Tools for Reliability Modeling and Characterization of Ferroelectric Devices

IUNET-UNIMORE

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OUTLINE

- **Ferroelectric Polarization**
  - Incomplete Compensation
  - Depolarization Dynamics

- **Reliability Issues in Ferroelectrics**
  - Endurance and Aging
  - Retention
  - Imprint

- **Tools for Reliability Characterization and Modeling**
  - Backswitching Measurements
  - FORC/URC/D-URC Measurements
  - Impedance Spectroscopy
  - Advanced Physics-based Simulations

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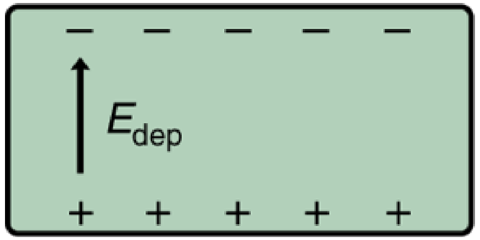
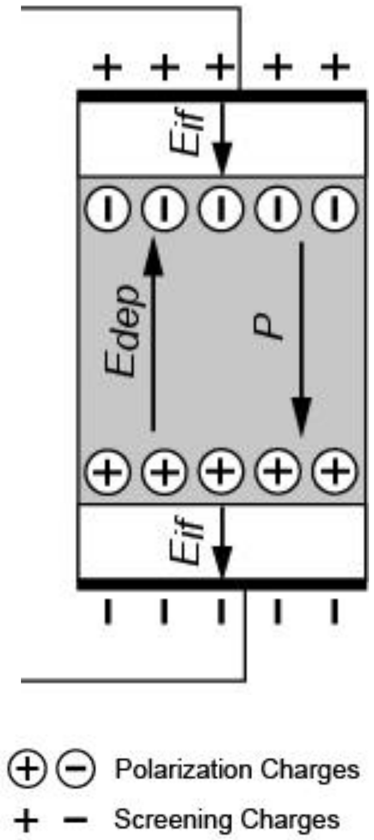
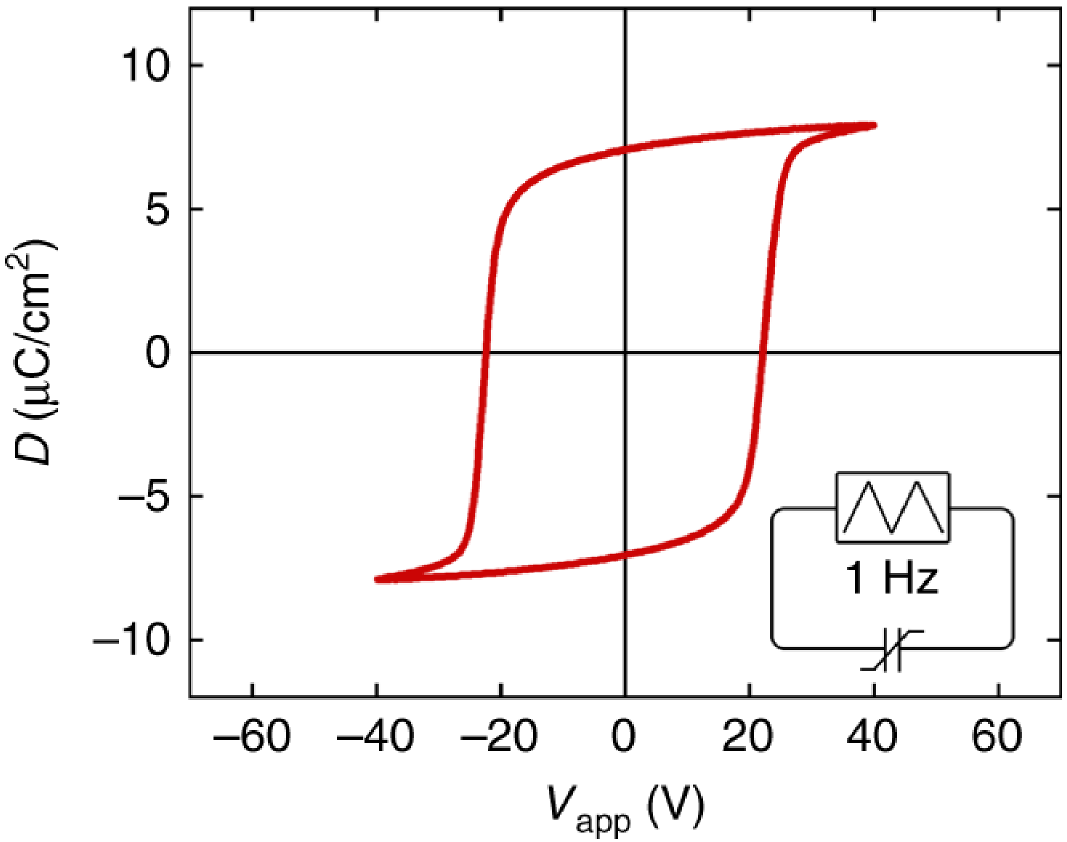
FERROELECTRIC POLARIZATION

- **Reversible spontaneous polarization**
  - **Allows polarization switching ☺**
  - **Implies depolarization field ☹**

- **D-V measurements let us get**
  - **Coercive Field(s)/Voltage(s)**
  - **Saturation Polarization(s)**
  - **Remnant Polarization(s)**
  - Relative Permittivity
  - Frequency Dependence







D. Zhao et al., Nat Commun 10, 2547 (2019)

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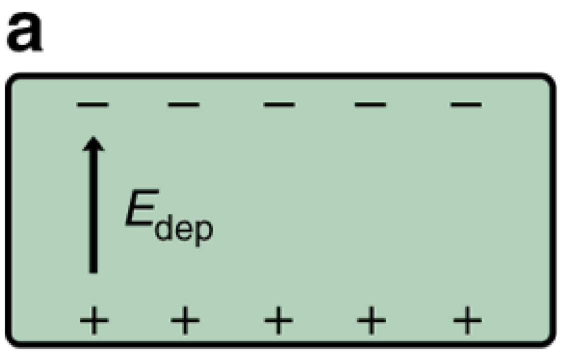
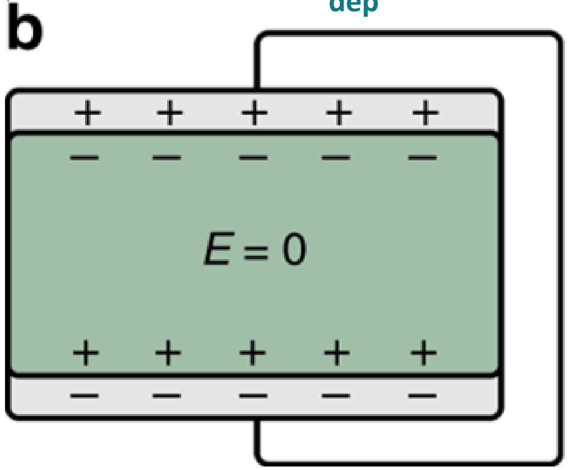
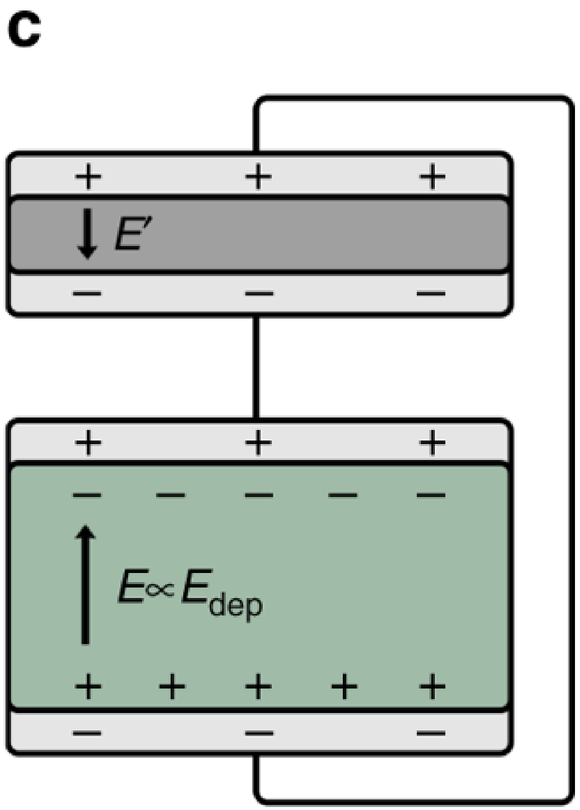
CHARGE COMPENSATION

- **What happens in case of incomplete compensation:**
  - **Ferroelectric slab (a): No compensation**
    - **No free charge can compensate: highest E_{dep}**
  - **MFM capacitor (b): Complete compensation**
    - **Free charge can completely compensate: no E_{dep}**
  - **MFM + Series capacitor or MDFM (c): Partial compensation**
    - **Free charge can partially compensate: some E_{dep}**







D. Zhao et al., Nat Commun 10, 2547 (2019)

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INCOMPLETE COMPENSATION

FIXIT

Some math shows what we can measure and calculate (case c)

- **Measuring D allows calculating:**
  - Voltage on the ferroelectric
  - Electric field in the ferroelectric
  - Polarization

$$E_{\text{ferro}} = \frac{V_{\text{app}}}{d} - \frac{D}{\varepsilon_0 \varepsilon_{\text{ferro}}} \cdot \frac{C_{\text{ferro}}}{C_{\text{ser}}}$$

KVL →

$$V_{\text{app}} = V_{\text{ferro}} + V_{\text{ser}}$$

$$V_{\text{ferro}} = \frac{Q_{\text{ferro}} - PA}{C_{\text{ferro}}} \qquad V_{\text{ferro}} = V_{\text{app}} - \frac{Q_{\text{ser}}}{C_{\text{ser}}}$$

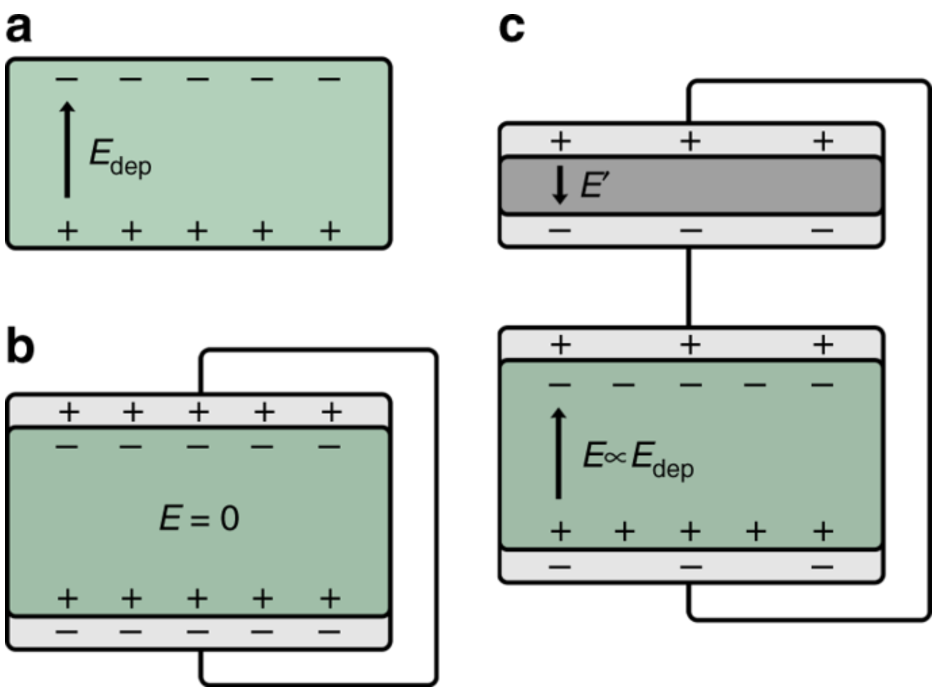
Charge continuity →

$$Q_{\text{ferro}} = Q_{\text{ser}} = V_{\text{ferro}} C_{\text{ferro}} + PA$$

$$V_{\text{ferro}} = \frac{C_{\text{ser}}}{C_{\text{ser}} + C_{\text{ferro}}} V_{\text{app}} - \frac{PA}{C_{\text{ser}} + C_{\text{ferro}}}$$

Electrostatics →

$$D = \frac{\varepsilon_0 \varepsilon_{\text{ferro}} V_{\text{ferro}}}{d} + P$$



D. Zhao et al., Nat Commun 10, 2547 (2019)

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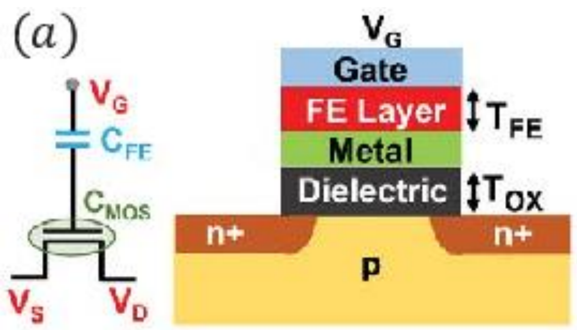
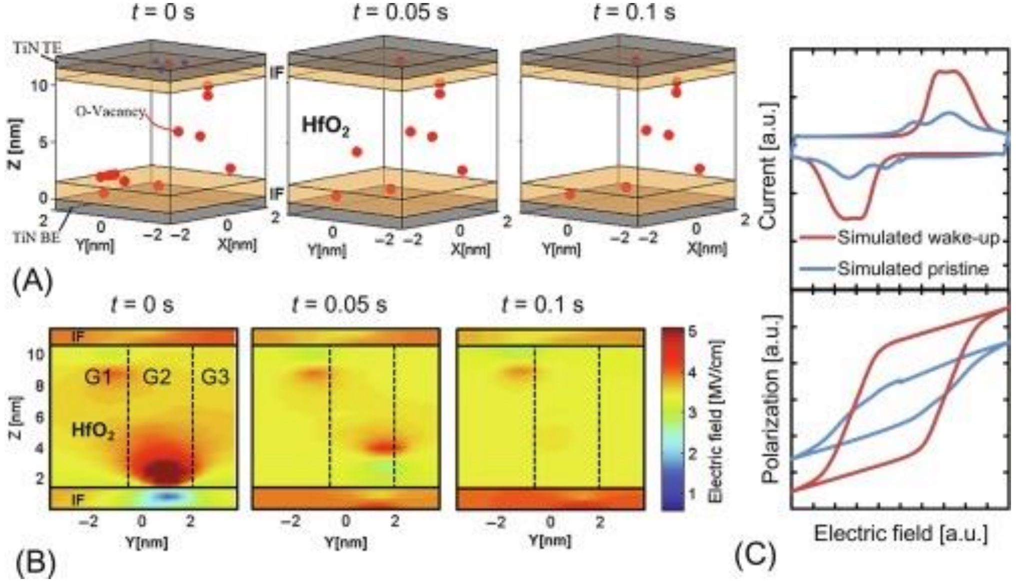
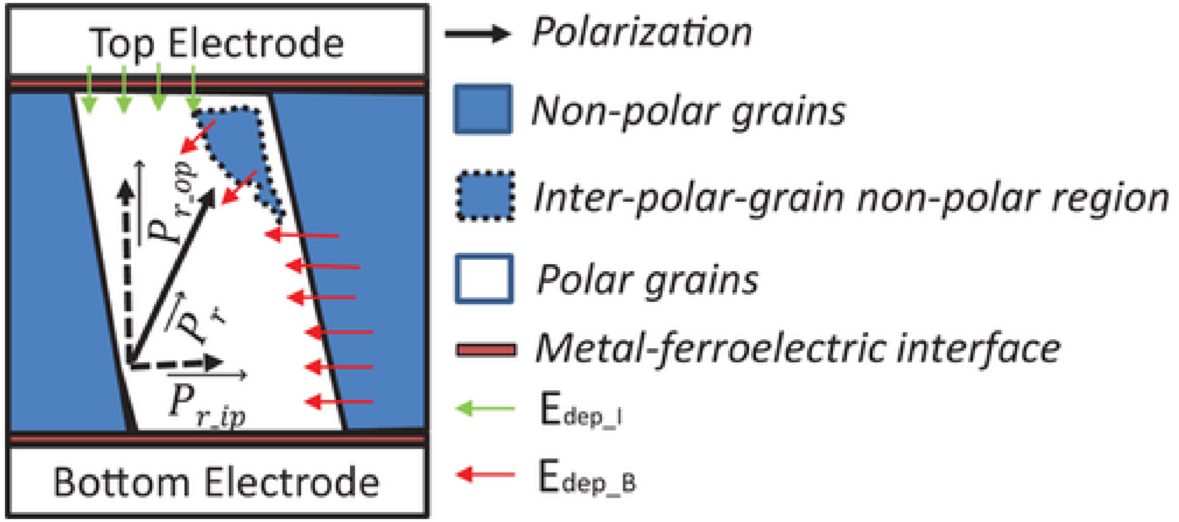
INCOMPLETE COMPENSATION

- **Measurements allow exploring depolarization dynamics (crucial for reliability)**
- **Possible causes of depolarization:**
  - **Series Capacitance (important in FeFETs)**
  - **Charge Screening Length / Dead Layers**
  - **Non-polar Grains**
  - **Defects**





M. Pešić, L. Larcher, in «Ferroelectricity in Doped Hafnium Oxide: Materials, Properties and Devices» 2019, Woodhead Publishing



F. Mehmood et al., Adv. Mater. Interfaces 2019, 6, 1901180

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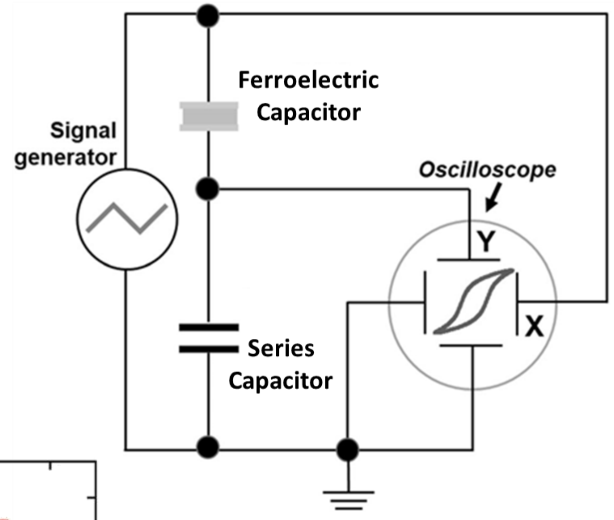
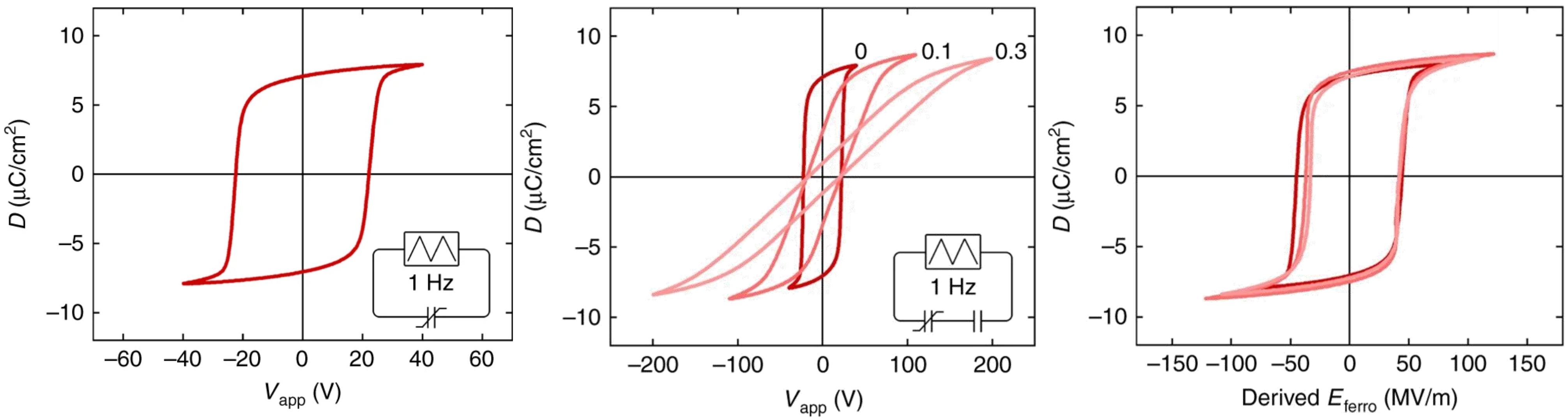
SAWYER-TOWER CIRCUIT

FIXIT

- **This circuit:**
  - **Directly measures displacement and remnant polarization**
  - **Relates depolarization field to suppressed remnant polarization**

$$V_{ser}@\,(V_{app} = 0) = \frac{PA}{C_{ser} + C_{ferro}} \qquad D = \frac{V_{ser}C_{ser}}{A}$$





D. Zhao et al., Nat Commun 10, 2547 (2019)

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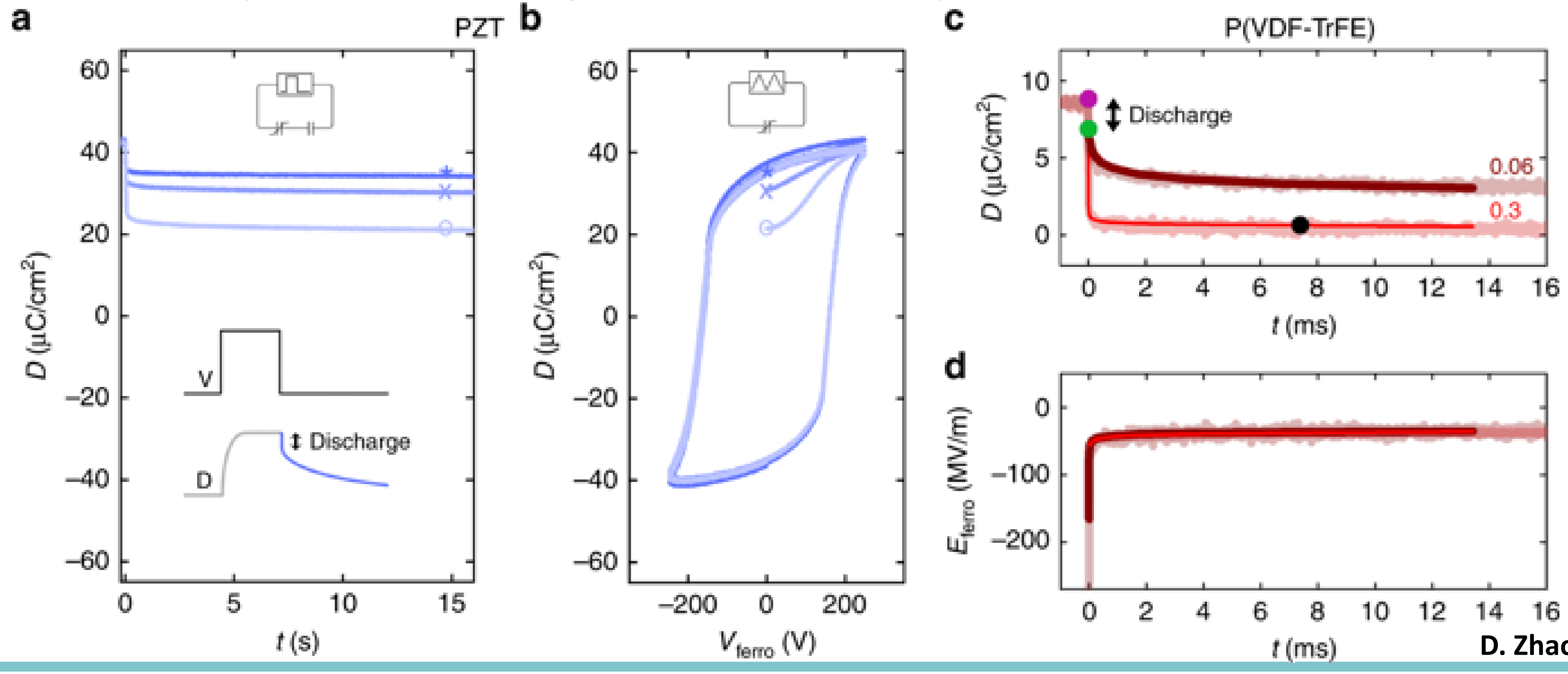
DEPOLARIZATION TRANSIENT

FIXIT

- **Transient of depolarization dynamics using a Sawyer-Tower circuit**
  - **Sawyer-Tower arrangement to “tune” partial compensation and depolarization field**
  - **Integrating current over time to get displacement**
  - **Linear polarization discharge and Ferroelectric depolarization**



D. Zhao et al., Nat Commun 10, 2547 (2019)

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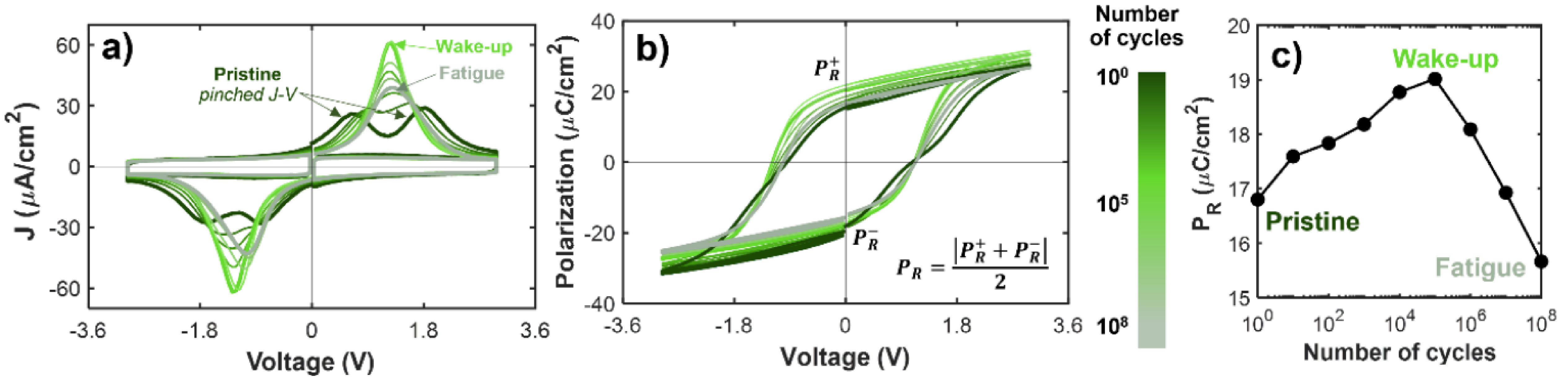
WAKE-UP AND FATIGUE

FIXIT

- **Key device features change along the device lifetime**
  - **Initial J-V characteristic is "pinched" (low P_R: needs "wake-up" cycling, typically 10^3 to 10^4)**
  - **After wake-up, highest P_R and well-behaved J-V (single switching peak)**
  - **Further cycling lowers P_R and some domains do not switch anymore (fatigue)**
  - **Eventually, the device fails (endurance)**

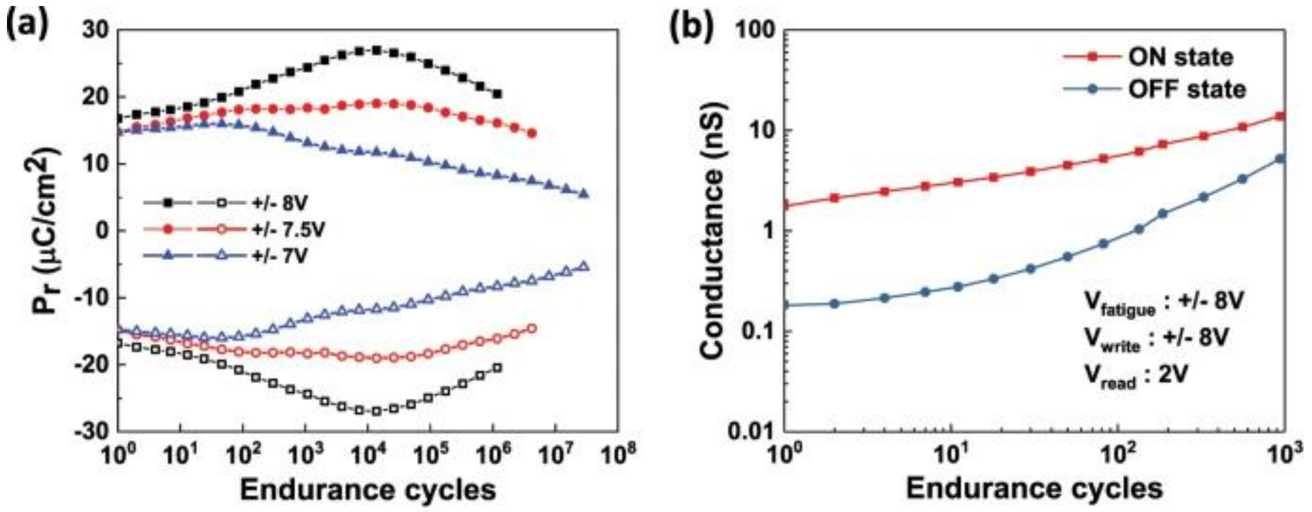


S. Vecchi et al., Adv Ele Mat, 2400204 (2024)

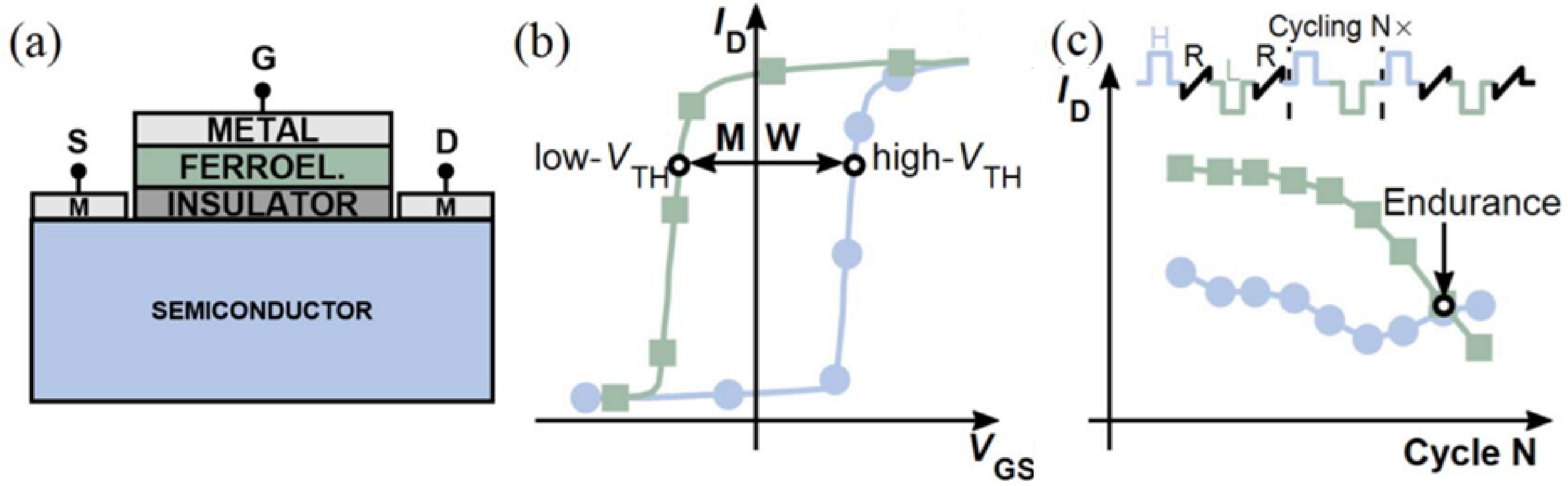
Funded by the European Union

ENDURANCE AND AGING

- **How many switching cycles can a ferroelectric device withstand?**
  - **Depends on the device structure**
    - FeFET/FTJ worse than FeRAM
  - **Depends on the applied bias/stress**
  - **Thought to be limited by**
    - IL/DE degradation
    - Phase changes and domain pinning
    - Defects generation in the stack (breakdown)



H. Ryu et al., Sci Rep, 9 20383 (2019)



N. Zagni et al., Proc. of IEEE, 111 2 (2023)

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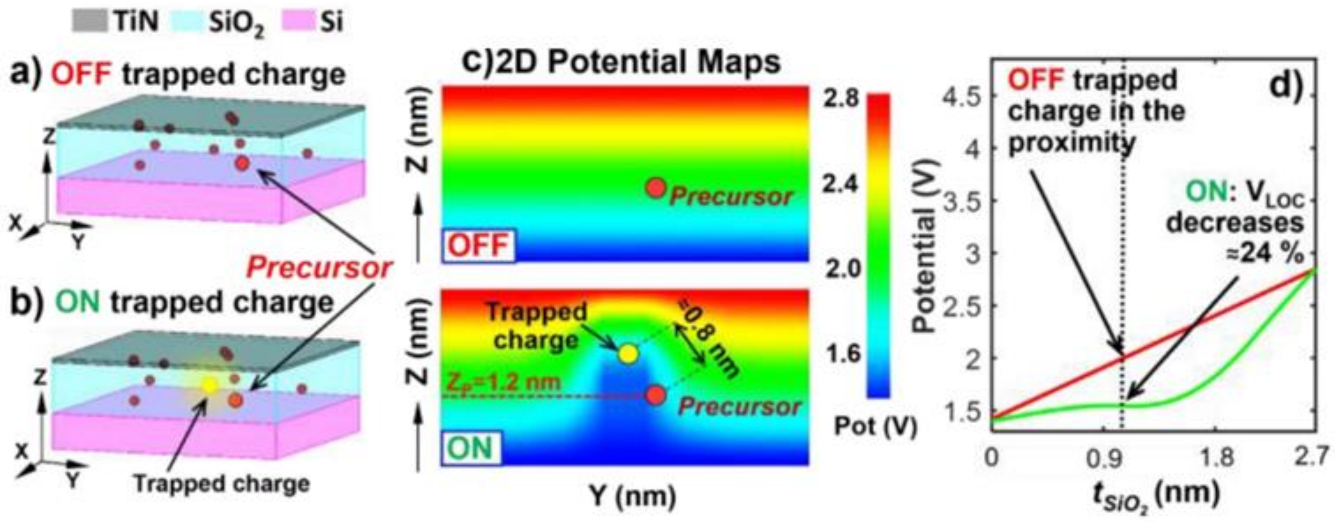
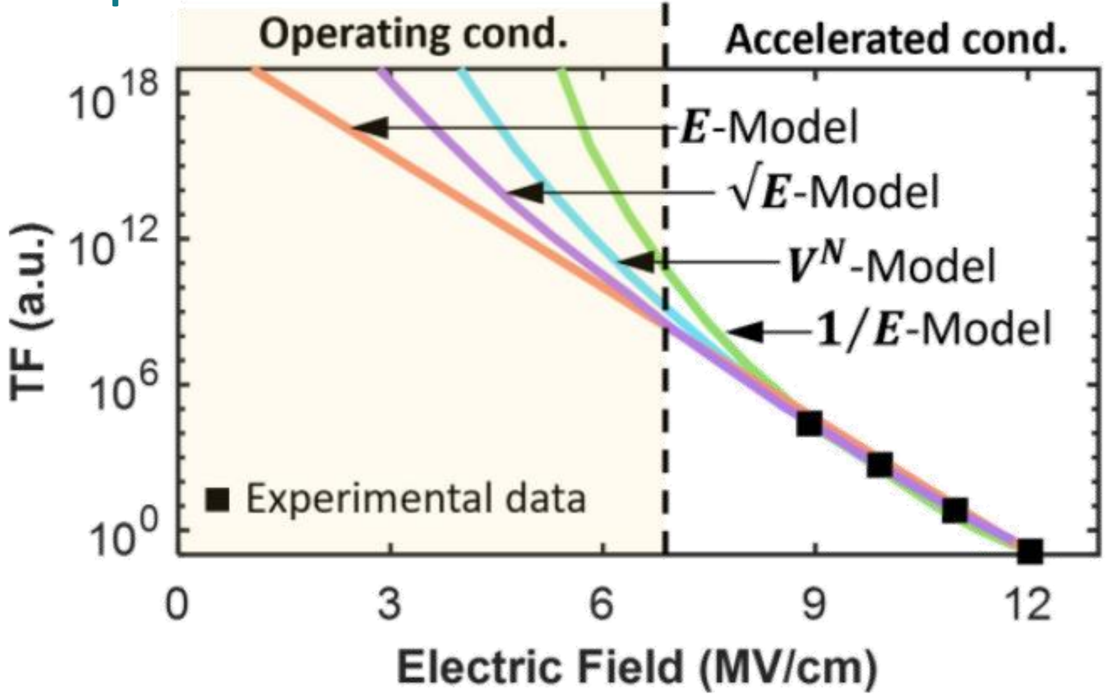
DIELECTRIC BREAKDOWN

- **Electric and temperature fields in the stack promote defect generation, eventually leading to breakdown**
  - **Many models in the literature: all agree on predicting device lifetime at high fields**
    - All agree on predicting device lifetime at high fields
    - Strongly diverge when projecting at operating conditions
  - **Recently introduced carrier injection model reconciles such discrepancies**
    - Highlights the role of carrier trapping into defect precursors
    - **Trapping in precursors facilitates defects generation**
    - **Trapping strongly affects internal electric field!!**





S. Vecchi et al., IEEE TDMR, 24 2 (2024)

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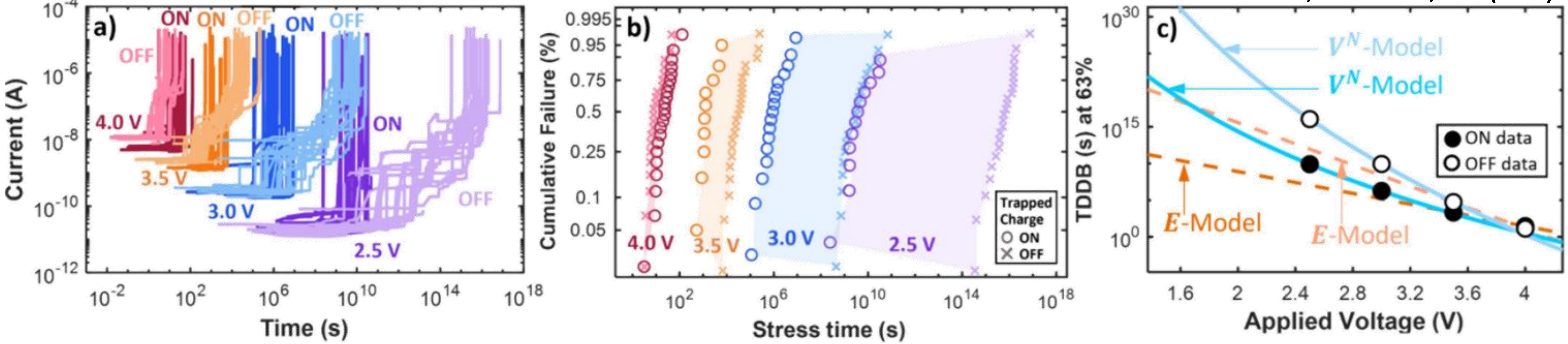
DIELECTRIC BREAKDOWN

FIXIT

- **Electric and temperature fields in the stack promote defect generation, eventually leading to breakdown**
  - **Features of BD as related to trapping are strongly material-dependent**
    - In HfO_2 it has been suggested that trapping at O vacancies (that may exist in 5 charge states, -2 through +2) accelerate BD!
    - In SiO_2 the same mechanism leads to a delay in BD dynamics!
    - What about in ferroelectric HfO_2? And in other material systems of interest (e.g., AlScN?)

  - **Internal field in ferroelectrics further complicated by 3D grain-dependent polarization**
    - Effect of trapped charge superposed to that of polarization (highly complex interactions between trapping and polarization)
    - Hard to predict how BD dynamics takes place in ferroelectrics

S. Vecchi et al., IEEE TDMR, 24 2 (2024)



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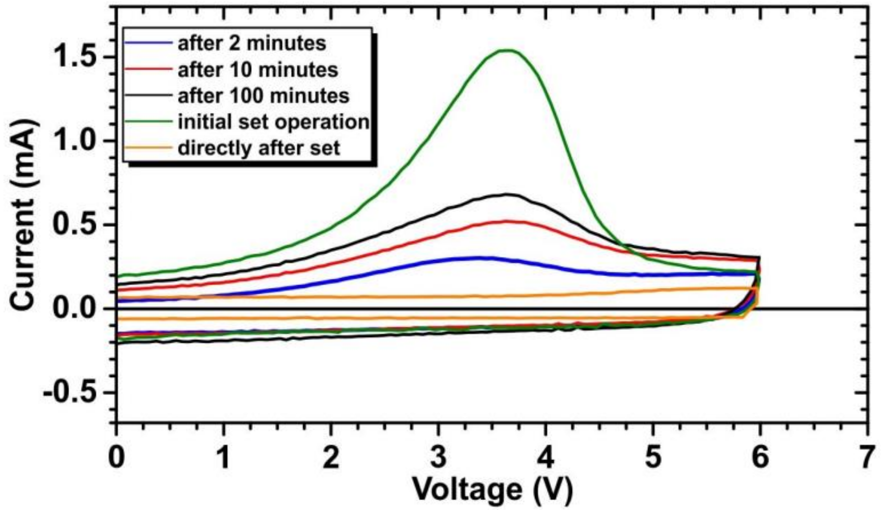
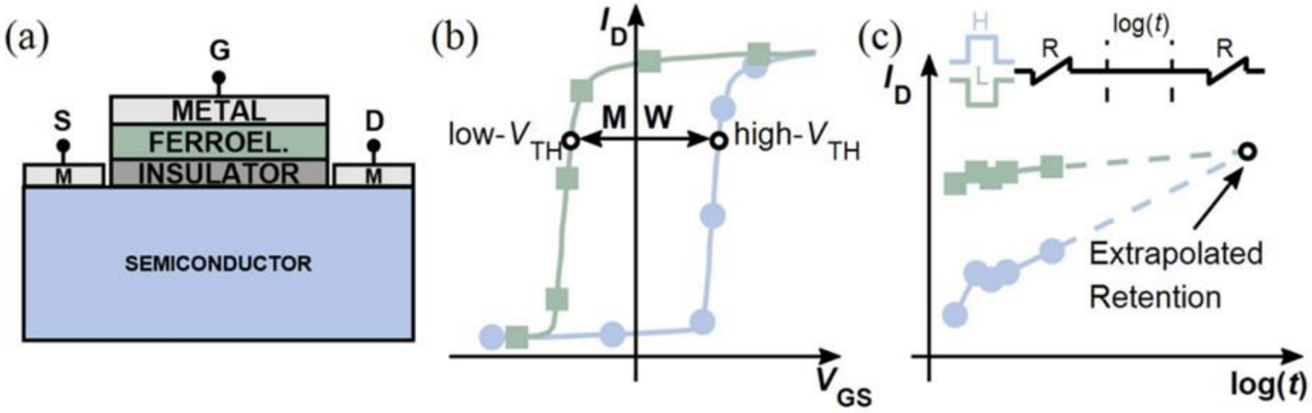
POLARIZATION STATE RETENTION

FIXIT

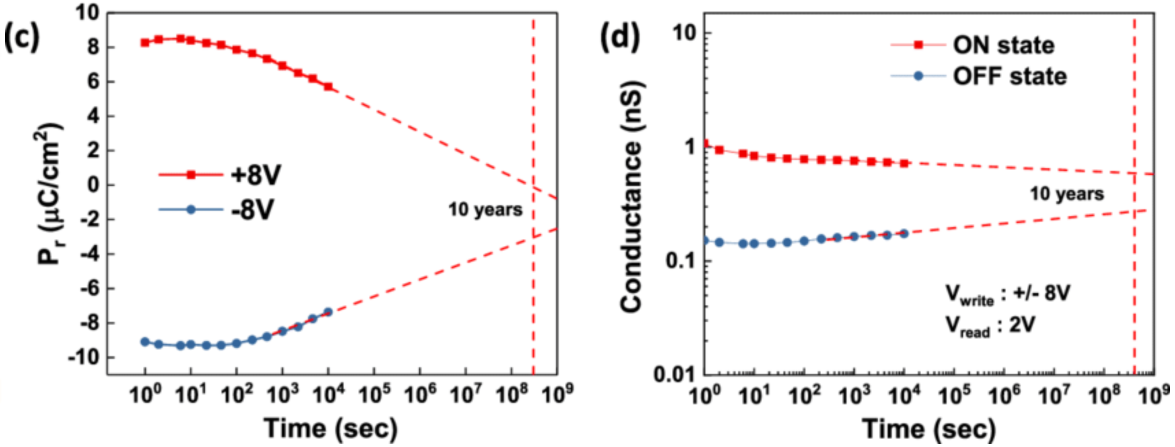
- **How long can we keep information stored in a ferroelectric device?**
  - **Depends on the device structure**
    - FeFET/FTJ worse than FeRAM
  - **Depends on the polarization state (implications for multi-level storage)**
  - **Thought to be limited by**
    - Depolarization field (in general)
    - Complex internal field distribution
    - Defects and associated trapped charge
    - Possible domain-domain interactions

B. Max et al., IEEE IMW (2019)





N. Zagni et al., Proc. of IEEE, 111 2 (2023)



H. Ryu et al., Sci Rep, 9 20383 (2019)

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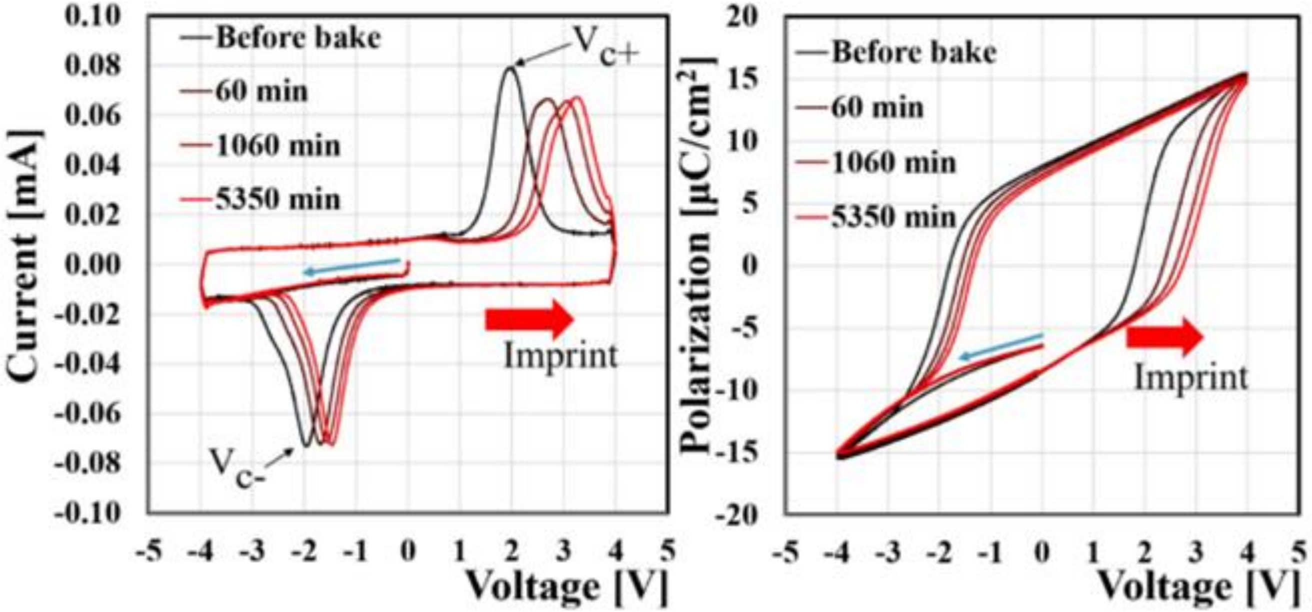
IMPRINT

FIXIT

- **Unique reliability feature of ferroelectrics**
  - **“Horizontal” shift of I-V and P-V curves with cycling: Ferroelectric develops a preferential polarization state!**
    - One polarization state becomes preferred over the other, which induces asymmetric retention loss at 0V
    - Changes the voltage required for (complete/partial) switching: critical for neuromorphic and in-memory computing!
  - **Coercive voltage shift toward either more positive or more negative values depending on the polarization**
    - If in the $-P_s$ ($+P_s$) state, $+E_C$ ($-E_C$) will increase (decrease)
  - **Imprint reported to depend on temperature and device baking**



N. Zagni et al., Proc. of IEEE, 111 2 (2023)

Phenomenon attributed to the electrostatic effect of electron trapping and de-trapping at defects and their redistribution across the device and at the FE/DE interface.

Two different imprint phenomena identified:

- **Time-dependent: shift of the P-V loop over time**
- **Fluid: a more dynamic effect that strongly depends on the characteristics of the switching pulse applied**

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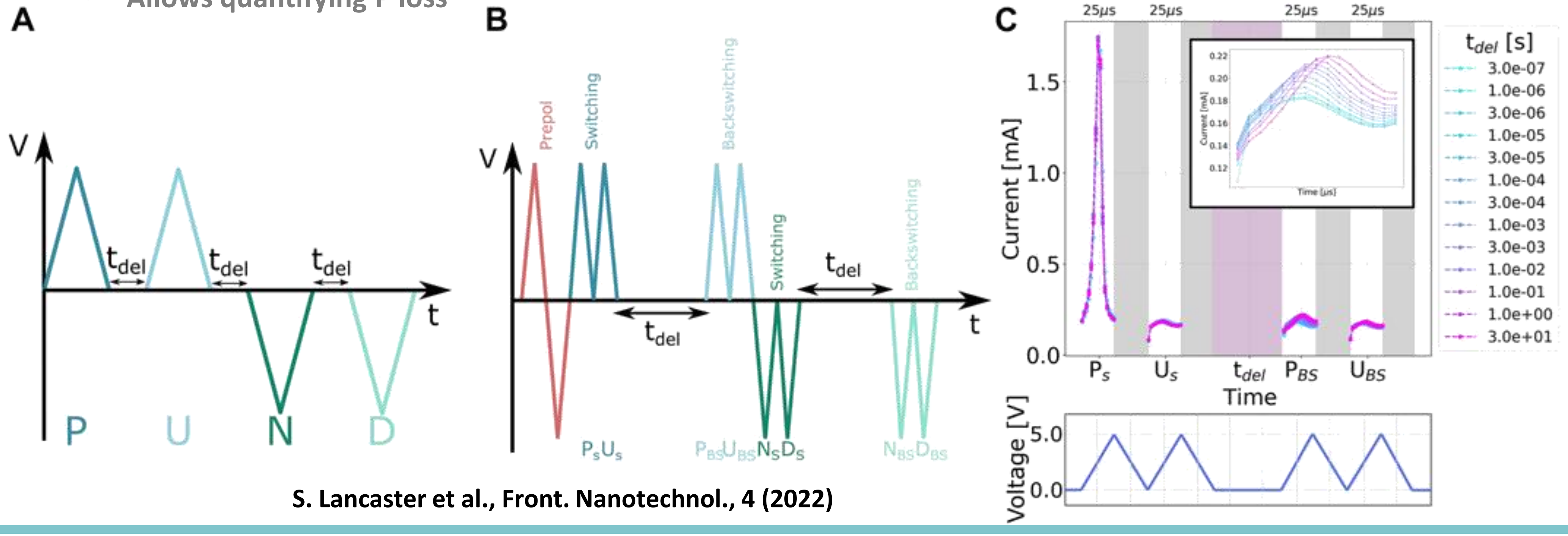
RETENTION AND BACKSWITCHING

- **Ferroelectric devices tend to lose their polarization**
  - **Competing effects of the depolarization field, internal bias field and charge trapping**
  - **Measurements done by extending the PUND concept introducing some delay in between pulses**
  - **Increasing delay results in more current detected in the back-switching pulses (both polarities)**
    - **Some domains flipped in the meantime**
    - **Allows quantifying P loss**



S. Lancaster et al., Front. Nanotechnol., 4 (2022)

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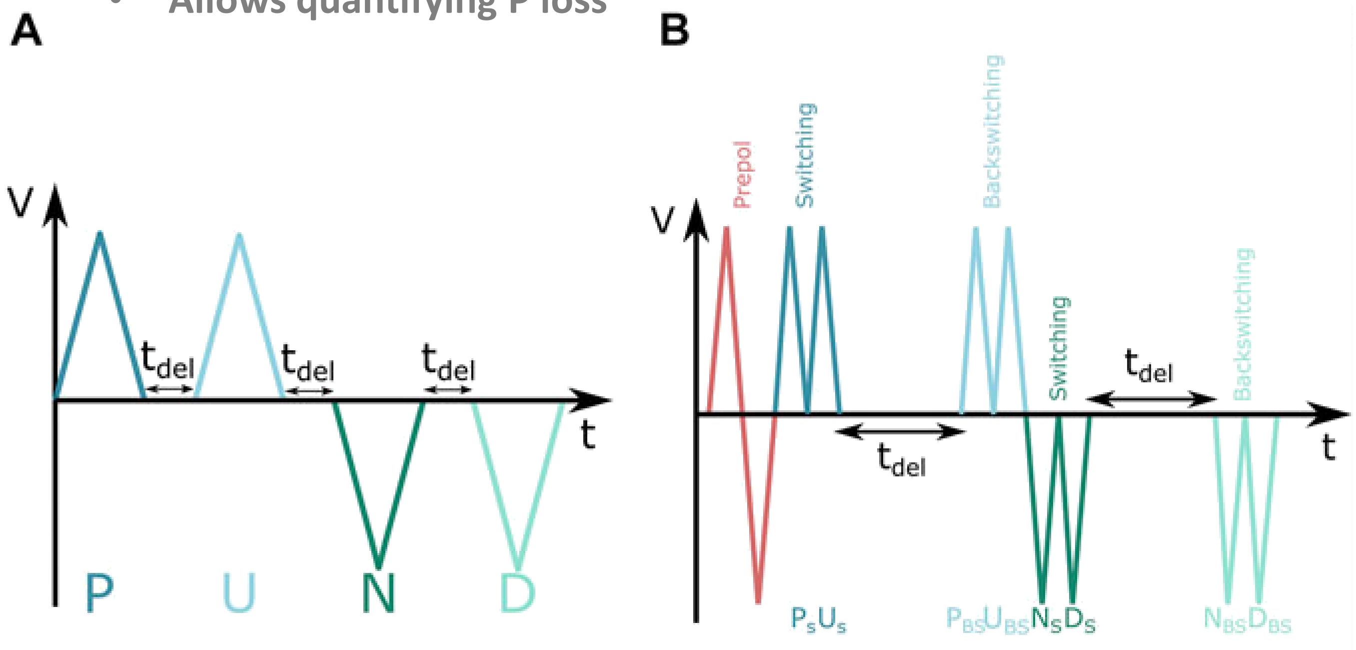

S. Lancaster et al., Front. Nanotechnol., 4 (2022)

$$P_{loss} = \int_0^{t_{pls}/2} (P_{BS} - U_{BS})dt$$

$$\widetilde{P_{loss}} = \frac{\int_0^{t_{pls}/2}(P_{BS} - U_{BS})dt}{\int_0^{t_{pls}/2}(P_S - U_S)dt}$$

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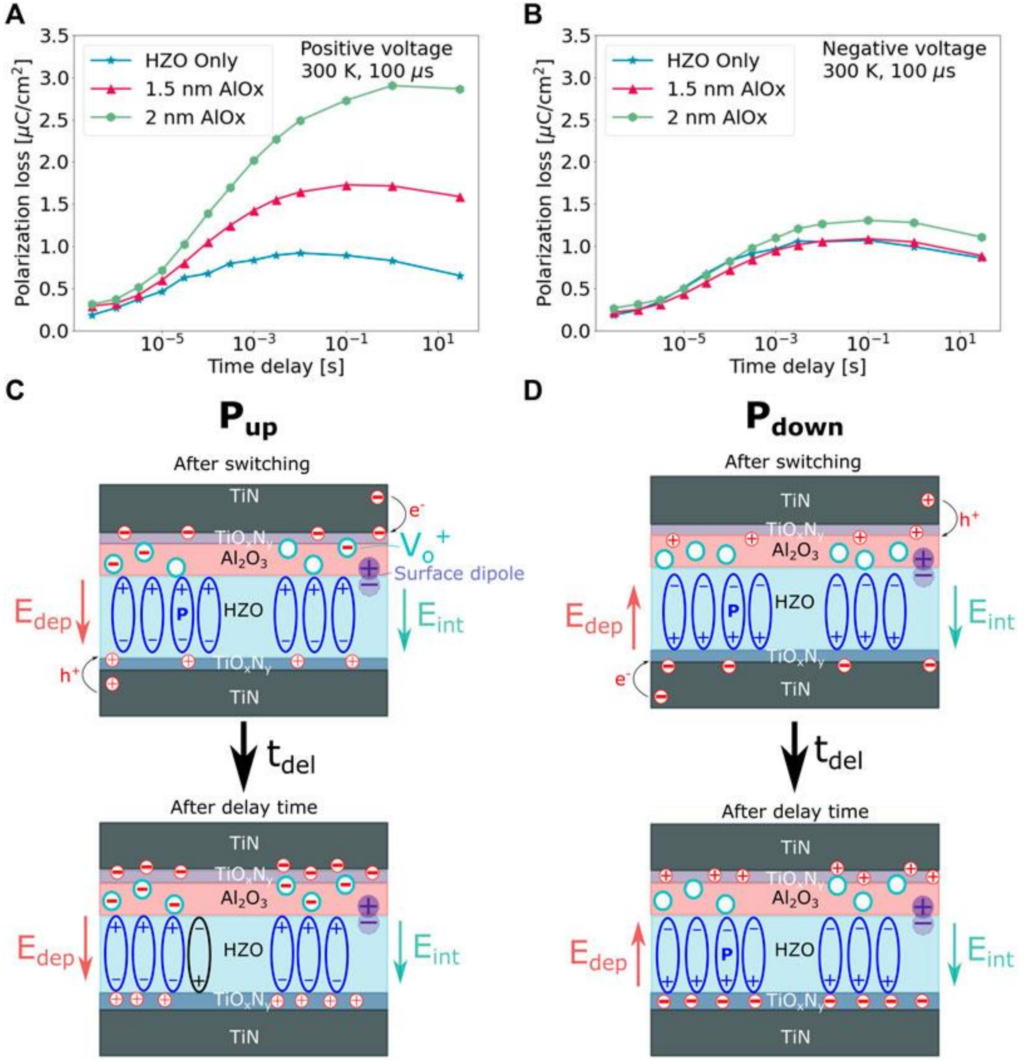
RETENTION AND BACKSWITCHING

FIXIT

- **Ferroelectric devices tend to lose their polarization**
  - **Polarization loss is asymmetric and depends on DE**
    - Thicker DE implies less charge injection and larger E_{DEP}
    - Different oxygen density in the two layers (DE and FE) may induce surface dipoles, while oxygen motion counteracts this surface dipoles field
  - **Asymmetric structure means asymmetric charge injection**
    - Facilitates P loss in one state more than in the other
  - **Short-term retention losses seem to saturate at 10s**



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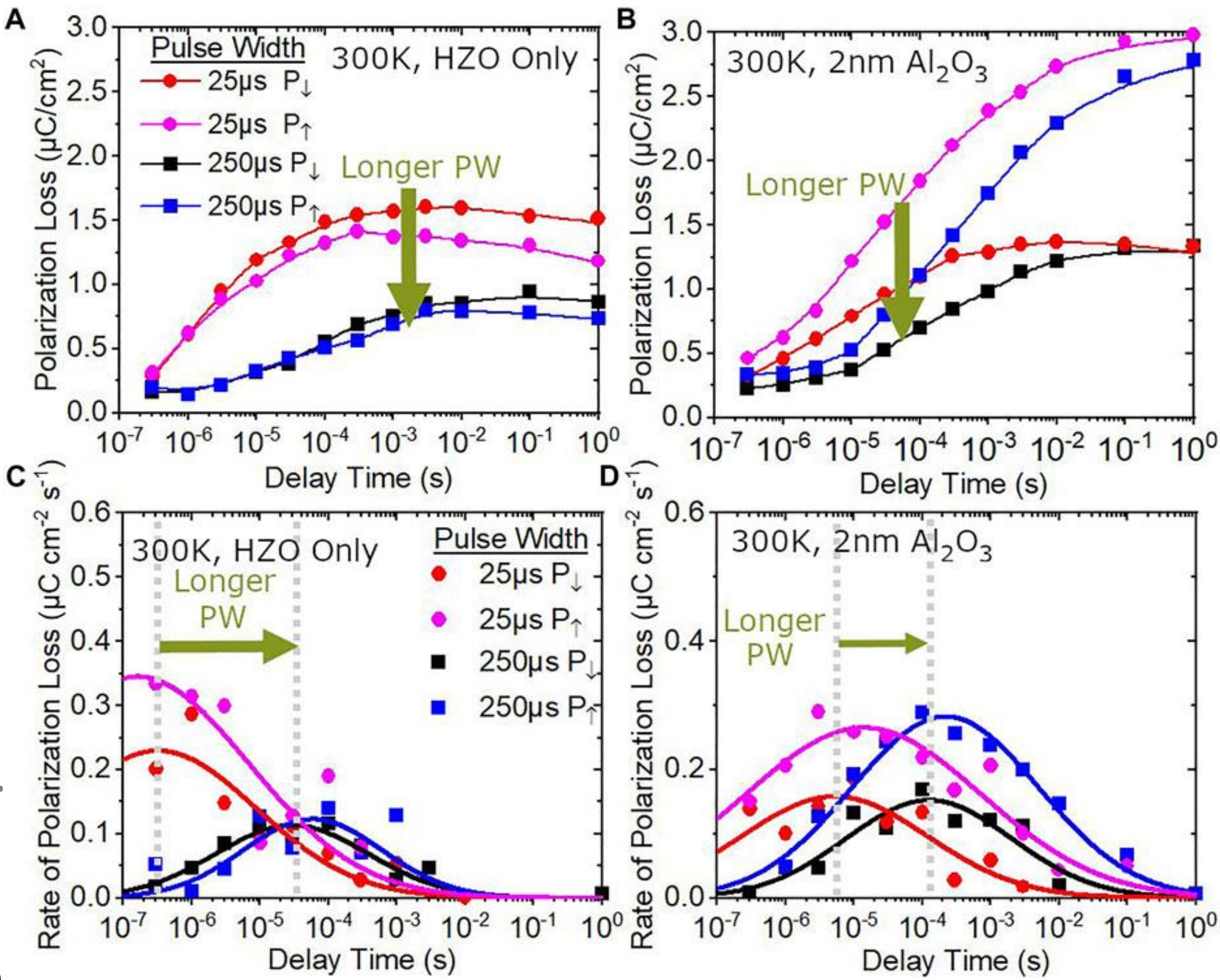
  - **Dependent also on pulse width**
    - Longer pulse widths decrease the rate of P loss and shift the polarization loss to longer times
    - This shift is consistent with a lower E_{DEP} due to enhanced screening caused by injected charge carriers.



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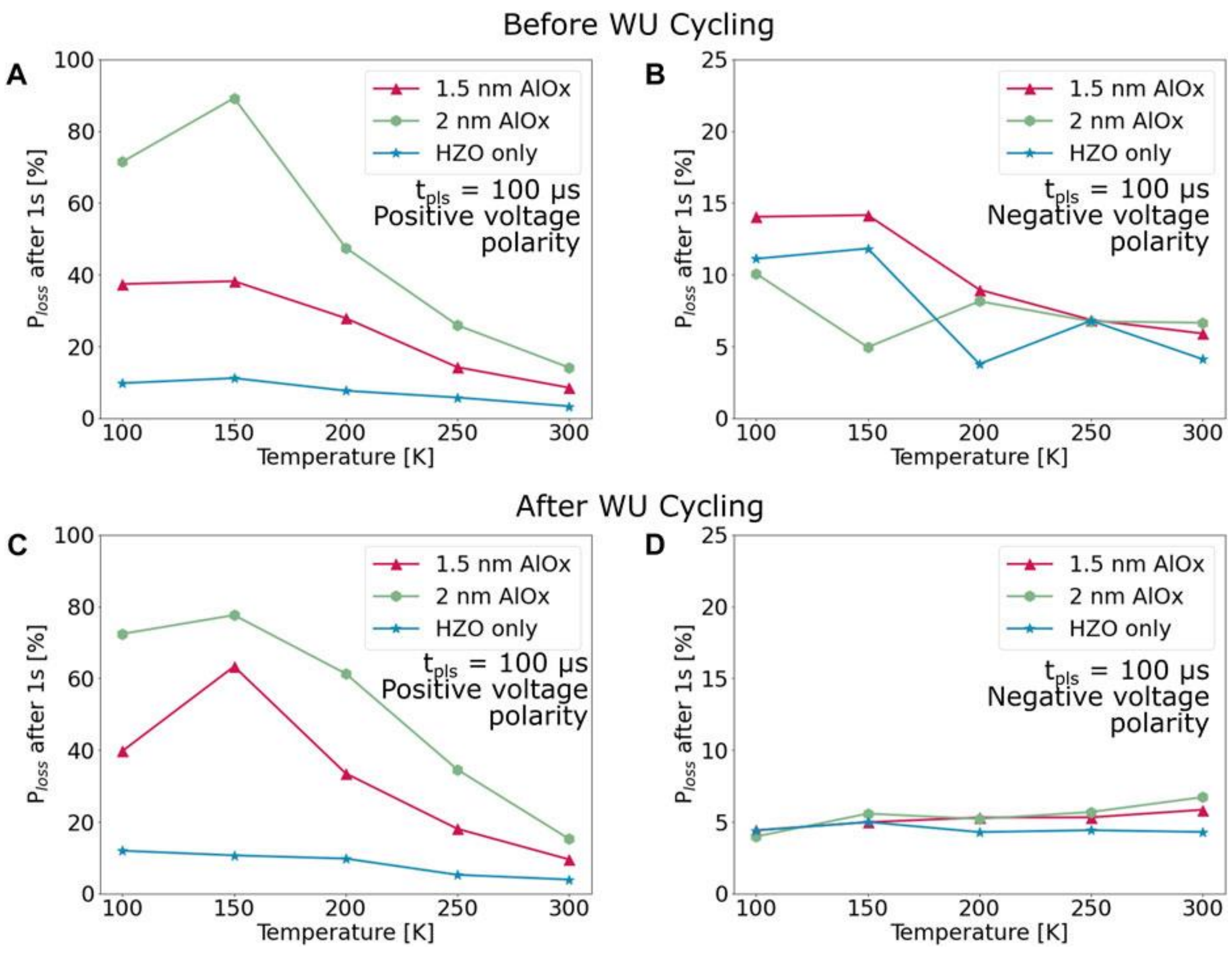
    - Longer pulse widths decrease the rate of P loss and shift the polarization loss to longer times
    - This shift is consistent with a lower E_{DEP} due to enhanced screening caused by injected charge carriers
  - **Dependent also on temperature**
    - Lower T slows down charge injection giving less screening and more P loss



S. Lancaster et al., Front. Nanotechnol., 4 (2022)

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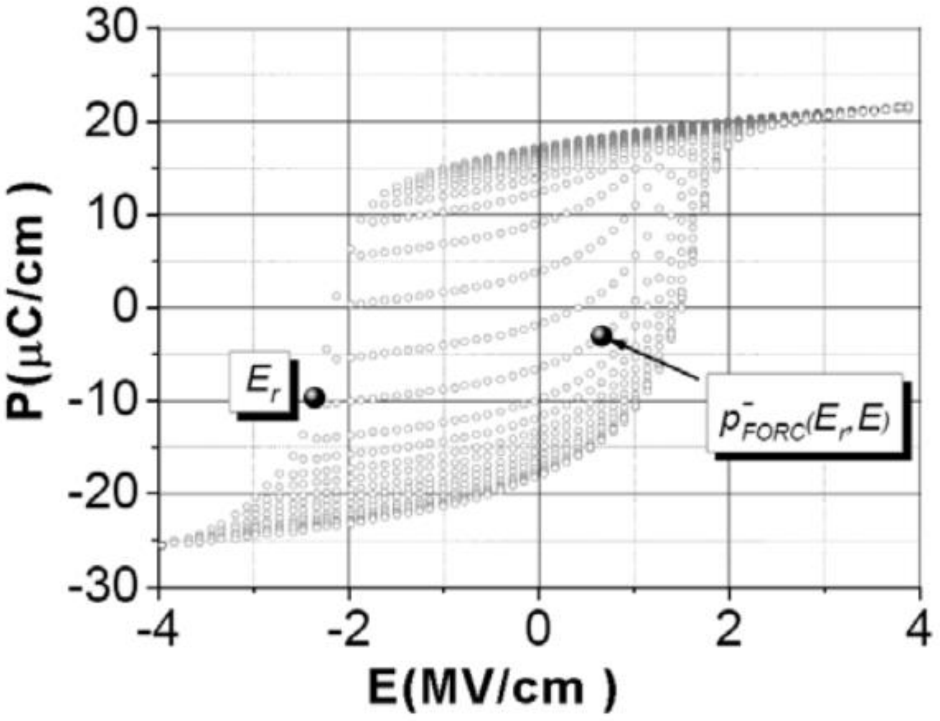
IMPRINT AND FORC/URC/D-URC

FIXIT

- **Imprint is typically assessed by:**
  - **Conventional P-V curves (measure the coercive voltage shift)**
  - **First-Order Reversal Curves (FORC)**
    - **Taken from magnetic materials characterization**
    - **Provide insight into the relative proportions of reversible and irreversible components of polarization**
  - **Measurements of minor hysteresis loops between E_{SAT} and a variable reversal field $E_R \in (-E_{SAT}, E_{SAT})$:**
    - *i*) saturation under a positive field $E \geq E_{SAT}$
    - *ii*) ramping down to the reversal value E_R
    - *iii*) increasing the field back to the positive saturation, with p_{FORC} a function of the actual and reversal field
    - iv) calculate the parameter ρ
  - **The FORC diagram is a contour plot of the FORC distribution, defined as the mixed second derivative of polarization p_{FORC} with respect to E_R and E**



$$\rho^-(E_r, E) = \frac{1}{2}\frac{\partial^2 p^-_{FORC}(E_r, E)}{\partial E\ \partial E}$$

L. Mitoseriu, Processing and Application of Ceramics, 3, 1-2 (2009)

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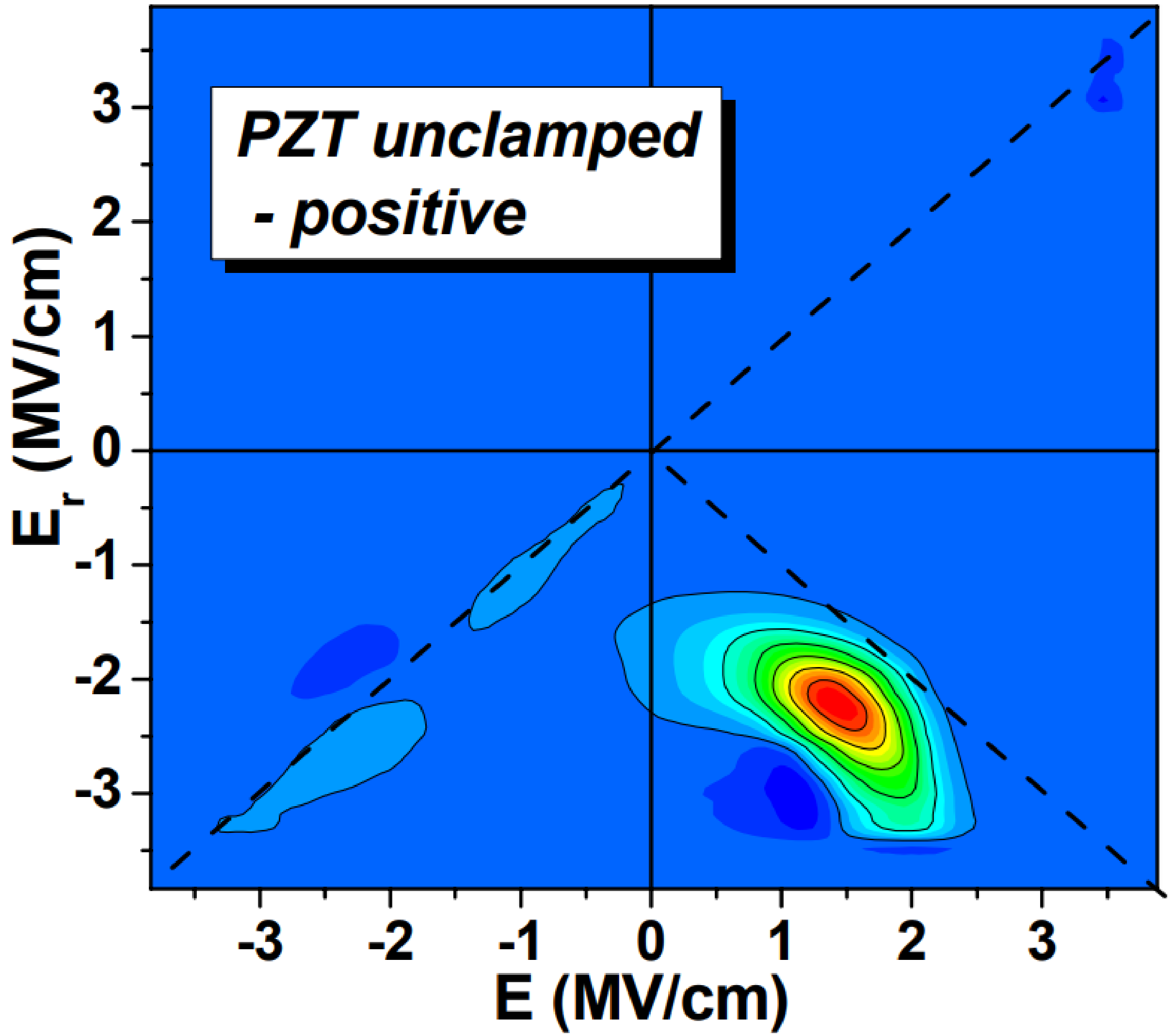
IMPRINT AND FORC/URC/D-URC

FIXIT

- **FORC plot**
  - **The 3D-distribution ρ(E_R, E) describes the sensitivity of polarization with respect to the reversal and actual electric field**
  - **Can be used to evaluate imprint by looking at the polarization spot position with respect to the main diagonal and off-diagonal axes**
  - **Can be used to get insights into reversible (along the main diagonal) and irreversible (along the off diagonal) components of switching**



L. Mitoseriu, Processing and Application of Ceramics, 3, 1-2 (2009)

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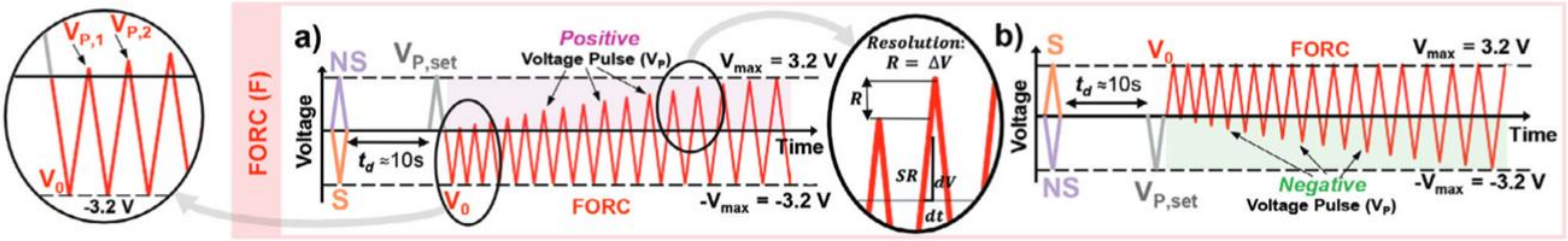
IMPRINT AND FORC/URC/D-URC

FIXIT

- **Advanced FORC-based methodologies to evaluate time-dependent and fluid imprint together**
  - **First-Order Reversal Curves (FORC)**
  - **Unipolar Reversal Curves (URC)**
  - **Delayed URC (D-URC)**
- **Time-dependent Imprint**
  - **Domains switched in one P harder to switch in the opposite P with increasing delay time**
- **Fluid Imprint**
  - **Upon partial switching into a given P state, the film develops a gradual preference for that P state**



S. Vecchi et al., Adv Ele Mat, 2400204 (2024)

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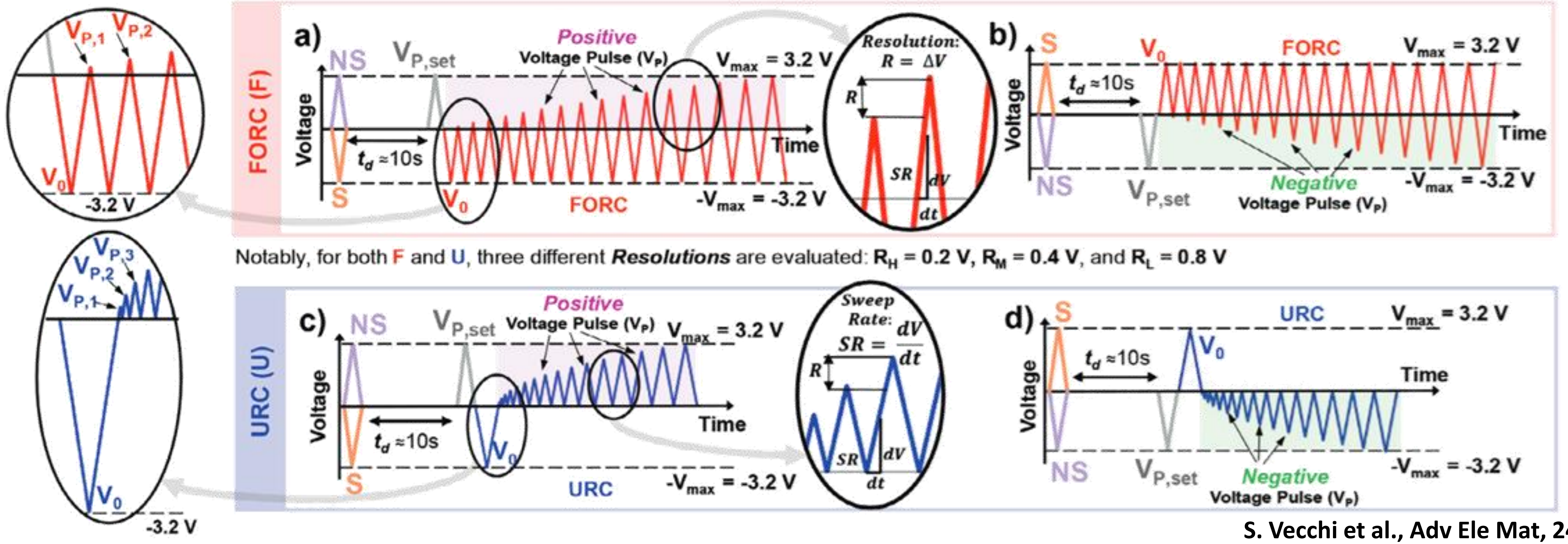
IMPRINT AND FORC/URC/D-URC

FIXIT

- **FORC and URC**
  - **We use a FORC waveform (modified to include pre-poling and pre-conditioning)**
  - **We also use a novel URC waveform (also with pre-poling and pre-conditioning)**
  - **For each pulse we can integrate the switched polarization above the time axis and compare FORC vs. URC**



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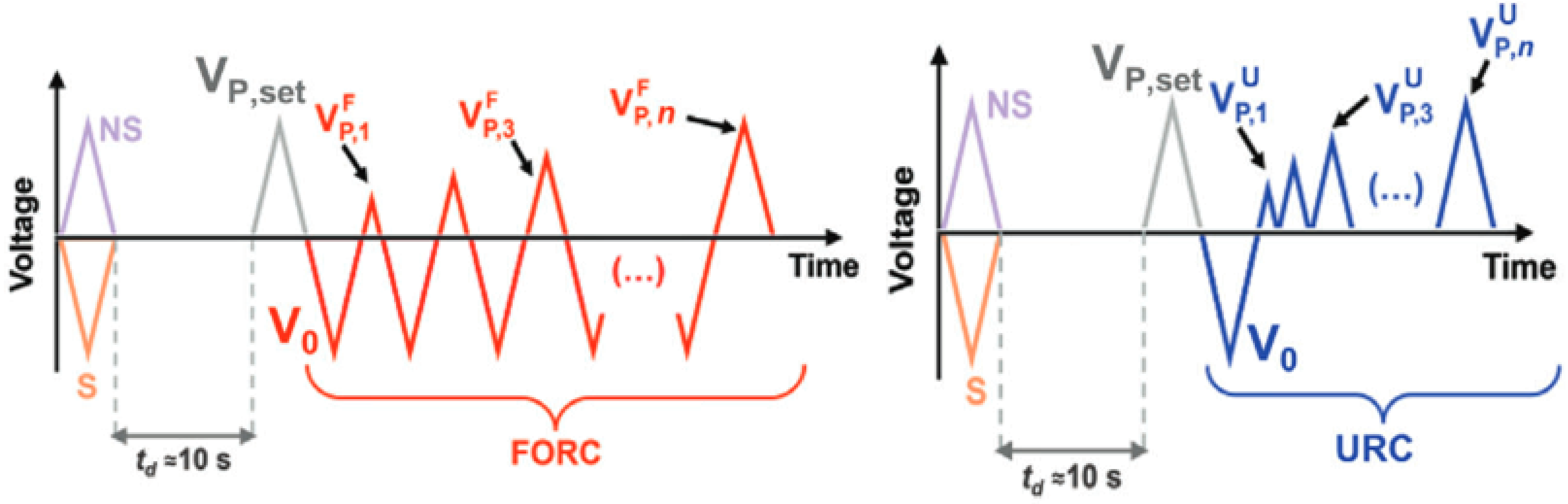
IMPRINT AND FORC/URC/D-URC

FIXIT

- **By defining appropriate switched polarization indicators for FORC and URC we can assume that**

  <u>If no imprint occurs, then the EFFECTIVE FORC switched P must equal the URC switched P for each pulse</u>



a) $\forall V_{P,i} \quad i = 2, \dots, n \quad (n = number\ of\ V_P\ for\ each\ R)$:

FORC:

$$P^F_{EFF,i}(V_{P,i}) = P^F(V_{P,i}) - P^F(V_{P,i-1})$$

Comparison

URC:

$$P^U(V_{P,i})$$

Here the polarization associated to the previous V_P is subtracted to compare the quantity of switched domains between FORC and URC

Notably, for $V_{P,1}$: $P^F_{EFF,1}(V_{P,1}) = P^F(V_{P,1}) = P^U(V_{P,1})$

S. Vecchi et al., Adv Ele Mat, 2400204 (2024)

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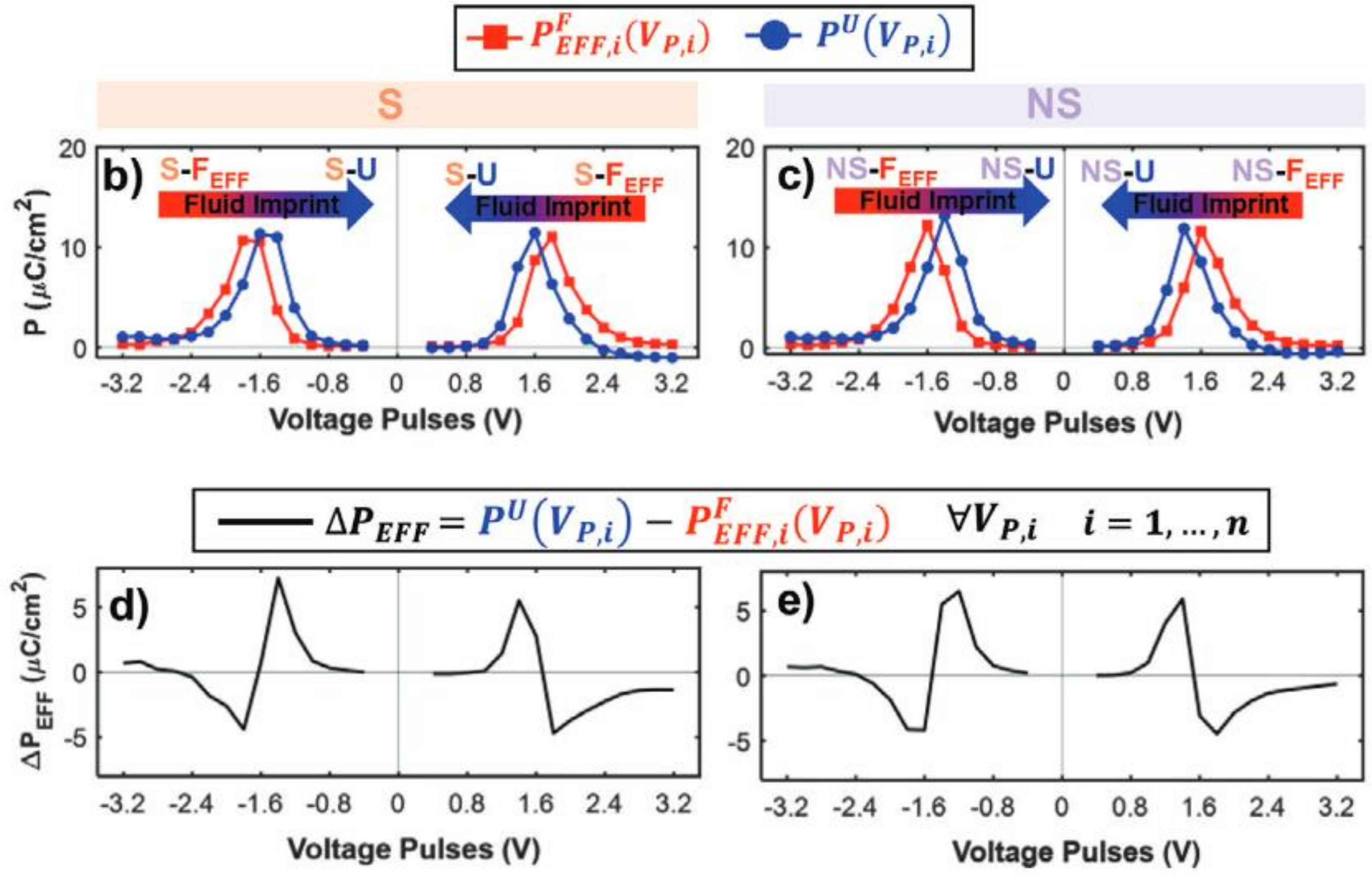
IMPRINT AND FORC/URC/D-URC

FIXIT

- **Easy to see that imprint occurs**

  The two curves are not the same and the URC curve anticipates the EFFECTIVE FORC regardless of polarity and pre-conditioning pulse properties

- **Manifestation of FLUID IMPRINT**



S. Vecchi et al., Adv Ele Mat, 2400204 (2024)

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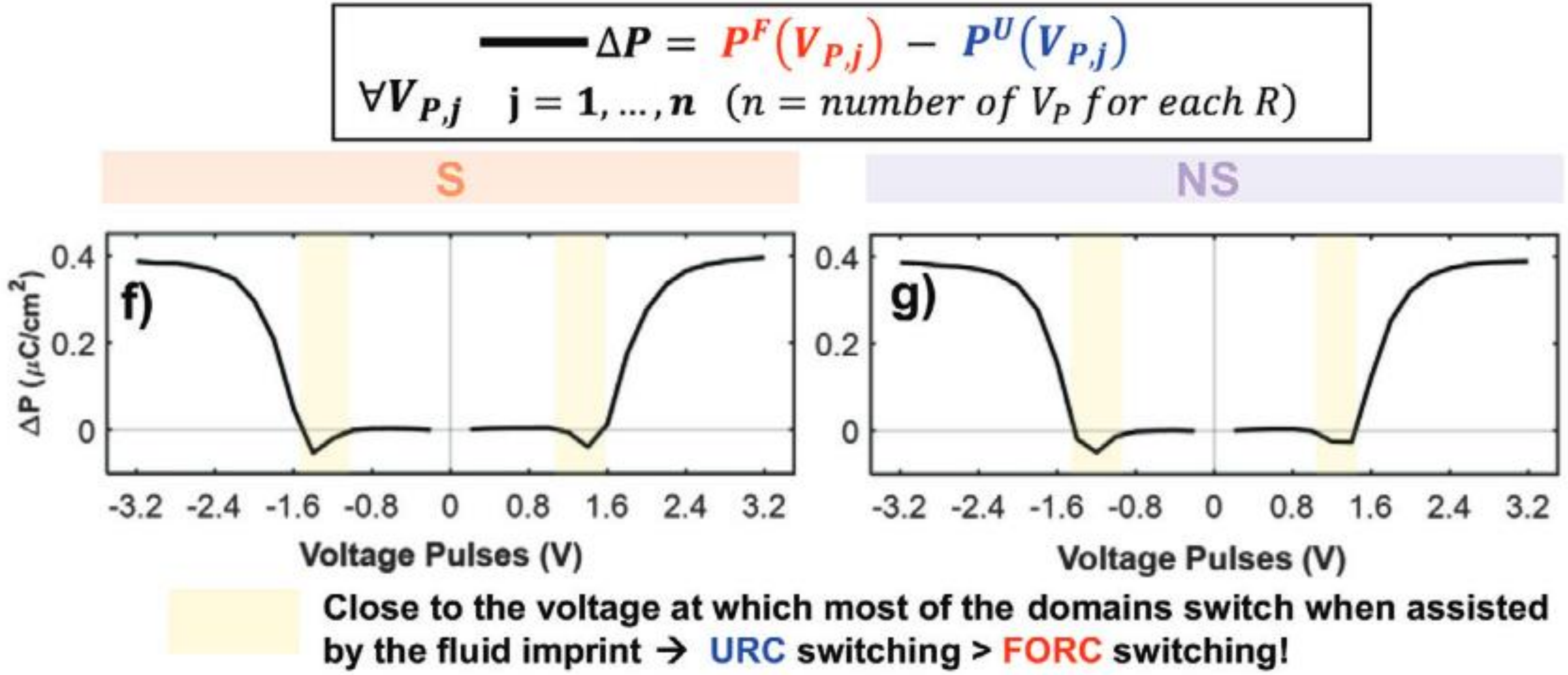
IMPRINT AND FORC/URC/D-URC

FIXIT

- **Direct comparison of FORC (not EFFECTIVE FORC) and URC reveals that fluid imprint can be quite strong!**



S. Vecchi et al., Adv Ele Mat, 2400204 (2024)

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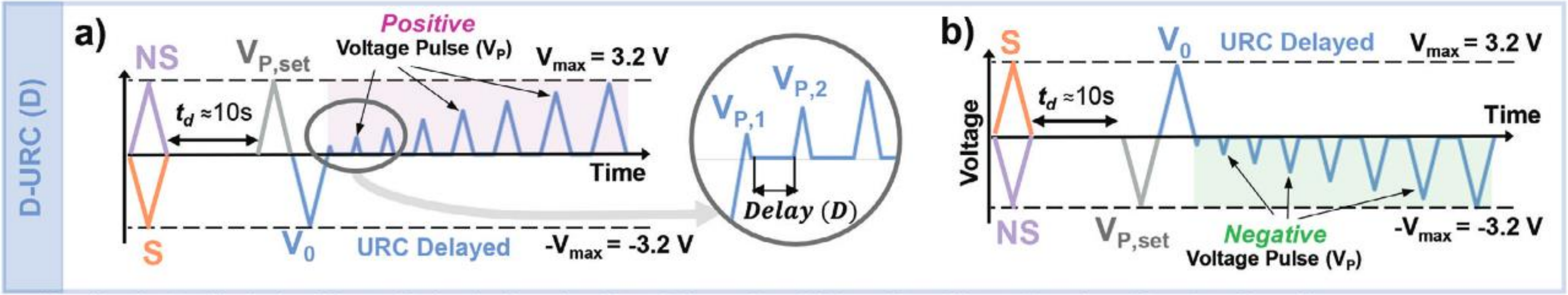
IMPRINT AND FORC/URC/D-URC

FIXIT

- **Time-dependent imprint can be evaluated using Delayed-URC (D-URC)**
- **Similar to URC, but a delay is inserted in between pulses**
- **Delay is constant but can be varied (here from 100us to 10s)**



Notably, for D, Six *Delay Times*: D_i, i = 1…6 → **D_1 = 100 µs, D_2 = 500 µs, D_3 = 50 ms, D_4 = 1 s , D_5 = 5 s , D_6 = 10 s**

S. Vecchi et al., Adv Ele Mat, 2400204 (2024)

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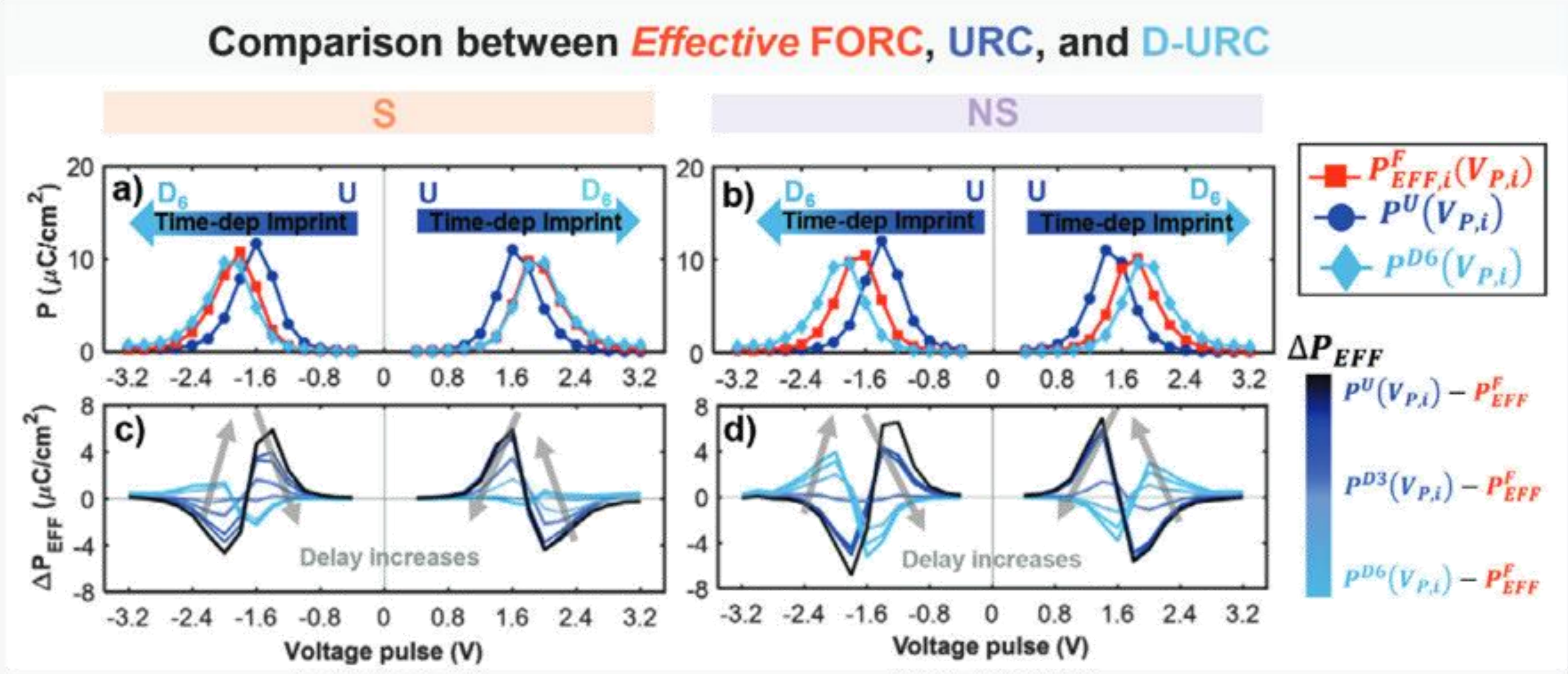
IMPRINT AND FORC/URC/D-URC

FIXIT

- **Results suggests that un-switched domains gradually develop a preference for their actual polarization state over time, which is another manifestation of time-dependent imprint.**

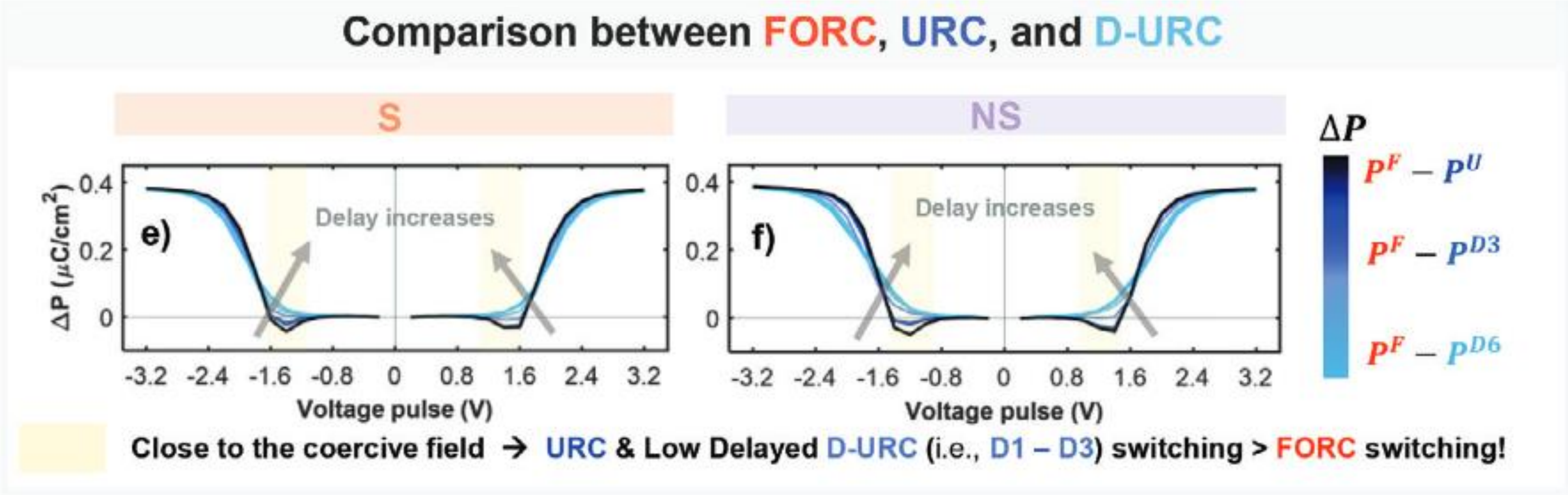


S. Vecchi et al., Adv Ele Mat, 2400204 (2024)

IMPRINT AND FORC/URC/D-URC

FIXIT

- **Direct comparison of FORC (not EFFECTIVE FORC) URC and D-URC confirms the time-dependent imprint!**
- **If the delay is short (less than approximately 1s) the advantage of partial switching is still present when one wants to further switch domains in the same direction**
- **If the delays is long enough (longer than approximately 1s) then the time-dependent imprint effect becomes dominant**



S. Vecchi et al., Adv Ele Mat, 2400204 (2024)

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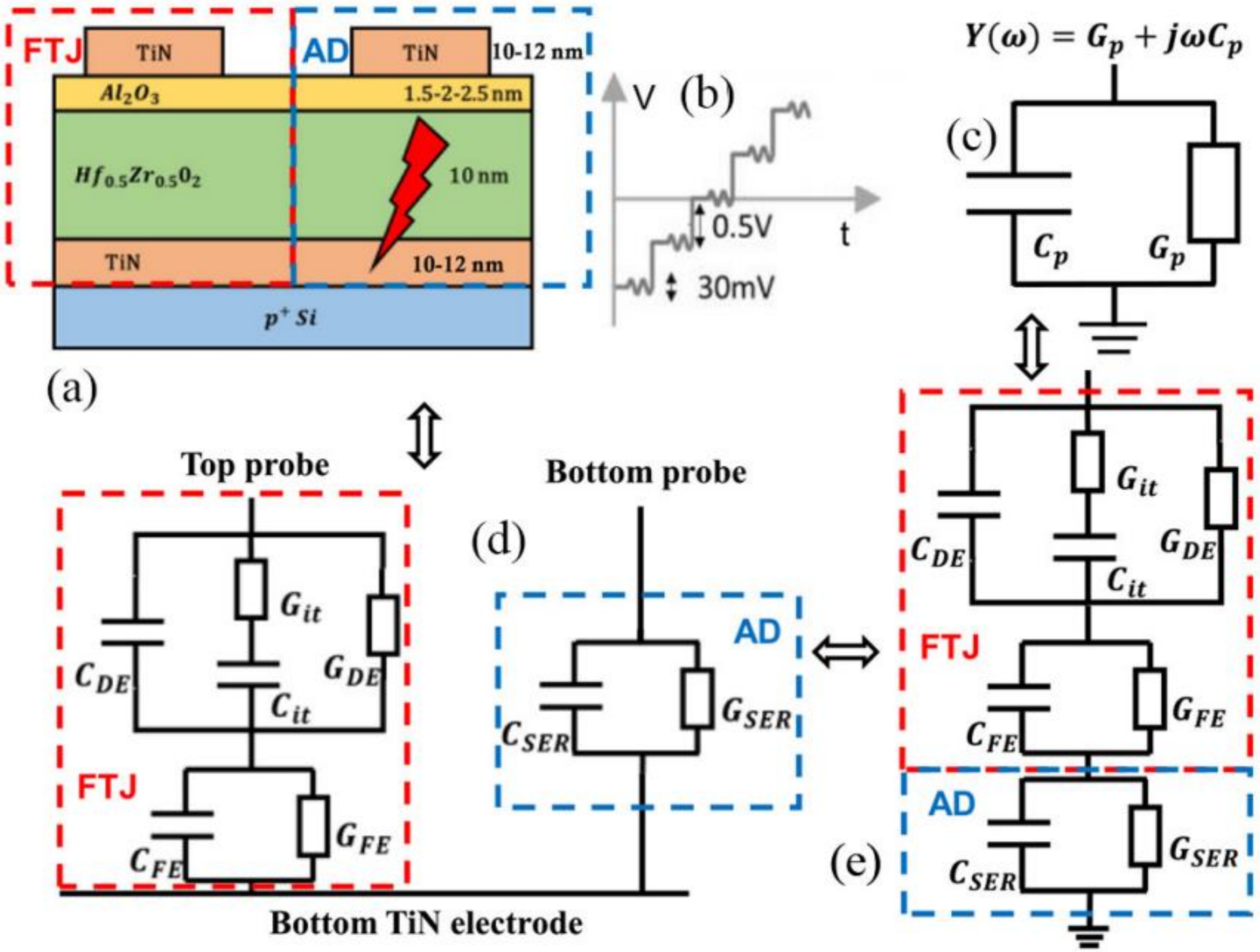
IMPEDANCE SPECTROSCOPY

- **Based on impedance measurements at different voltages and frequencies (multi-voltage C-f/G-f)**
  - **Can reveal many different interesting quantities involved in device operation and reliability**
    - Ferroelectric (and dielectric) permittivity
    - Conductance of the different layers (leakage and associated defects)
    - Parasitic contributions (access impedance)
    - 1st-order approximation of interface defects and/or dead/interface layers
  - **Classical AC impedance measurements at:**
    - Different DC bias (thus different polarization)
    - Different AC frequencies
  - **Needs an appropriate small-signal device model**
    - Must include salient features of the device stack
    - Needs to consider access (series) impedance



L. Benatti et al., IEEE TDMR, 22 3 (2022)

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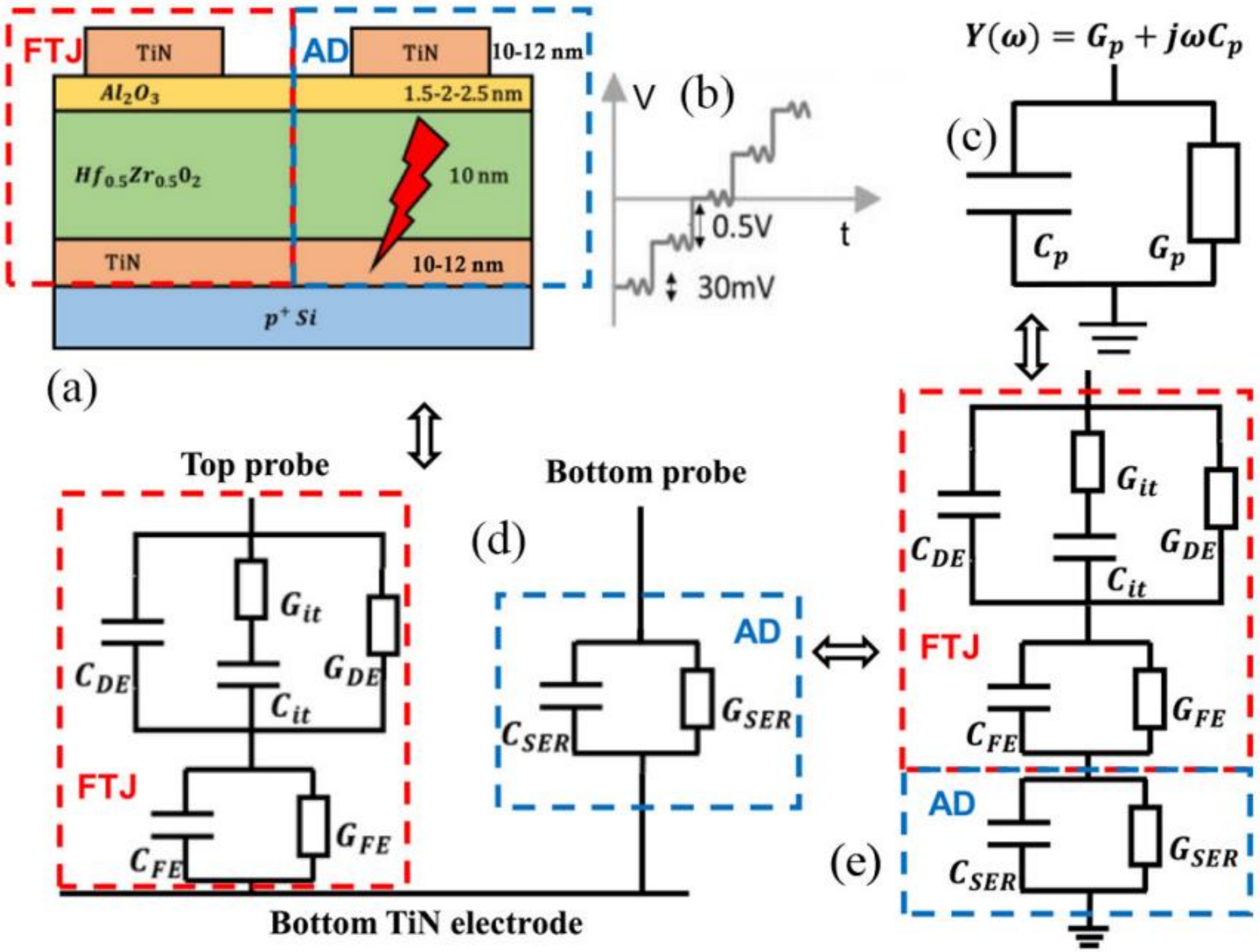
IMPEDANCE SPECTROSCOPY

FIXIT

- **Based on impedance measurements at different voltages and frequencies (multi-voltage C-f/G-f)**
  - **For each different DC bias**
    - Apply AC signal with fixed amplitude and frequency
    - Measure AC current and calculate impedance
    - Change AC signal frequency and start over
  - **Output data interpretation with the model**
    - Calculate equivalent admittance of the model
    - Impedance (admittance) at each V and f value
    - For each different DC bias find the model parameters values that allow best matching the measured admittance and the equivalent model admittance at all frequencies
  - **Test structure details may play a role**
    - Direct (metal) or indirect (AD) access to BE
    - Presence of access impedance element in the model



L. Benatti et al., IEEE TDMR, 22 3 (2022)

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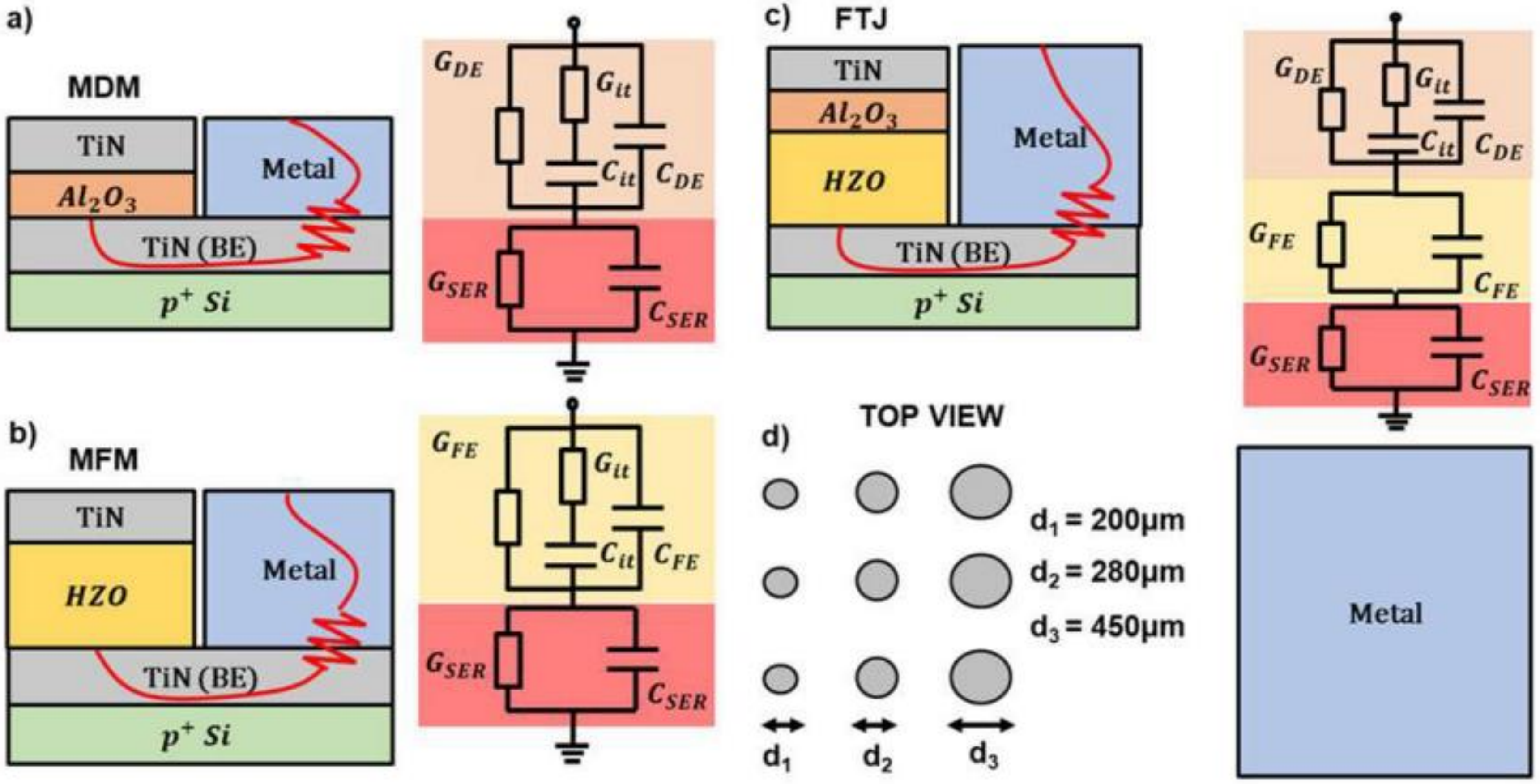
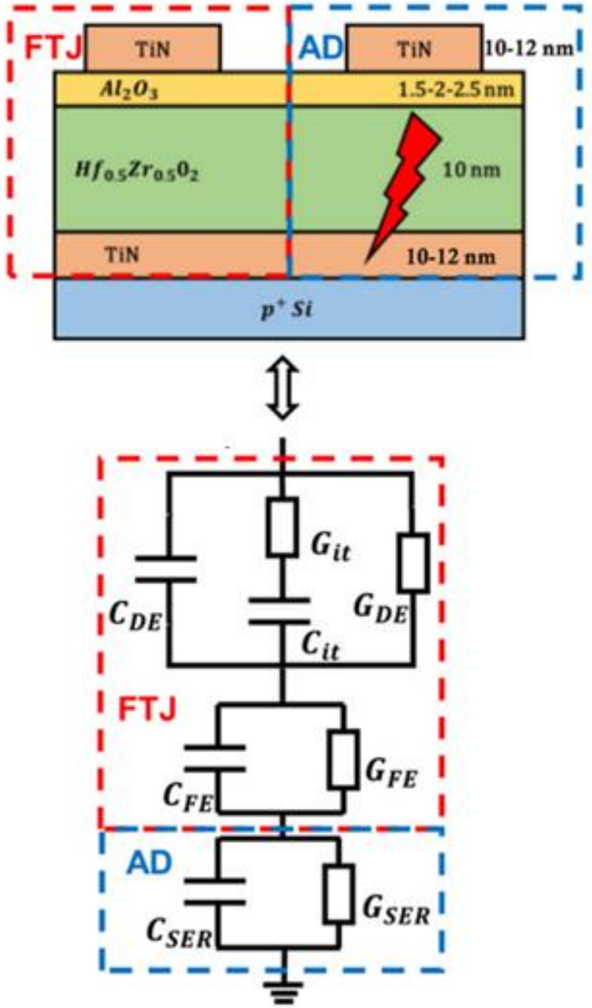
IMPEDANCE SPECTROSCOPY

- **Example for MFM, MDM, MFDM (FTJ) structures with direct/indirect BE access**





L. Benatti et al., IEEE TDMR, 22 3 (2022)

L. Benatti et al., IEEE TDMR, 23 3 (2023)

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IMPEDANCE SPECTROSCOPY

FIXIT

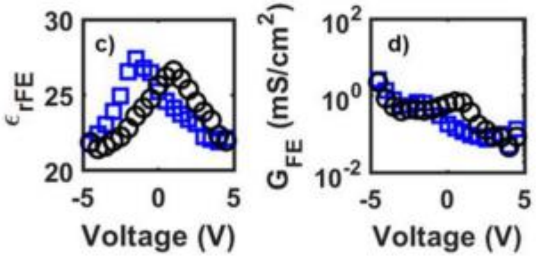
- **Model free parameters must not depend on frequency**
  - **Frequency dependence can be incorporated using explicit mathematical formulation**
  - **For instance, 1st-order dielectric permittivity dependence on frequency**
- **Polar and non-polar composition of ferroelectric can be included**
  - **Area factor considers the relative abundance of polar vs non polar area**
- **A few examples where known and free parameters are highlighted**

$$C_{FE} = \varepsilon_{FE}\frac{A}{t_{FE}} \quad with\ \varepsilon_{FE} = \varepsilon_0[A_f\varepsilon_{r,OR} + (1 - A_f)\varepsilon_{r,NOR}]$$

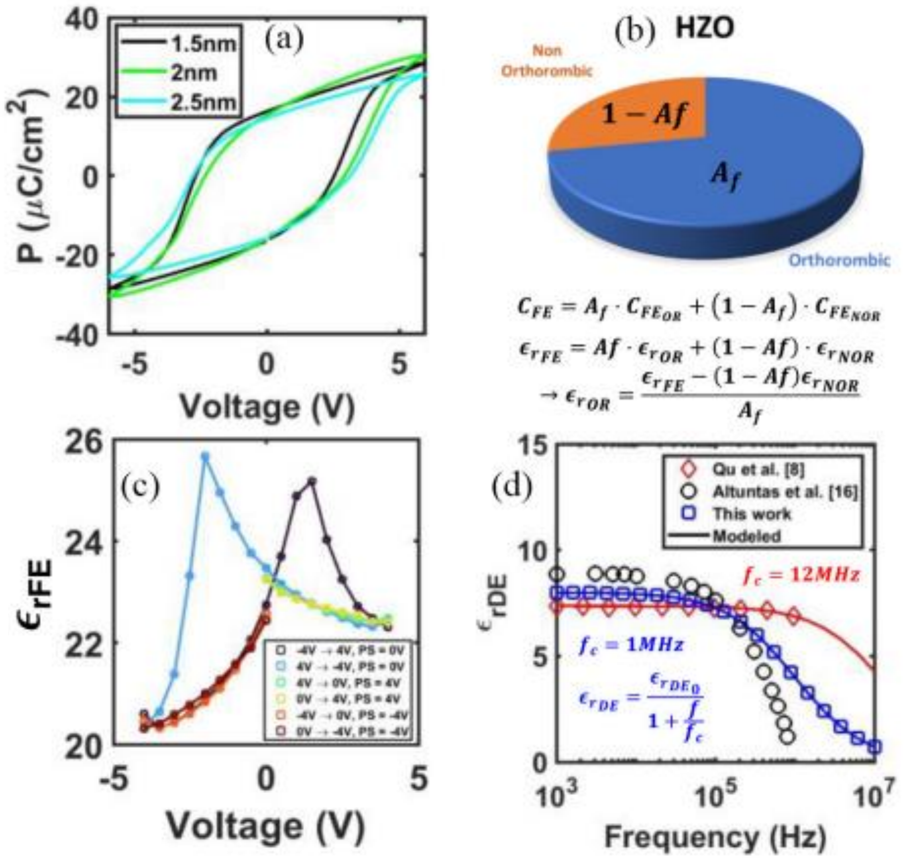
$$C_{DE} = \varepsilon_{DE}\frac{A}{t_{DE}} \quad with\ \varepsilon_{DE} = \varepsilon_0\frac{\varepsilon_{rDE,0}}{1 + \frac{f}{f_C}}$$

G_{DE} *expected to be* $\propto A$ *and* $e^{-t_{DE}}$

G_{FE} *expected to be* $\propto A$



L. Benatti et al., IEEE TDMR, 22 3 (2022)



- **P-dependent ε_{FE} and G_{FE} spontaneously pop out!**

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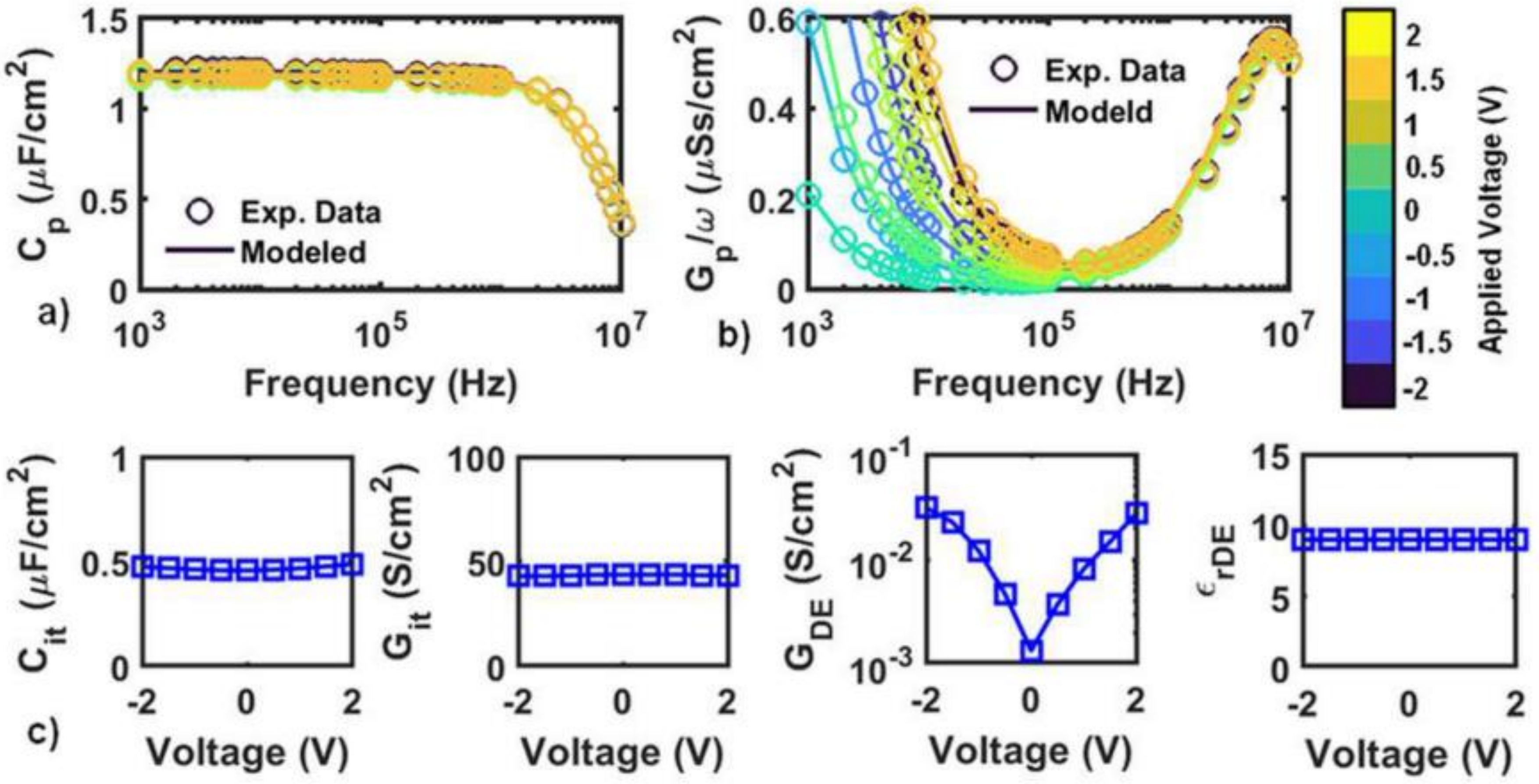
IMPEDANCE SPECTROSCOPY

FIXIT

- **Results for an MDM structure**
  - **TiN/Al_2O_3 (6nm)/TiN**
- **Data typically plotted as C_p vs. f and G_p/ω vs. f**
- **Low-frequency kick in G_p/ω associated with leakage**
- **High-frequency bump in G_p/ω associated with traps (but access impedance plays a key role here)**
- **Correct evaluation of dielectric permittivity and leakage profile vs. voltage**



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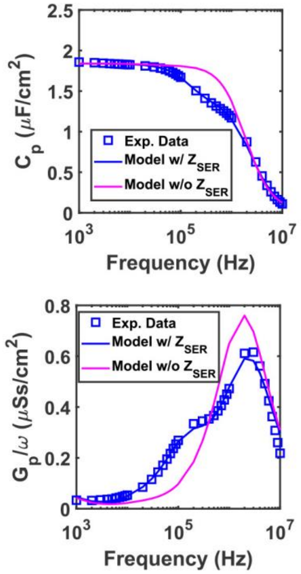
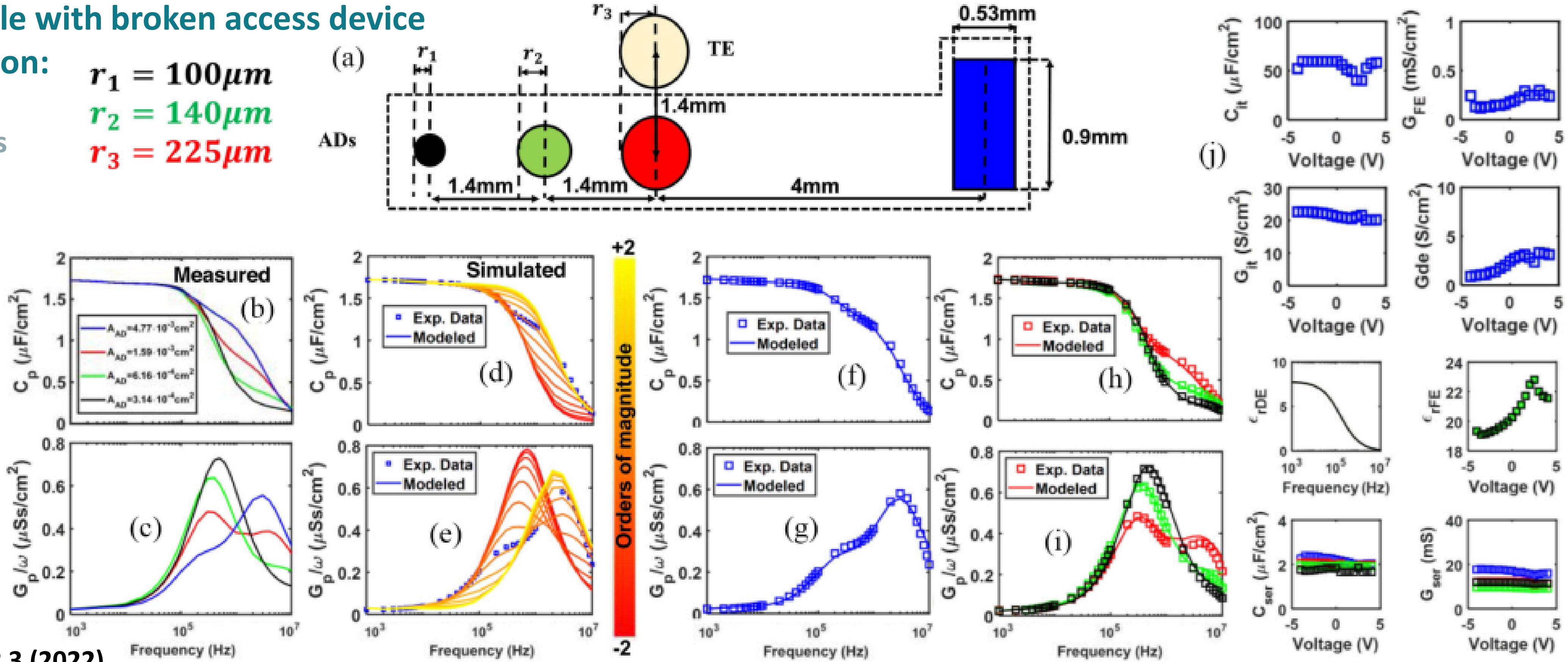
IMPEDANCE SPECTROSCOPY

FIXIT

- **Relevant effect of the access impedance**
  - **Results on TiN/Al_2O_3 (1.5nm)/HZO (10nm)/TiN with different A and access impedance (indirect access)**
  - **C_{SER} compatible with broken access device**
  - **Critical effect on:**
    - C_p roll-off
    - G_p/ω kicks





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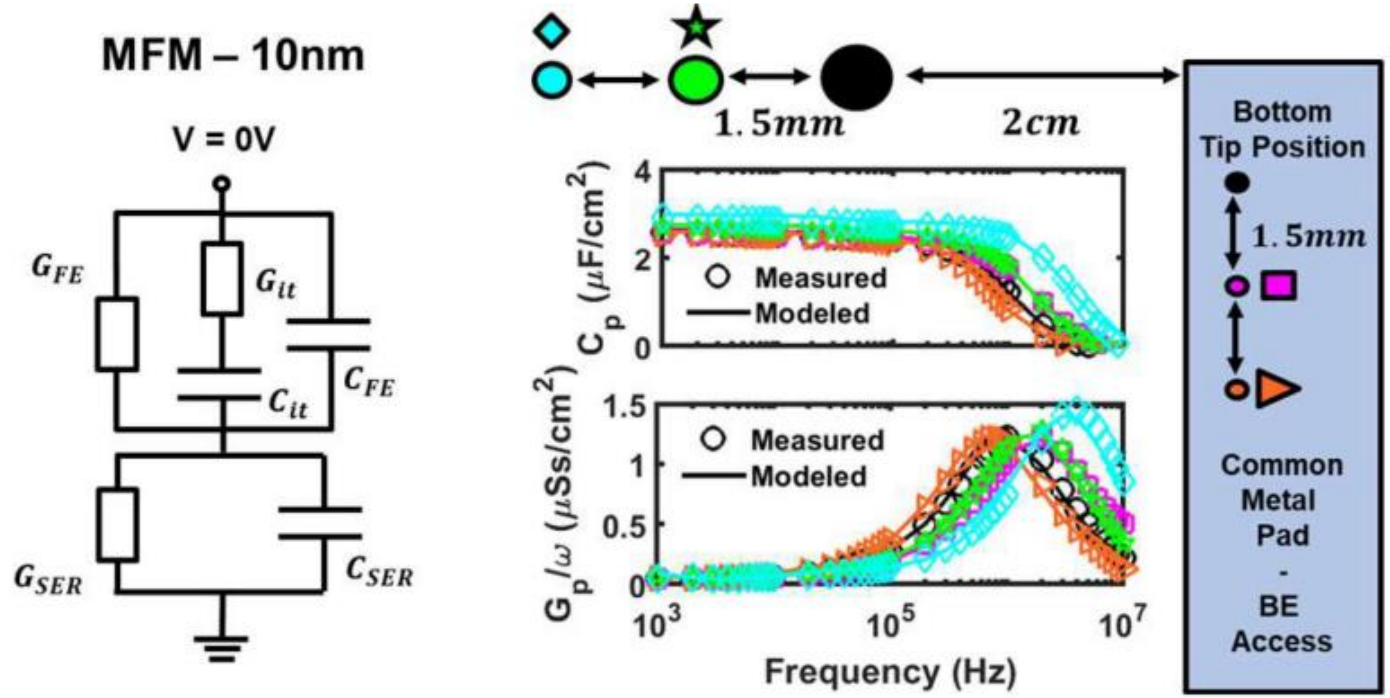
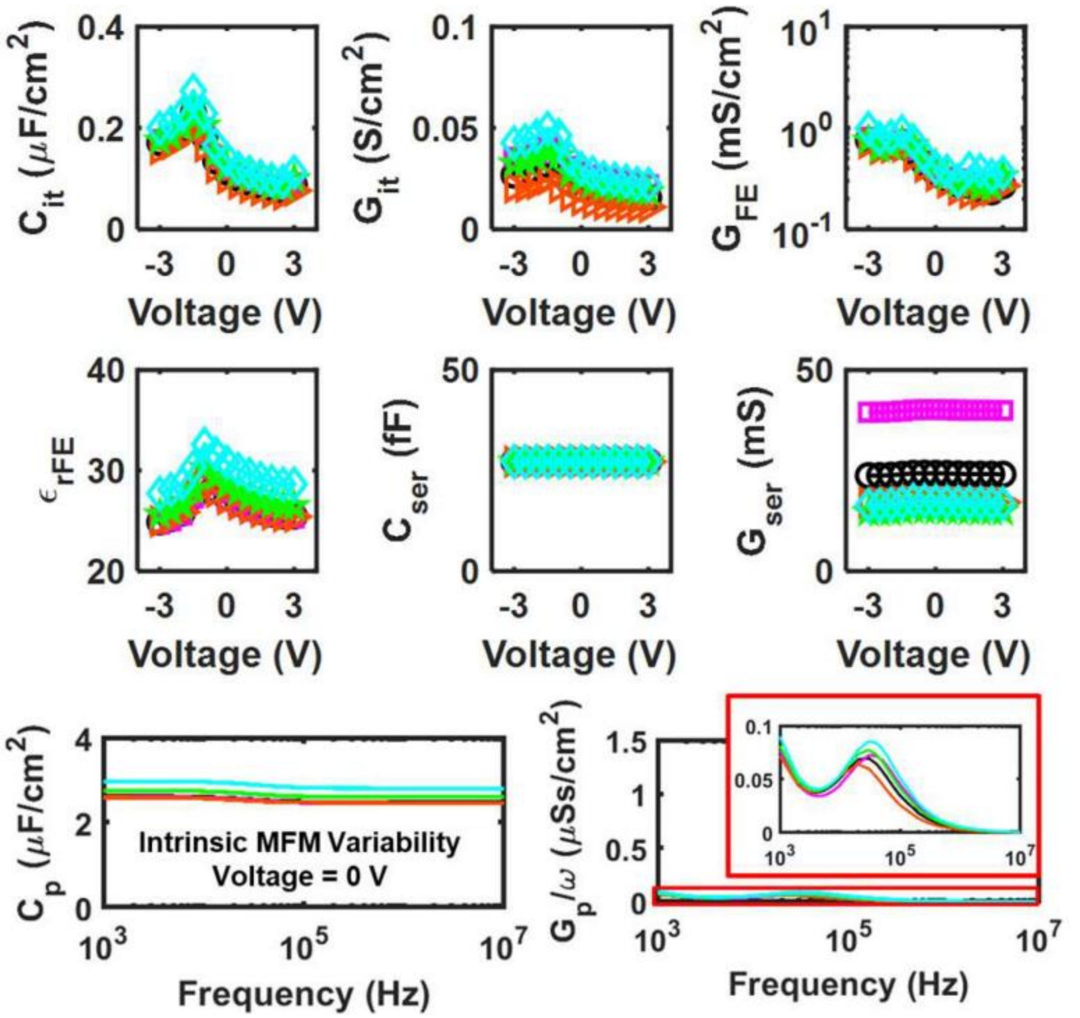
IMPEDANCE SPECTROSCOPY

FIXIT

- **Results for an MFM structure**
  - **TiN/HZO (10nm)/TiN**
- **Excellent match with experiments**
- **Access to intrinsic device characteristics and variability**





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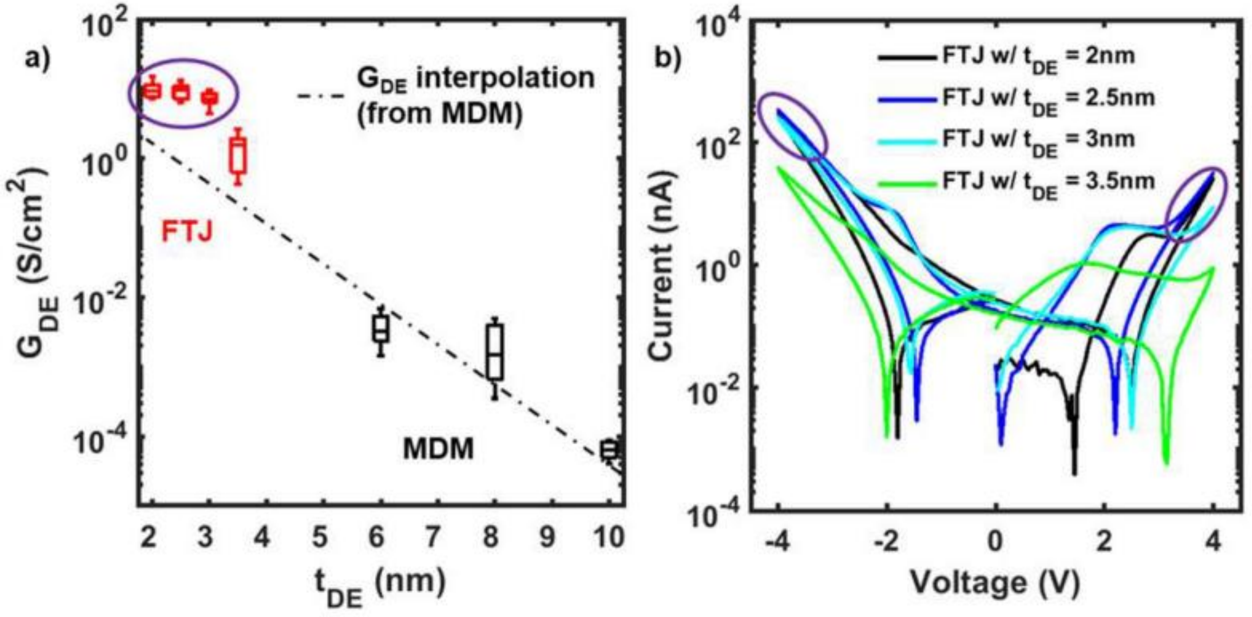
WHAT CAN WE LEARN FROM IT?

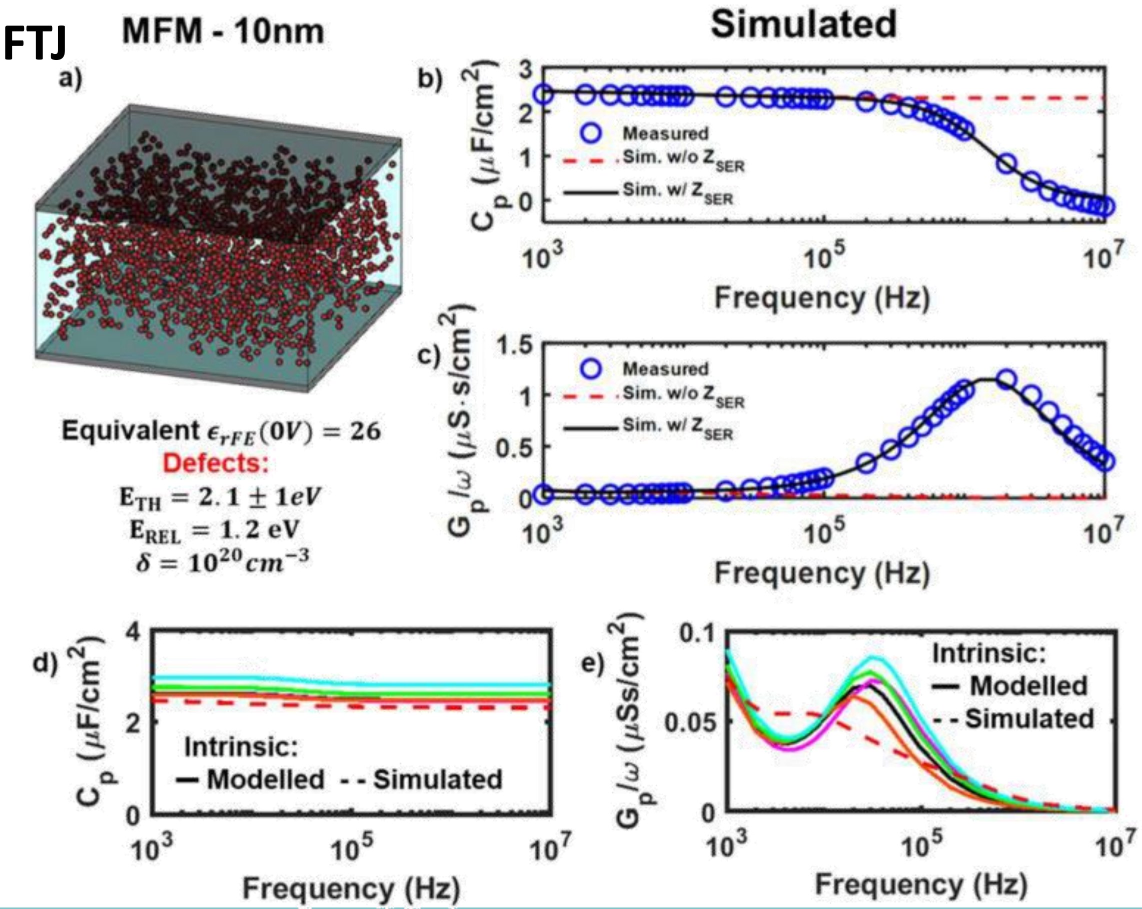
FIXIT

- **The effect of series impedance is real**
  - **Confirmed using physics-based simulations with AMAT's Ginestra**

L. Benatti et al., IEEE TDMR, 23 3 (2023)

- **Dielectric properties do not «scale well» with thickness in FTJ**
  - **Ultra-thin DE layers in FTJ are leakier than expected**
    - **Their properties may be dominated by interfaces**
  - **Role of the dielectric layer in FTJ may be more complex**





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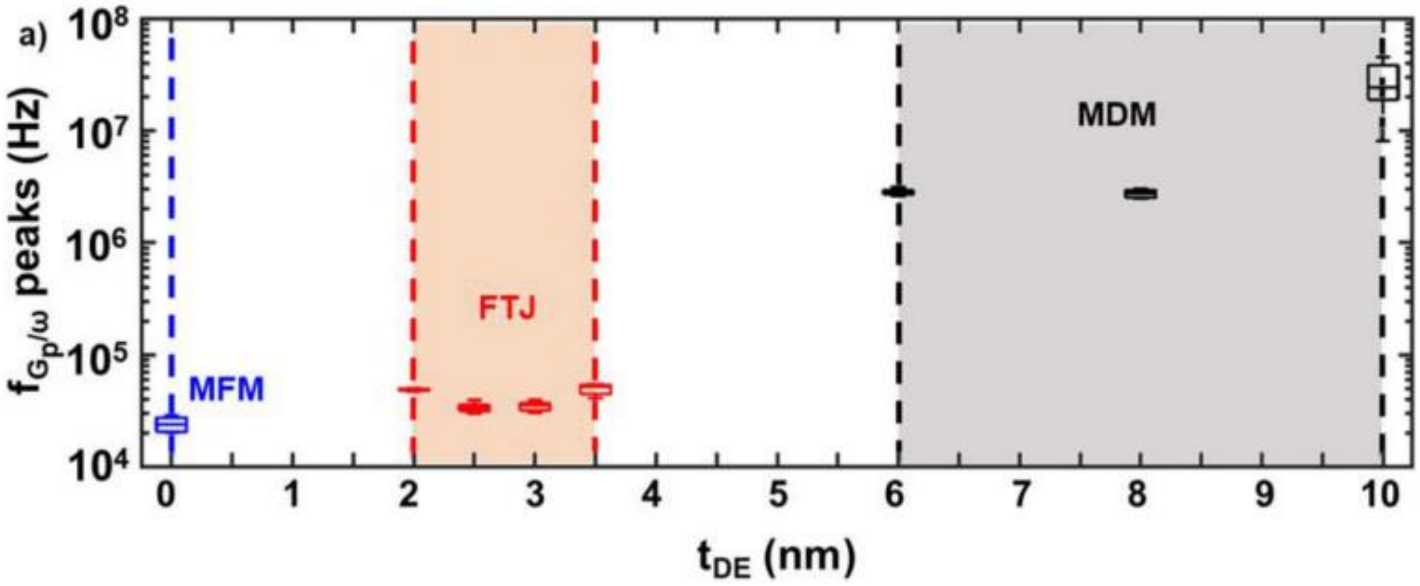
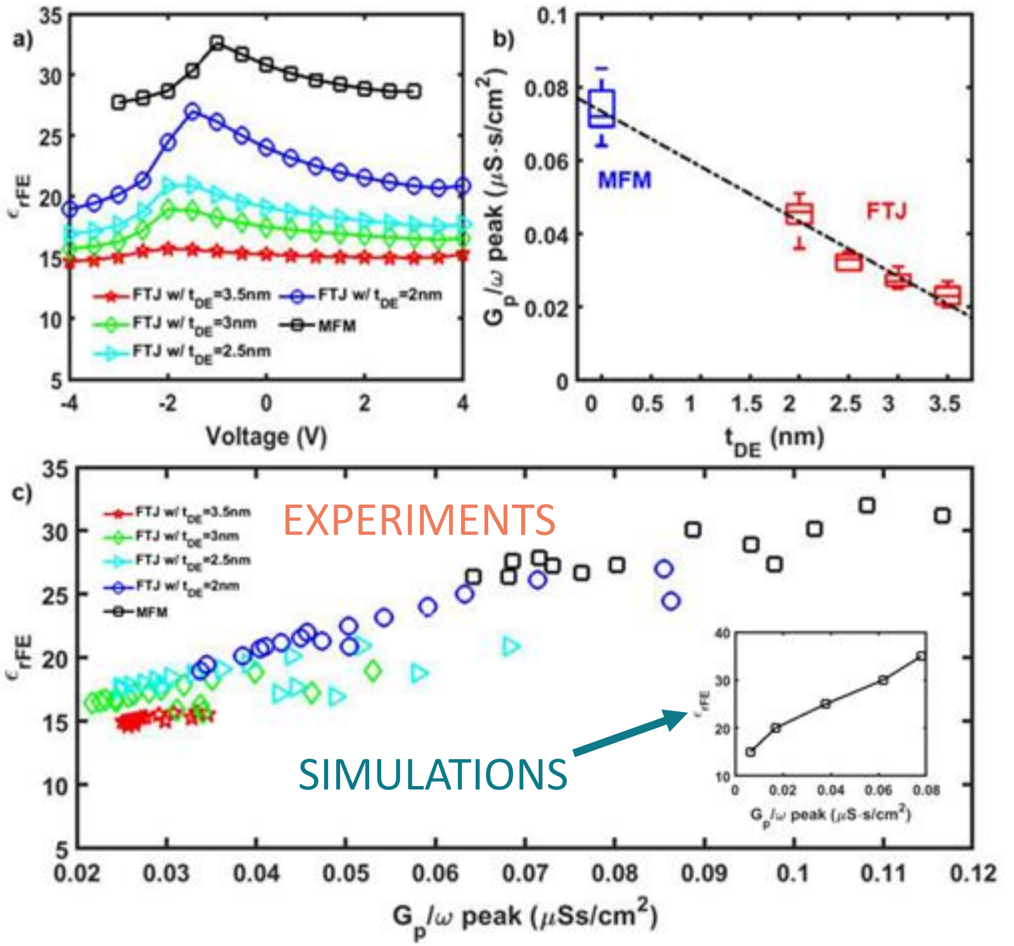
WHAT CAN WE LEARN FROM IT?

- **Interplay between DE and FE properties**
  - **FE permittivity (polar composition) influenced by DE thickness**
  - **Strongly relates to G_p/ω peak magnitude**
  - **Also G_p/ω peak frequency changes with device structure**
  - **Previously thought to be only related to interface traps***
  - **<u>Does a thicker DE inhibit o-FE formation?</u>**

L. Benatti et al., IEEE TDMR, 23 3 (2023)





* Y. Qu et al., IEEE T-ED, 67 12 (2020)

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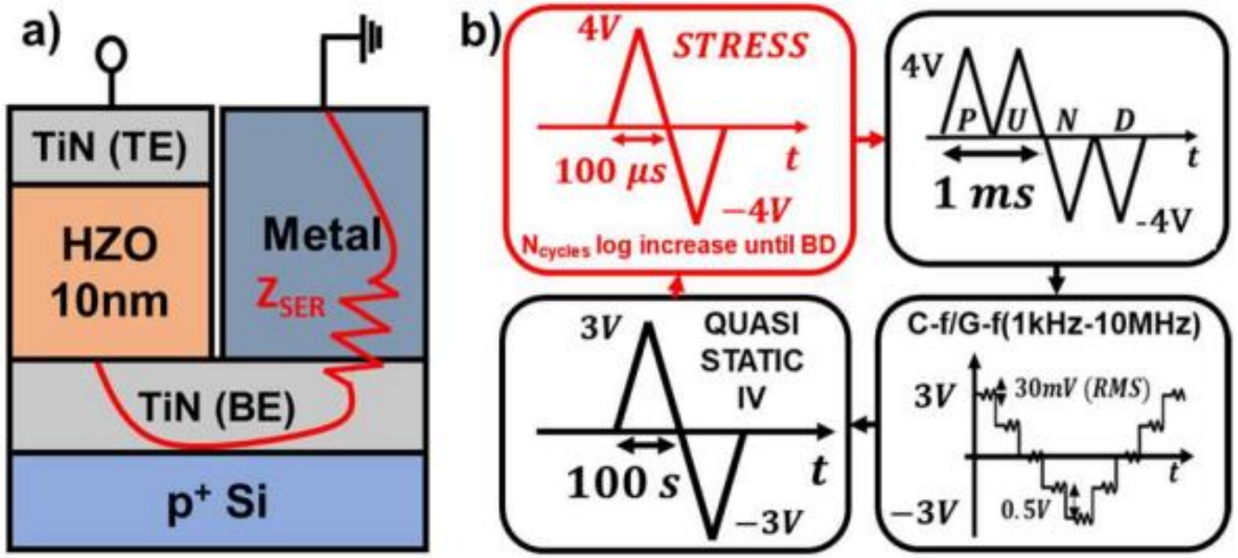
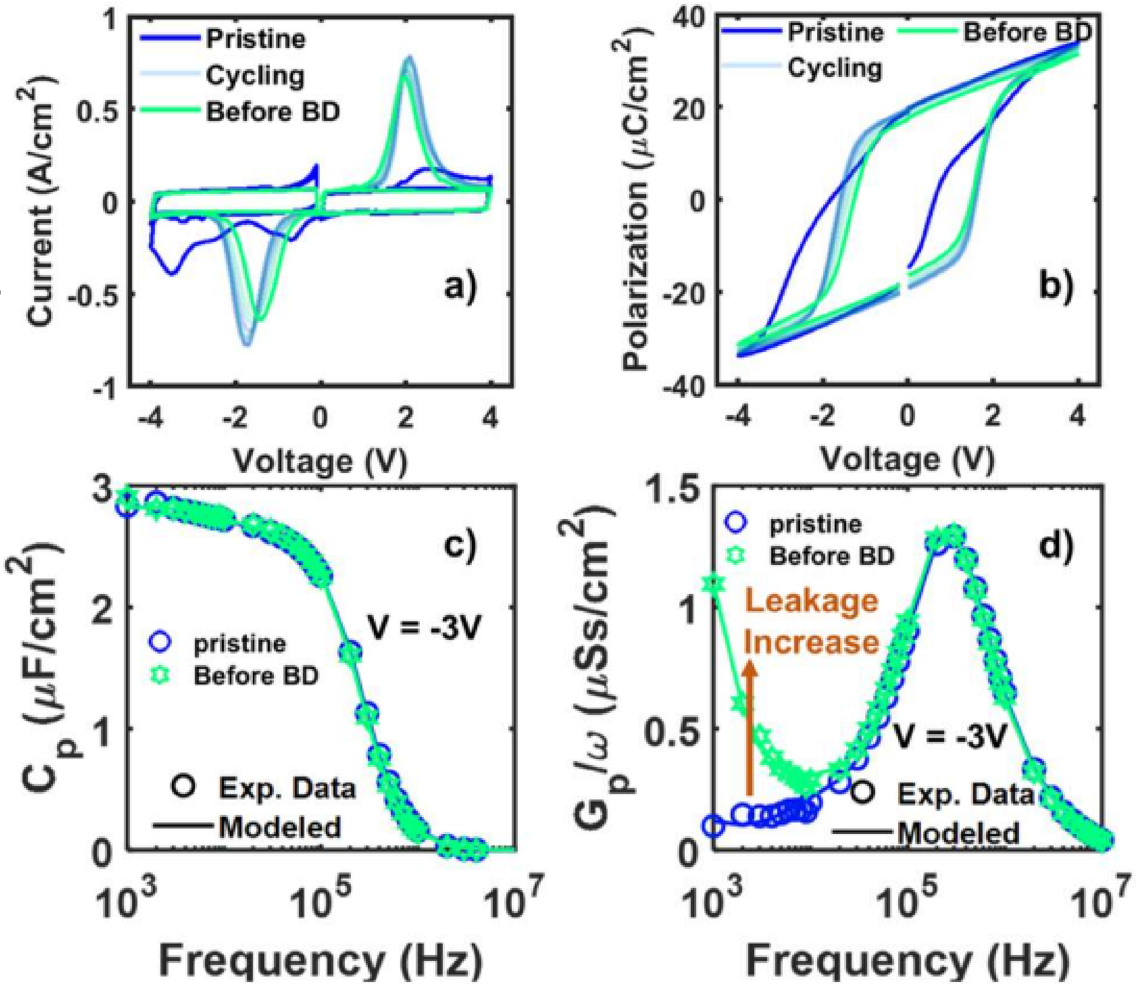
ENDURANCE AND AGING

FIXIT

- **Understand endurance failure and aging mechanisms**
  - **Stress-Measure sequence until device failure**
    - **Stress = Log-spaced triangular dual voltage waveform(s)**
    - **Measure = Sequence of PUND, ultra-slow I-V, multi-V C-f/G-f**
    - **<u>From each measurement extract key indicators</u>**
      - **PUND → P-V curves, P_R, P_{SAT}, E_C**
      - **Ultra-slow I-V → Leakage and switching current together**
      - **Multi-V C-f/G-f → FE and DE properties**

L. Benatti et al., IEEE IRPS (2023)





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ENDURANCE AND AGING

- **Understand endurance failure and aging mechanisms**
  - **Stress-Measure sequence until device failure**
    - **Stress = Log-spaced triangular dual voltage waveform(s)**
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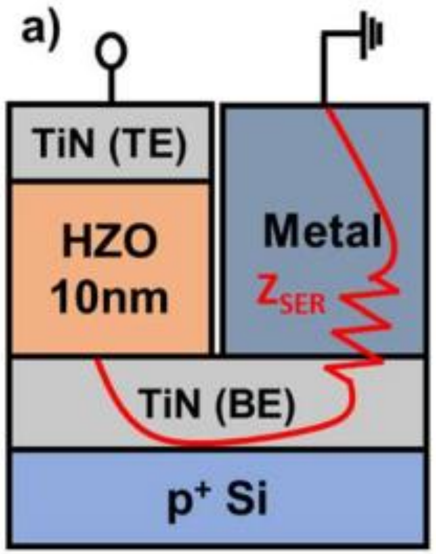
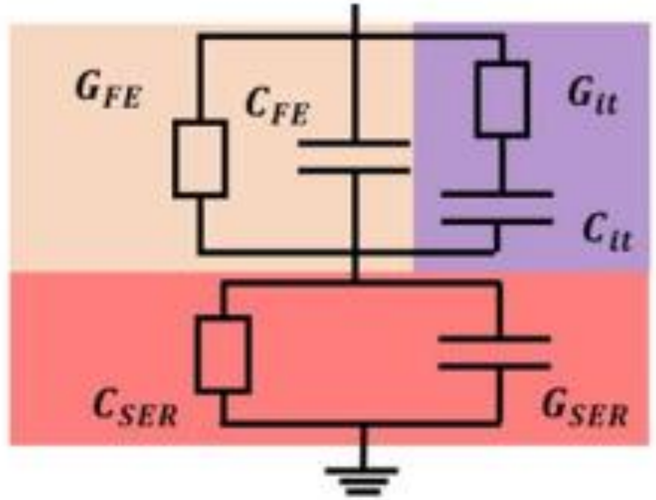
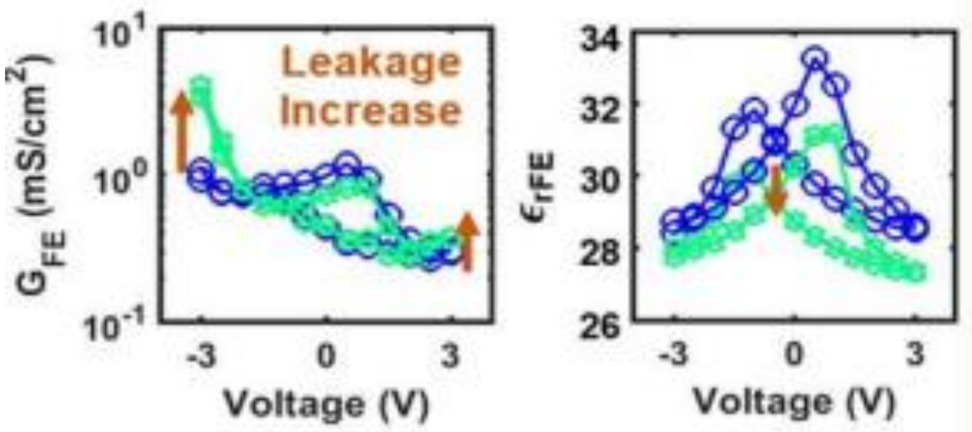
      - **PUND → P-V curves, P_R, P_{SAT}, E_C**
      - **Ultra-slow I-V → Leakage and switching current together**
      - **Multi-V C-f/G-f → FE and DE properties**

EXAMPLE OF INTERESTING DE/FE PROPERTIES

- **Leakage is asymmetric vs. voltage**
- **Leakage degradation is also asymmetric**
- **Permittivity degrades as well with aging**







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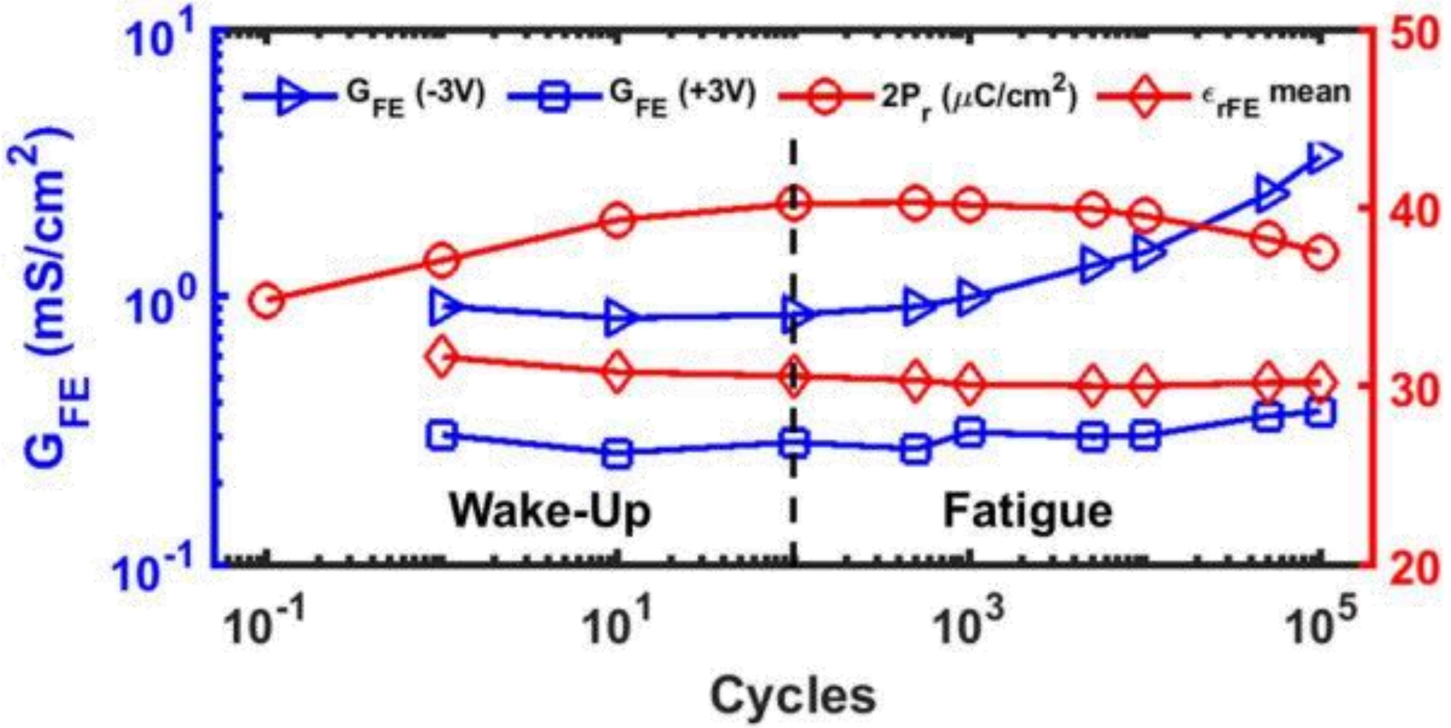
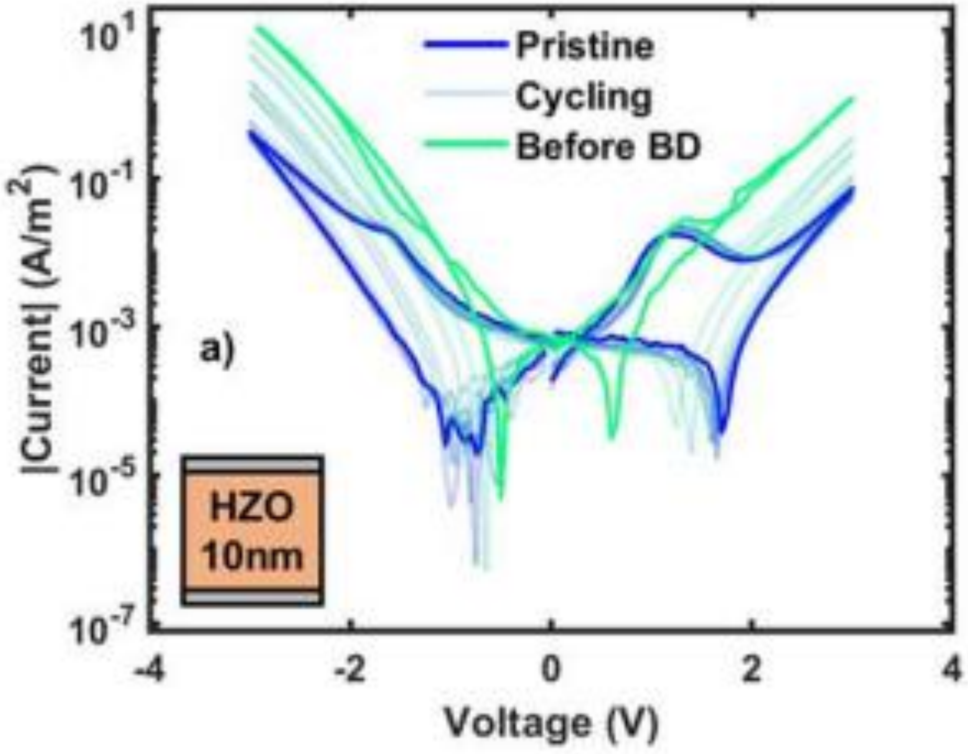
ENDURANCE AND AGING

FIXIT

- **Understand endurance failure and aging mechanisms**
  - **Plot relevant indicators vs. cycles to get insights**
    - G_{FE} at extreme voltages (±3V in this example) from multi-V C-f/G-f
    - $2P_R$ from PUND (identify wake-up, fatigue, failure stages)
    - ε_{FE} from multi-V C-f/G-f
    - Entire ultra-slow I-V curves





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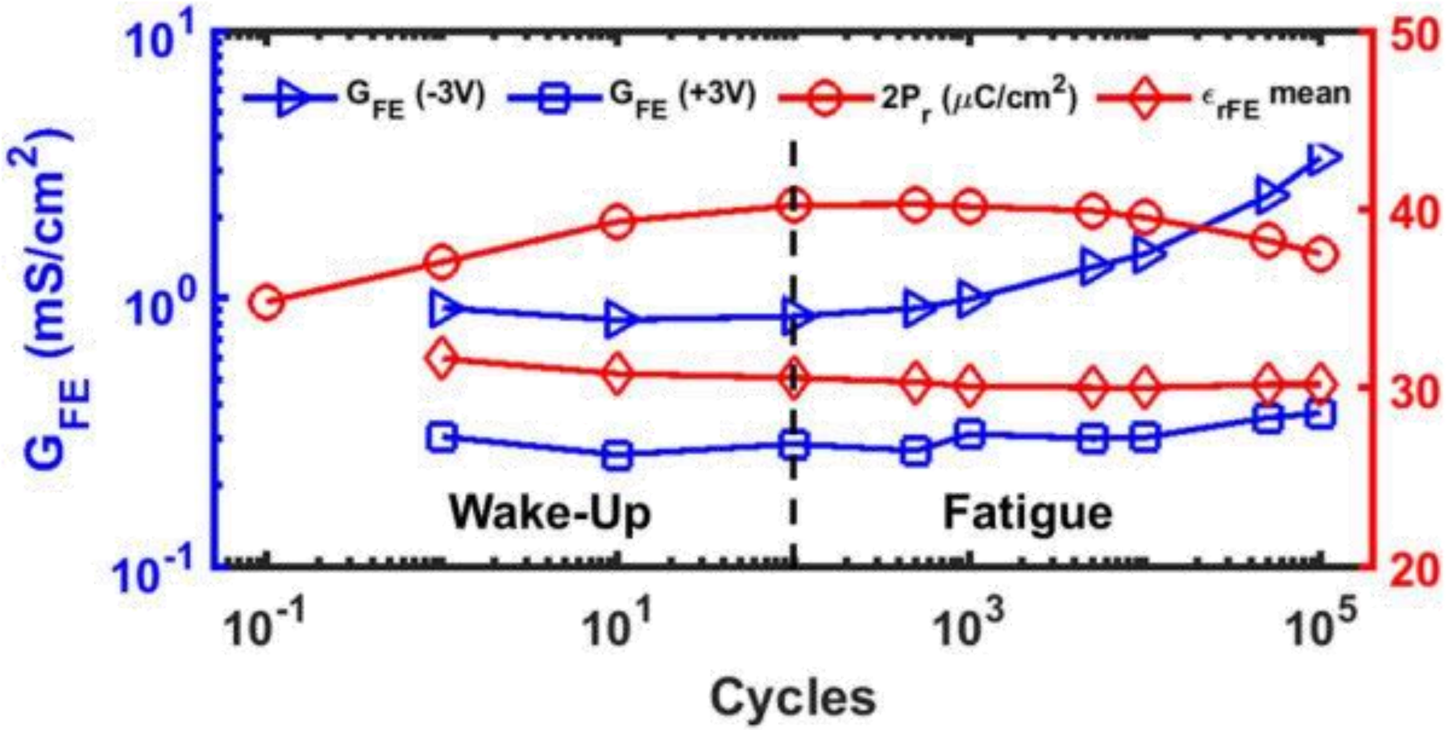
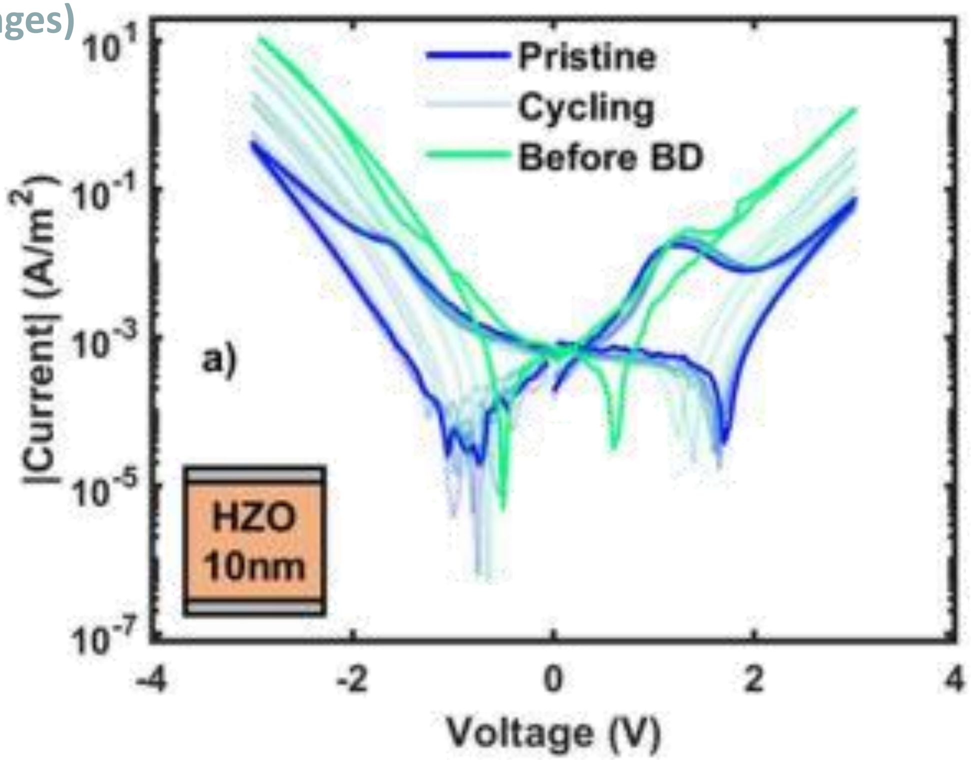
ENDURANCE AND AGING

- **Understand endurance failure and aging mechanisms**
  - **Plot relevant indicators vs. cycles to get insights**
    - Wake-up not associated with massive defect generation
    - Defect generation happens during fatigue and is not symmetric
    - Equivalent FE permittivity degrades during fatigue (compositional changes)





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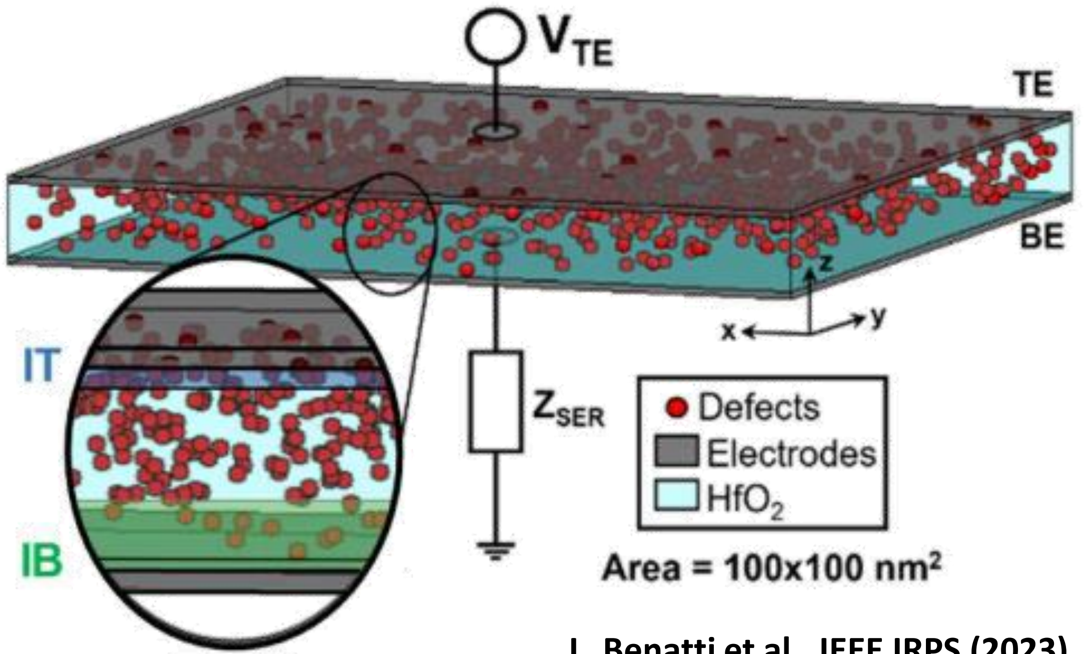
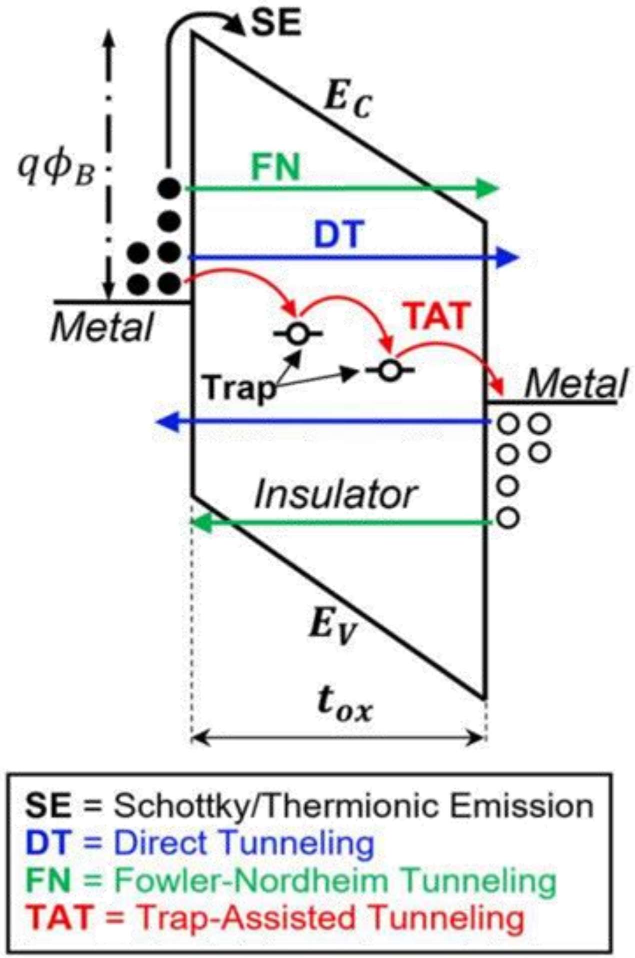
ENDURANCE AND AGING

FIXIT

- **Understand endurance failure and aging mechanisms**
  - **Couple insights with advanced simulations**
    - Ginestra simulations include defects and interfacial layers
    - All relevant conduction mechanisms considered
      - Including trap-assisted tunneling with trap-to-trap contribution
    - Series impedance extracted from multi-V C-f/G-f included as well



L. Benatti et al., IEEE IRPS (2023)



S. Vecchi et al., IEEE ESSDERC (2022)

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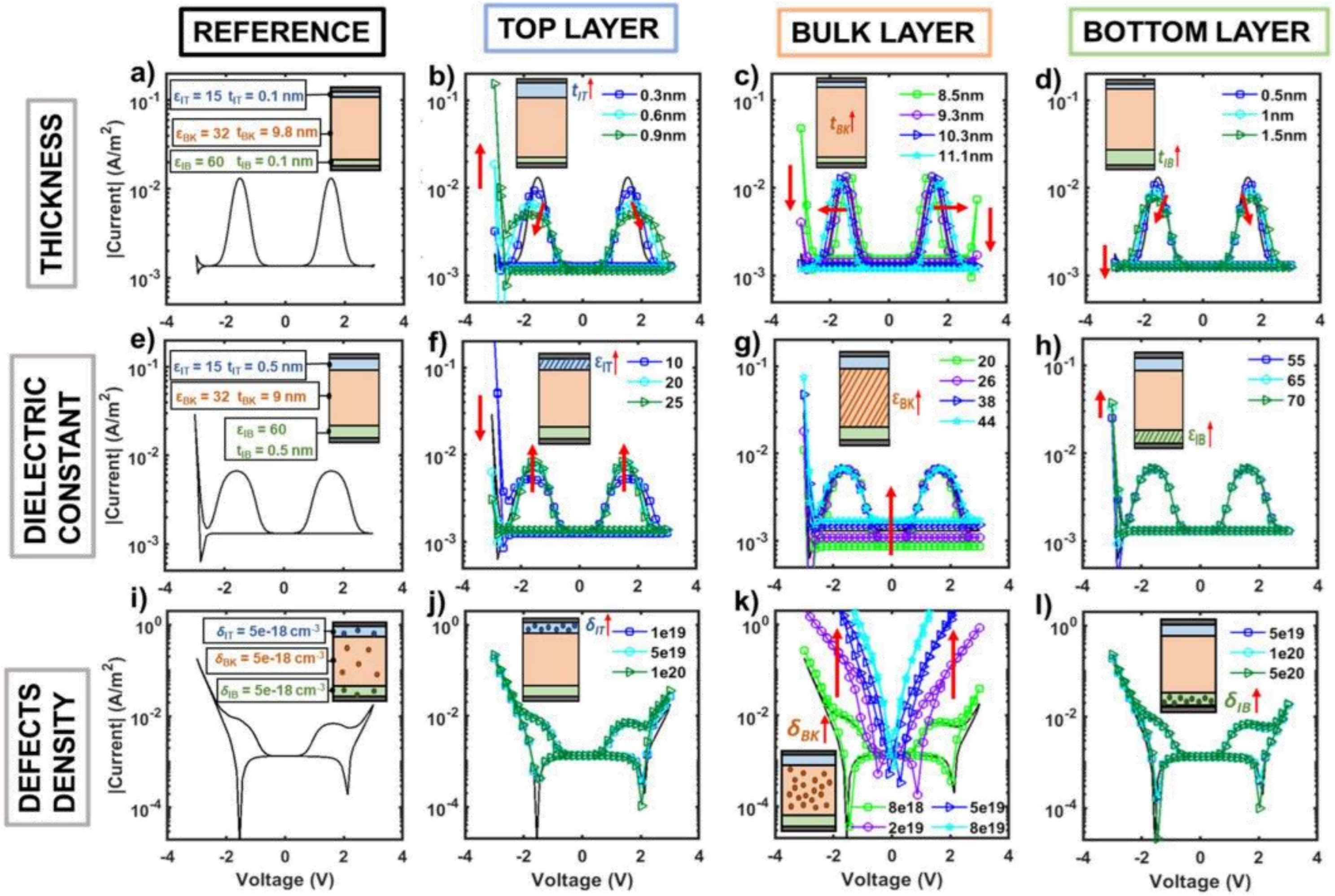
ENDURANCE AND AGING

FIXIT

- **Understand endurance failure and aging mechanisms**
  - **Perform a sensitivity analysis to get hints on key material and defect properties that affect I-V curves**

  - **Defect density in the FE bulk**
  - **Thickness and permittivity of the top interfacial layer**



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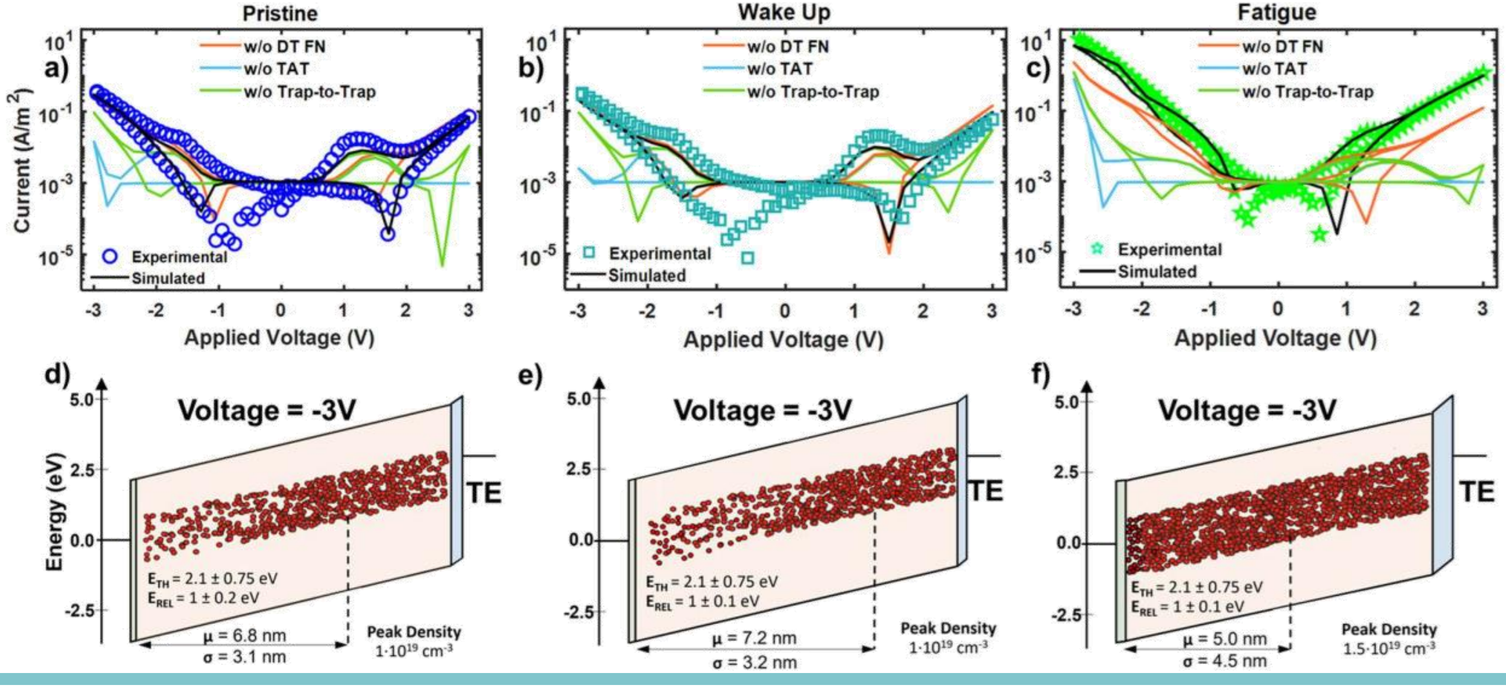
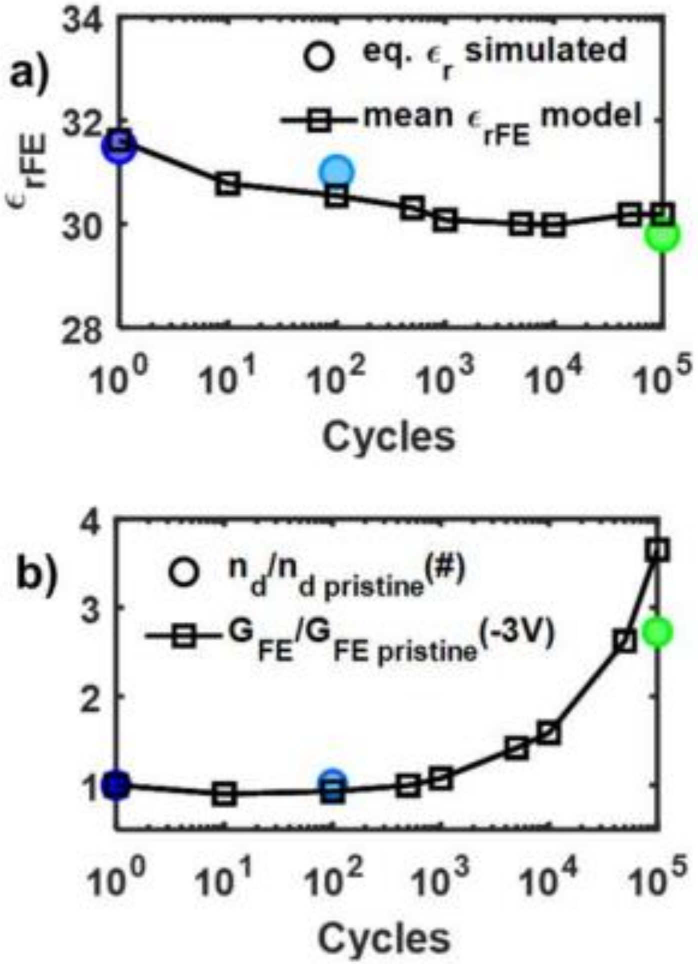
ENDURANCE AND AGING

FIXIT

- **Understand endurance failure and aging mechanisms**
  - **Reproducing the ultra-slow I-V curves in simulations requires:**
    - Including TAT and trap-to-trap contribution in leakage
    - Rearranging defect spatial distribution to transition from pristine to wake-up
    - Increasing defect density and degrading the top IL to get the fatigued curve
    - Top IL thickens at the expenses of the FE layer → overall eq. permittivity drops
    - Features in-line with what extracted from the multi-V C-f/G-f indicators





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COMMON THREADS OF RELIABILITY ISSUES

FIXIT

- **All the most relevant reliability issues in ferroelectrics stem from a complex interplay of a few phenomena**
  - **Granular nature of the ferroelectric material**
    - **Polar and non-polar grains with different orientations**
  - **Charge trapping centres (defects)**
    - **At the interface between materials**
    - **In the bulk of the different materials**
    - **Their possible field-temperature-gradient driven motion/re-distribution in the stack**
  - **Complex depolarization 3D field distribution in the device**
    - **Due to the field associated to charged defects and the local polarization of the grains**
    - **Domain pinning/de-pinning due to charge**
    - **Charge trapping/de-trapping influenced by grain polarization**
  - **Interface(s) degradation/thickening/thinning and compositional change**
  - **Phase changes in the ferroelectric (transitions between polar and non-polar)**
  - **Defects generation due to applied/internal field and charge injection**

- **<u>A VERY HARD MATTER! Requires sophisticated simulations, dedicated experiments, careful interpretation!</u>**

- **There's plenty of room at the bottom (of reliability studies in ferroelectrics)**

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