Negative Capacitance Ferroelectric Devices for Radiation Detection Applications

A. Morozzi$^{(a,*)}$, A. Rossi$^{(b,a)}$ and F. Moscatelli$^{(c,a)}$

(a) INFN of Perugia, via Pascoli 1, 06123 Perugia, Italy.
(b) Department of Physics and Geology, University of Perugia, Perugia, Italy
(c) Istituto Officina dei Materiali (IOM) CNR, Perugia, Italy

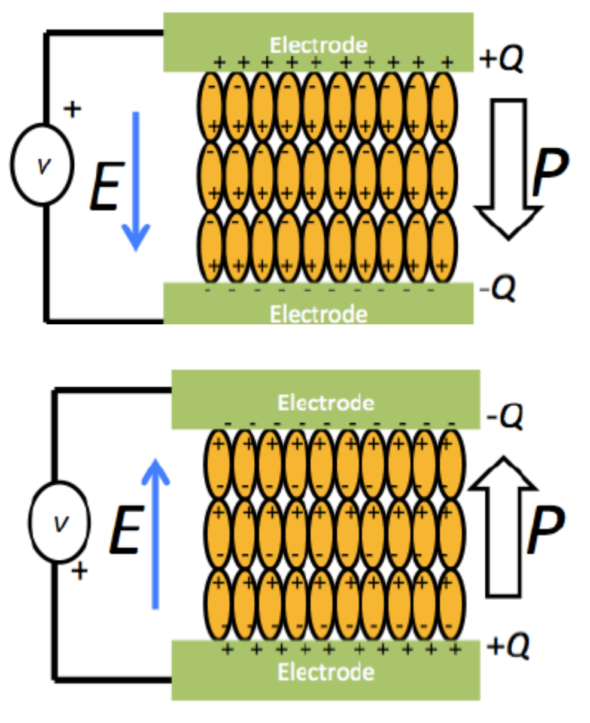
* arianna.morozzi@pg.infn.it

The HiEnD Project

- The **HiEnD project** intends to analyze and design high-energy efficient electronic devices based on innovative ferroelectric materials by exploiting the Negative Capacitance working principle.
- The potentiality of **Negative Capacitance** devices will be explored thanks to advanced **TCAD** (Technology Computer Aided Design) modeling and measurements, aiming at devising High Energy Physics experiments detection systems for future colliders, featuring **self-amplified, segmented, high granularity sensors**.

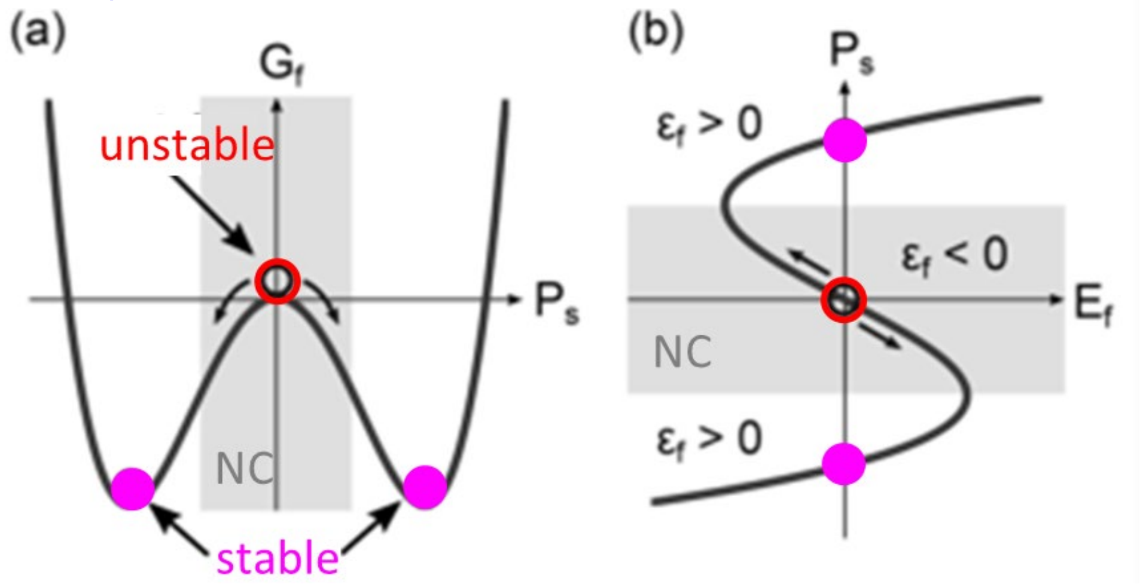
NC Working principle

- FE materials show a polarization P_s even when E_f is not applied.
- In equilibrium, the FE material resides in one of the wells.
- P_s can be reversed by the application of an external $E_f > E_C$.

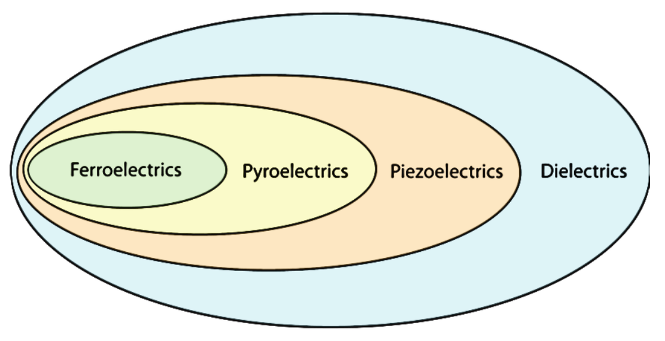


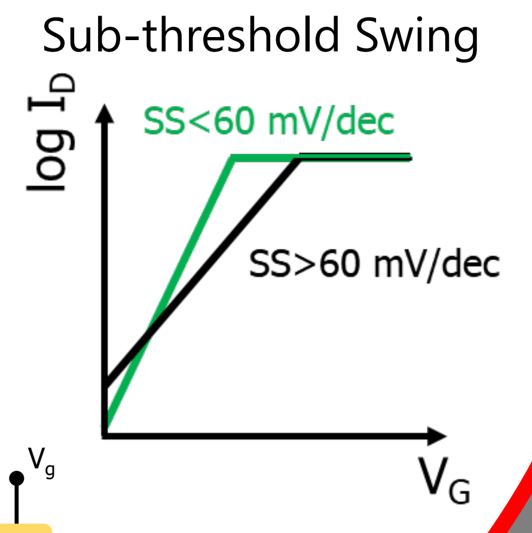
a) FE free energy vs polarization landscape at $E_f = 0$.
b) For low P_s, the relative permittivity ε_f is negative. The state of negative permittivity is thermodynamically unstable [5].

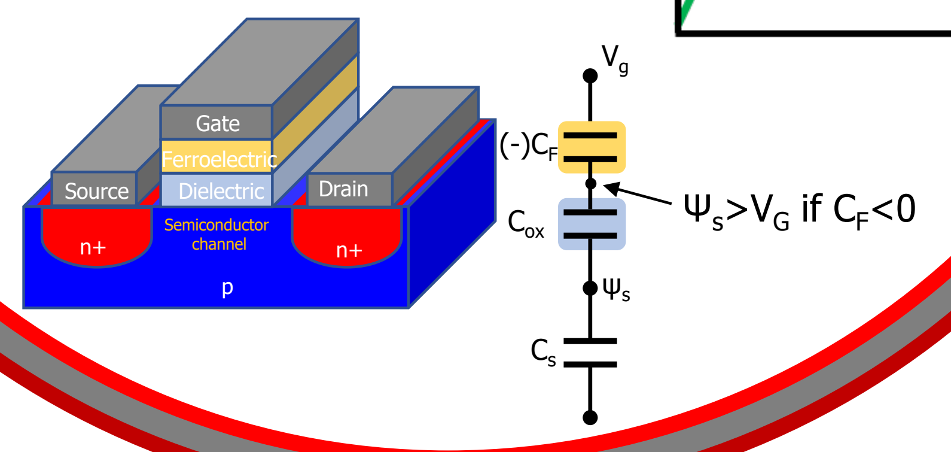
P_s spontaneous polarization E_f Electric Field
E_C coercive field



Negative Capacitance Field Effect Transistors

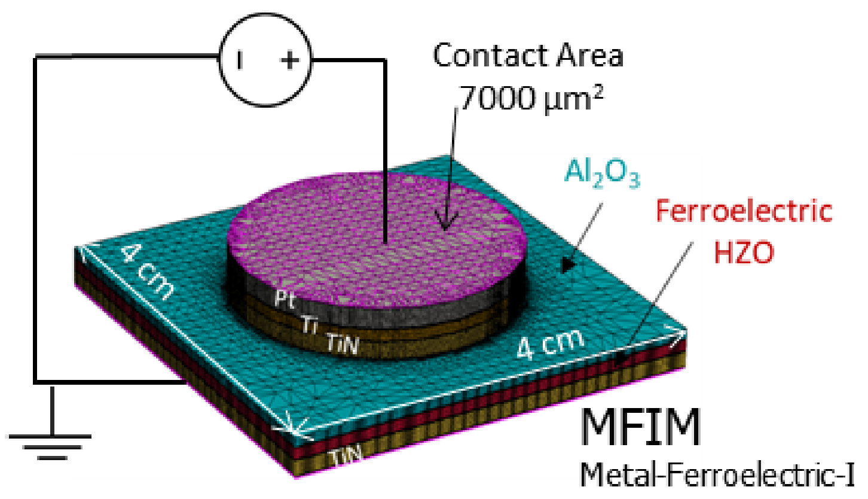


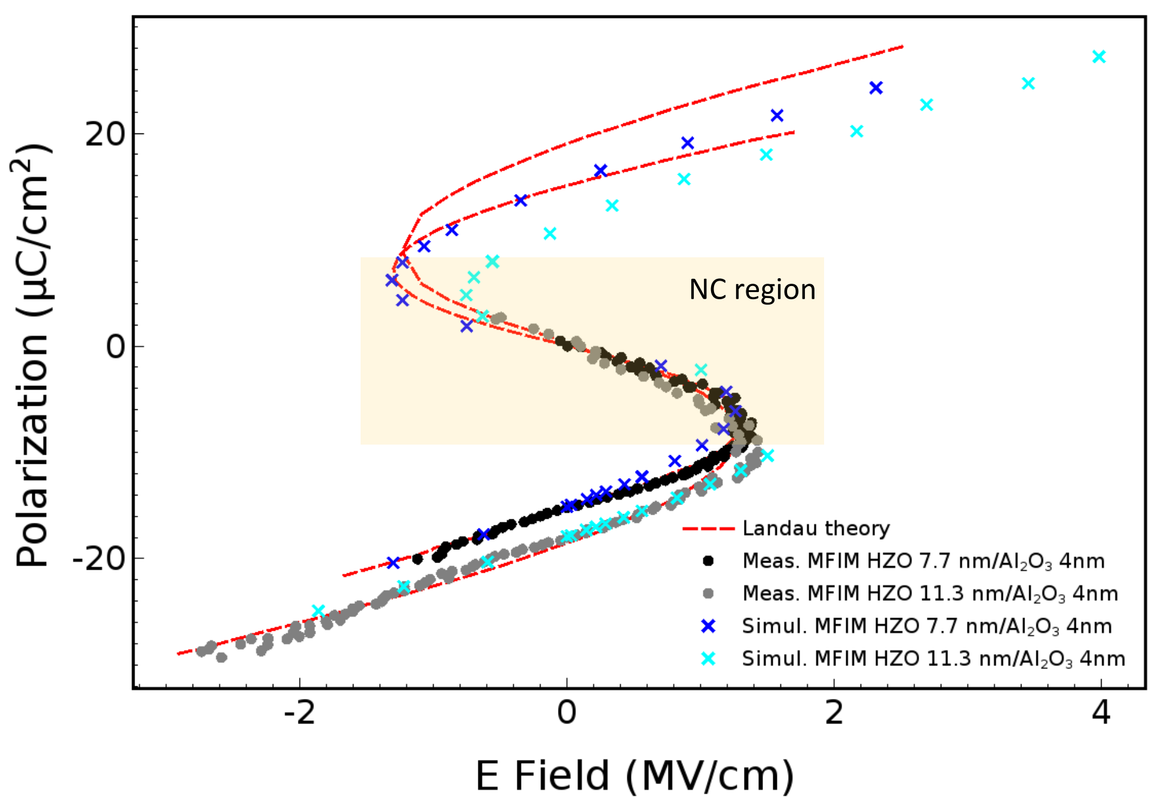


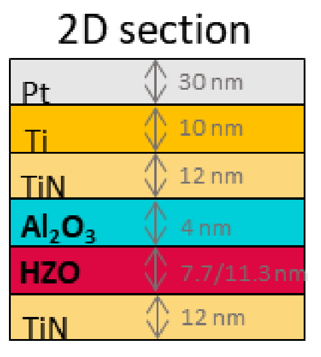


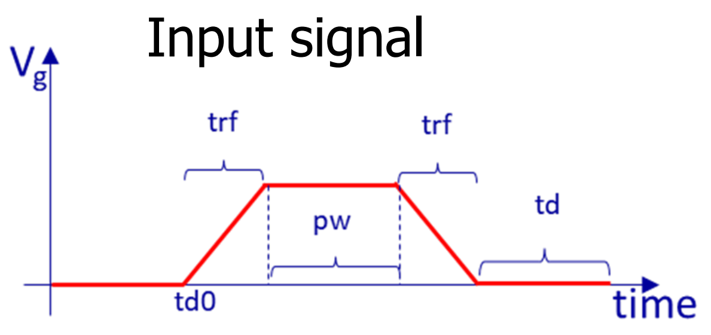
TCAD modeling of MFIM structures

- Development of **ad-hoc material libraries** to describe the properties of the FE material HZO not included within the TCAD environment [1,2].
- **Ginzburg-Landau-Khalatnikov (GLK) equation.** The charge-boost NC phenomenon only takes place after proper capacitance matching between dielectric and ferroelectric materials [3].
- Pulsed Charge-Voltage (Q-V) measurements are necessary to access the ferroelectric NC region during switching by preventing charge injection [4].









The **NC region** corresponds to the **negative slope** of the S-shaped Landau P-E curve.

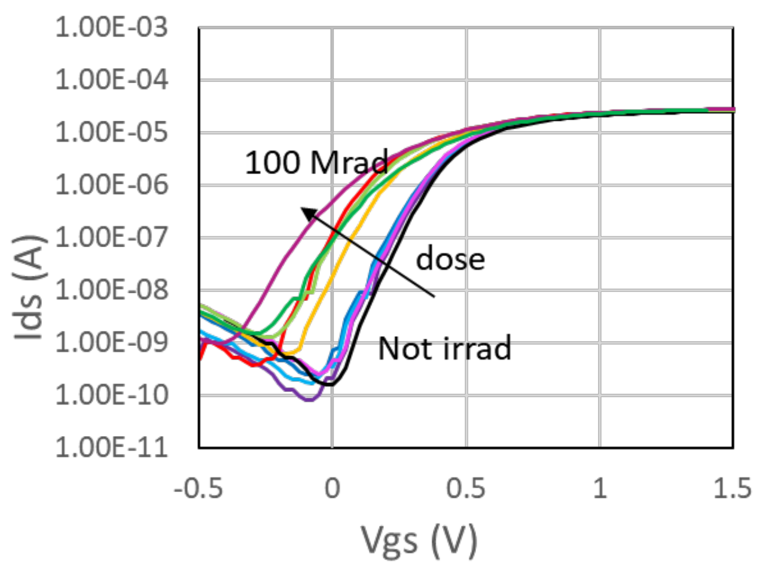
NC-FETs

- A negative capacitor in the gate stack of a FET can provide a step-up voltage, which can potentially overcome the fundamental limit in the subthreshold swing (SS < 60mV/dec), fostering the design of a single-transistor amplification [6].
- An X-ray irradiation and characterization campaign has been set to assess the NC-FET radiation hardness.

Radiation Damage Effects

- Increasing of the SS with the dose
- Increasing of the I_{OFF} → I_{ON}/I_{OFF}
- V_{th} shifts with Xray dose increase
- Saturation of the radiation damage effects at the higher doses

X-ray irradiation campaign at INFN Genova up to 100 Mrad.



Conclusions

- ✓ Use of **the TCAD modeling** approach as a **predictive tool** to optimize the design and the operation of the new generation **NC-FET** devices for the future HEP experiments.
- ✓ The analysis and results obtained for MFIM capacitors can be extended to the study of NC-FETs.
- **Ongoing**: In-depth investigation of radiation damage effects induced by irradiation on innovative NC-FETs.

References

1. A. Morozzi et al 2022 JINST 17 C01048.
2. A. Morozzi et al., Solid-State Electronics, Vol. 194, 108341, 2022.
3. H.Agarwaletal.,IEEE Electron Device Letters,vol.40,no.3, pp.463-466,2019
4. M. Hoffmann et al., 2018 IEEE IEDM, 18-727 (2018).
5. M. Hoffmann et al., APL Mater. 9, 020902 (2021).
6. S. Salahuddin and S. Datta, Nano Letters, vol. 8, no. 2, 2008, pp. 405-410.

Funded by the European Union
NextGenerationEU

Acknowledgment
I would like to express my sincere gratitude to R. Mulargia and E. Robutti for their invaluable assistance with the X-ray irradiation, and for the experimental measurements.