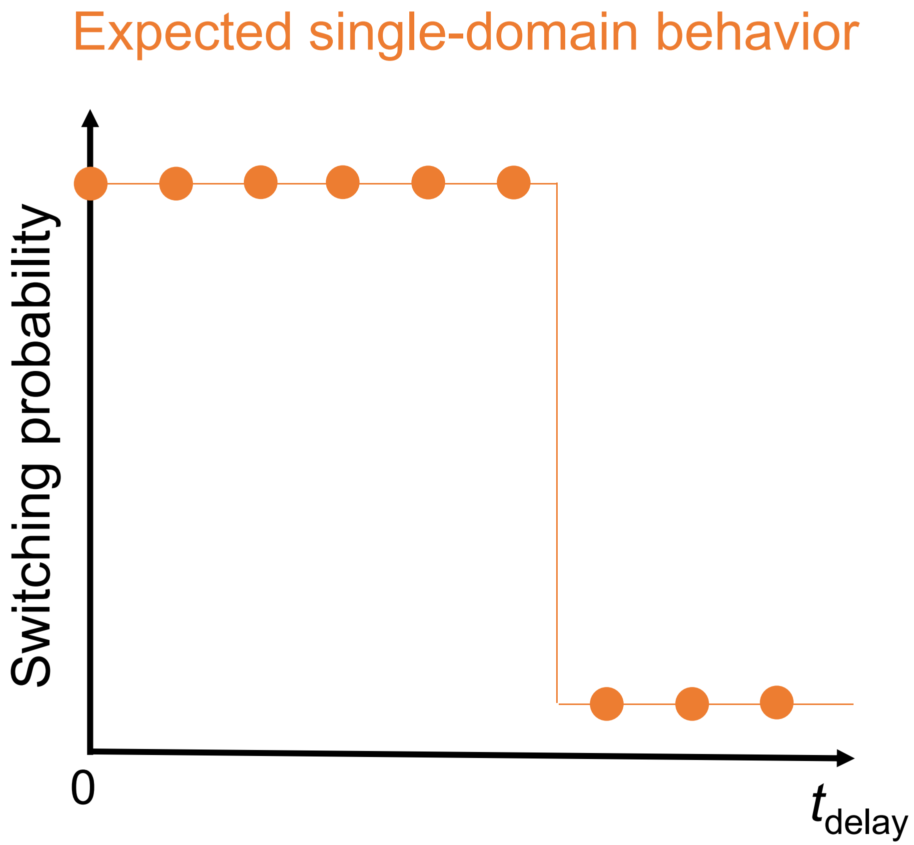
0

S_p: switching probability of domain #2

- Highly t_{delay}-dependent switching probability of domain #2
- Intrinsic polarization relaxation in single FE domain, never observed before

Polarization switching stochasticity in single domain



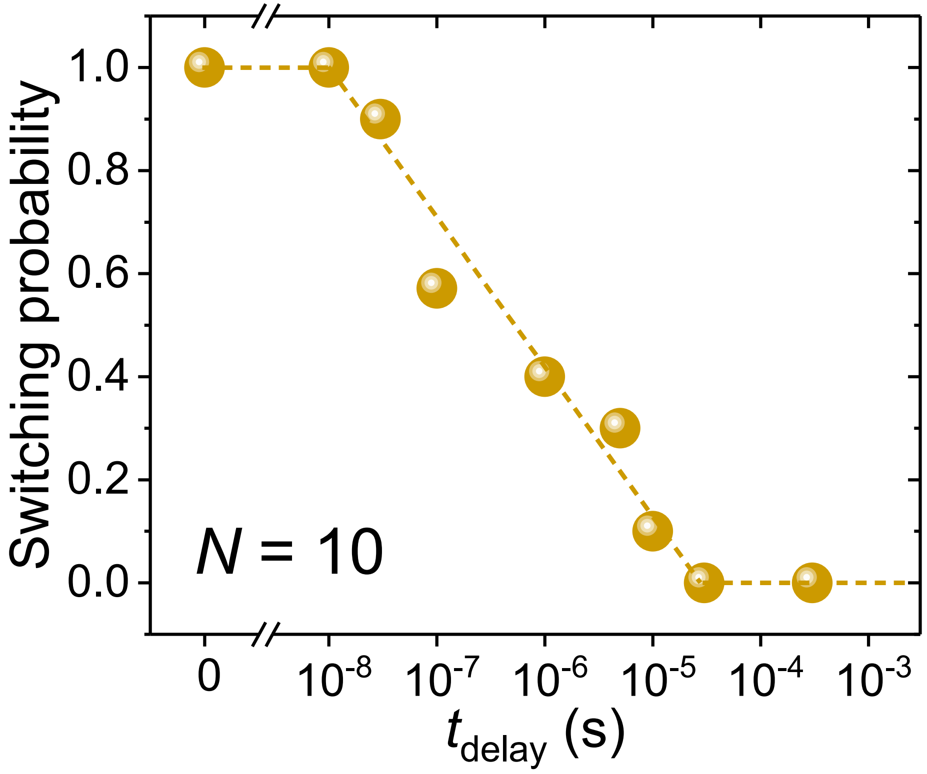


- Broad stochasticity even in a single domain!

Polarization switching stochasticity in single domain

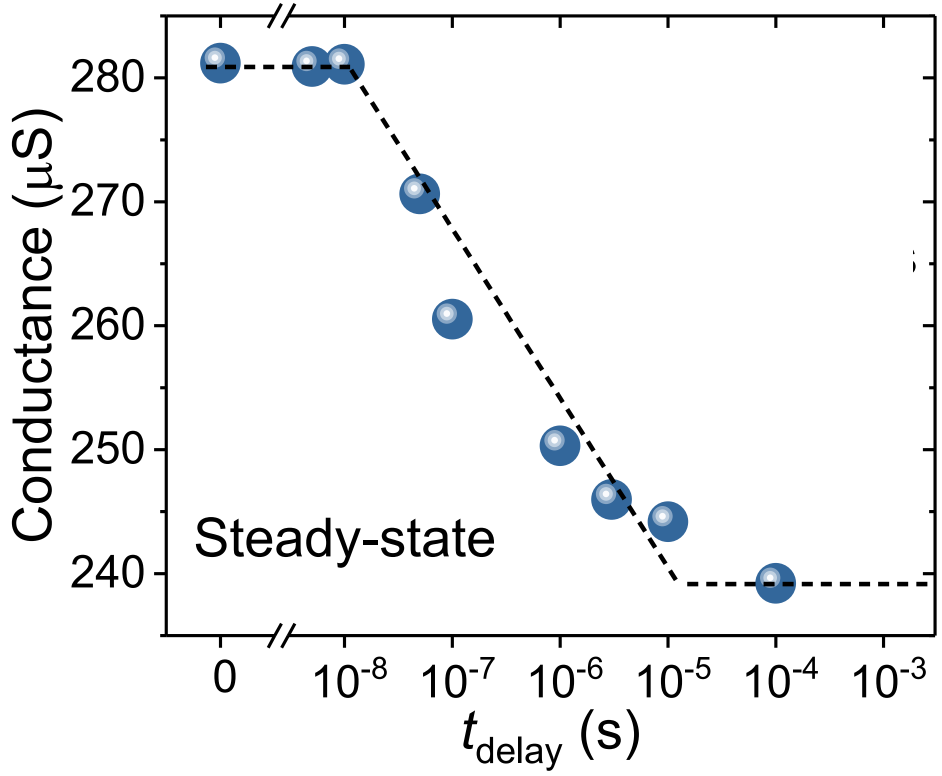
W/*L* = 40 nm/50 nm

Single domain



W/*L* = 20 μm/40 nm

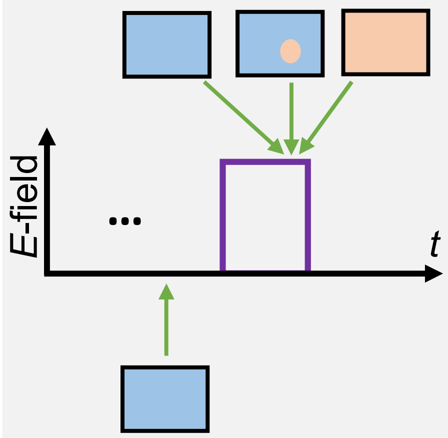
Domain ensemble



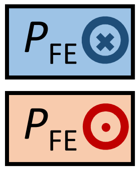
- Broad stochasticity even in a single domain!
- Single-domain stochasticity underlies large-area ensemble behavior!

Understanding stochastic domain switching

NLS model



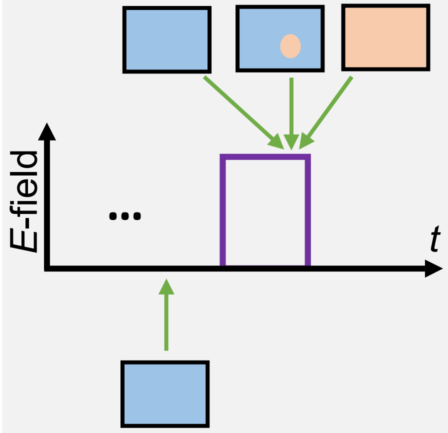
NLS assumes near-instant domain expansion after seed nucleation



- Traditional NLS model fails to explain the stochastic domain behavior

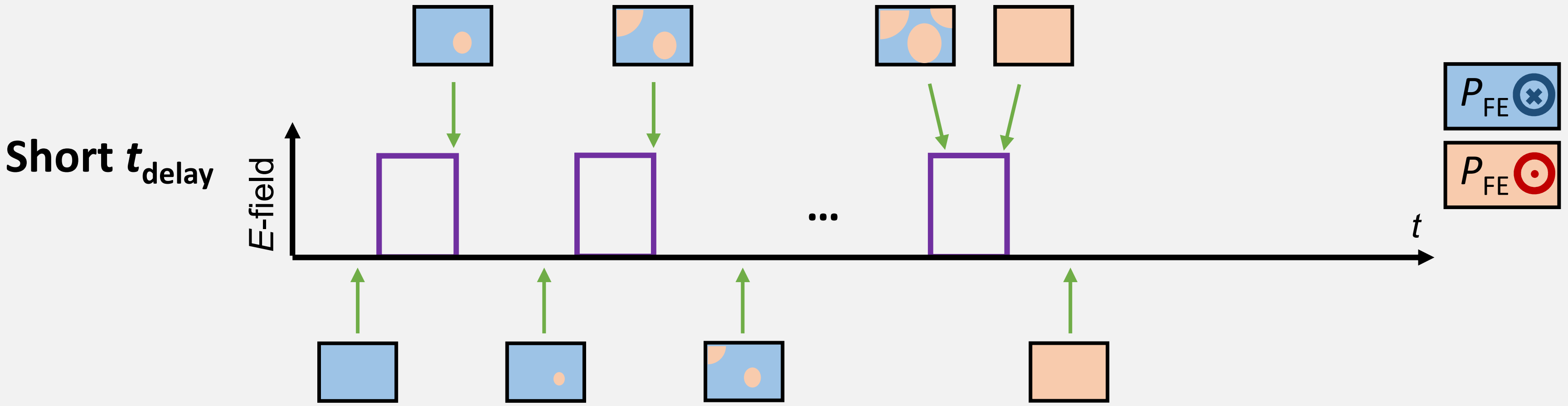
Possible physics: accumulation and relaxation of reversed-polarity regions in a single domain

NLS model



NLS assumes near-instant domain expansion after seed nucleation

Proposed model: nucleation + domain wall instability

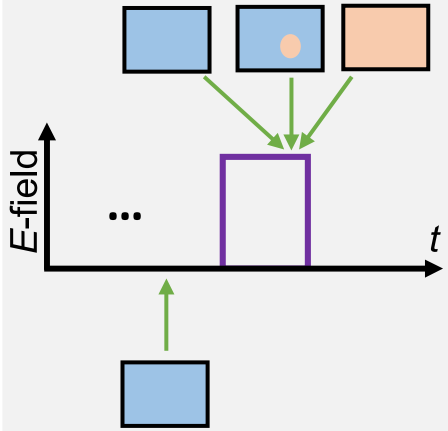


Early study at Purdue: Saha, *APL* 2019

- Consideration of both nucleation and domain wall movement might be needed

Possible physics: accumulation and relaxation of reversed-polarity regions in a single domain

NLS model



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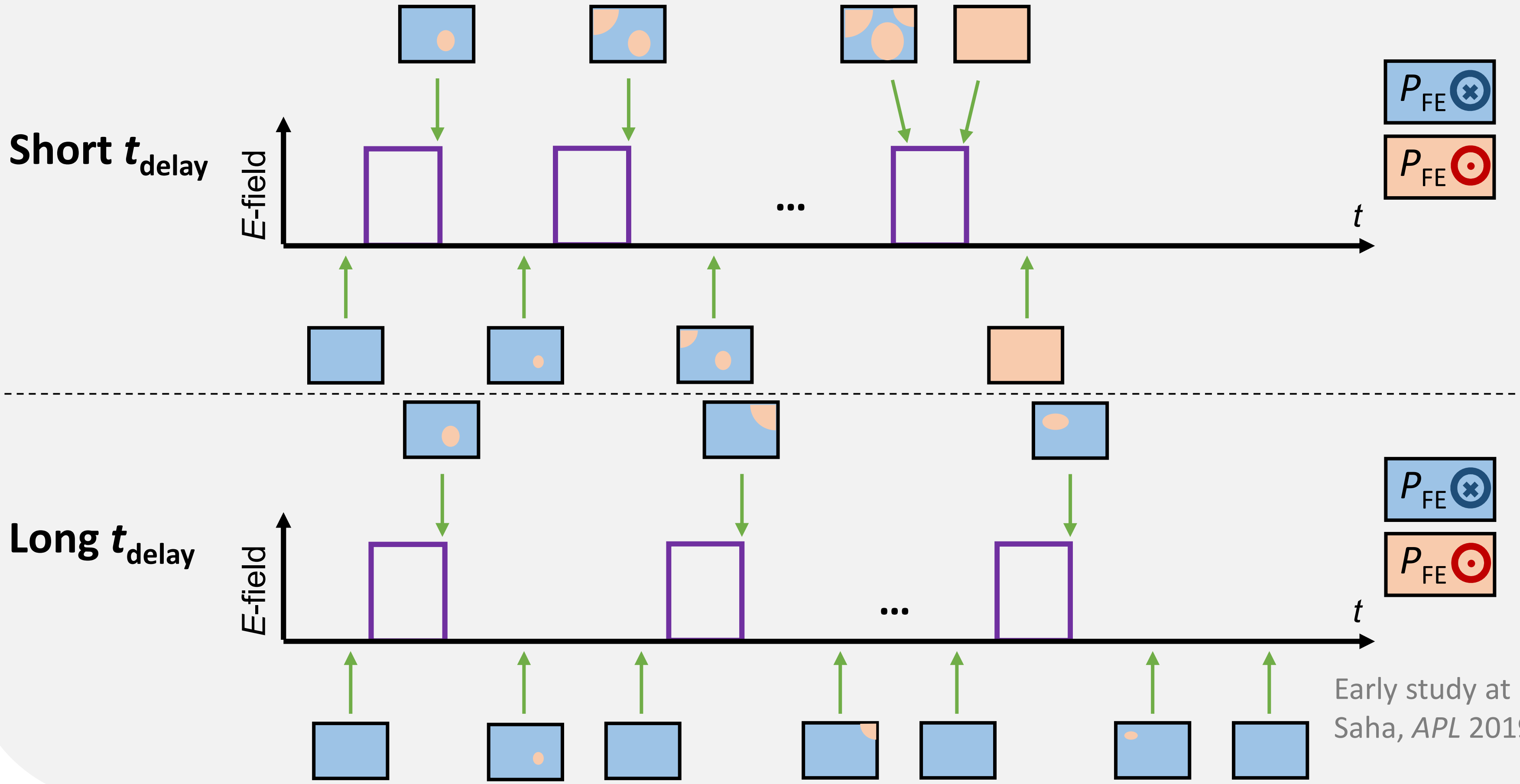

Early study at Purdue: Saha, *APL* 2019

- Reconsideration of NLS theory for FE switching in HZO might be necessary

Conclusions

- Nanoscale BEOL oxide-channel FE-FETs for FE switching dynamics study
- Fast (< 10 ns) and low-voltage (< 1.7 V) single-domain switching
- Single-domain stochasticity of polarization accumulation and relaxation dominates large-area ensemble behavior
- Reconsideration of NLS model for HZO might be necessary
- Sheds light on FE memory and in-memory-computing applications

Acknowledgements

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- MIT.nano
- SRC and SRC liaisons
- Unrestricted seed grant from Intel through the MIT AI Hardware Program