Negative Capacitance Ferroelectric Devices for Radiation Detection Applications

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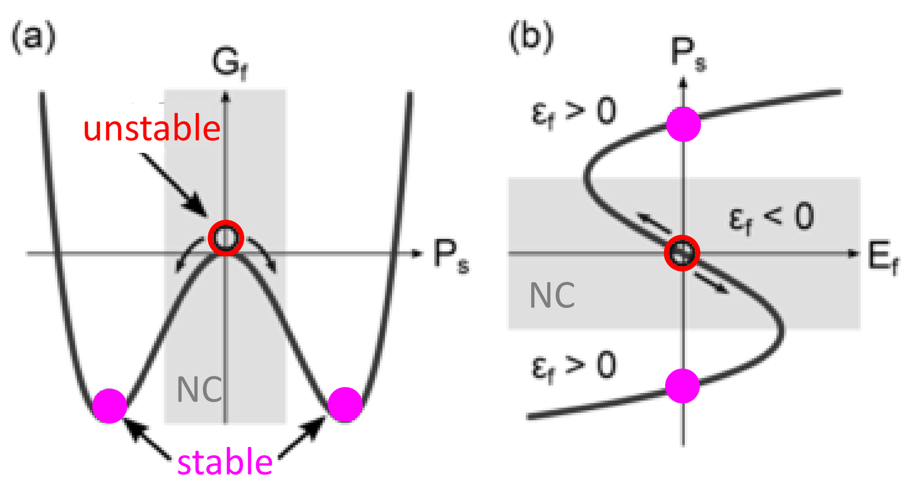
The NegHEP Project

- ✓ The **INFN-CSN5 NegHEP** (**NEG**ative capacitance field effect transistors for the future **H**igh **E**nergy **P**hysics applications) project proposes the use of innovative **Negative Capacitance** (NC) devices in particle detection systems for the next generation High Energy Physics (HEP) experiments at future colliders, featuring **self-amplified**, **segmented**, **high granularity sensors**.
- ✓ 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 amplificator.
- ✓ The NC features of doped HfO_2 in NC-FET [1] is explored with advanced TCAD (Technology Computer Aided Design) modeling.
- ✓ An X-ray irradiation and characterization campaign has been set to assess the NC-FET radiation hardness.

NC Working principle

- ✓ Ferroelectrics materials show a polarization P_s even when E_F is not applied.
- ✓ In equilibrium, the ferroelectric material resides in one of the wells.
- ✓ P_s can be reversed by the application of an external E_f larger than E_C.



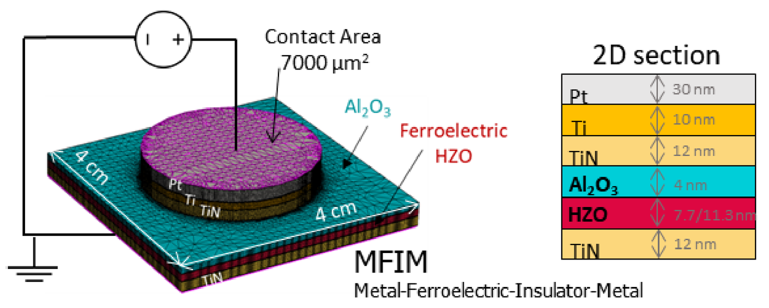
E_f Electric Field, E_C coercive field, P_s spontaneous polarization.

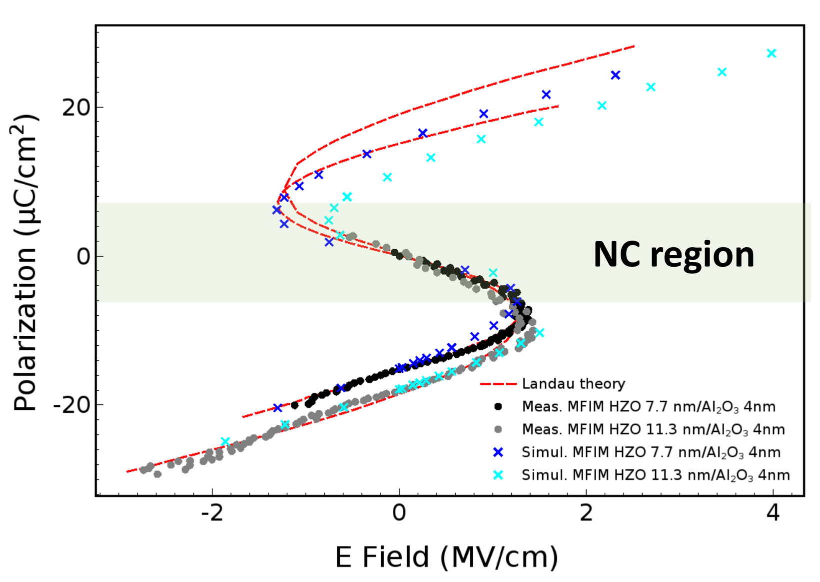
(a) Ferroelectric free energy vs polarization landscape at the zero electric field (E_f = 0).

(b) Polarization vs E_f dependence derived from (a). For low P_s, the relative permittivity ε_f is negative. The state of negative permittivity is thermodynamically unstable [2].

TCAD modeling of MFIM structures

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

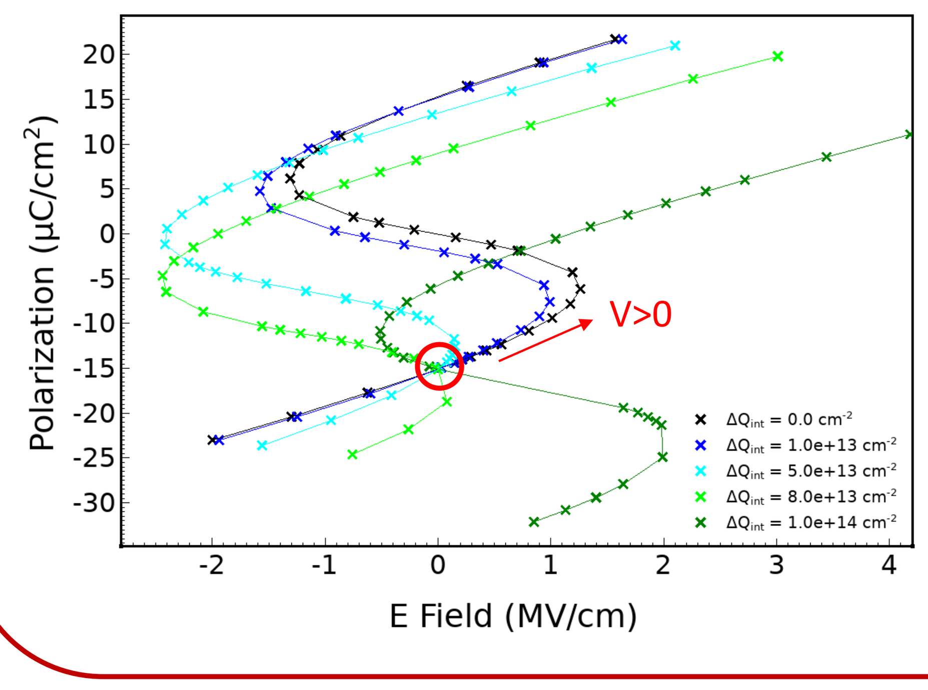




Measured [5] and simulated Polarization-E_F curves for a MFIM structure 4 nm Al_2O_3 over HZO 7.7 and 11.3 nm. E_F is across the FE material. The **NC region** corresponds to the **negative slope** of the S-shaped Landau P-E curve.

Radiation Damage Effects

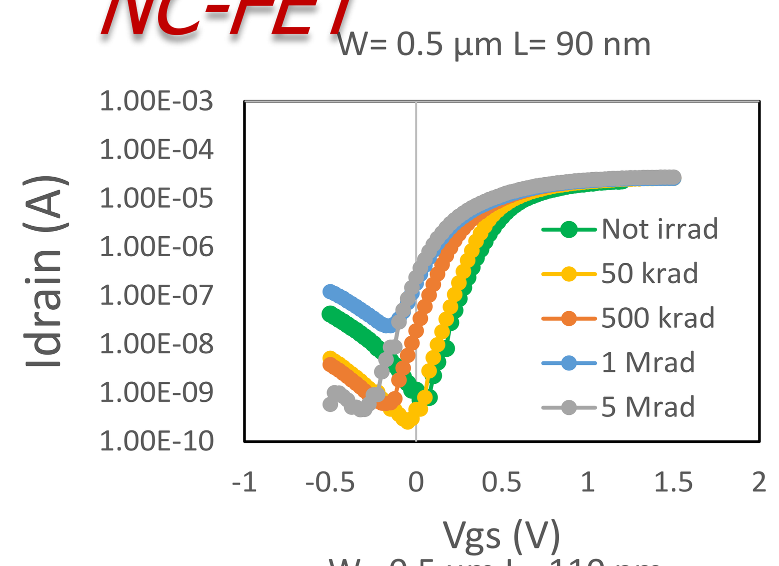
The overall Q_{int} can be accounted for as the sum of charge already present before irradiation $Q_{int}(0)$ and an additional positive fixed charge $\Delta Q_{int}(\phi)$ at the HZO/Al_2O_3 interface of increasing values, aiming at mimic increasing X-ray doses (ϕ).

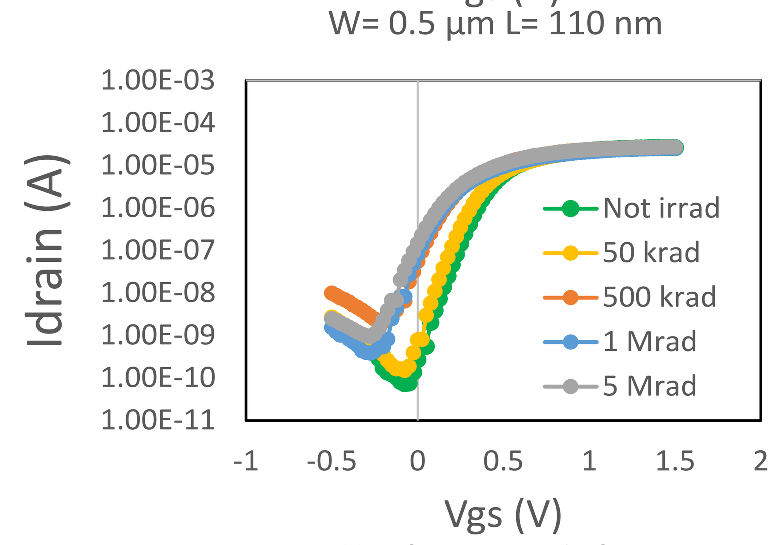


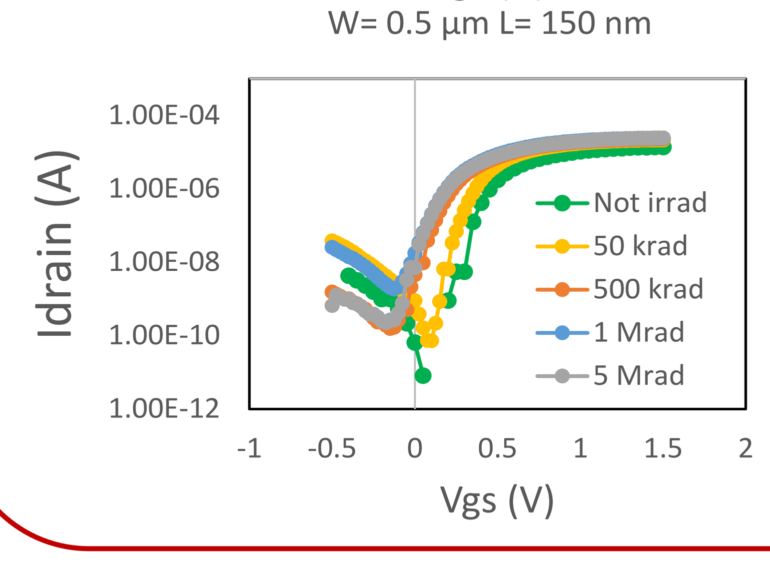
Simulated P-E curves for a MFIM stack (4 nm Al_2O_3 over HZO 7.7 nm). **Surface damage effects** induced by X-rays have been accounted for with the parameter $\Delta Q_{int}(\varphi)$ in the overall fixed oxide formula:

$$Q_{int}(\varphi) = Q_{int}(0) + \Delta Q_{int}(\varphi).$$

NC-FET







- ✓ Ultra-thin HfO_2-based **n-channel NC-FETs** featuring different W/L characteristics. The gate length (L) ranges from 70 to 150 nm, while the width (W) is 0.25, 0.5, 1 and 5 µm.
- ✓ I_{ds}-V_{gs} transfer characteristics for different W/L options.
- ✓ X-ray irradiation campaign at INFN Genova up to 5 Mrad.
- ✓ Method proposed by McWhorter: the effects of oxide charge and interface traps can be disentangled from the subthreshold-current curve of a MOSFET in saturation [6].

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 in the HL-LHC scenario.
- ✓ The analysis and results obtained for MFIM capacitors can be straightforwardly extended to the study of NC-FETs.
- ✓ Irradiation and measurements campaign ongoing at INFN Genova and Perugia.
- ✓ In-depth investigation of radiation damage effects induced by irradiation on innovative NC-FETs.

References

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