Ferroelectric Materials and Devices: AC Impedance Characterization, BEOL FE-TFTs for Analog AI Accelerators

Jesús A. del Alamo

with Taekyong Kim, Yanjie Shao, John Huang, Elham Borujeny, Tyra Espedal, Jorge Navarro, and Dimitri Antoniadis

Massachusetts Institute of Technology

SRC Exploring Frontiers:
Ferroelectric Materials and Devices Workshop – Unveiling Challenges and Opportunities

Sponsorship: SRC LMD, MIT AI Hardware Program

MIT AI Hardware Program

Workshop discussion topics

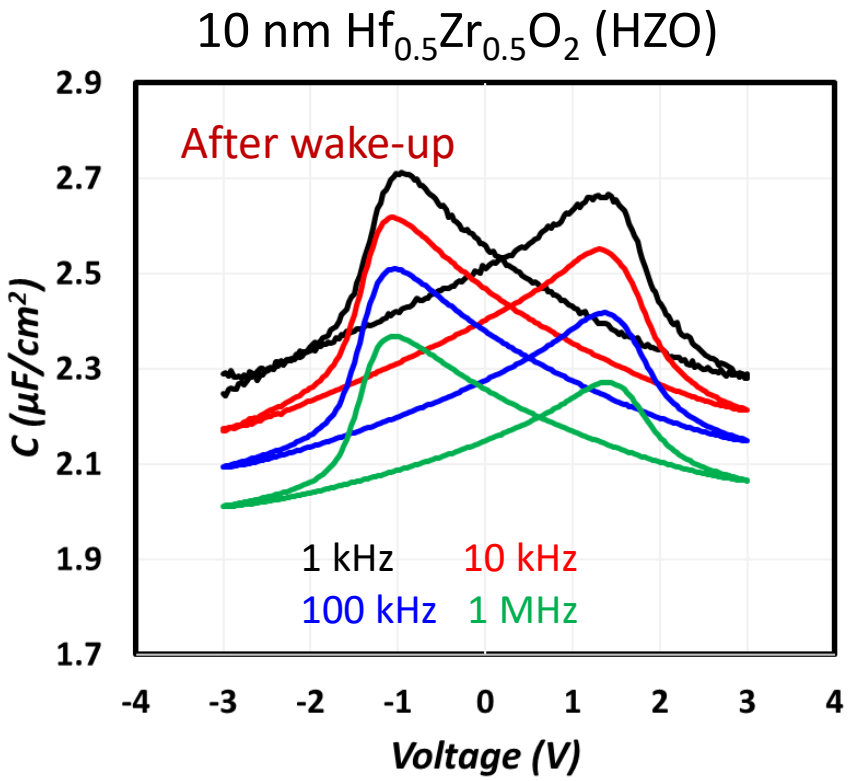
2020-LM-3000
2024-LM-3237

1. What innovations are required for improving endurance?
2. Metrology needs in characterizing FE material defects with respect to fatigue, wakeup and dielectric breakdown?

2023-LMD 3140

3. What is the roadmap towards developing low voltage FE transistors?
4. FE thin films for tunnel junction devices – Three years from now?

AC Impedance characterization: C-V and G-V



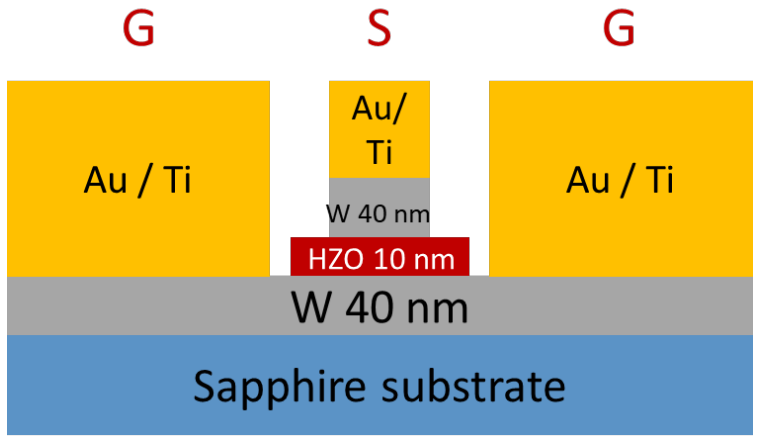
C-V characteristics:

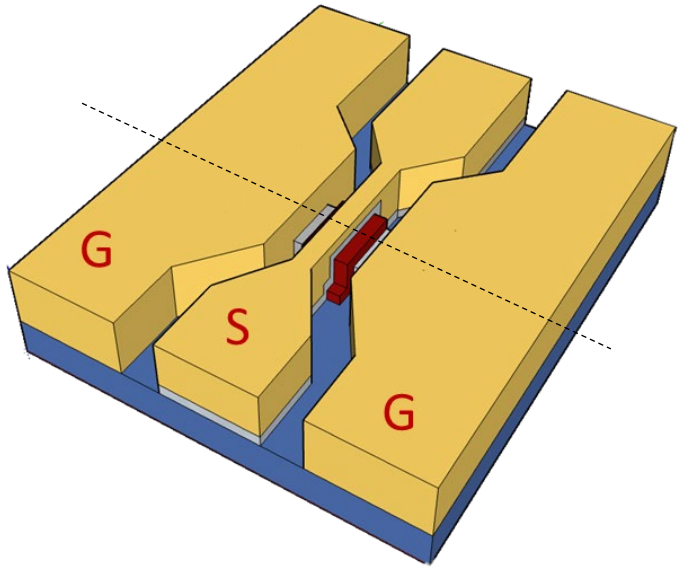
- "Butterfly" shape
- Asymmetric
- Frequency dispersion

Our goals:

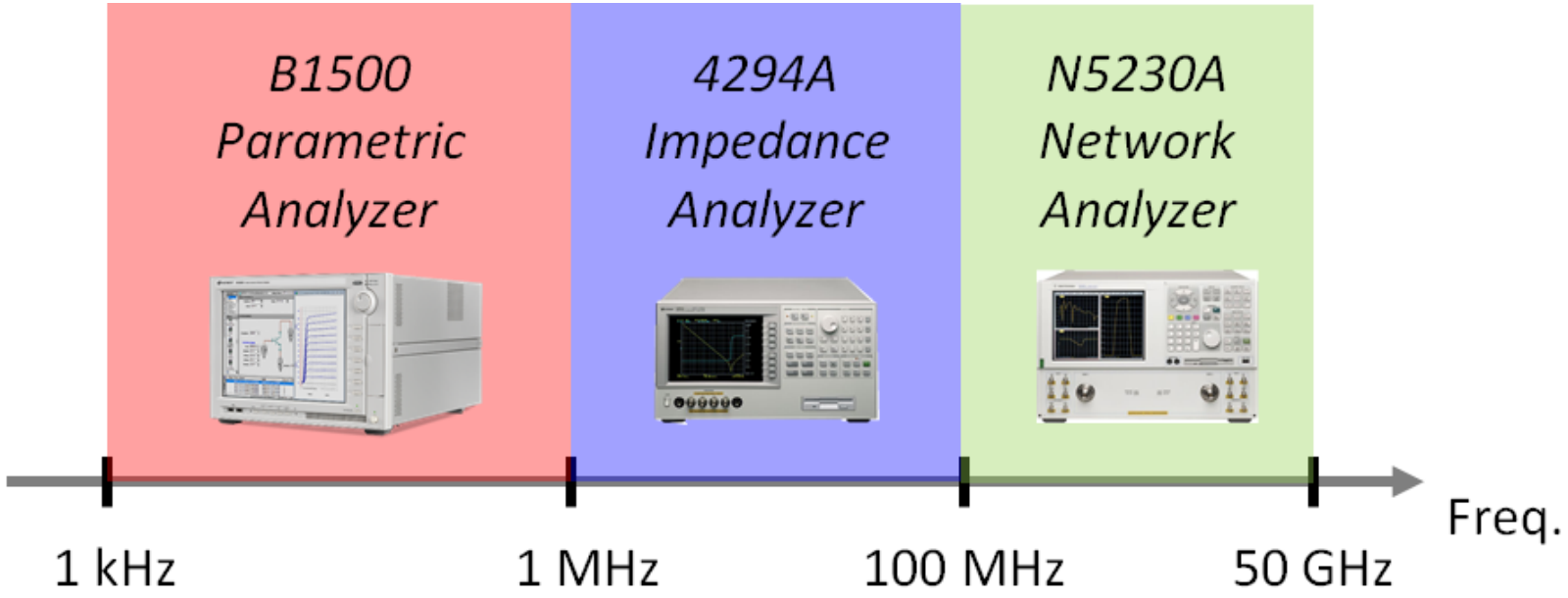
1. Accurate AC impedance characterization
2. Physics of C-V and G-V characteristics
3. Application to understand endurance, imprint, wake up, fatigue, etc.

Experimental





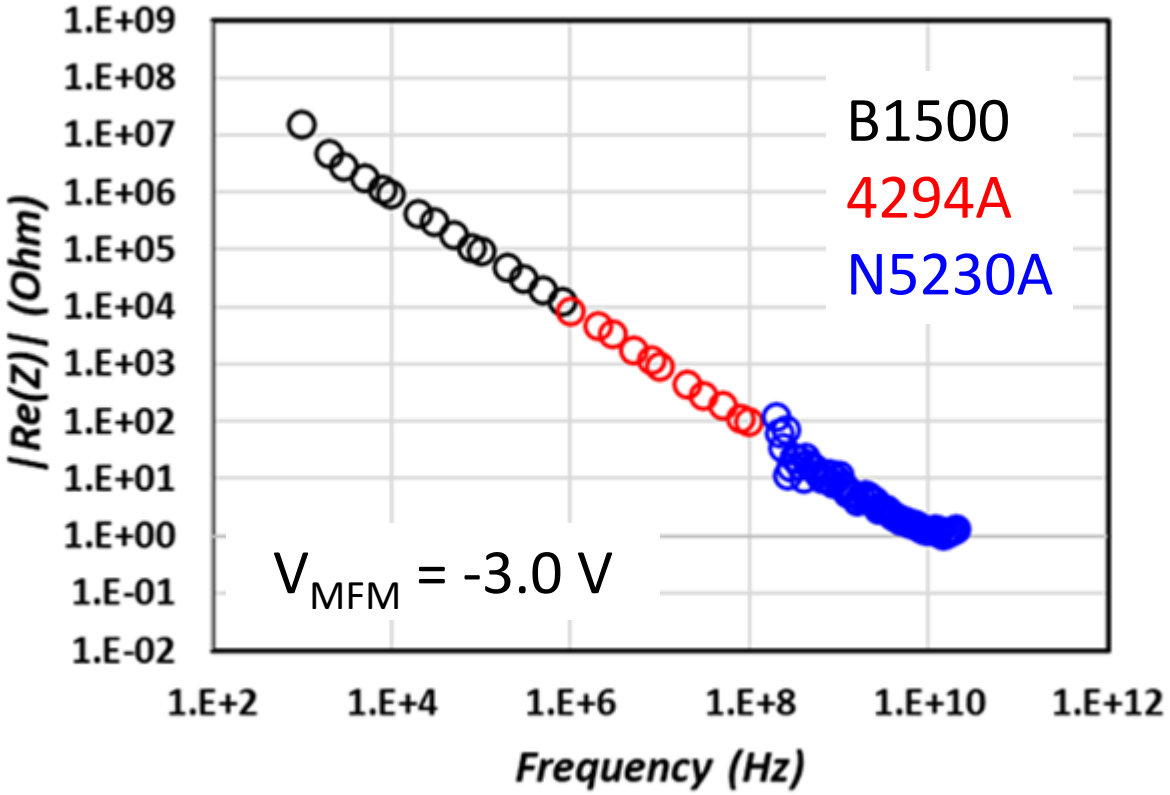
Kim, IEDM 2023



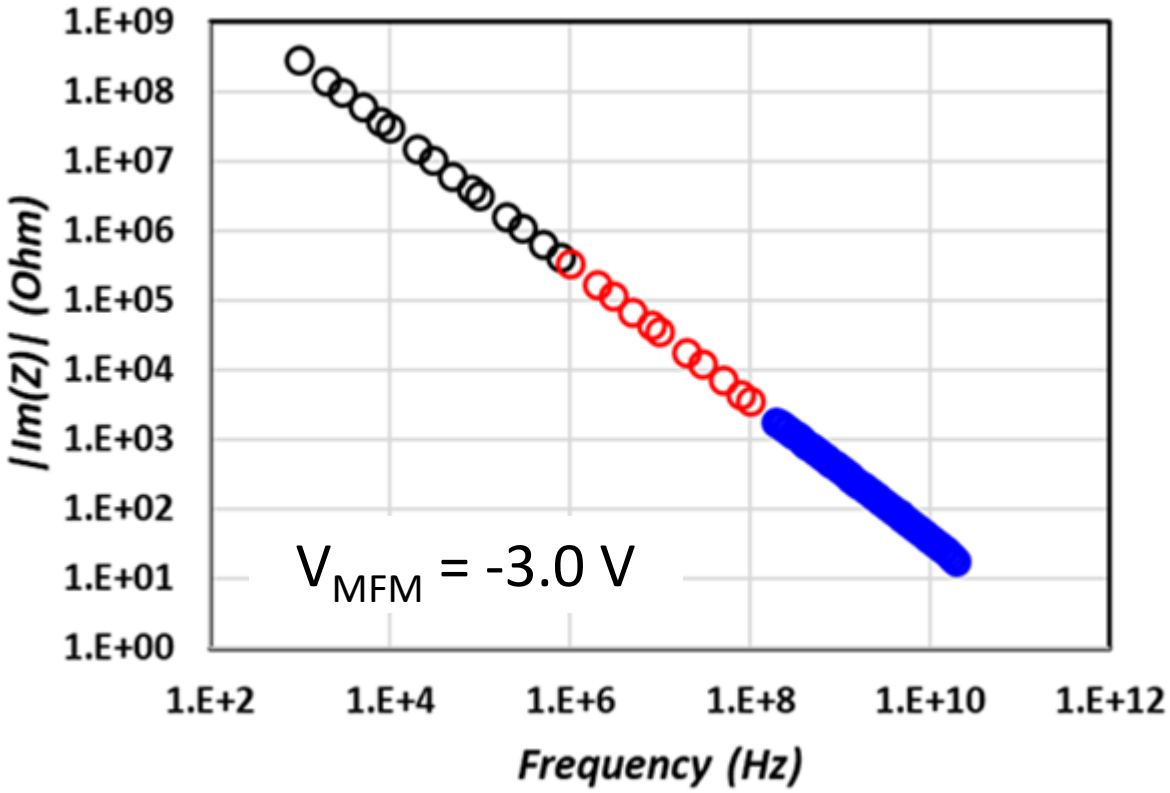
- MFM structure on low-loss coplanar waveguide
- Characterization from 1 kHz to 10 GHz
- Accurate calibration and de-embedding of parasitics

Intrinsic impedance measurements

|Re(Z)|

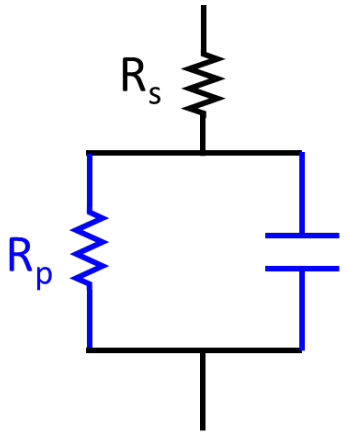


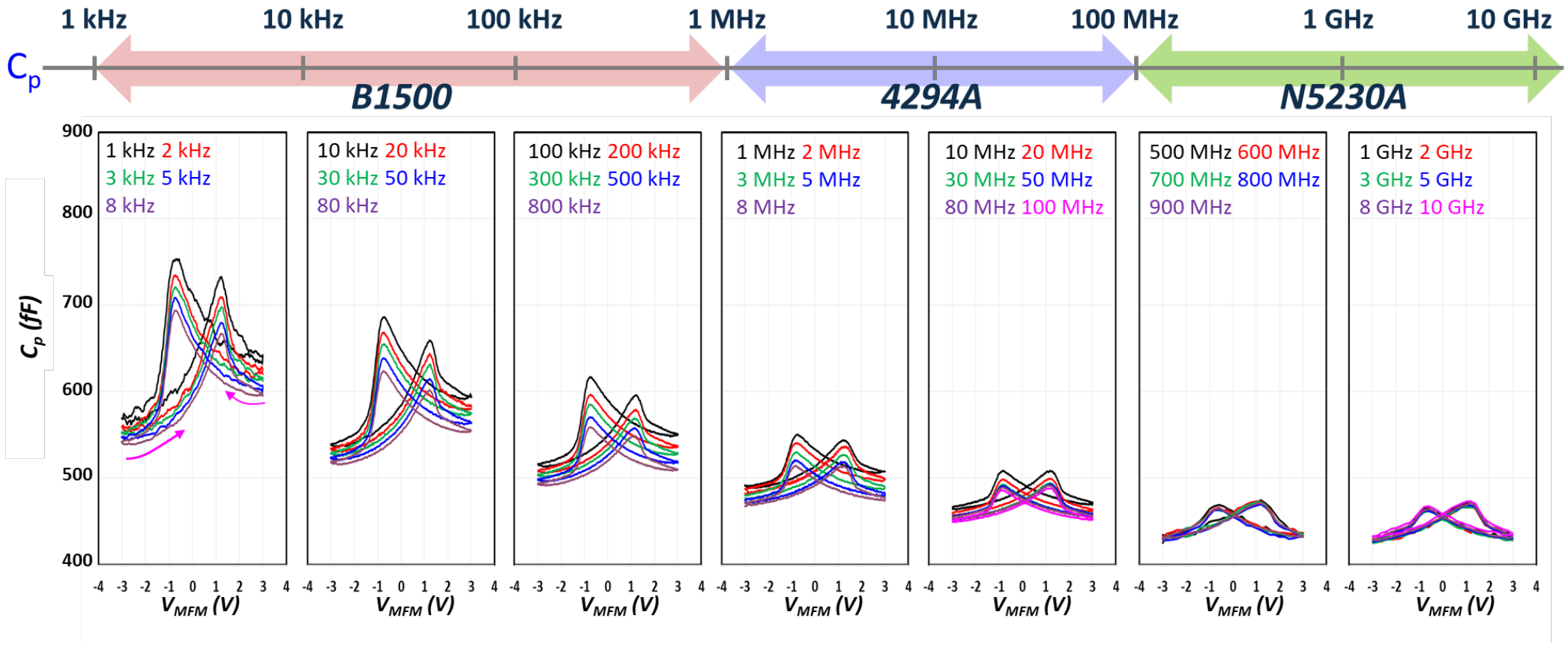
|Im(Z)|



Accurate stitching at frequency boundaries

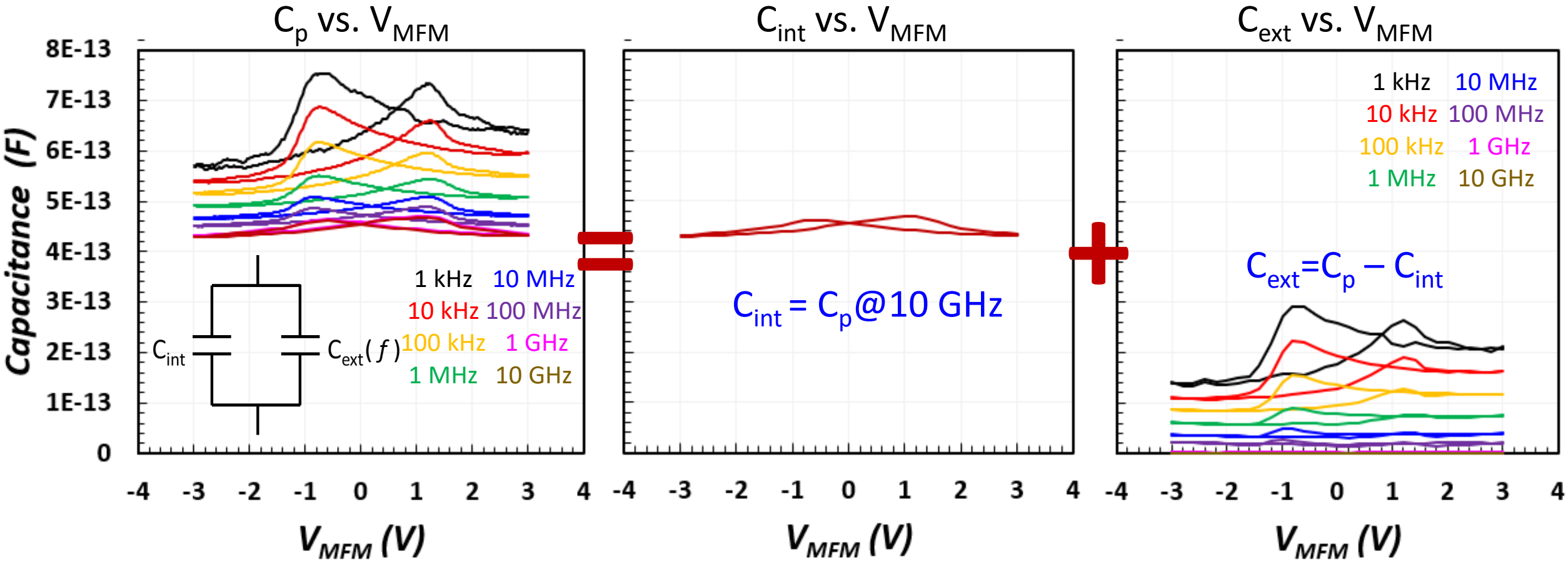
C_p: bias and frequency dependence





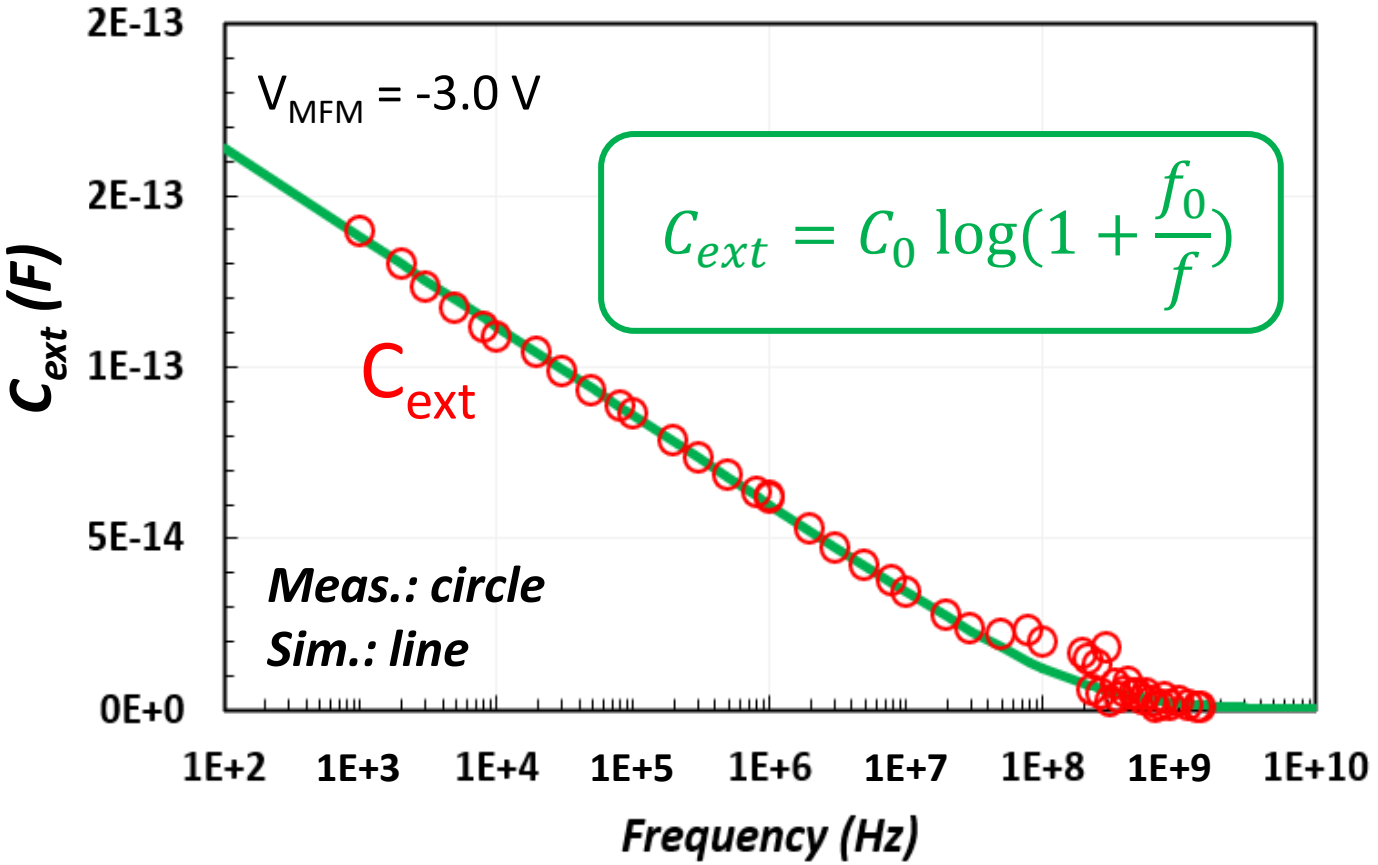
- V-dependent butterfly behavior persist in GHz regime
- f↑ → C_p↓ until about 1 GHz, then f independent

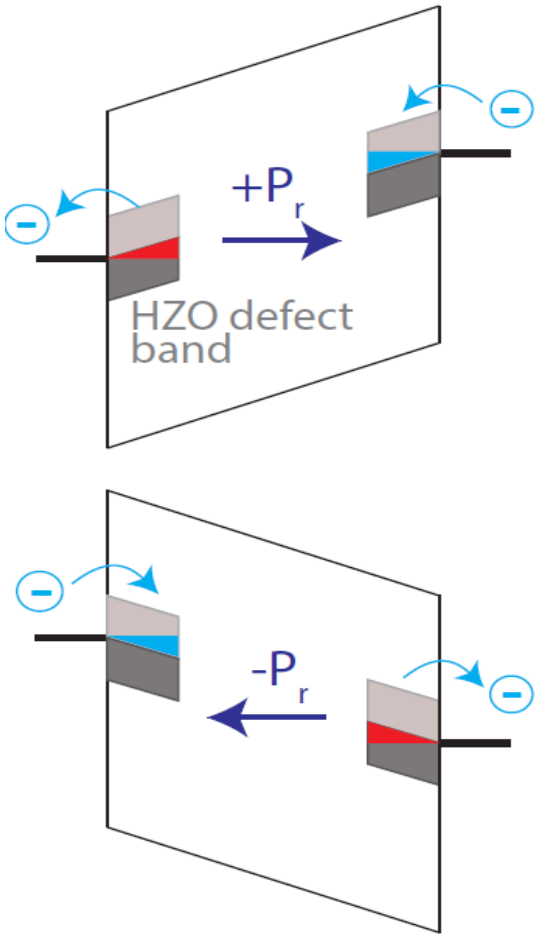
C_p interpretation: $C_p(f) = C_{int} + C_{ext}(f)$



- *Intrinsic* C (C_{int}): butterfly shape, frequency independent
- *Extrinsic* C (C_{ext}): butterfly shape; f ↑ → C_{ext} ↓

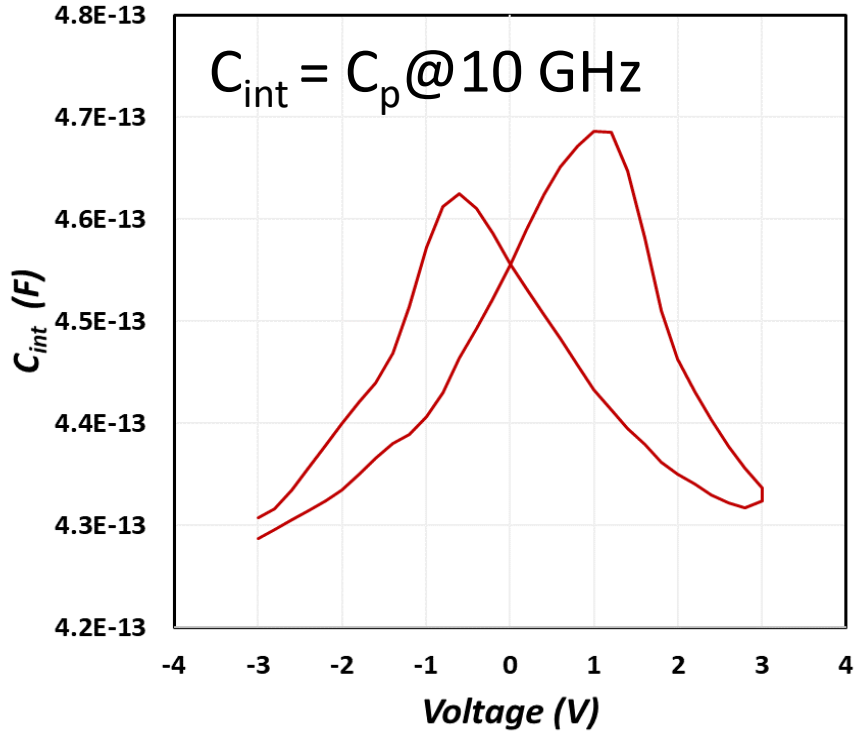
Physics of frequency-dependent C_{ext}

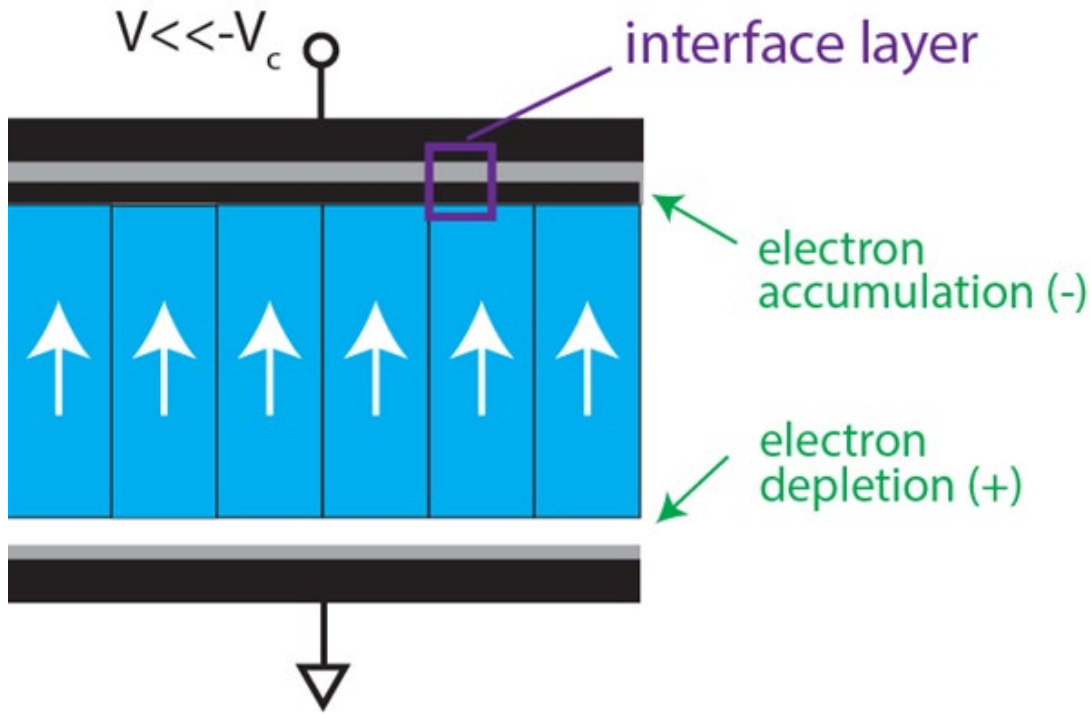




- $C_{ext}(f)$ well described by logarithmic decay function with f_o~ 0.1 GHz
- Consistent with e^- trapping in HfO_2 border traps (Cai, TED 2020; Johansson, TED 2013)

Physics of C_{int}





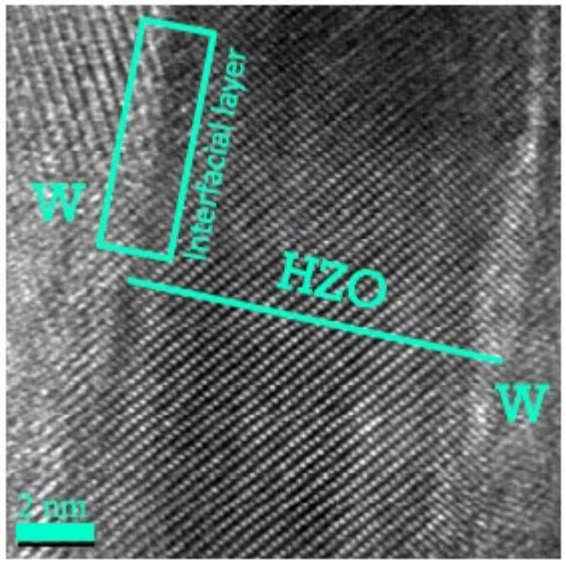
Hypothesis:

- Interfacial layers at M/F boundaries in good electrical contact with metal plates
- Charge at plates supported by electron depletion and accumulation at interfacial layers
- $C_{int} \approx 1/|Q|$

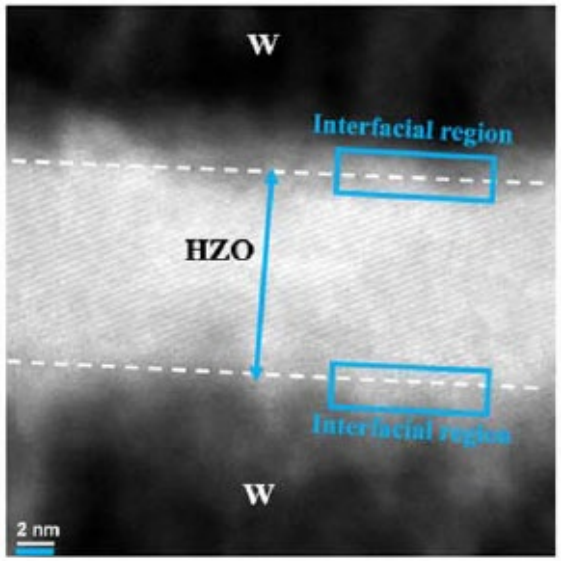
Kim, IEDM 2023

Nature of interfacial layer

Metal oxide at metal/HZO interface



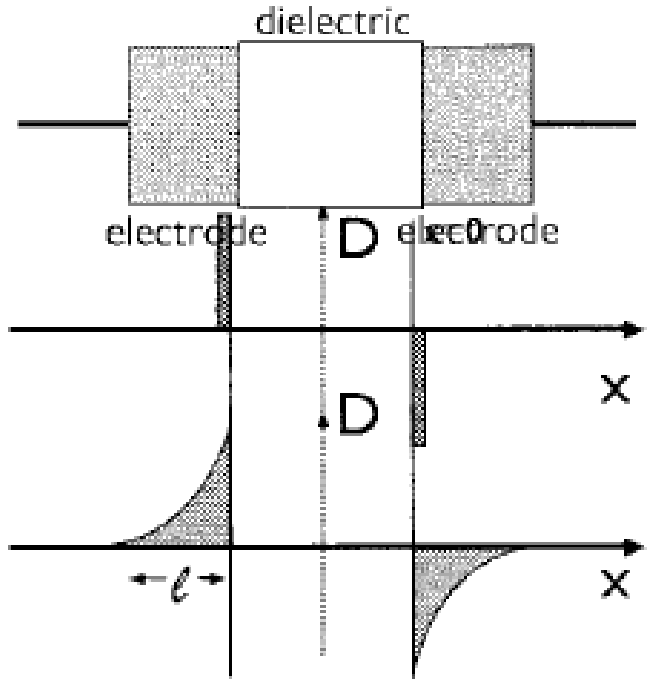
Kashir, AEM 2021



Yadav, Nanotech 2022

WO_x at interface

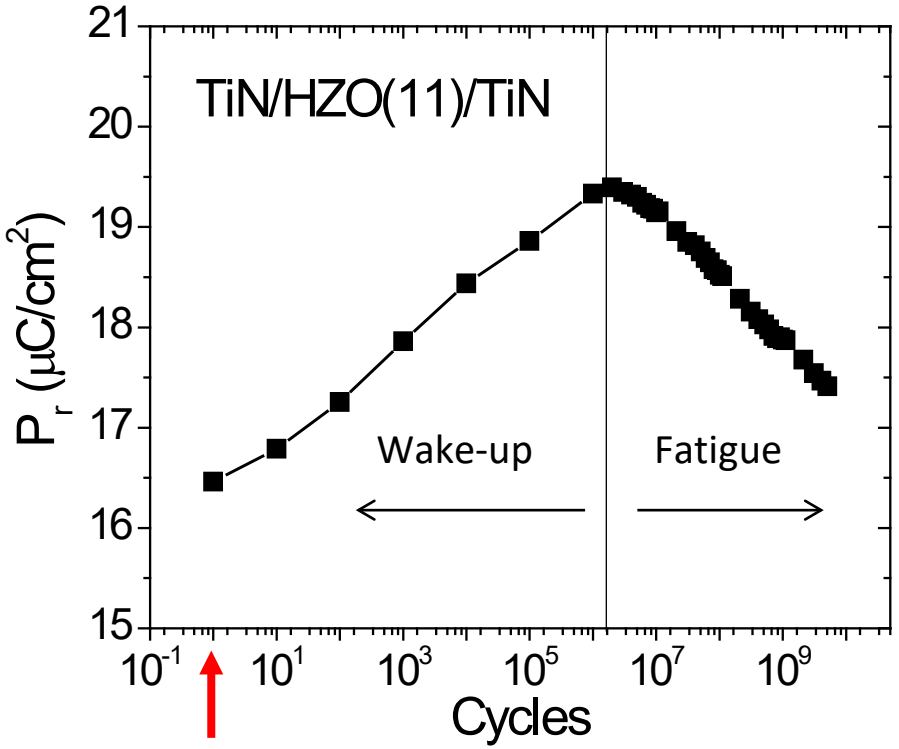
Electric field penetration into metal (finite screening length)



Black, TED 1999

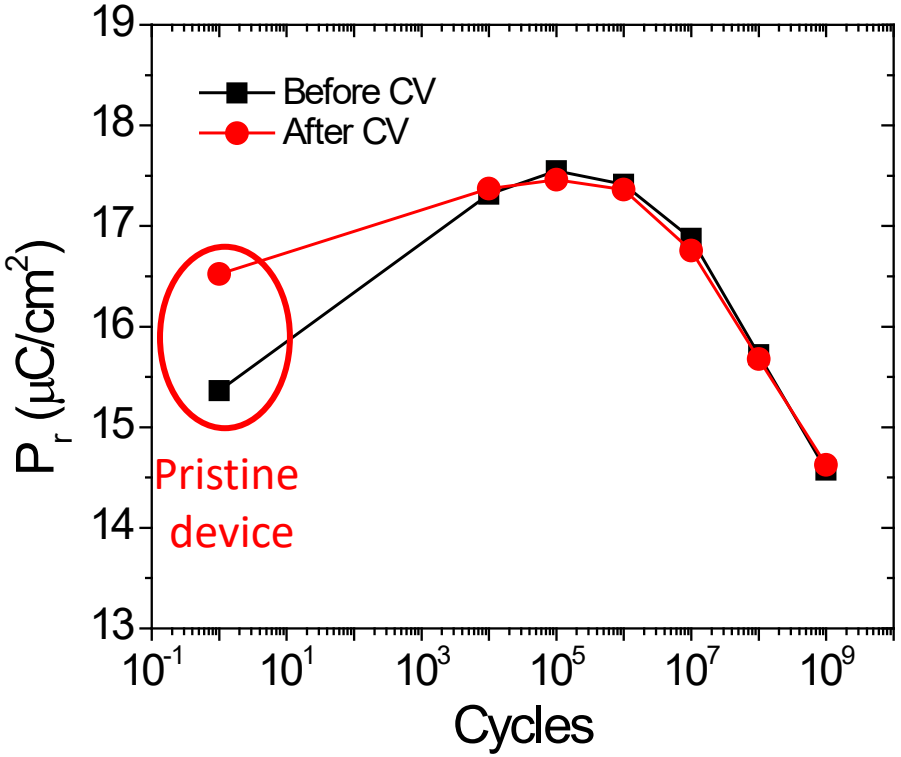
C-V study of wake-up and fatigue: evolution of P_r

Typical bipolar endurance experiment



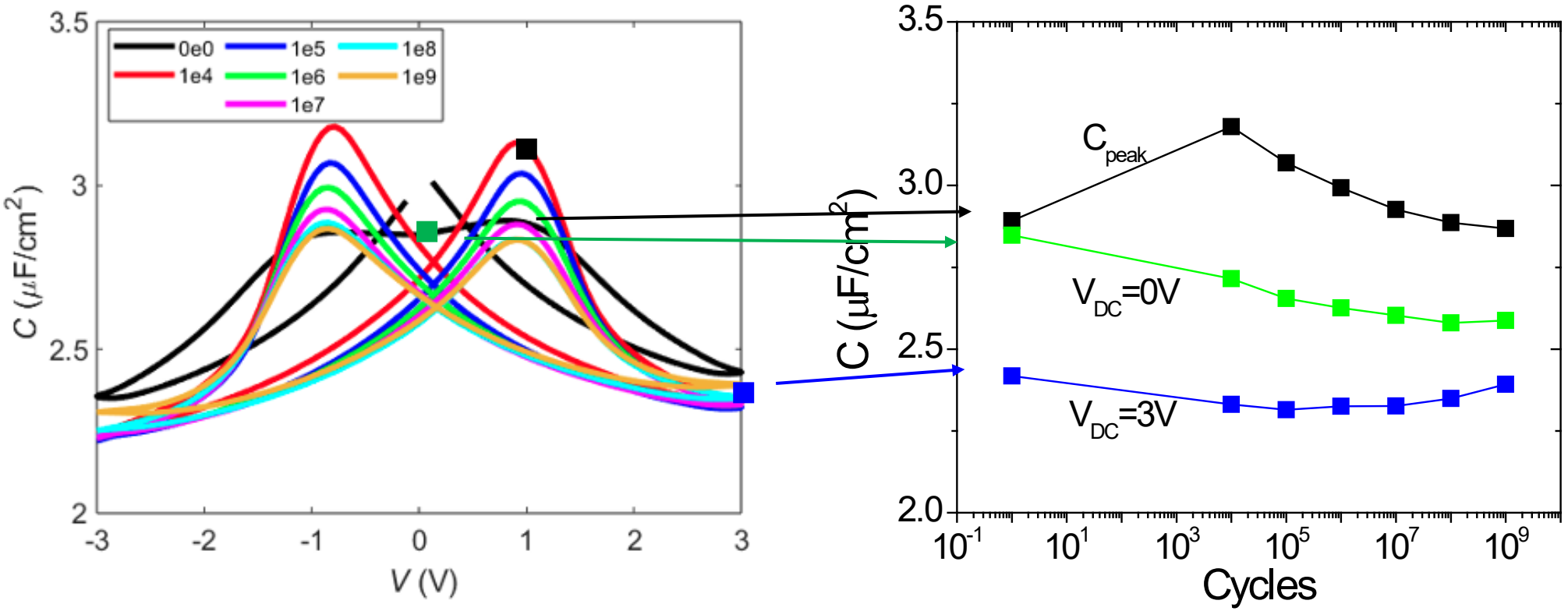
Virgin device

Including CV



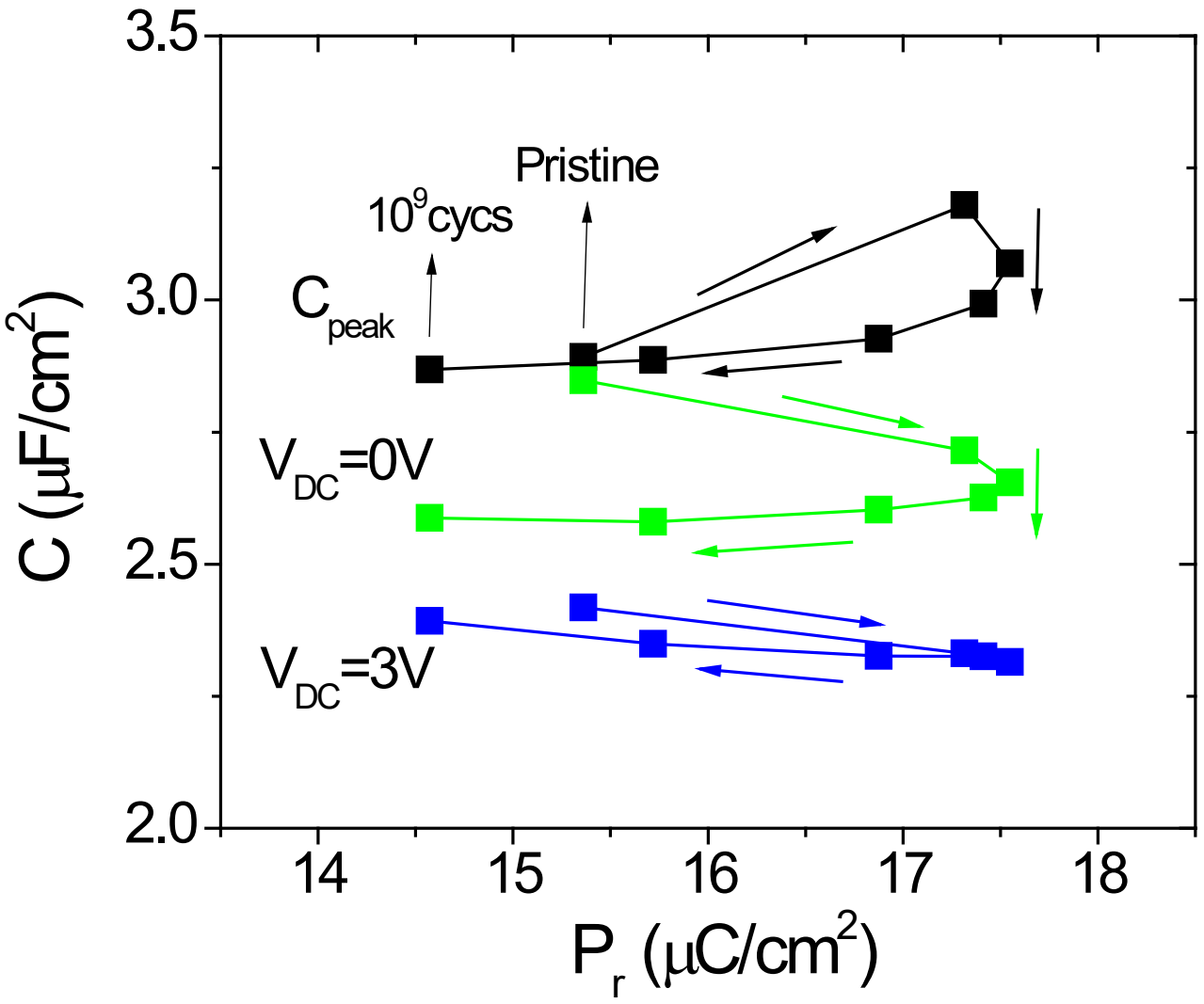
- CV speeds up wake up
- CV doesn't affect fatigue

C-V study of wake-up and fatigue: evolution of C



- C peak emerges during wake up
- C(0 V), C_{peak} and C(+3 V) fatigue in different ways

C-V study of wake-up and fatigue: correlation of C and P_r



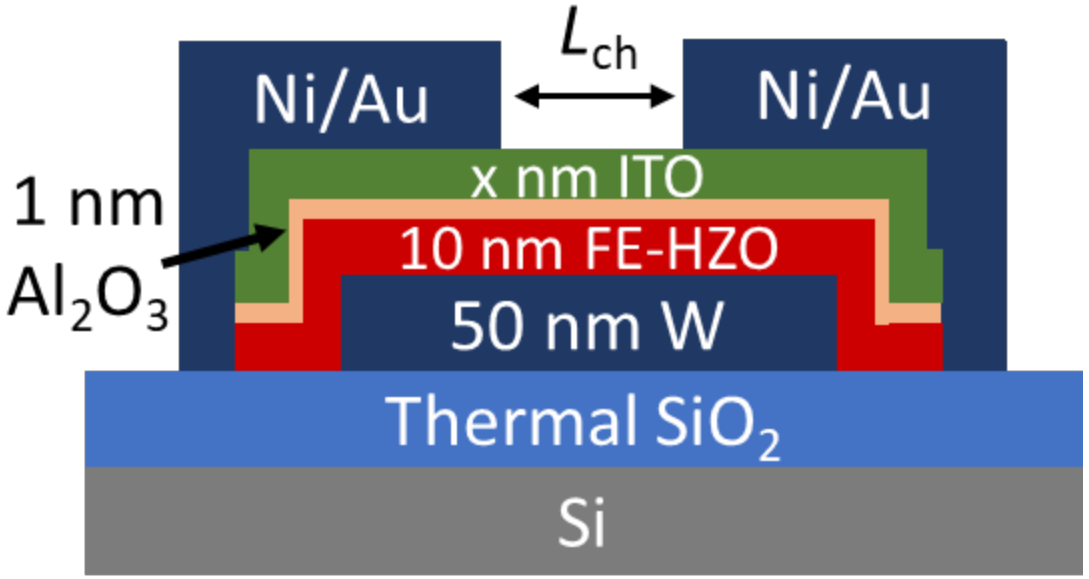
C_{peak}:
- *increases* during wake up
- *decreases* during fatigue

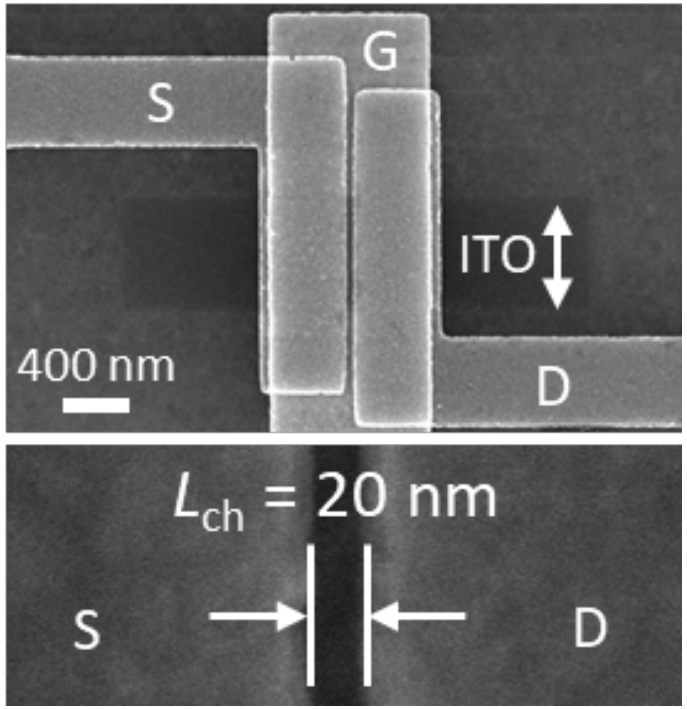
C(0 V):
- *decreases* during wake up
- *stable* during fatigue

C(+3 V):
- *decreases* during wake up
- *increases* during fatigue

Next steps: Why??

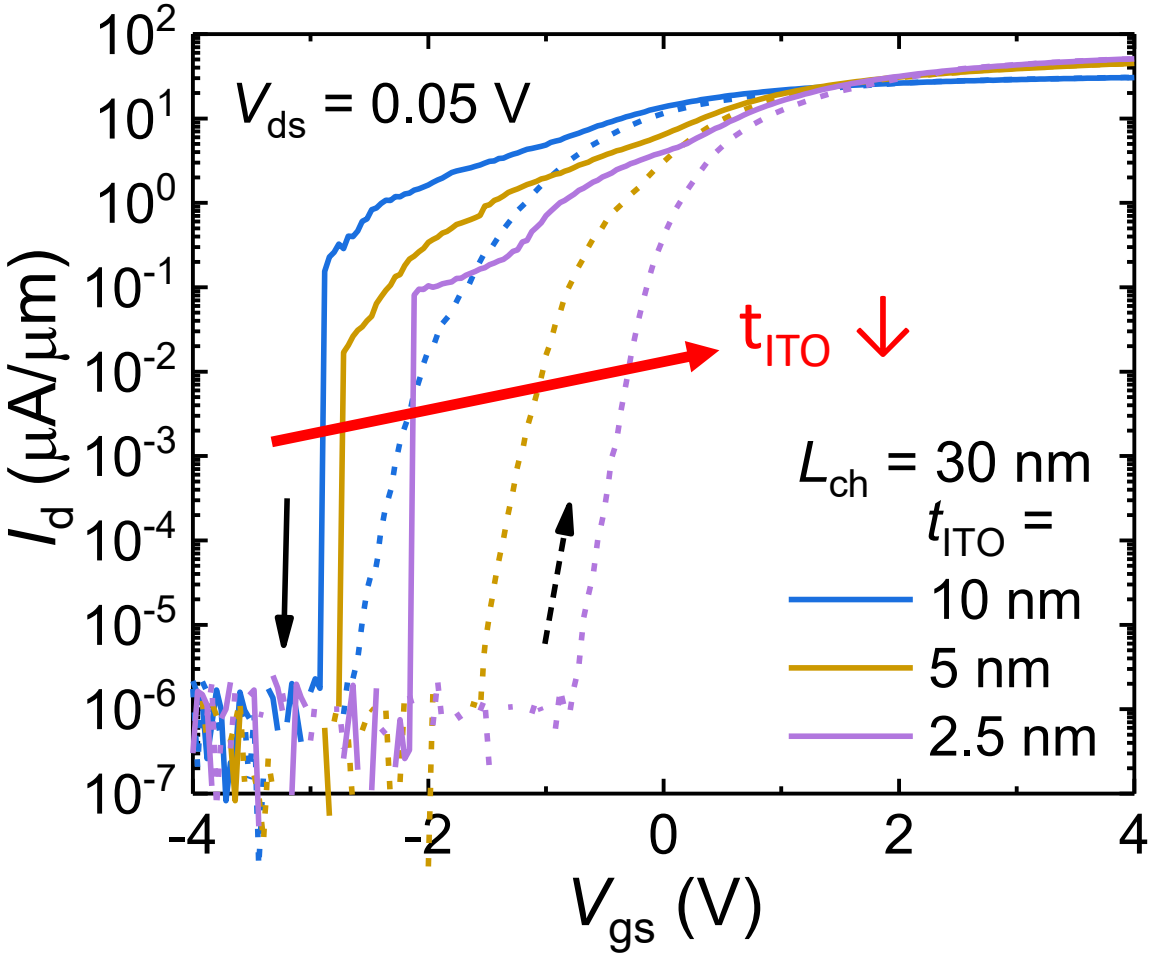
Scaled BEOL FE-FETs with ITO channel

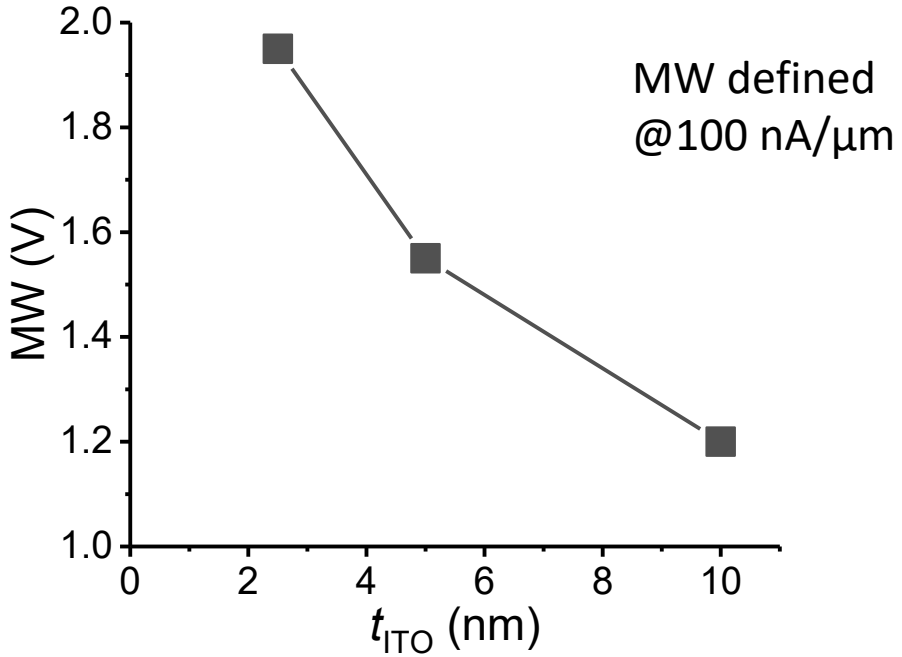




- Back-gate configuration with MFIS structure
- Path for low V operation: thin, highly doped channel → ITO
- BEOL-compatible thermal budget

Memory Window: ITO thickness scaling





ITO thickness ↓ → MW ↑, $\Delta V_t > 0$

Next steps:

- studying analog polarization switching
- endurance