Modeling and simulation of ferroelectric materials for neuromorphic computing

IUNET - UDINE

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NanoElectronic Devices and Circuits
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COMPUTING EVOLUTION

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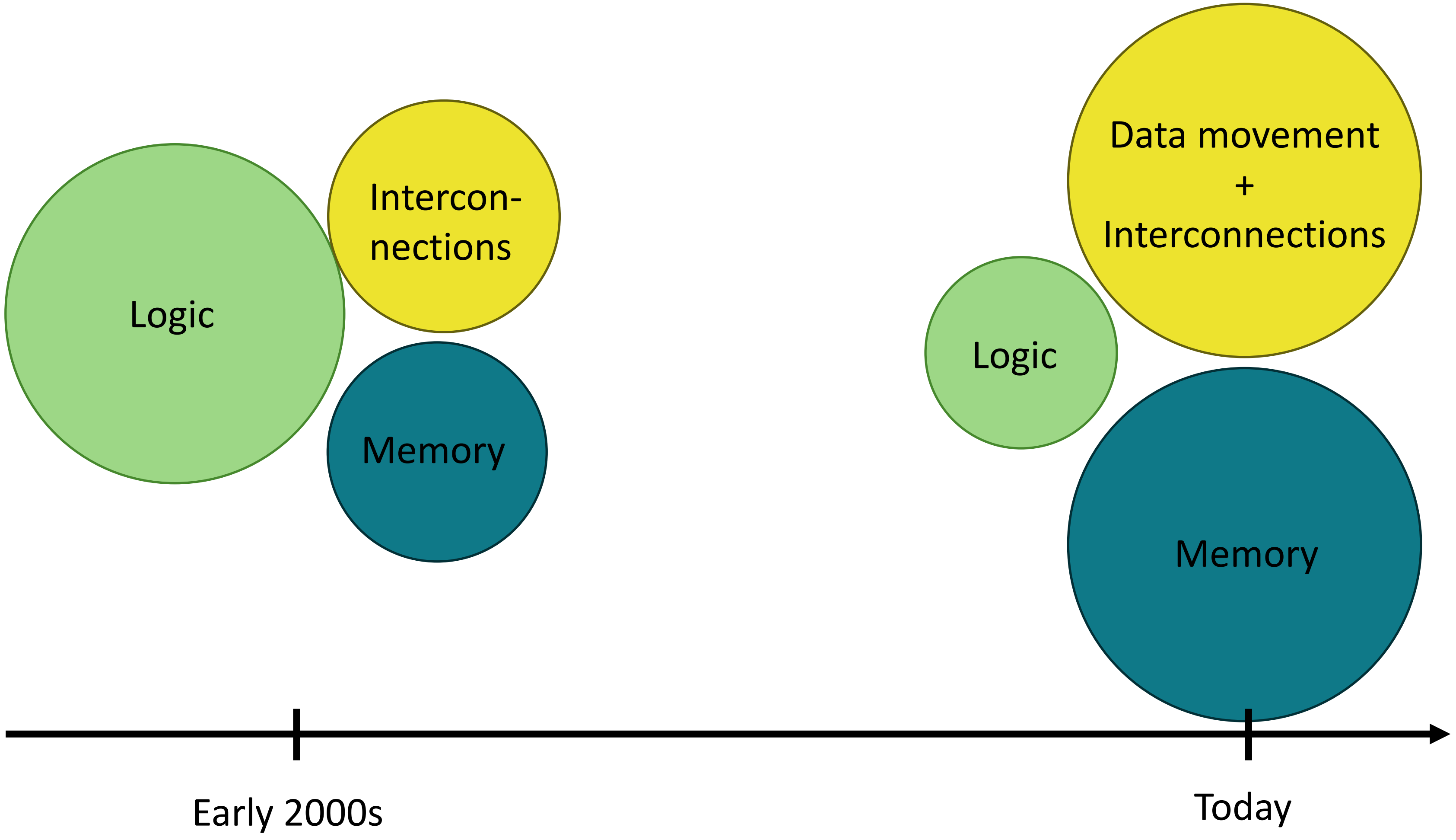


Evolution of the computing cornerstones, from IEEE ESSDERC 2022

- **Computing today** is mainly driven by **data** and **unconventional applications: AI** and **Machine Learning**
- **New architectures** and **paradigms** inspired by brain functionalities: **Neuromorphic computing**

NEUROMORPHIC COMPUTING

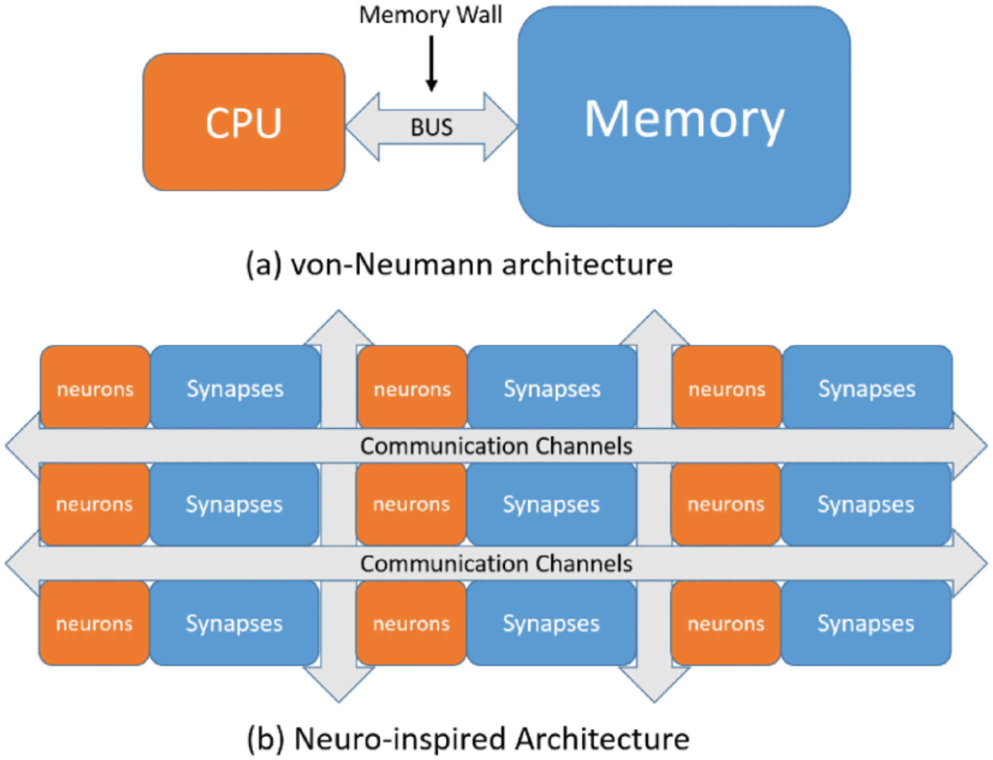
- Diffusion of computing systems based on **neural networks** and **artificial intelligence** → very **energy intensive**

new computing paradigms

In-Memory Computing to overcome **CPU ⇔ memory data transfer**

dedicated hardware

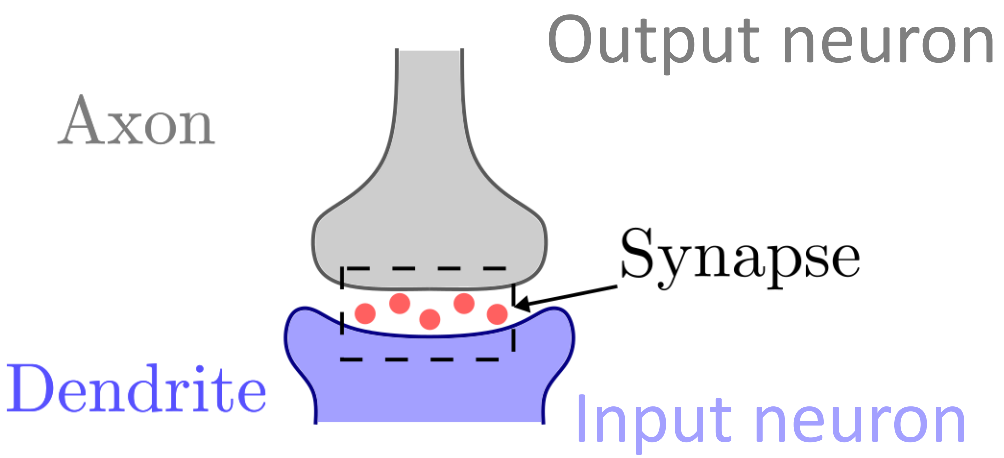
Memristors: programmable resistors



[S. Yu, Proc. IEEE 2018]

MEMRISTORS

- **Biological neural networks: interconnections** between **neurons** thanks to **synapses**
- **Synapses** weigh the **electrical signals** transmitted and received by **neurons**
- How can we create an **artificial synapse**? → **Memristors**
- **Memristors:** passive devices, can be switched from a **high resistive state** (HRS) to a **low resistive state** (LRS) in a **non-volatile** manner
- Types of memristors: Phase-Change Memories, Resistive-RAM, **Ferroelectric-based devices**



	PCM	RRAM	FTJ	FeFET
Area	4-50 F^2	4-50 F^2	1-10 F^2	6-50 F^2
Retention	10 y	10 y	10 y	1 y
Endurance	10^6-10^9	10^3-10^9	10^7	10^6-10^9
Switching Energy	$\sim$ 10 pJ	$\sim$ pJ	10 fJ	$\sim$ fJ

Data from Chen *et al., Advanced Electronic Materials* 2022 and Semiconductor Memory Devices and Circuits by Shimeng Yu

OUTLINE

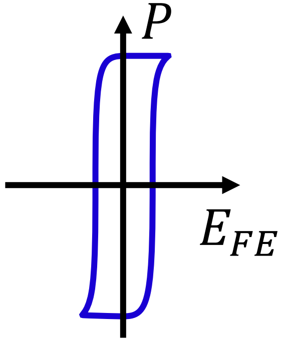
- Ferroelectric materials
- Ferroelectric Tunnel Junctions (FTJs)
    - Large signal operation
    - Small signal operation
- Ferroelectric Field Effect Transistors (FeFETs)
- Conclusions

FERROELECTRIC MATERIALS

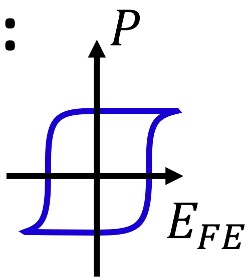
- **Ferroelectric materials** exhibit **hysteresis** in their **Polarization-Electric field** characteristic

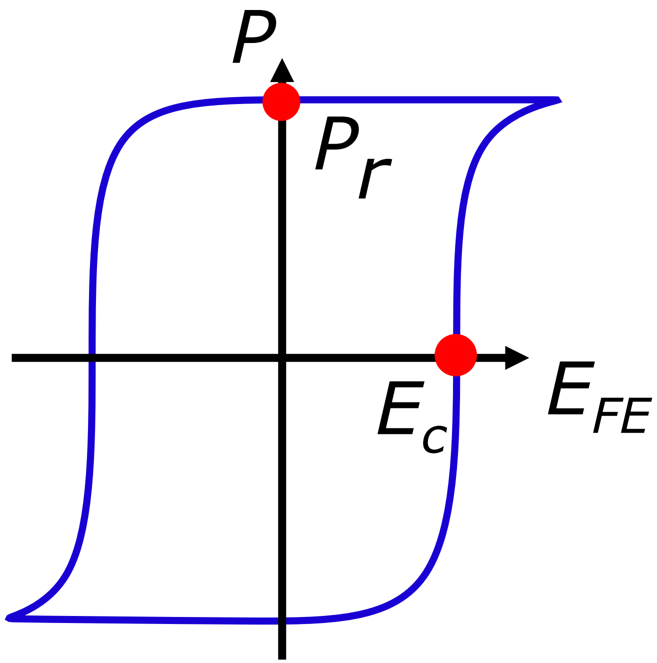
- Notable features: **Coercive field** E_C, **remnant polarization** P_r, **depolarization field** E_{dep}, **multi-domain** nature

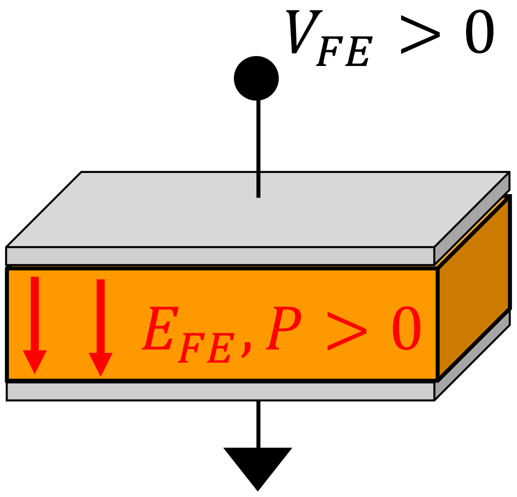
- **Perovskites**:
  - high P_r
  - **low** E_C



- **Hafnium-based**:
  - lower P_r
  - **higher** E_C







DESCRIPTION OF THE FERROELECTRIC

The total ferroelectric polarization is written as a **spontaneous** or **critical polarization** P_S plus a polarization induced proportional to the electric field [1-4]:

$$P_T = P_S + \varepsilon_0(\varepsilon_{FE} - 1)E_{FE}$$

ε_{FE} is the so-called background polarization

The thermodynamic potential related to a **uniform free standing ferroelectric** is written according to the Landau theory of second-order phase transition

$$f(P_s) = \alpha {P_s}^2 + \beta {P_s}^4 + \gamma {P_s}^6 - EP_s \ [J/m^3]$$

(we assume polarization only along one direction)

The order parameter refers to the critical part of the polarization: P_S

[1] A. K. Tagantsev, Ferroelectrics 375, 19, (2008); [2] C.H. Woo and Y. Zheng, Appl. Phys. A 91, 59–63 (2008); [3] T. Rollo *et al.* , Nanoscale 12, 2020, (10), 6121-6129; [4] J. Bizindavyi et al., Commun Phys 4, 86 (2021).

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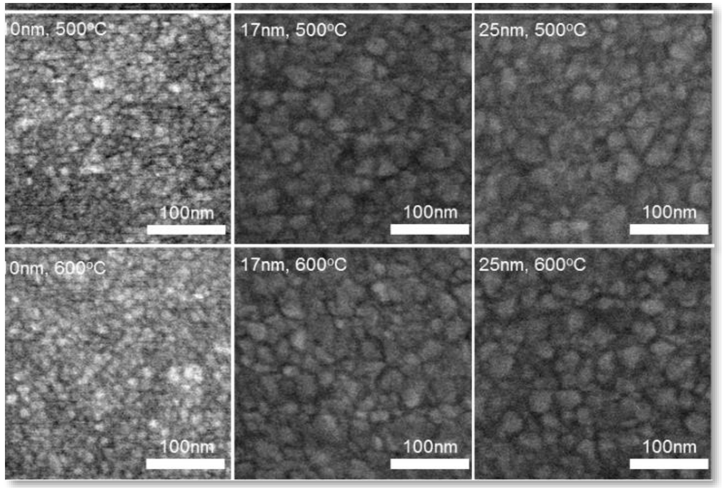
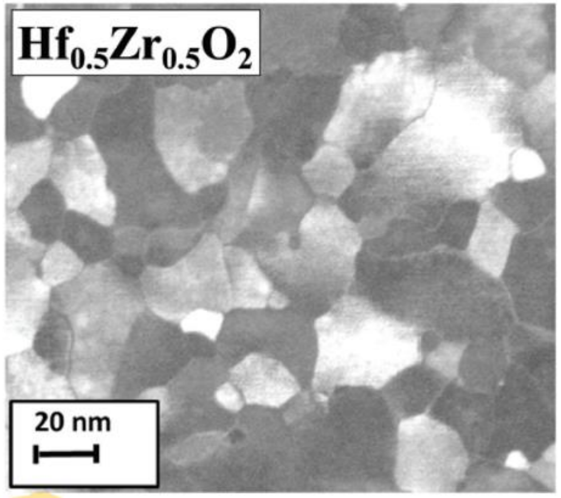
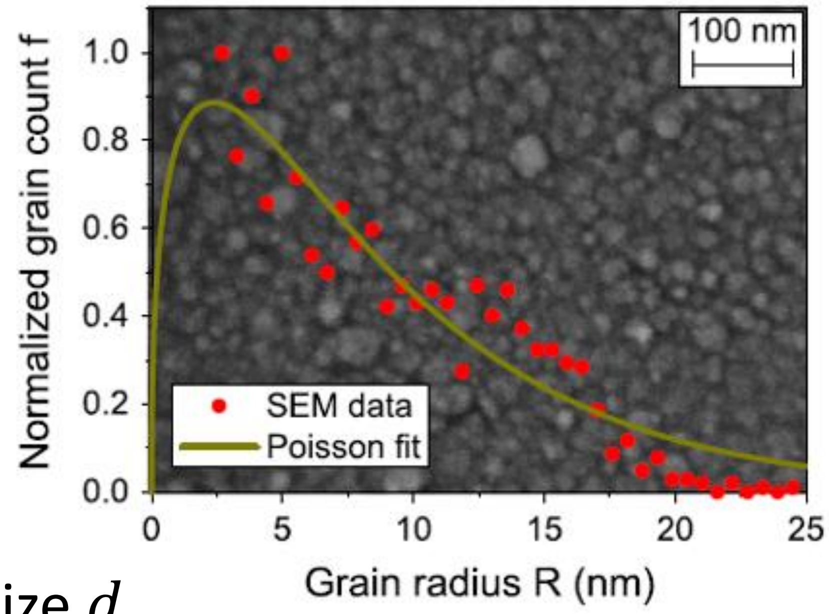
MULTIPLE DOMAINS (1/2)

HfO_2 based ferroelectrics are **polycrystalline** → there are **grains**

A uniform polarization is expected inside each grain → ferroelectric **domains**







- In our models we introduce built-in grains having fixed size d

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DOMAIN WALL COUPLING CONSTANT k (1/2)

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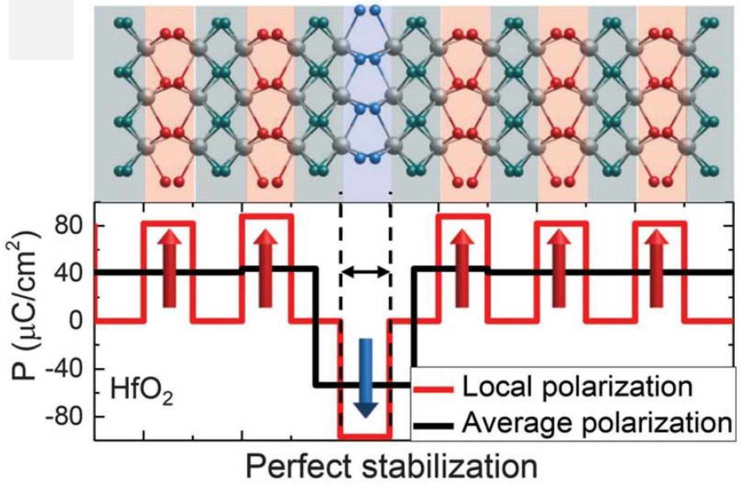
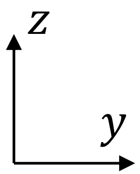




Domain wall energy

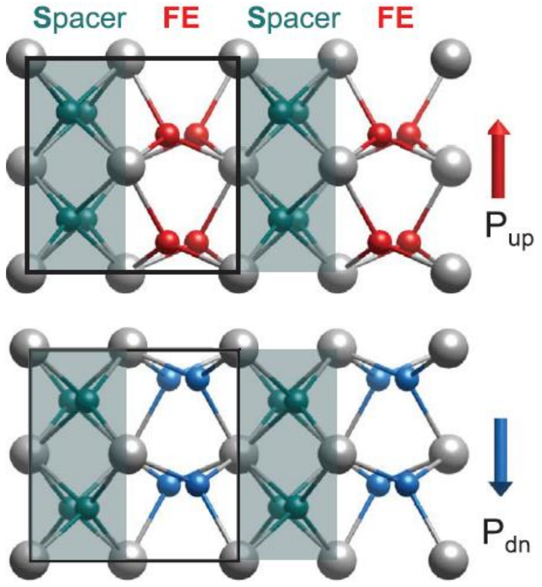
$$E \sim k \left(\frac{dP_z}{dy}\right)^2$$

- orthorhombic ferroelectric structure of HfO_2: periodic stacking of alternate 2-dimensional spacer and ferroelectric layers [1]
- HfO_2 has polar transverse optical phonons with flat bands [1]

phonon dispersion relation $\omega(q) = \omega(0) + k_0 q^2$

where $k_0 = 0$ and k_0 is related to k

[1] H.-J. Lee et al., *Science* , vol. 369, no. 6509, p. 1343–1347, 2020



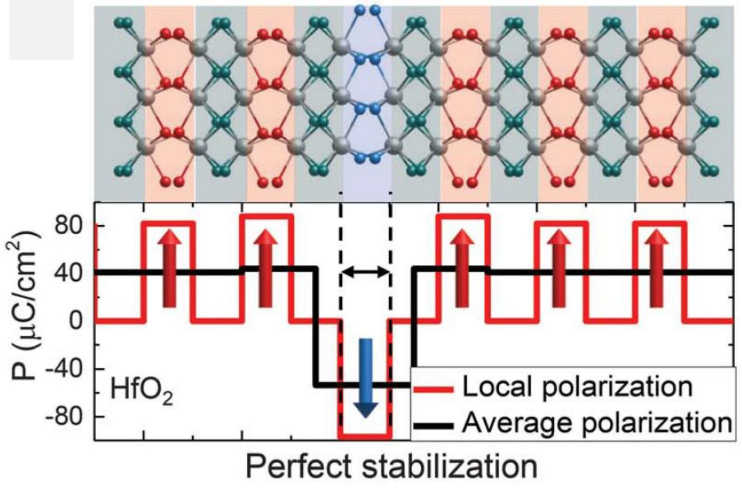
($Pca2_1$) orthorhombic phase

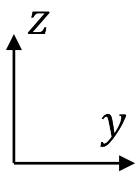
$k = 0$

No energy penalty in the formation of oppositely polarized domains (180°) with domain walls of vanishing thickness

DOMAIN WALL COUPLING CONSTANT k (2/2)

FIXIT





Domain wall energy

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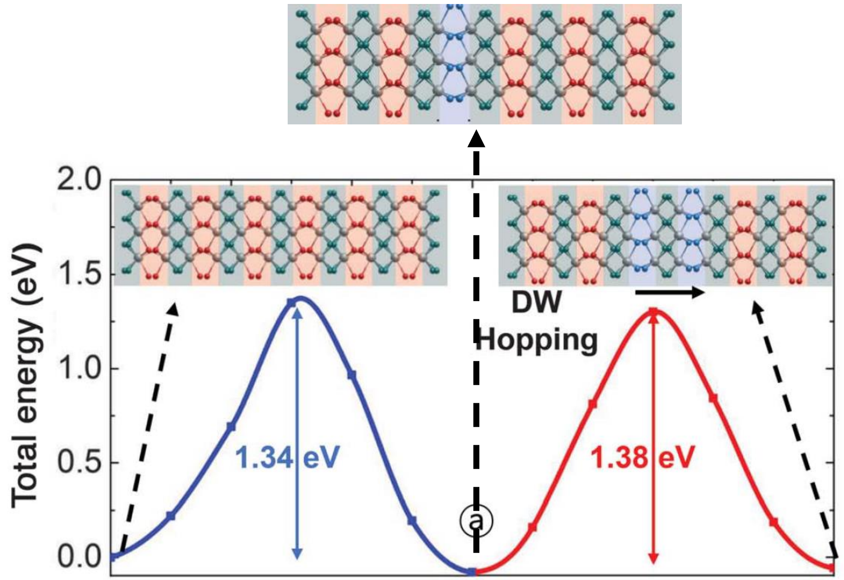

weakly interacting domain walls + zero group velocity of the relevant polar modes (g ~ 0, by the flat bands of HfO_2)

→ domain walls do not propagate efficiently and can move only by hopping over a large energy barrier

[1] H.-J. Lee et al., *Science* , vol. 369, no. 6509, p. 1343–1347, 2020

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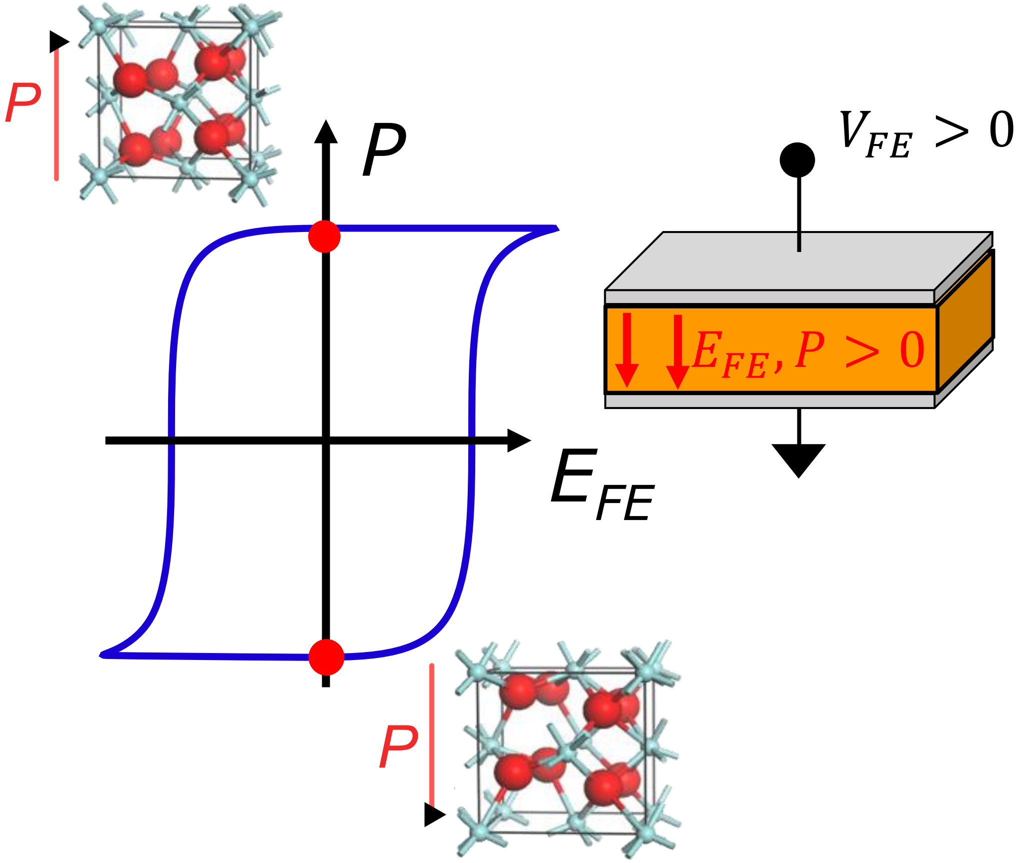
FERROELECTRIC TUNNEL JUNCTIONS

- **Exploit** the **spontaneous polarization** state to **modulate** the **tunneling barrier** of the device
- **Write voltage** large enough to **ensure polarization switching** (typically 1-1.2 MV/cm for hafnium-based ferroelectrics)
- Trade-off for **read voltage**: small enough to **preserve polarization state** (no read distub), large enough to **sense** the **tunneling current**
- Design metrics: **Tunneling-Electro Resistance** (TER) and **absolute current values**

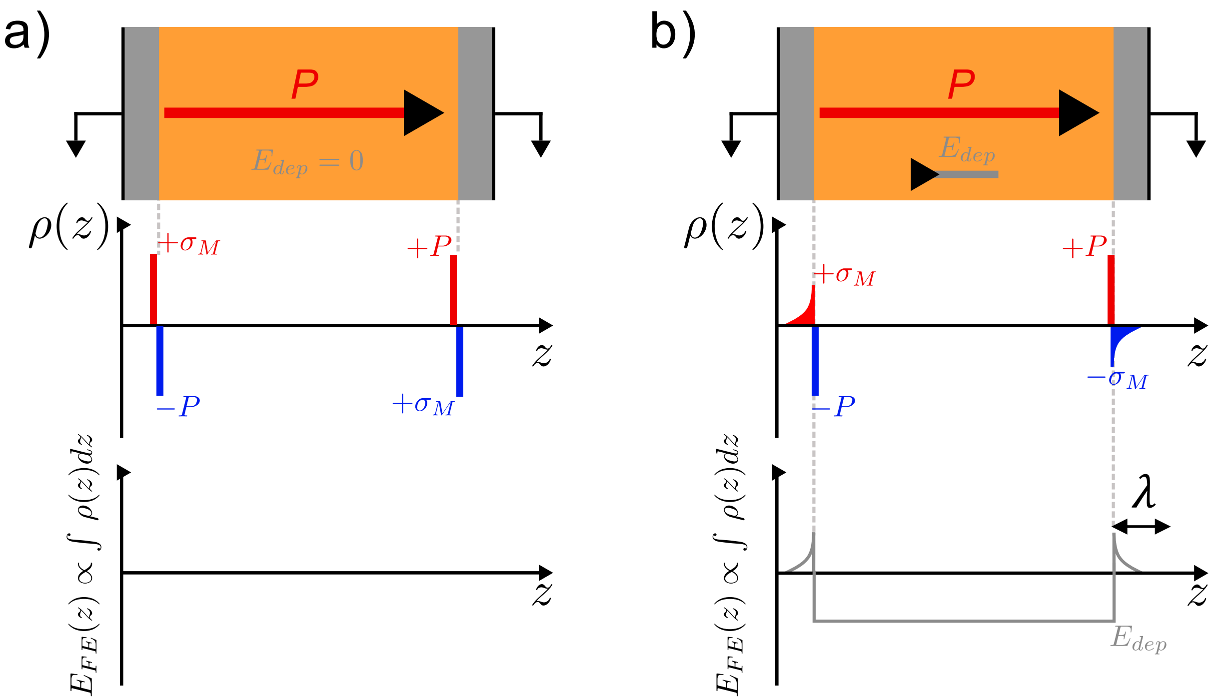


$$TER = \frac{I_{ON} - I_{OFF}}{I_{OFF}}$$

DEPOLARIZATION FIELD IN MFM

FIXIT

- **First FTJ** device **concept**, **proposed** by Leo **Esaki** [Esaki *et al.*, IBM Tech. Discl. Bull, 1971]
- Spontaneous polarization produces a **depolarization field**
- In vacuum → $E_{dep} = -\frac{\vec{P}}{\varepsilon_0 \varepsilon_{FE}}$
- In an **MFM stack** it depends on the metal **screening length**



Screening length [1] $\lambda = \frac{h}{q}\sqrt{\frac{\varepsilon_0 \varepsilon_M}{3m_0}} \cdot \left(\frac{3}{8\pi}\right)^{1/3} \cdot \left(\frac{1}{n_0}\right)^{1/6}$

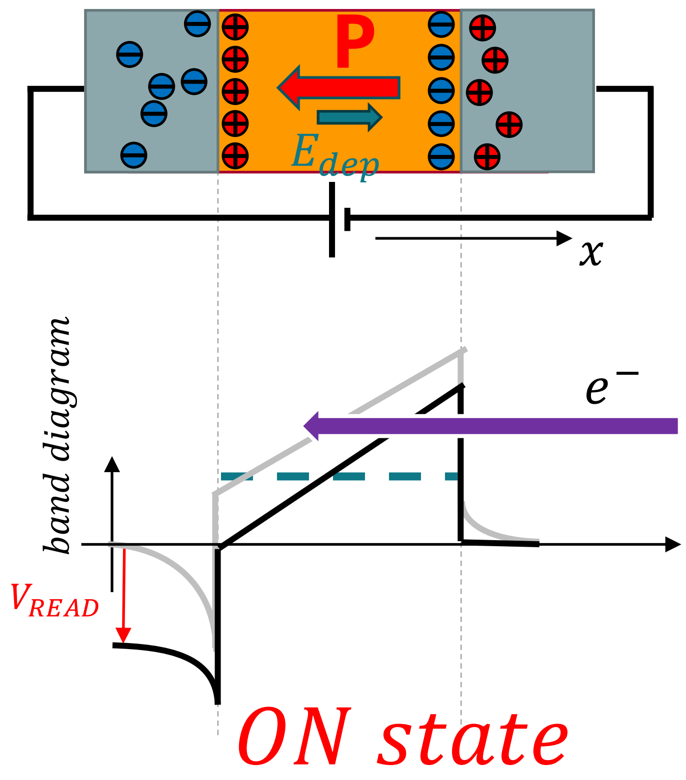
ε_M: relative permittivity of the metal

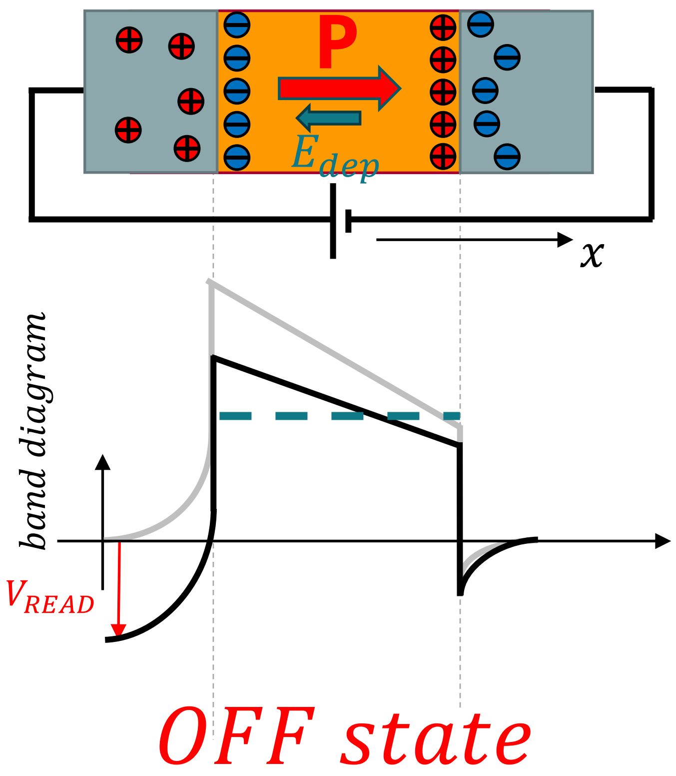
m_0: electron effective mass

n_0: equilibrium metal electron density

[1] Mehta *et al.*, JAP, vol. 44, n. 8, pp. 3379–3385, 1973.

TUNNELING BARRIER HEIGTHS

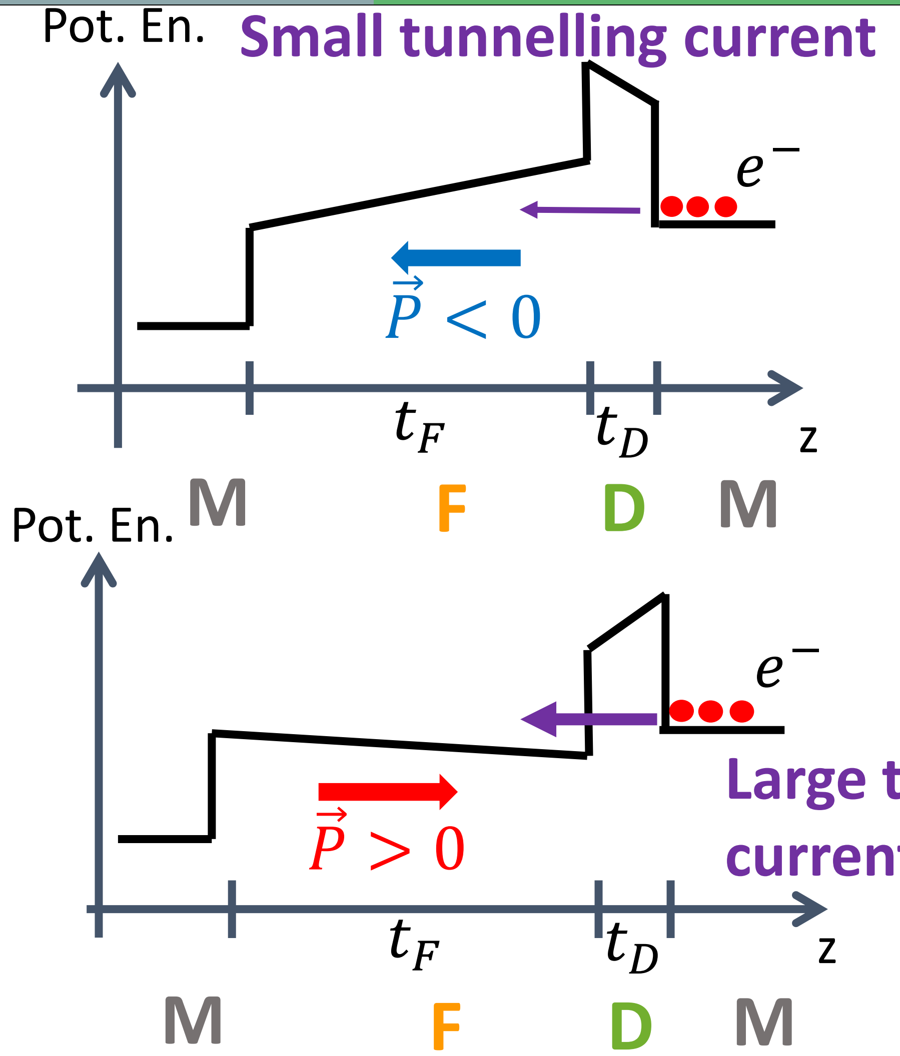


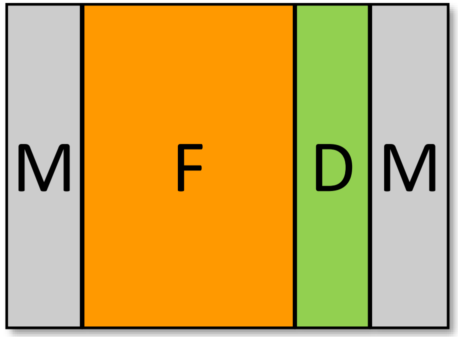


- Different effective heights of the tunneling barriers.
- Need for very thin FE layers (<5nm) to allow for large enough current densities.

MFDM-FTJ WORKING PRINCIPLE

- **Different polarization** states ⇒ **different** band bending and **tunnelling current** ⇒ can operate as **memristors**
- **Tunneling** barrier **decoupled** from the ferroelectric **switching** layer
- **Band profile** at the **FE-DE interface** depends on **polarization** plus possible **trapping**





TUNNELING CURRENT MODEL

FIXIT

The tunnelling read current, I_R, is estimated as the sum of the $I_{R,i}$ in each domain resulting from a Landauer model

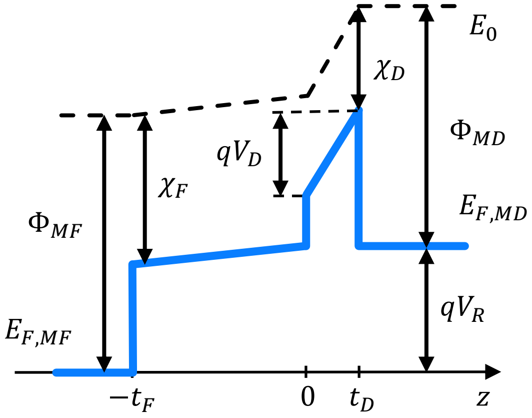
$$I_{R,i} = \frac{q}{\pi\hbar}\int_{-\infty}^{+\infty}\sum_{k_x,k_y} T_i(E_\perp)\left[f_{0,MD}\left(E_\perp+\epsilon(k)\right)-f_{0,MF}\left(E_\perp+\epsilon(k)\right)\right]dE_\perp$$

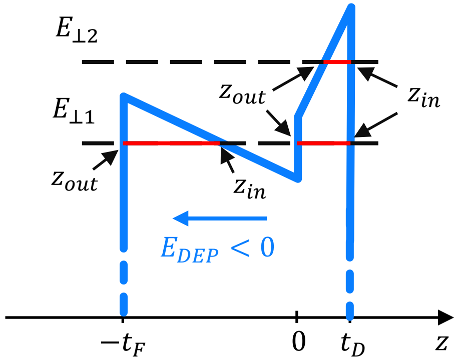
$$= \frac{A\,K_B T\,m_\parallel q}{2\pi^2\hbar^3}\int_{-\infty}^{+\infty} T_i(E_\perp)\left\{F_0(E,E_{fMD})-F_0(E,E_{fMF})\right\}dE_\perp$$

$$F_0(E,E_f) = \ln\left[1+\exp\left(\frac{E_f-E}{K_B T}\right)\right]$$

R. Fontanini *et al.* , IEEE EDTM, 2021

The transmission coefficient $T_i(E_\perp)$ is calculated accordingly with the WKB approximation

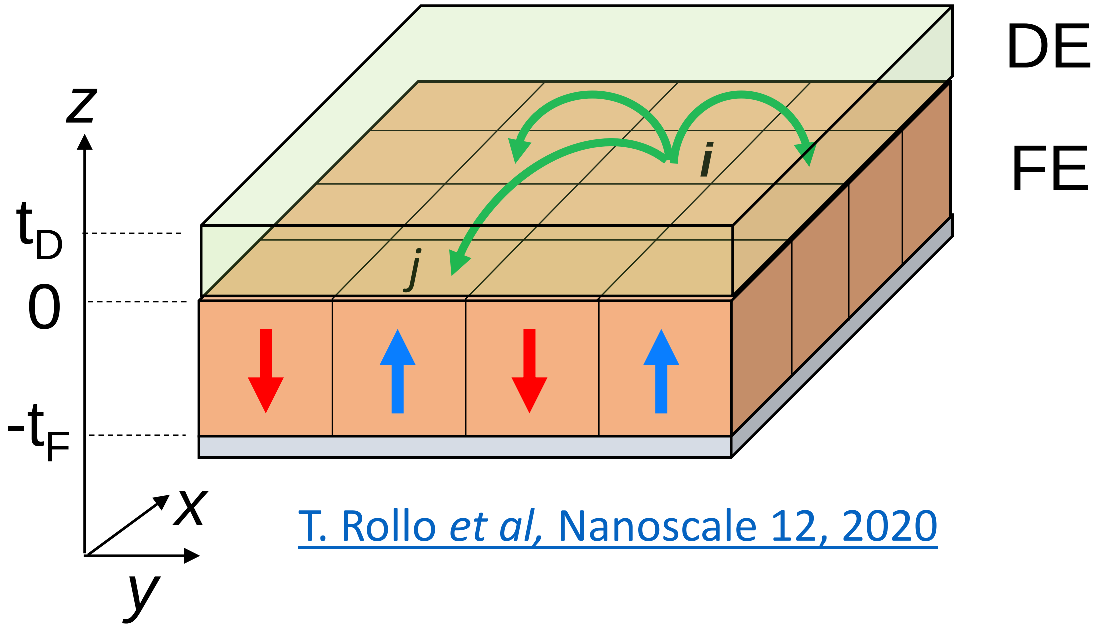




$$T_i(E_\perp) = \exp\left[-2\int_{z_{in}(E_\perp)}^{z_{out}(E_\perp)}\sqrt{\frac{2m_0}{\hbar^2}\left(E_{C,i}(z)-E_\perp\right)}\,dz\right]$$

DEPOLARIZATION FIELD IN MFDM

- The presence of the **dielectric layer** introduces:
  - **Imperfect screening** of polarization → **depolarization field**
  - **Electrostatic coupling** between **ferroelectric domains**



T. Rollo *et al*, Nanoscale 12, 2020

- **3D description** of the stack **necessary** due to the **multidomain** nature of the **ferroelectric**

$$C_{i,j} = \left(\frac{1}{d^2} \int_{D_i} G_{D,j}(\bar{r})\ d\bar{r} \right)^{-1}$$

- **Coupling** between ferroelectric domains **expressed** in terms of **capacitances**

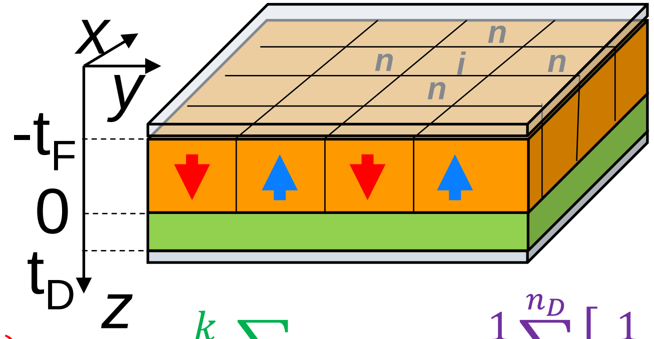
$C_{i,j}$: capacitance between i-th and j-th domain
$G_{D,j}(\bar{r})$: Green's function relative to j-th domain

SIMULATION MODEL BASED ON LGD THEORY

FIXIT

- Our **in-house developed** simulator solves both **ferroelectric dynamics** (dP_i/dt) and **trap occupation** (df_T/dt) equations
- Ferroelectric dynamics based on **Landau-Ginzburg-Devonshire (LGD)** theory and **Landau-Khalatnikov (LK)** model
- **General** model and theory applicable to **different** device **stacks** and **materials**
- **Interface traps** have **utmost importance** in the **depolarization term**

Landau-Khalatnikov



T. Rollo *et al*, Nanoscale 12, 2020

$$t_F \rho \frac{dP_i}{dt} = -\left(2\alpha P_i + 4\beta P_i^3 + 6\gamma P_i^5\right) t_F - 2 t_F \frac{k}{d^2} \sum_n (P_i - P_n) - \frac{1}{2} \sum_{j=1}^{n_D} \left[\frac{1}{C_{i,j}} + \frac{1}{C_{j,i}}\right] (P_j + Q_{T,j}) + \frac{C_D}{C_0} V_T$$

LGD theory term | Ferroelectric free energy term | Domain coupling term | Depolarization + Electrostatic term | Interface traps

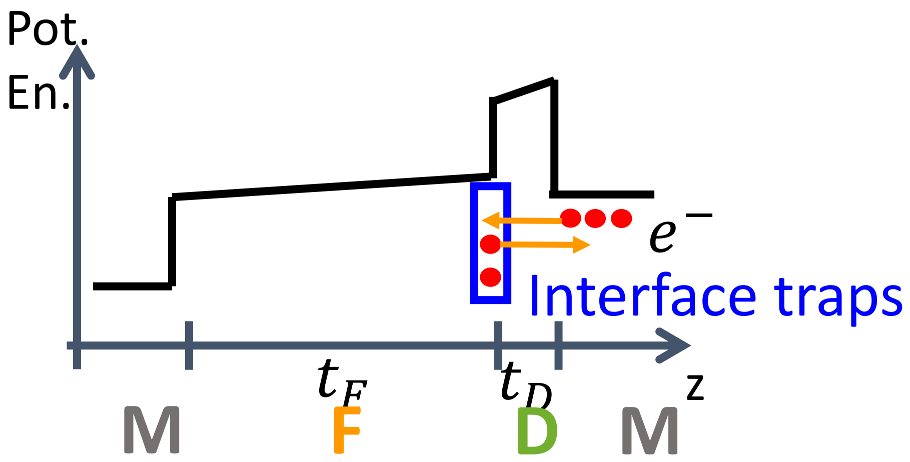
OUTLINE

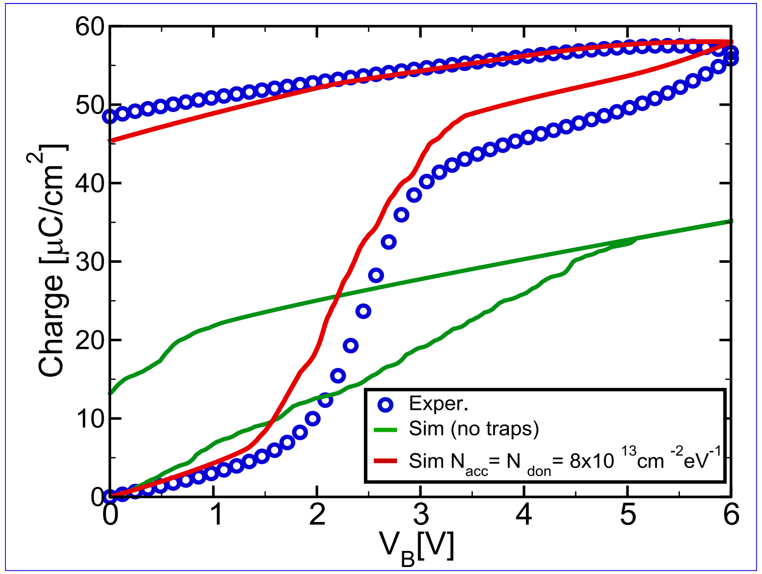
- ✓ Ferroelectric materials
- Ferroelectric Tunnel Junctions (FTJs)
  - Large signal operation
  - Small signal operation
- Ferroelectric Field Effect Transistors (FeFETs)
- Conclusions

WHY DO WE NEED TRAPS?

FIXIT

- **Traps**: available **states in the energy gap** of a material
- **Necessary** to explain **experimental behaviour** of **FTJs**
- **Influence several aspects** of **operation** and **design** of **FTJs**
  - **Large signal** regime
  - **Read current**

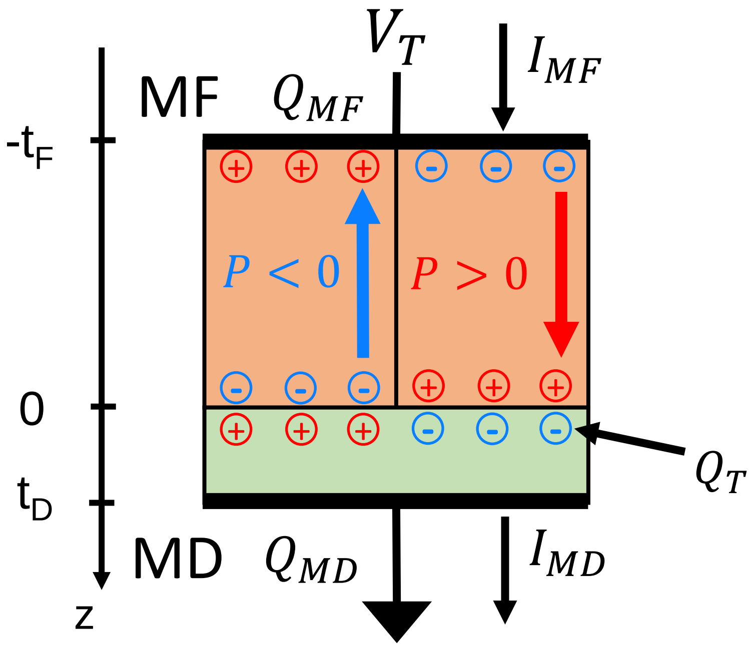


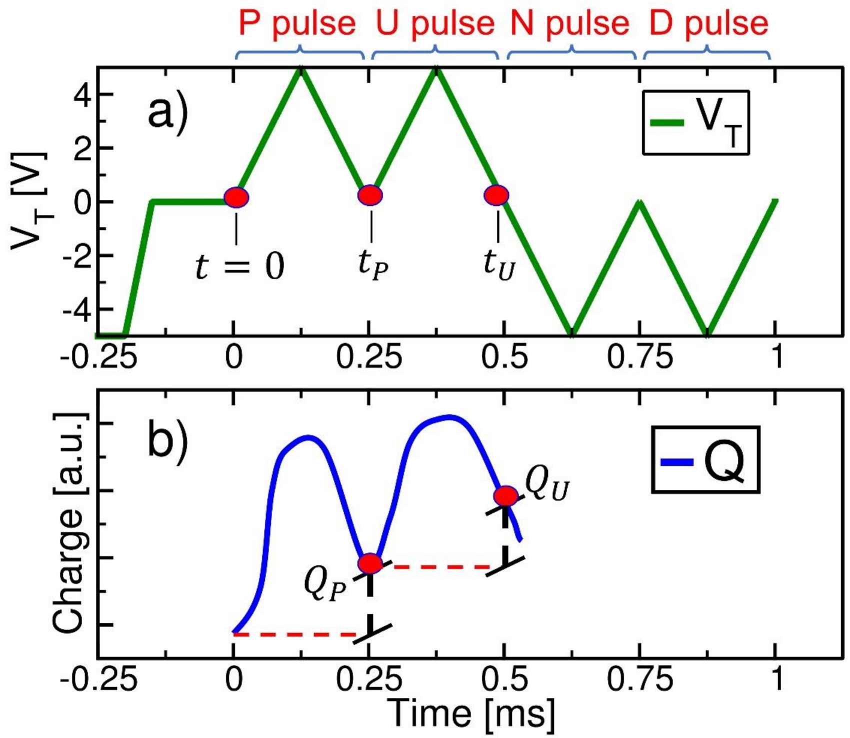


R. Fontanini *et al.*, ESSDERC 2021

PUND AND DEPOLARIZATION (1)

FIXIT





- P_{AV}: average spontaneous polarization (**simulated quantity**)
- $E_{DP,AV}$: **depolarization field** related to polarization screening by **interfacial charge Q_T**

- $Q_P(t) = \int_0^{t_P} I_{MF}(t')dt'$
- $Q_U(t) = \int_{t_P}^{t_P+t} I_{MF}(t')dt'$

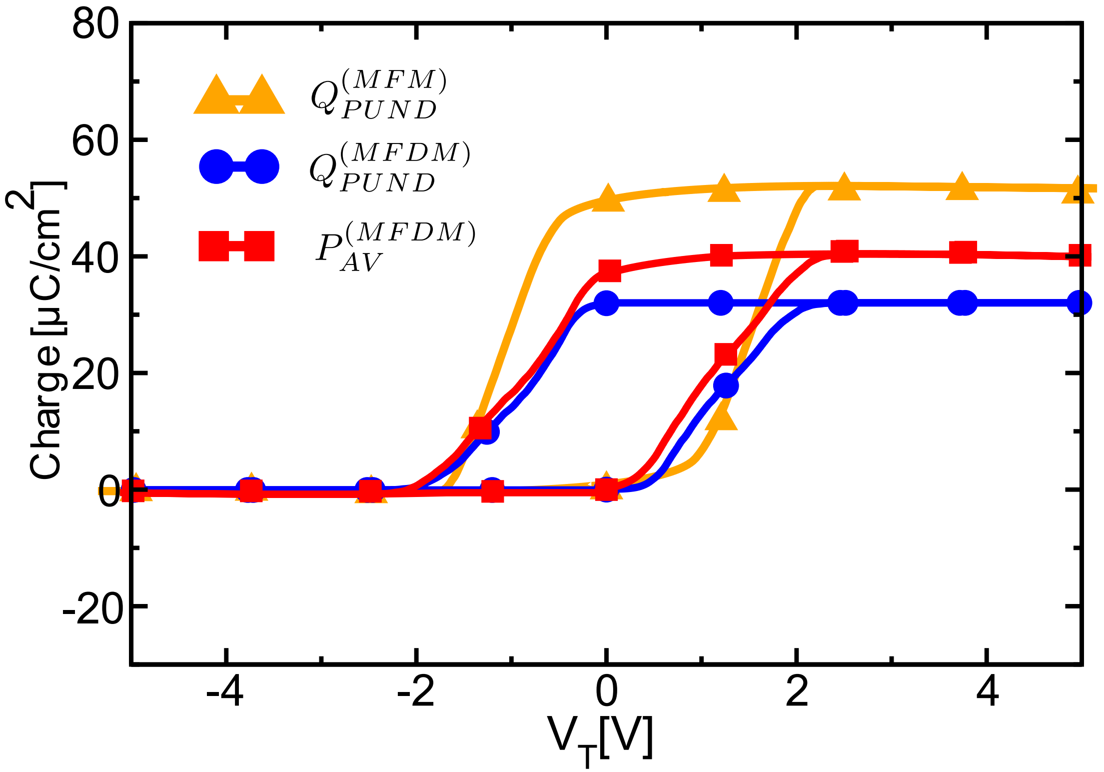
- $\varepsilon_0 \varepsilon_F E_{DP,AV} \simeq -\frac{C_F}{C_0}\left(P_{AV} + Q_{T,AV}\right) + C_S V_T$

- $\boldsymbol{Q_{PU}} = Q_P - Q_U = P_{AV}^{(P)} - P_{AV}^{(U)} + \varepsilon_0 \varepsilon_F \left(E_{DP,AV}^{(P)} - E_{DP,AV}^{(U)}\right) + [Q_{QT,MF}^{(P)} - Q_{QT,MF}^{(U)}] + +[Q_{lkg}^{(P)} - Q_{lkg}^{(U)}]$

PUND AND DEPOLARIZATION (2)

- In an **MFM stack: negligible depolarization, no trapping, similar leakage** during **P** and **U** pulses → $Q_{PU} \approx P_{AV}^{(P)} - P_{AV}^{(U)} \approx 2P_r$

- **Not true** in **general**! Particularly *not* in **MFDM stacks**



ERROR IN PUND MEASUREMENTS

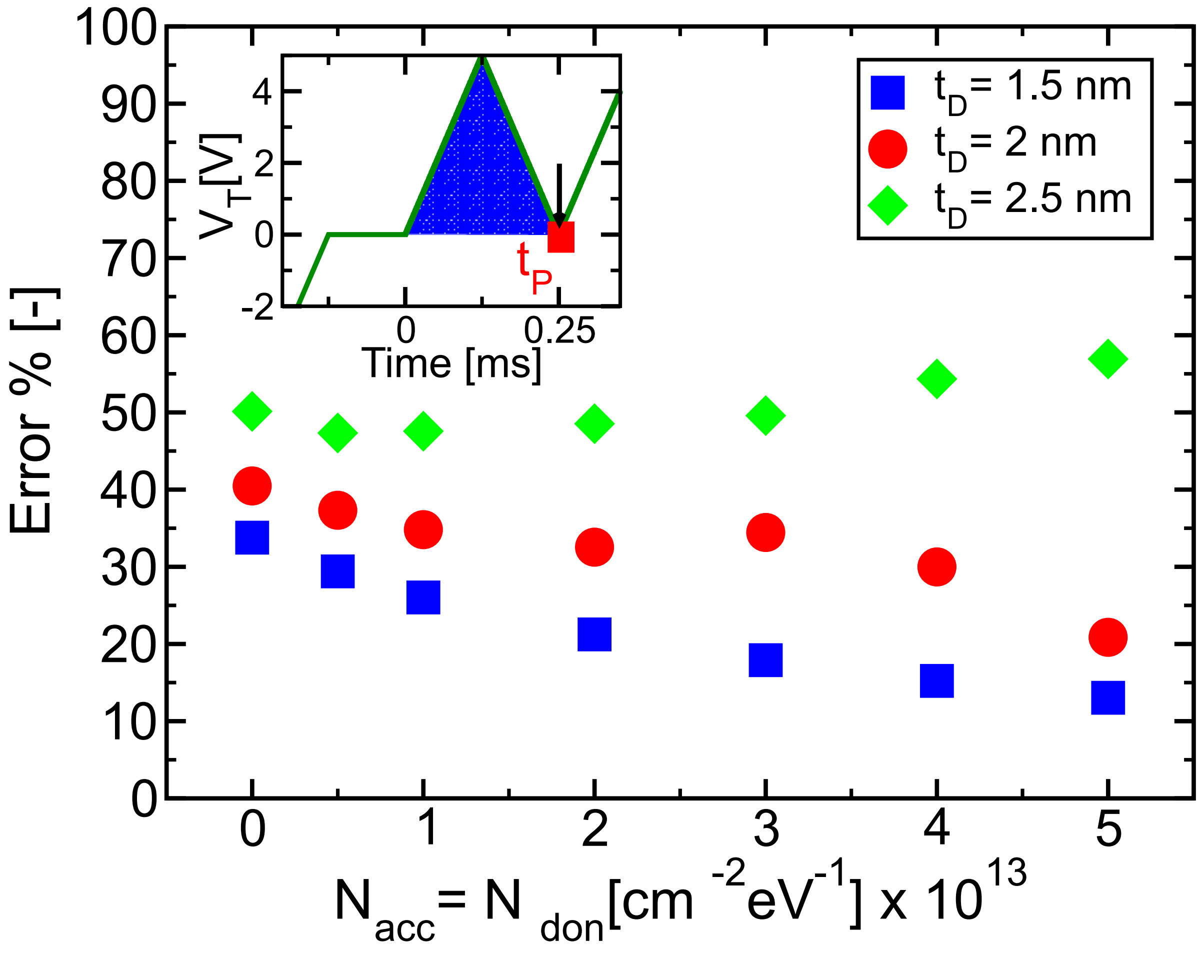
FIXIT

- **Relative error** introduced when estimating $P_{AV}^{(P)}$ with Q_{PU} **defined as**

$$Error = \left| \frac{Q_{PU} - P_{AV}^{(P)}}{P_{AV}^{(P)}} \right|$$

- **Error reduces** for **increasing trap density** → **reduction** of the **depolarization field**

- **Difficult** to provide **fixes** to extract the 'actual' $2P_r$



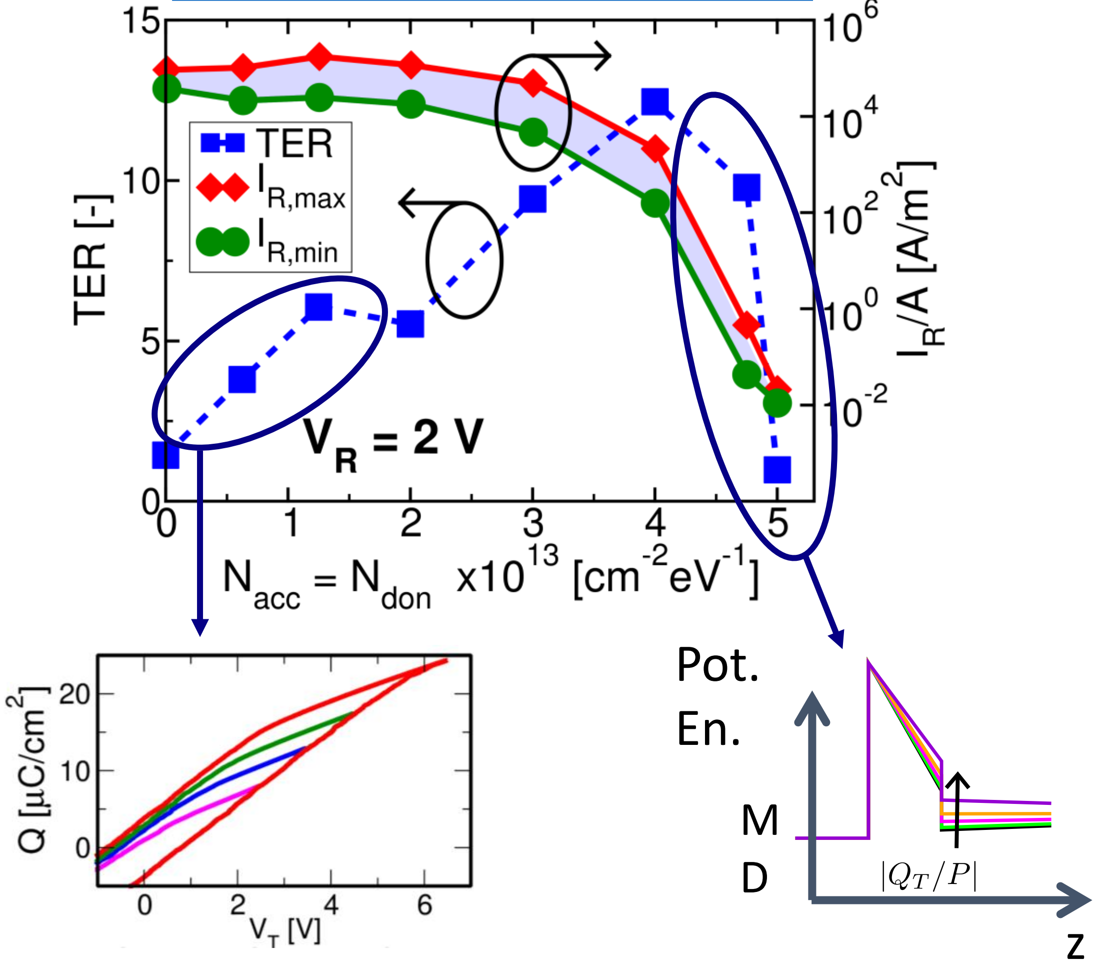
M. Segatto *et al.*, JEDS 2022

TRAPS AND READ CURRENT

FIXIT

- **Tunnelling current influenced by band bending of the structure**
- **Conduction band** at **FE-DE interface** regulated by net charge: **Polarization + trapped charge**
- **Sweet spot** for trap **density**: too low → depolarization, too high → low tunnelling current
- **Open issue**: how can we **engineer** the **trap density** in **actual devices**?

R. Fontanini *et al.*, IEEE TED 2022



TER: Tunnelling Electro Resistance

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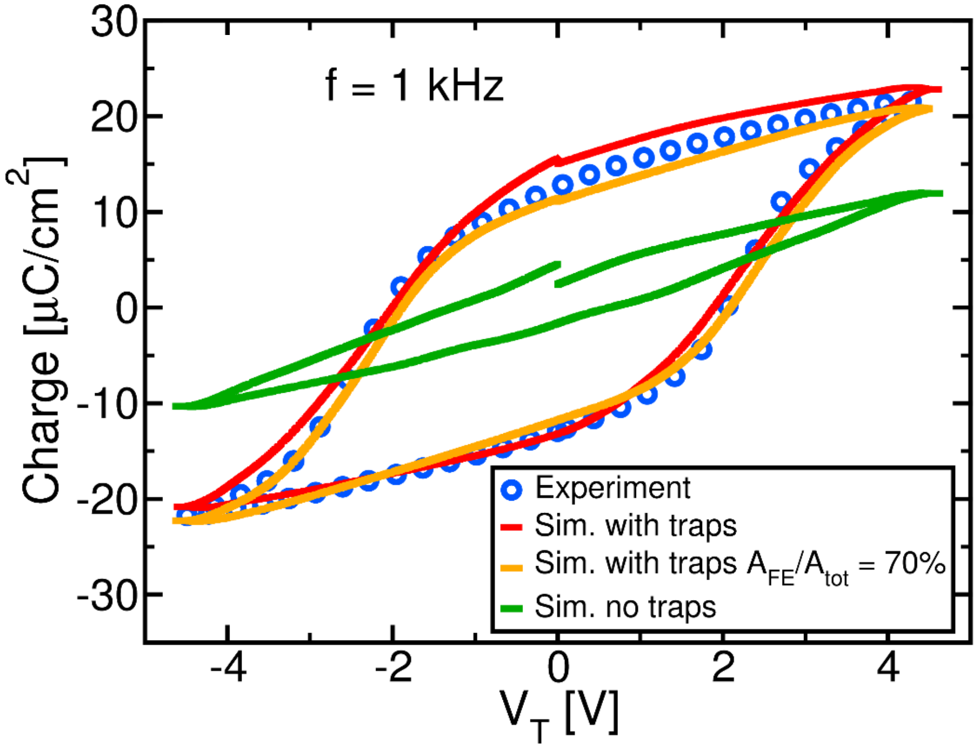
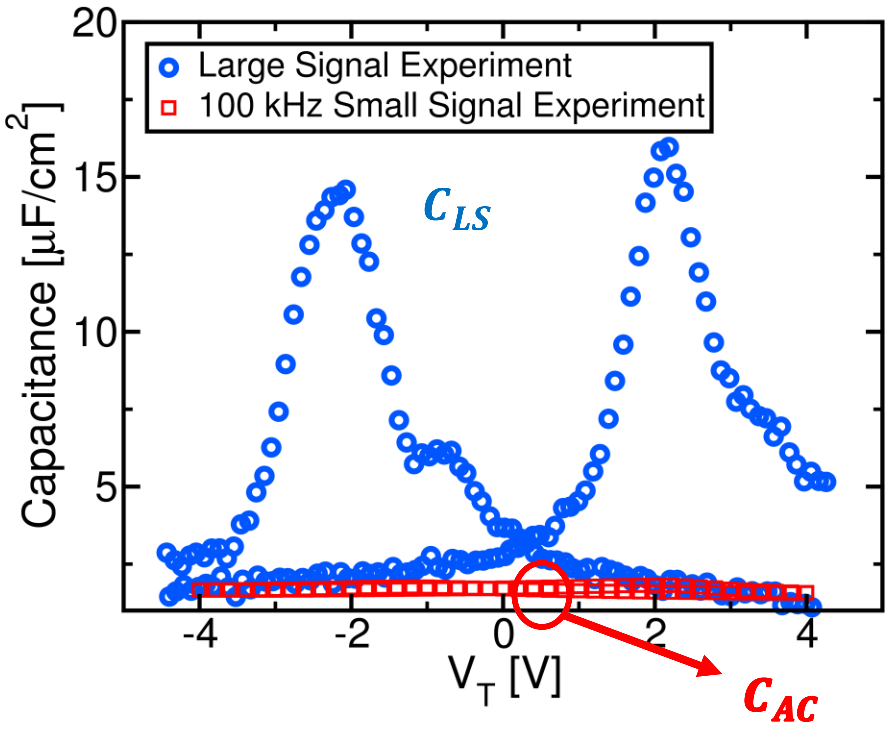
CALIBRATION ON LARGE-SIGNAL P-V

- **Simulations with traps** show **good agreement** with **large-signal P-V** characteristic
- **Simulated P-V** characteristic **without trapping** is much **more tilted and narrower** [1]
- **Agreement** is **maintained** even **if we consider that only a fraction of the HZO layer is ferroelectric FE area** ($A_{FE}/A_{tot}<1$)



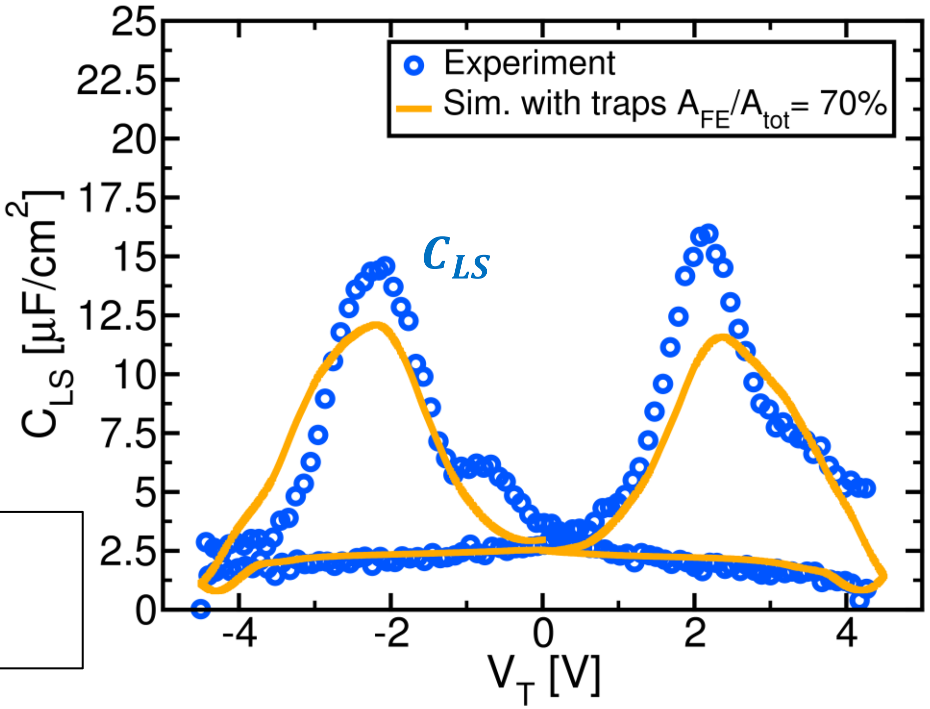
[1] HW Park *et al.*, Nanoscale 2021

LARGE-SIGNAL C-V



f = 1 kHz

$$C_{LS} = I_{FTJ}\left[\frac{dV}{dt}\right]^{-1}$$



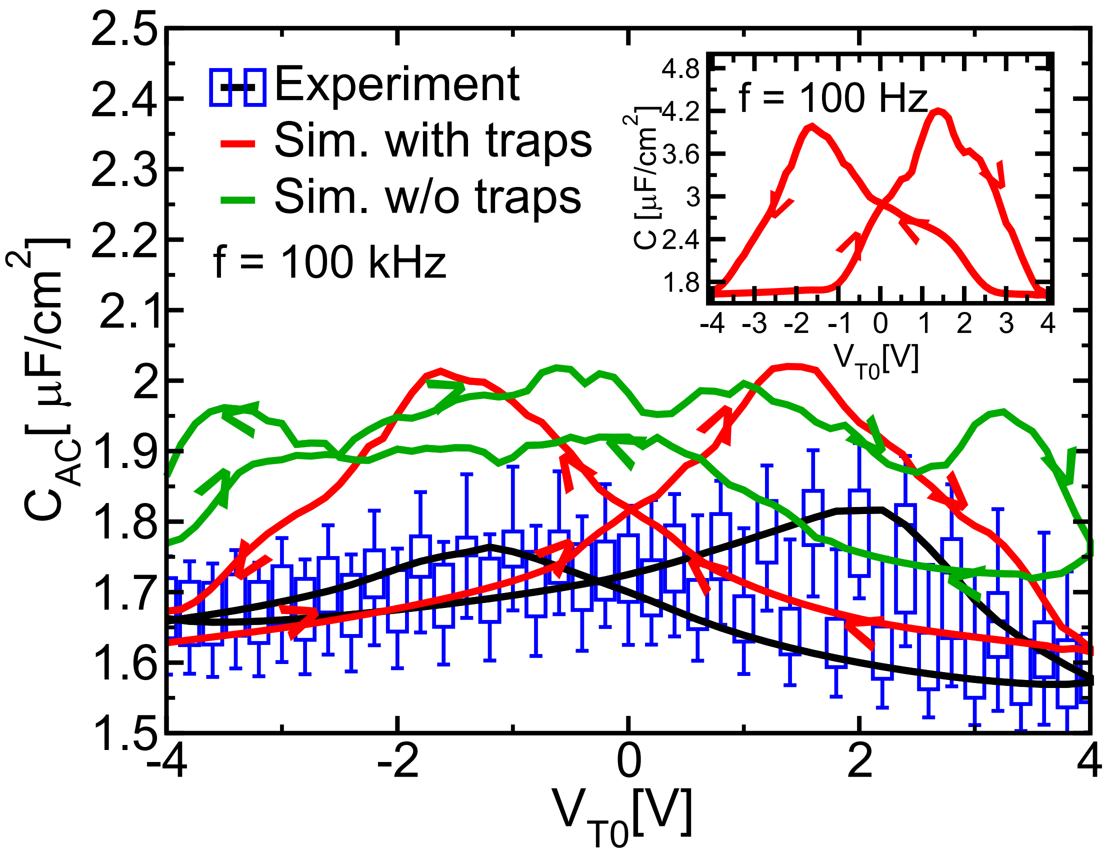
- **Large-signal *equivalent capacitance* (C_{LS})**
- **Agreement** between **experiments** and **simulations** is **good**
- **Large signal capacitance** is much **larger than small-signal capacitance (C_{AC})**

AC SIMULATIONS: HIGH & LOW FREQUENCY

- **Simulations without traps** report a **significant discrepancy** with **experimental data**

- **Simulated AC capacitance C_{AC}** at **high f** shows **qualitative agreement** with experiments

- At **low f** the **agreement** is **worse** due to **traps effect** (inset)



SUMMARY

- **Ferroelectric Tunnel Junctions** are a **promising hardware candidate** to enable **Neuromorphic Computing**
- The **dielectric layer** present in MFDM stacks plays a **key role** for **charge trapping** and **depolarization field**
- **Charge trapping** is **necessary** to explain **experimental behaviour** of **FTJs** in large and small signal regimes

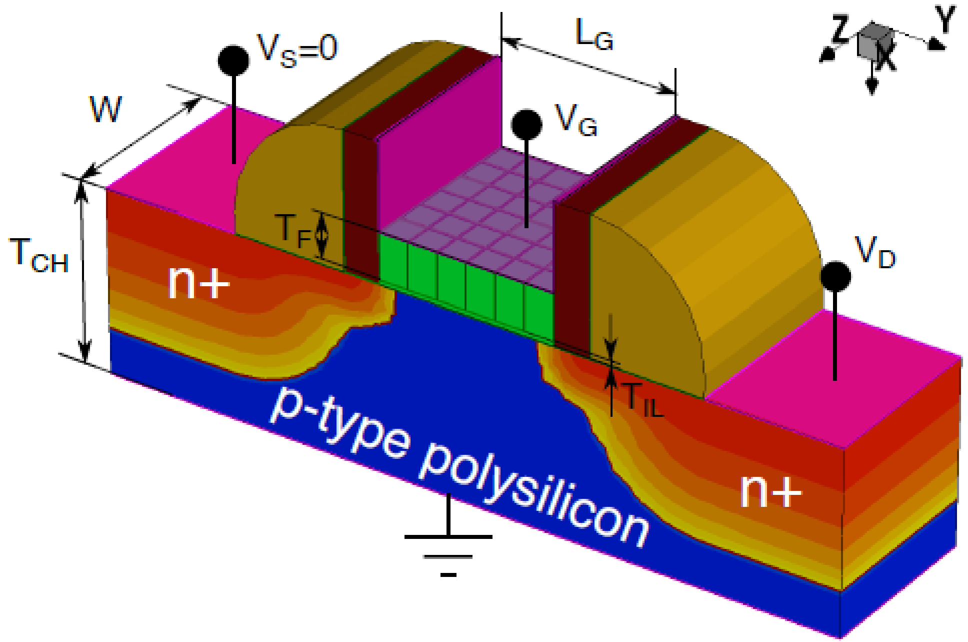
Funded by the European Union

OUTLINE

- ✓ Ferroelectric materials
- ✓ Ferroelectric Tunnel Junctions (FTJs)
  - ✓ Large signal operation
  - ✓ Small signal operation
- Ferroelectric Field Effect Transistors (FeFETs)
- Conclusions

Funded by the European Union

MODELLING FRAMEWORK



- **Ferroelectric Transistors (FeFETs):** ferroelectric layer integrated in the gate stack of a transistor above the dielectric
- **Non-destructive** readout of the **ferroelectric polarization** by probing the **source to drain current**

- **Link between potential and charge is non-linear in the semiconductor** → superposition of effects can’t be used as in MFIM FTJs

TCAD solver

TCAD SIMULATIONS

In TCAD solvers, usually, two models are available to simulate the ferroelectric materials behaviour:

- **Preisach model**
- **Landau-Ginzburg-Devonshire (LGD) theory and Landau-Khalatnikov (LK) model**

TCAD tool Sentaurus-Device package [1] couples:

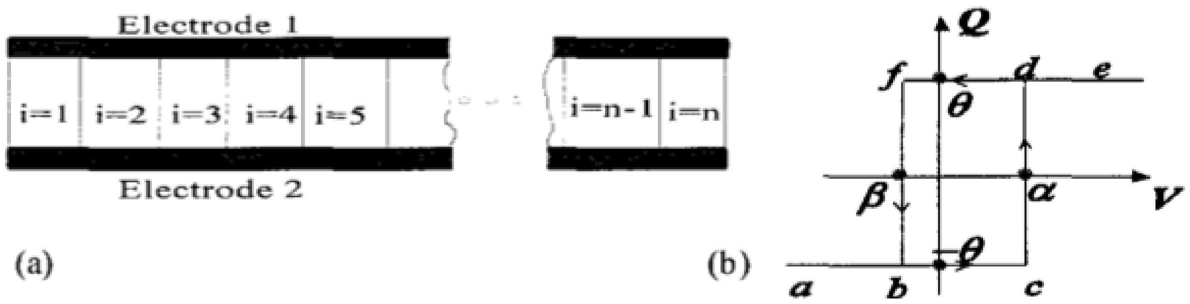
Preisach/LGD-LK+Poisson Equation+Drift Diffusion

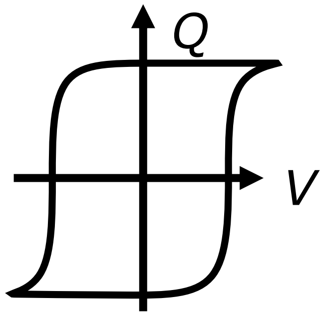
[1] Synopsys Inc., Sentaurus Device User Guide, V-2023.12

TCAD SIMULATIONS

Preisach model

- Phenomenological model of ferroelectric hysteresis
- Describe a macroscopic system that can be represented as a superposition of simple hysteresis units (a), and each unit has a rectangular hysteresis loop (b): switching charge 0, and the coercive voltages a and B, for each unit can be different





B. Jiang *et al*., Computationally Efficient Ferroelectric Capacitor Model for Circuit Simulation, 1997 Symposium on VLSl Technology Digest of Technical Papers , p.141

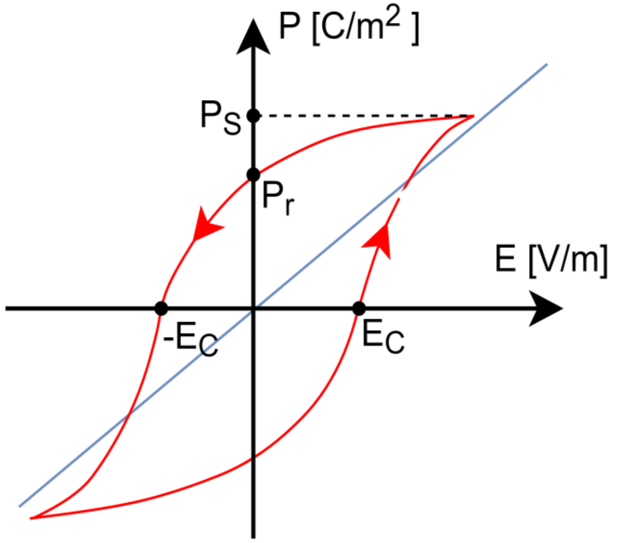
Preisach model

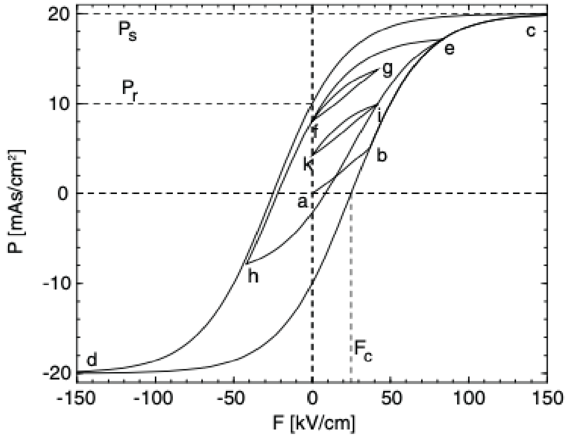
- Relation between electric field E_{FE} and spontaneous polarization P described with hyperbolic tangent:

$$P(E_{FE}) = m \cdot P_S \cdot \tanh[w \cdot (E_{FE} \pm E_C)] + P_{off}$$

$$w = \frac{1}{2E_C} \ln \frac{P_S+P_r}{P_S-P_r}$$

- The model also correctly accounts for the history dependence of ferroelectric capacitor (memorizing turning points) and can simulate minor loops nesting (thanks to m and P_{off} parameters) [1]





[1] Synopsys Inc., Sentaurus Device User Guide, V-2023.12

Landau-Ginzburg-Devonshire (LGD) theory and Landau-Khalatnikov (LK) model

- Ferroelectric behavior is described in the continuum space [1]

Total potential energy of the system

$$U = \int_{vol.} \alpha_i \boldsymbol{P}_i{}^2 + \beta_i \boldsymbol{P}_i{}^4 + \gamma_i \boldsymbol{P}_i{}^6 +$$

Landau Free energy

$$+\nabla_i \psi \boldsymbol{P}_i - \frac{\varepsilon_0}{2} |\nabla \psi|^2 + \psi \rho_S$$

Electrostatic energy

$$+\frac{k_i}{2} |\nabla \boldsymbol{P}_i|^2 \; dx_i$$

Domain wall energy

Kinetic equation
(Landau–Khalatnikov equation: LKE)

$$\rho \frac{\partial P_i}{\partial t} = -\frac{\delta U}{\delta P_i}$$

P: spontaneous polarization
ρ: ferroelectric resistivity [Ω·m]

FERROELECTRIC WITH BUILT-IN DOMAINS

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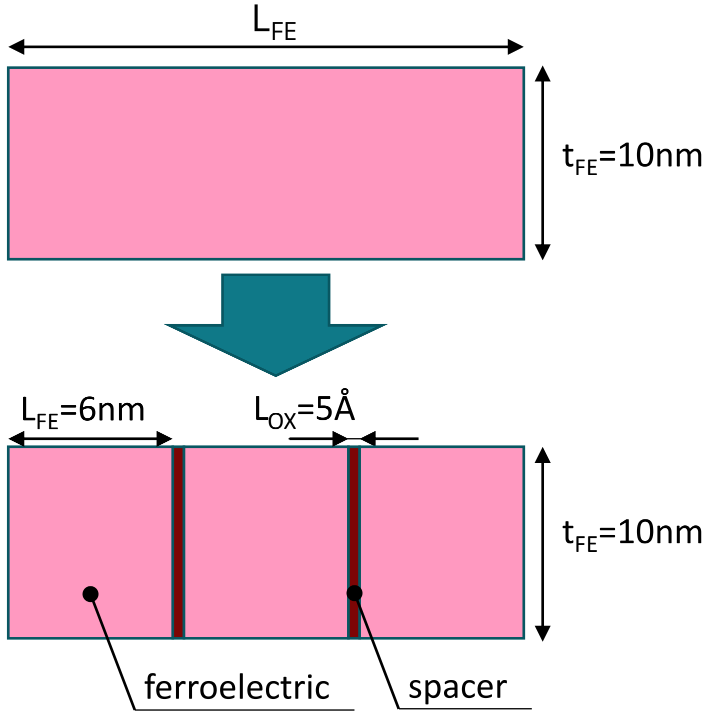
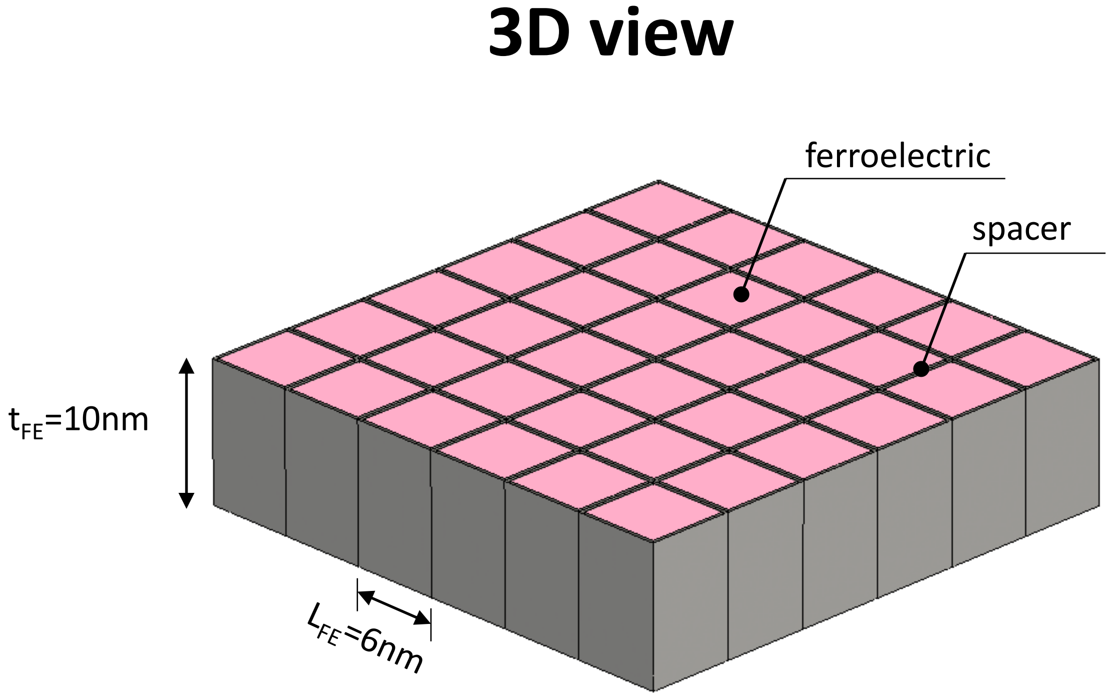


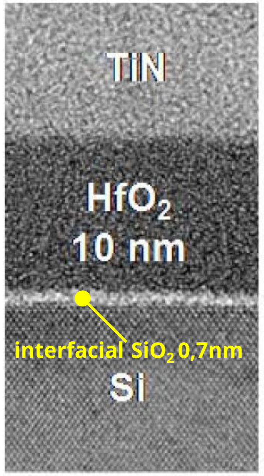


- As seen before, inside each grain the ferroelectric polarization is constant
  - relaxed contraints on the real space discretization
- Due to the presence of the interlayer oxide, the coupling between different grains is given by the electrostatic energy term only

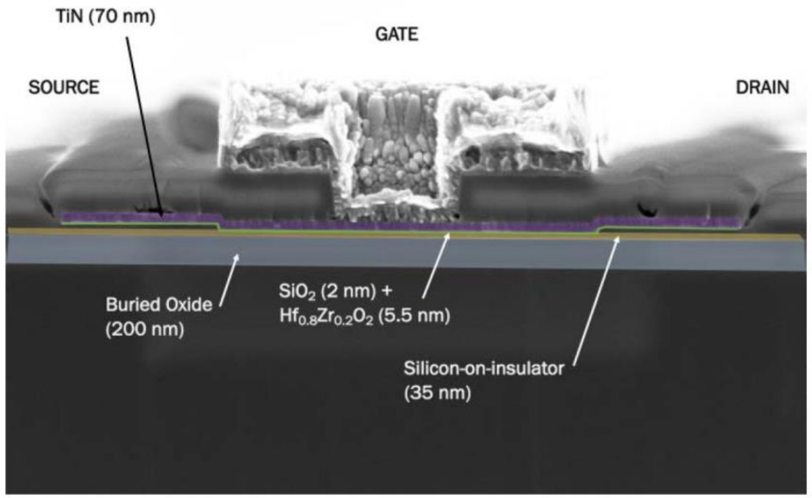
INTERFACIAL SiO_2 OXIDE LAYER (IL)

FIXIT

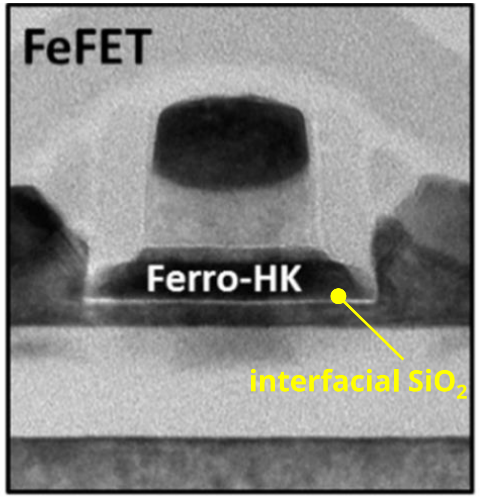
- In between the ferroelectric material and the semiconductor channel there is a thin SiO_2 interfacial layer that must be included in simulations



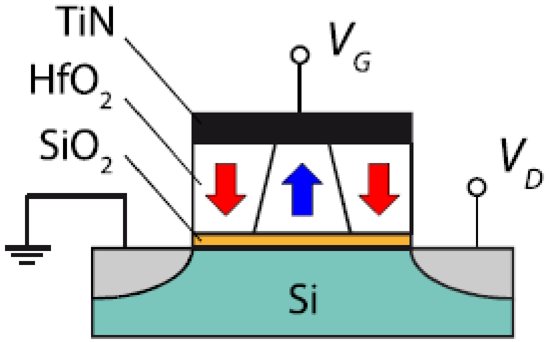
Toprasertpong et al., Proc. IEEE, 2019



Chatterjee et al., IEEE EDL, vol.38, n.10, 2017



Dunkel et al., Proc. IEEE, 2017



Mulaosmanovic et al., IEEE TED, vol. 68, n.9, 2021

The introduction of a dielectric IL plays an important role in the operation and in the modelling of the device

INFLUENCE OF TRAPS

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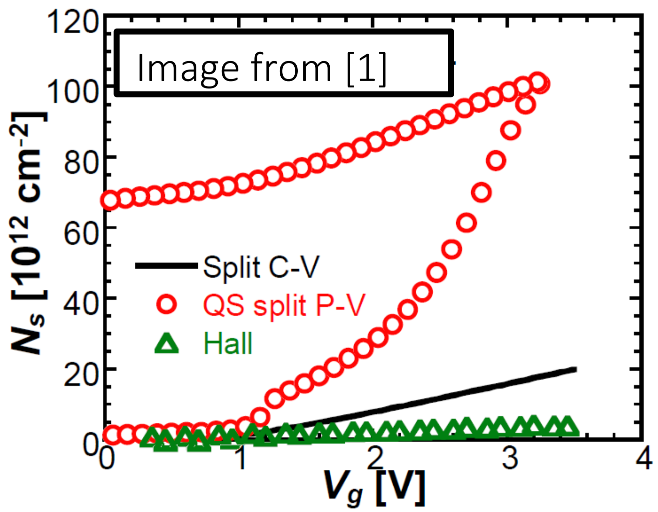

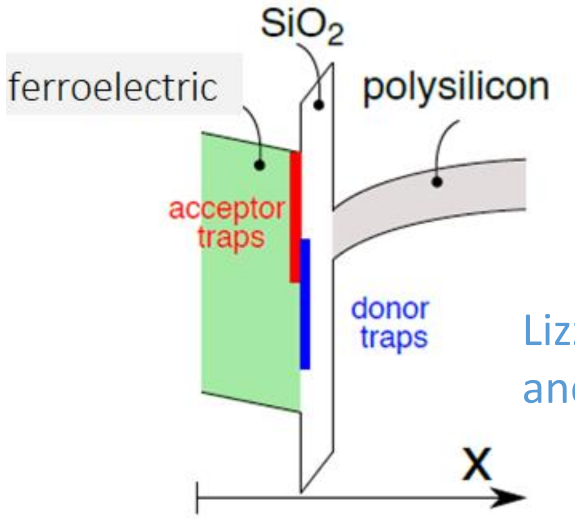

Lizzit *et al.*, ESSDERC 2021 and ESSDERC 2022

- Experimental results based on Hall and split-CV measurements suggest that most of the trapped charge compensating the ferroelectric polarization is located in the IL (or at the FE-DE interface) [1].

- We introduce interfacial traps

$$D_{it,acc} = 8 \times 10^{13}\mathrm{cm}^{-2}\mathrm{eV}^{-1}$$
$$D_{it,don} = 1 \times 10^{14}\mathrm{cm}^{-2}\mathrm{eV}^{-1}$$

- Traps exchange carriers with the silicon channel via tunneling (Nonlocal Tunneling [2]).

[1] K. Toprasertpong *et al.*, Proceed. of IEDM 2019.
[2] Synopsys Inc., Sentaurus Device User Guide, Q-2019.12.

ANALYSIS OF EXPERIMENTAL FEFETS (1/2)

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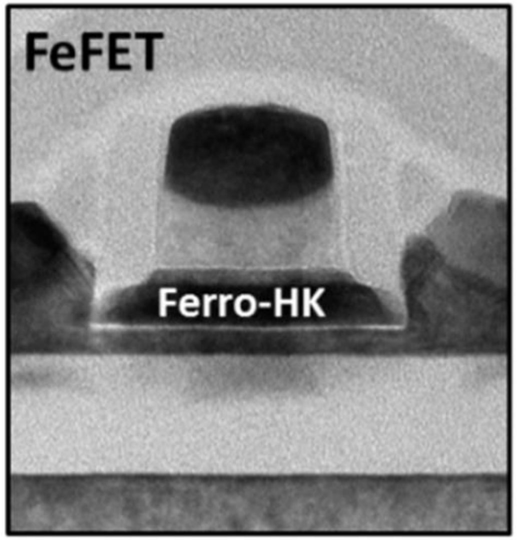
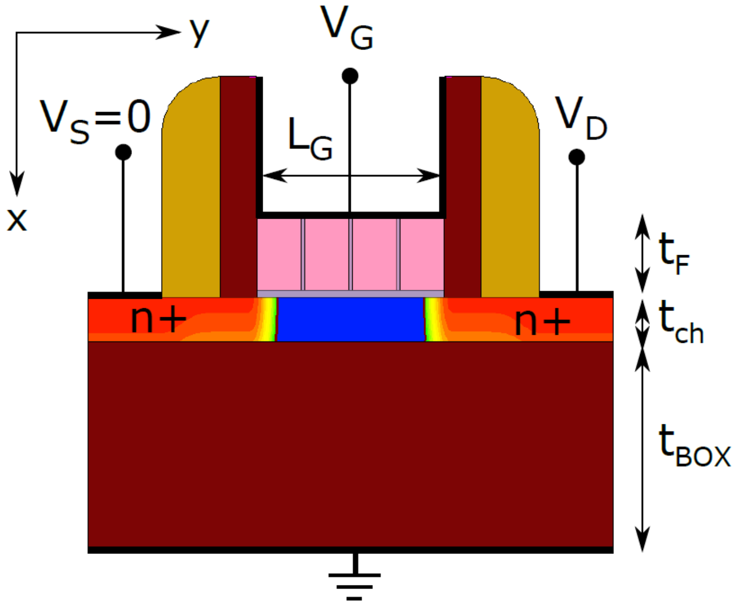


SIMULATED DEVICE



SIMULATED DEVICE

T_{Fe}=10 nm
T_{ch}=6 nm
L_G=24 nm
$T_{IL,SiO2}$ =1 nm

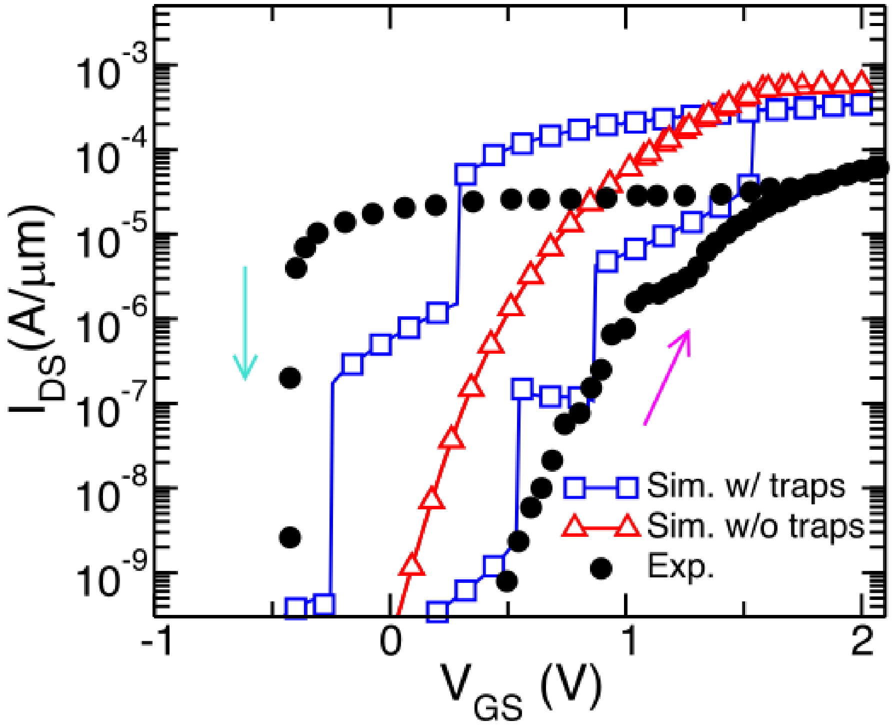
- Fully Depleted SOI experimentally demonstrated in [1][2].
- Simulated FeFET (**2D simulation**) with 4 ferroelectric grains of 6 nm length [3].

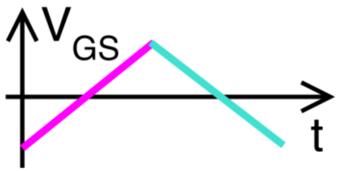
[1] H. Mulaosmanovic *et al.*, IEEE Electron Device Letters, pp.294-297, 2020.
[2] Dünkel *et al.*, IEDM, 2017.
[3] D. Lizzit *et al.*, ESSDERC, 2021.

ANALYSIS OF EXPERIMENTAL FEFETS (2/2)

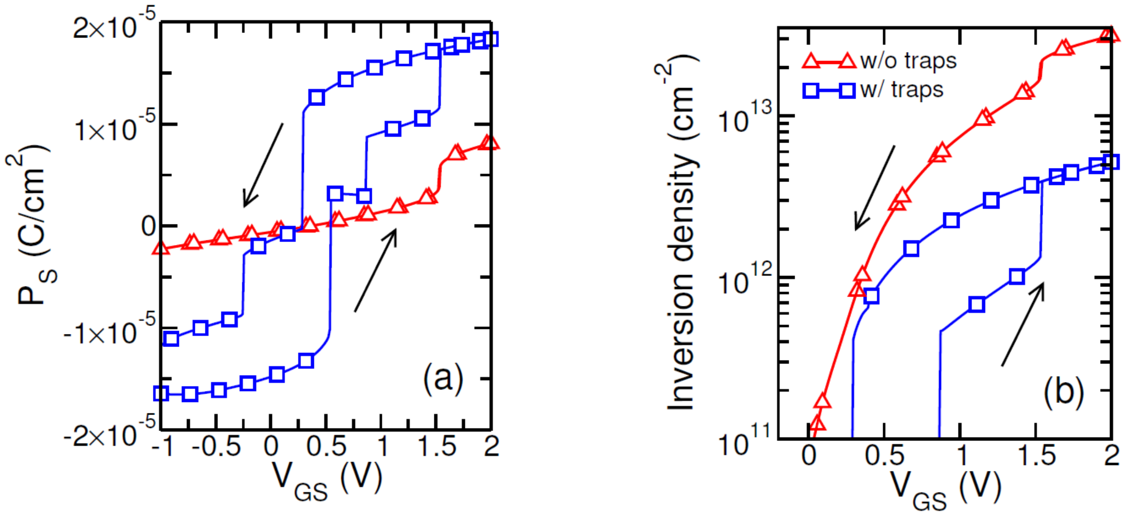
FIXIT

D. Lizzit *et al.*, ESSDERC, 2021





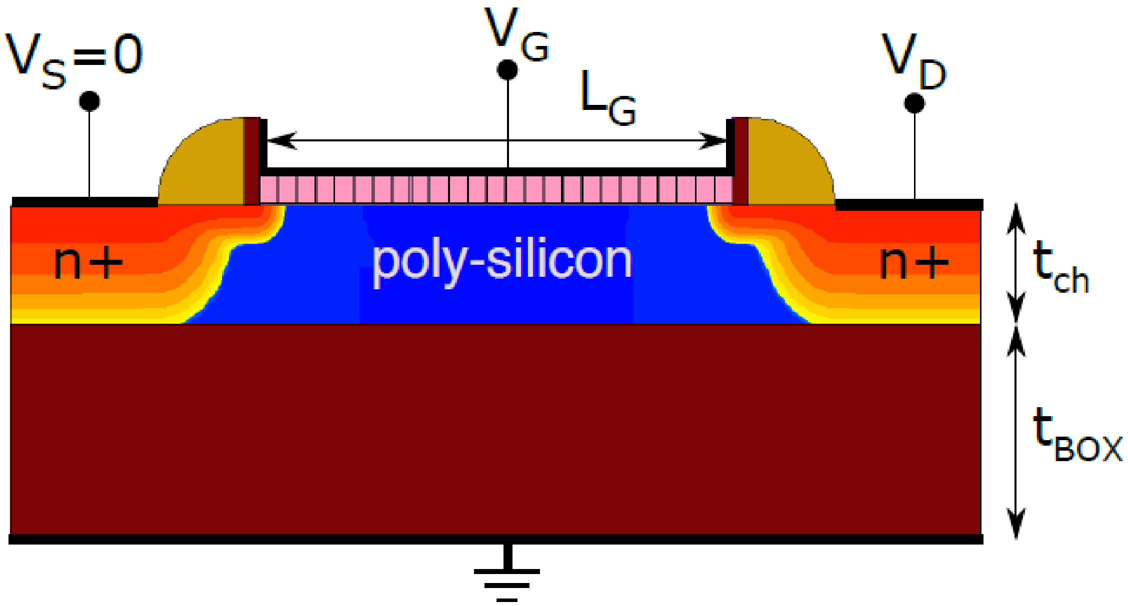
Experimental results obtained with forward and backward quasi-static V_{GS} sweep

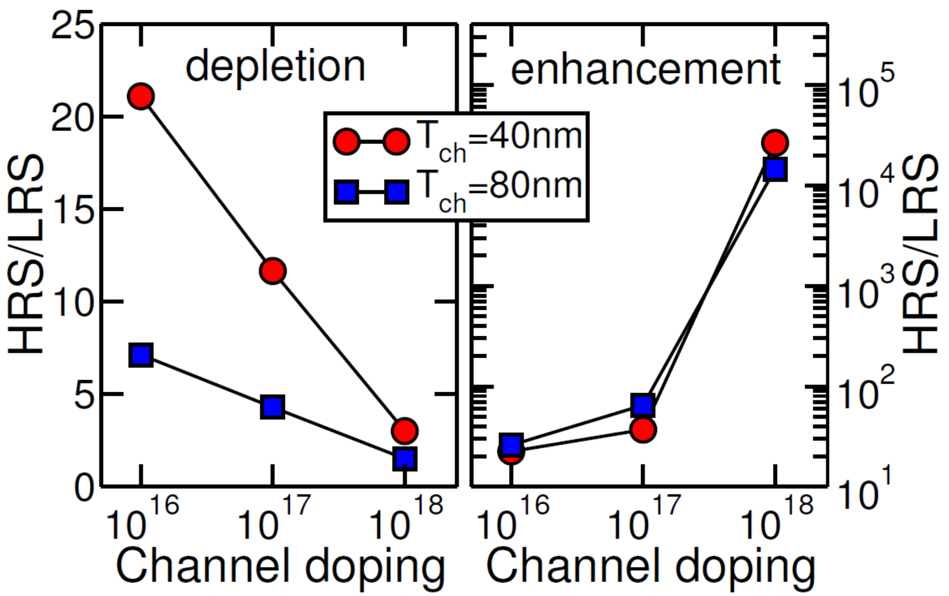


- The inclusion of traps in simulations strongly enhances the hysteresis of both the I_{DS}-V_{GS} and the P-V_{GS} curves.
- With traps the N_{INV} values are consistent with exper. estimates in silicon FeFETs [K. Toprasertpong et al., Proceed. of IEDM 2019]

DESIGN OF BEOL COMPATIBLE FEFETS (2D SIM.)

FIXIT



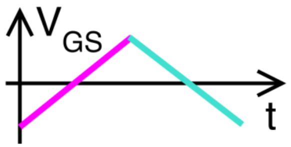


- HRS: high resistive state
- LRS: low resistive state

Evaluated at fixed V_{DS} and VGS

T_{Fe}=10 nm
T_{ch} =40/80 nm
L_G =150 nm
T_{IL} =1 nm

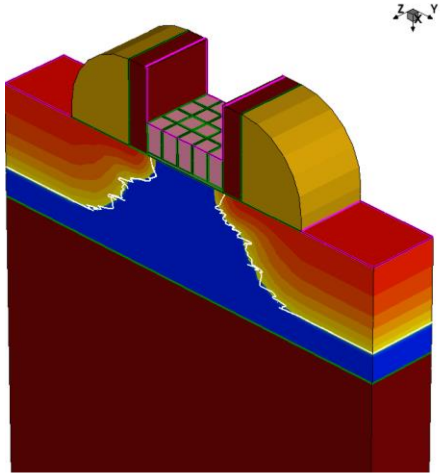
quasi-static voltage ramps

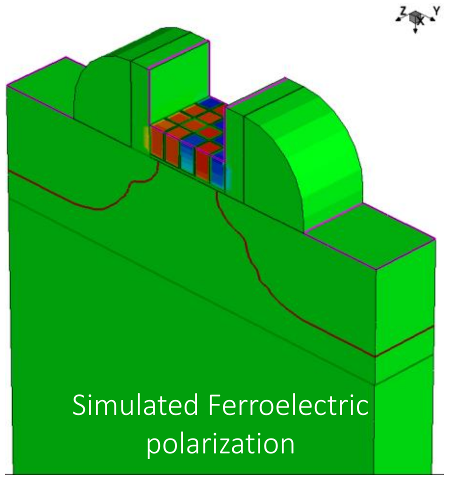


- For depletion-mode the HRS/LRS ratio decreases with T_{ch}
  - the effective channel thickness of conductive channel increases with T_{ch}.
- Enhancement-mode is less sensitive to T_{ch} because I_{DS} is carried by the inversion layer.

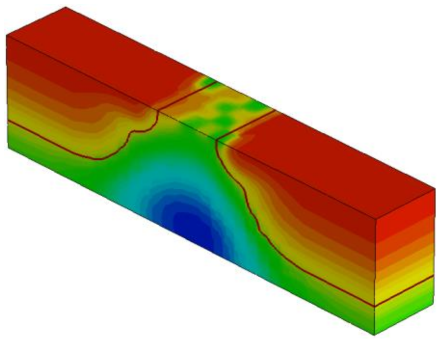
SOME REMARKS (1/2): 3D VS 2D SIMULATIONS

FIXIT

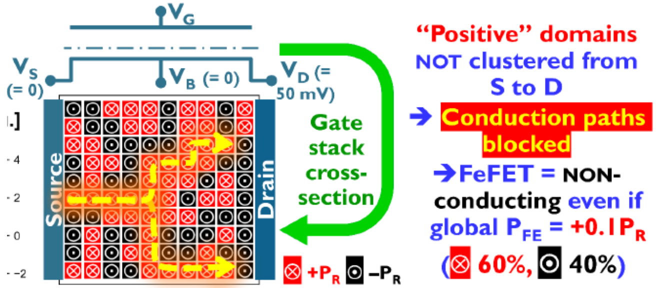




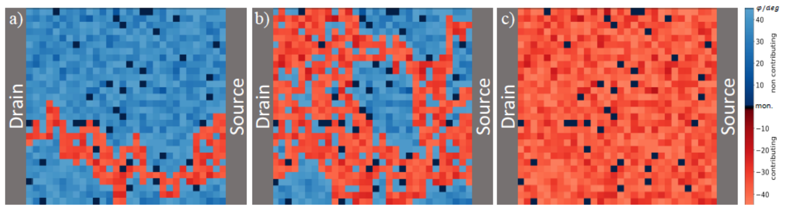
Simulated Ferroelectric polarization



Simulated electron density in the poly-Si channel



Xiang et al., Proceedings of IEDM 2020

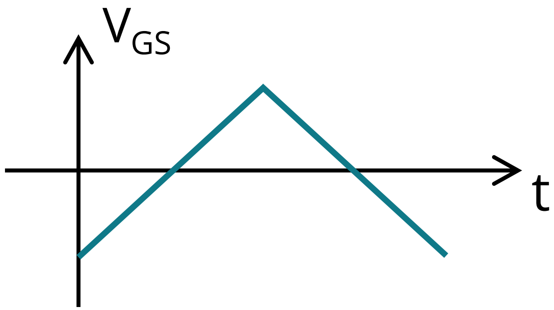


Müller et al., Proceedings of IEDM 2020

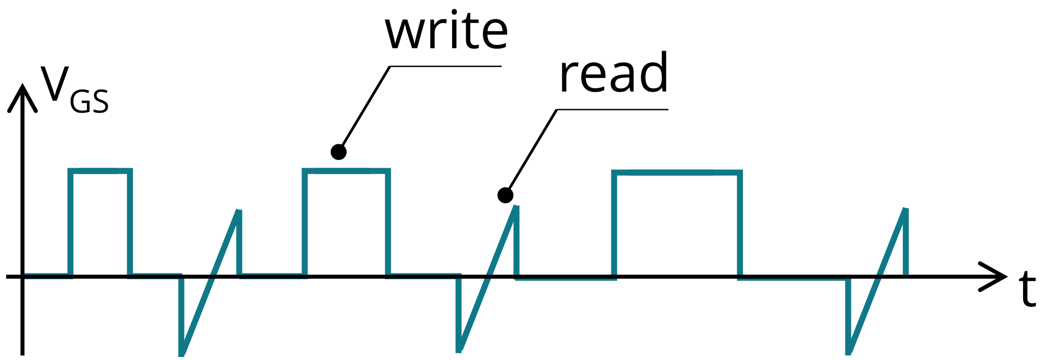
- Need for 3D FeFET simulations:
- to account for percolative conductive paths.
- 3D simulations wash abrubt steps in the I_{DS} curves observed in 2D simulations
- 3D simulations appear indispensable in order to investigate the multi-level operation of FeFETs

SOME REMARKS (2/2): GATE BIASING SCHEME

FIXIT



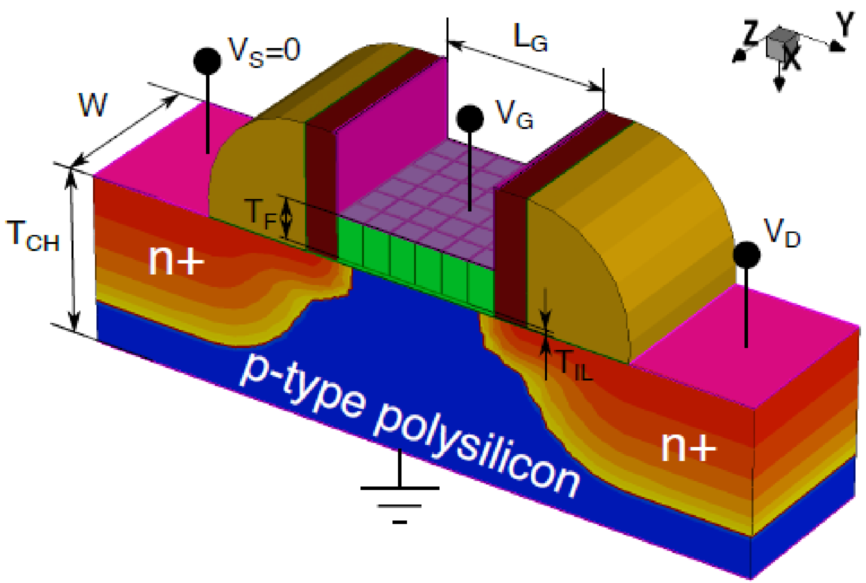
quasi-static
voltage ramps



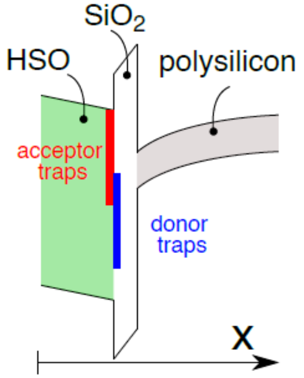
Pulsed

- To investigate how many resistive states we can accommodate in the device, we need a pulsed gate voltage biasing scheme

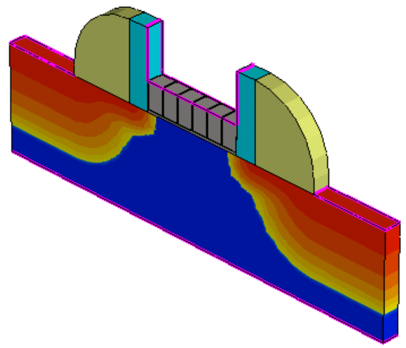
2D VERSUS 3D SIMULATIONS



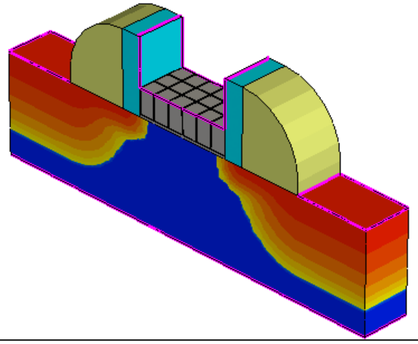
D.Lizzit *et al.*, IEEE ESSDERC 2022



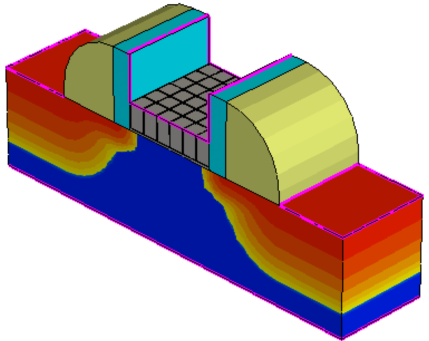
- Donor trap density
  - $D_{IT,donor} = 1 \times 10^{14}\ eV^{-1}cm^{-2}$
- Acceptor trap density
  - $D_{IT,acceptor} = 8 \times 10^{13}\ eV^{-1}cm^{-2}$



quasi 2D FeFET (6x1 domains)



3D FeFET (6x3 domains)



3D FeFET (6x6 domains)

SETTING MULTIPLE CONDUCTANCE STATES (1)

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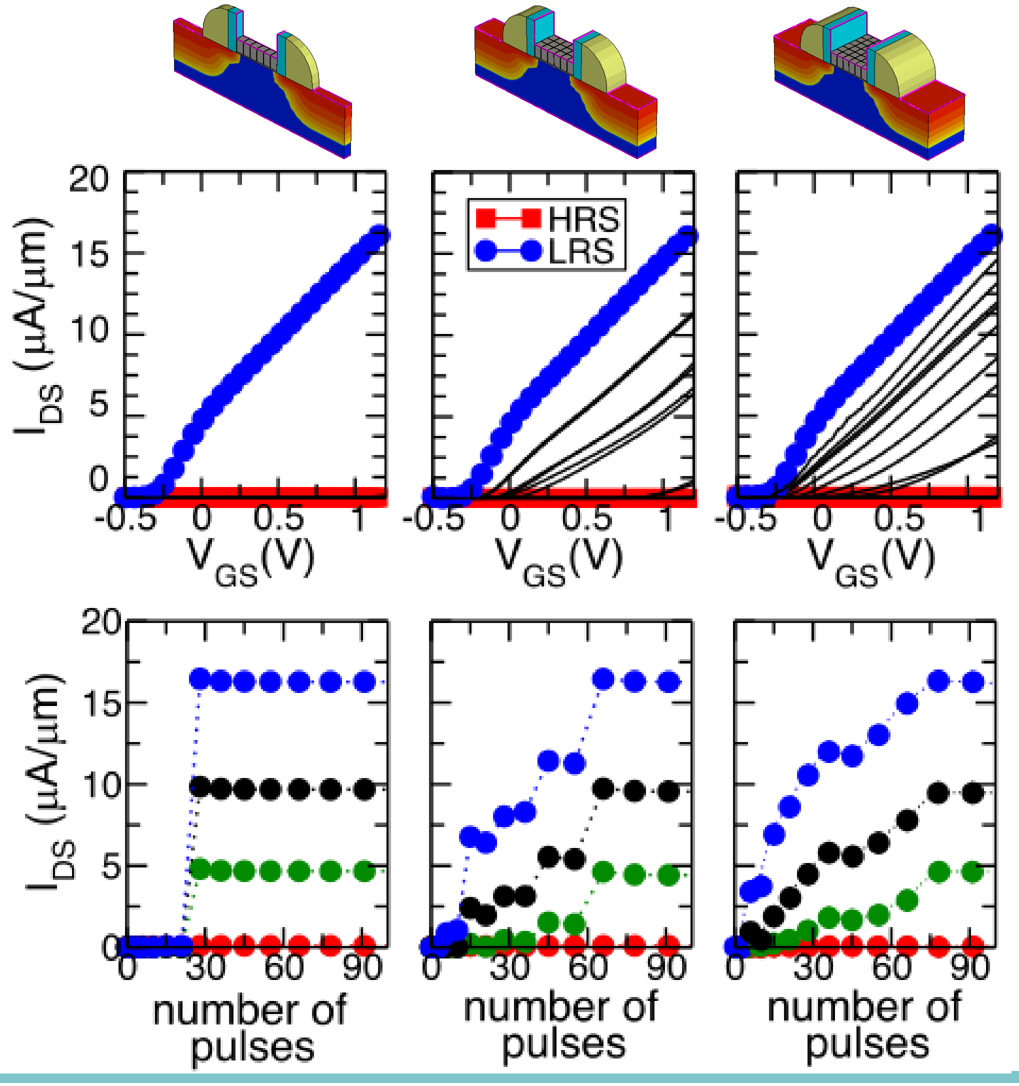
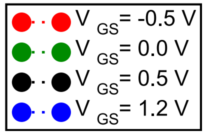
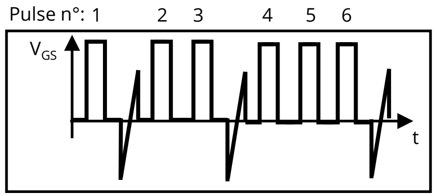
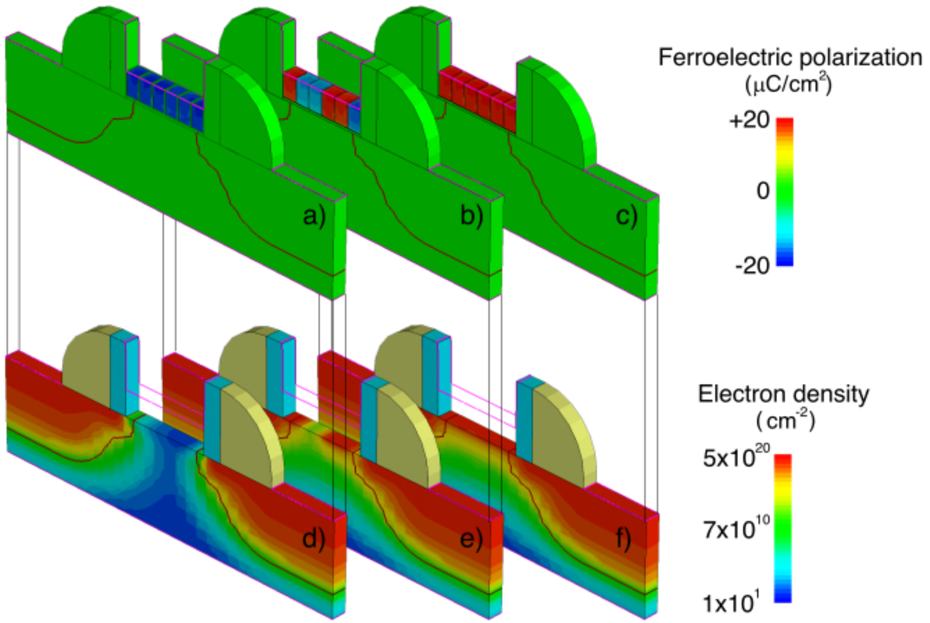




- The 6×1 FeFET exhibits a digital behavior → because any domain with negative polarization precludes the formation of a source to drain conduction path.

D. Lizzit *et al.*, IEEE ESSDERC 2022





SETTING MULTIPLE CONDUCTANCE STATES (2)

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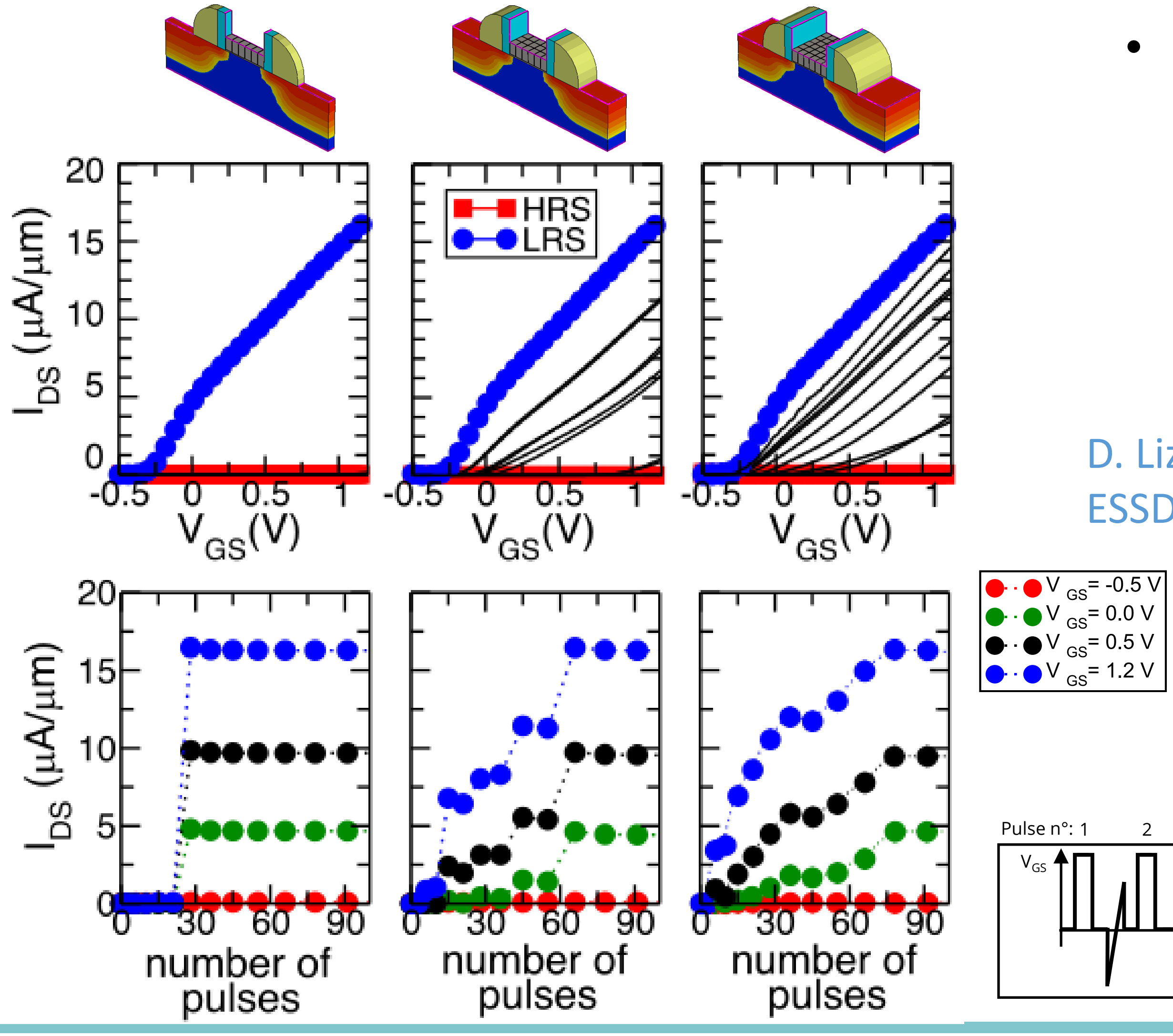
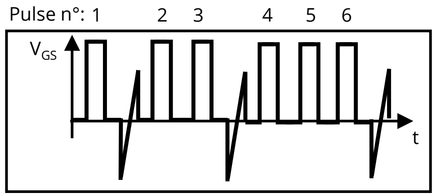
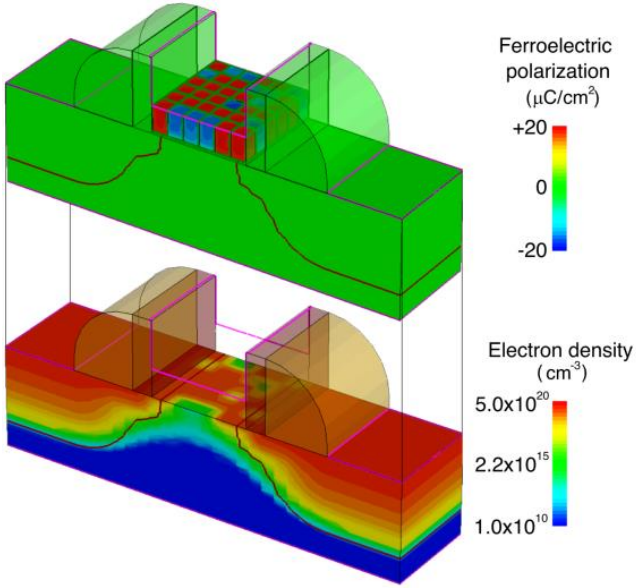
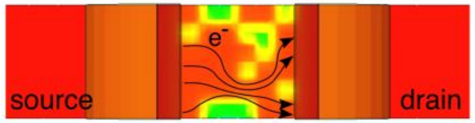


- FeFETs having 3 and 6 domains along the device width exhibit several intermediate V_{th} values or, equivalently, intermediate current levels in the readout mode.

D. Lizzit *et al.*, IEEE ESSDERC 2022







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SUMMARY

FIXIT

- **FeFET architecture** allows to:
  - **decouple** the **readout** and **write** operations
  - obtain **read currents** that can be quite **higher than in FTJs**
- Accumulative switching behaviour and **percolation current paths** offer a **powerful pathway** for a **multi-level memristor operation**
- **Accumulative switching** depends on:
  - **density of traps** and their **emission** and **capture** rates
  - the **features** of the V_{GS} **waveforms**, including the **delay times** between the groups of **potentiation pulses**

OUTLINE

- ✓ Ferroelectric materials
- ✓ Ferroelectric Tunnel Junctions (FTJs)
  - ✓ Large signal operation
  - ✓ Small signal operation
- ✓ Ferroelectric Field Effect Transistors (FeFETs)
- Conclusions

CONCLUSIONS

- **Ferroelectric-based devices** are **promising candidates** for **low-power neuromorphic computing applications**
- Understanding and modelling their operation is of **paramount importance**
- **Simulations** are essential to gain **insight** into the **behavior** and **design** of these **devices**