Negative Capacitance Field Effect Transistors for the future **H**igh **E**nergy **P**hysics applications

NegHEP

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NegHEP

The project NegHEP won the CSN5*
Grant for young researchers (bando n. 21188/2019).

"A call to award funding for six research projects with a two-year duration to foster excellence among young researchers working in the Institute's fields of research and technological development (accelerators, electronics/Information technology, detectors, interdisciplinary research)."

The total budget is

- Up to 150 k€ for 2 years + 2 years research grant.

*Commissione Scientifica Nazionale 5

RESEARCH TEAM

INFN Perugia
INFN Genova

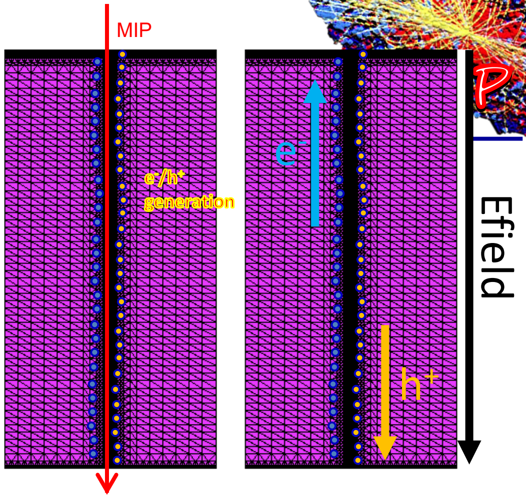
Engineering Dept. – Univ. Perugia

Physics Dept. – Univ. Genova

Trento Institute for Fundamental Physics and Applications

Motivations

- ❑ Innovative Detectors for High-Energy Physics applications
  - ✓ High granularity, thin layers.
  - ✓ Radiation hardness.
  - ✓ Fast response.



- ❑ Continuous increasing in electronics performance demand
  → Continuous scaling of transistors:
  - ✓ Increase of leakage currents.
  - ✓ Increase heat-up → high effort for cooling → thermal runaway.
  - ✓ Radiation resistance/tolerance.

- ❑ Low signals detection in thin layers:
  - ✓ minimum detectable signal is dominated by the switching threshold of a digital switch (e.g. ≈1 ke$^-$ for 28 nm technology, <100 e$^-$ for sub 10-nm technology).

Motivations

- **Would it be possible the concept of pixelated detector with sufficiently small cells to be read out entirely by simple inverters exploiting the NC “self-amplification”?**

Proposed solution: Negative capacitance (NC) FETs

- By replacing the standard insulator with a ferroelectric insulator of the right thickness it should be possible to implement a step-up voltage transformer that will amplify the gate voltage thus enabling low voltage/low power operation
  → advantages in nano-electronics domain applications.

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

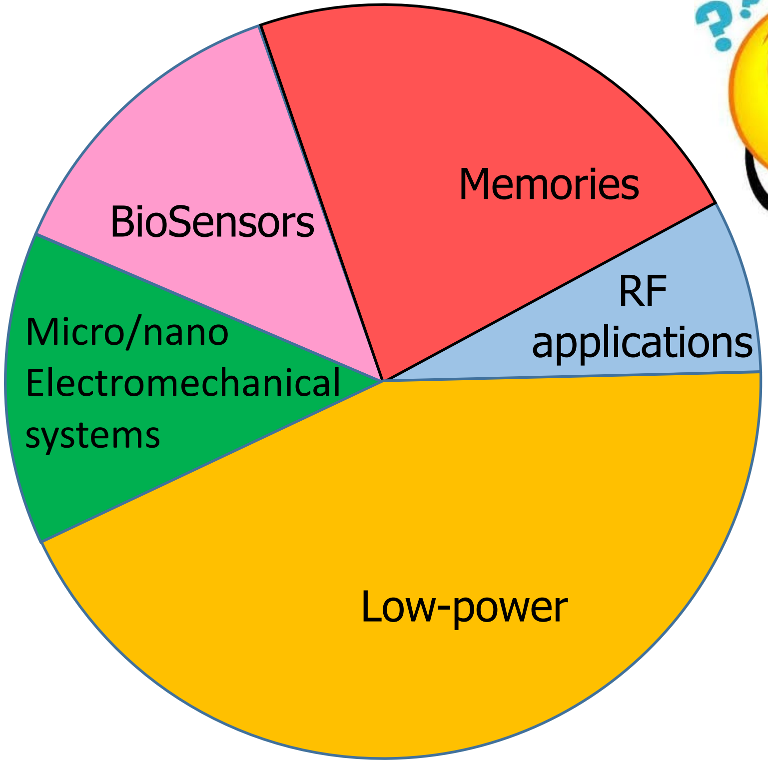
- NC will foster particle detection with extremely thin layers and the fabrication of sensors with very low parasitic capacitances (intrinsic and extrinsic).

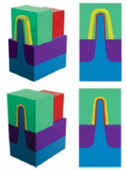
[1] S. Salahuddin and S. Datta, Use of Negative Capacitance to Provide Voltage Amplification for Low Power Nanoscale Devices, Nano Letters, Vol. 8, No. 2, pp. 405-410 (2008).

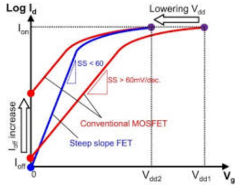
NegHEP Project

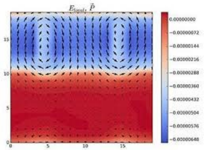
- Project goals:
  - ✓ Application of Negative Capacitance working principle to "self-amplificated" segmented, high-granularity detectors for HEP experiments.
  - ✓ Advanced TCAD model development and validation (test):
    - ✓ ad-hoc customization of TCAD library to study ferroelectric materials, aiming at evaluating the potentiality of Negative Capacitance Transistors.
    - ✓ Test structures manufacturing and testing before/after X-ray irradiation.
  - ✓ Investigation of Radiation damage effects induced by irradiation on NC-FETs (conventional FETs vs NC-FETs).
- Collaboration with:

Application fields of the Negative Capacitance





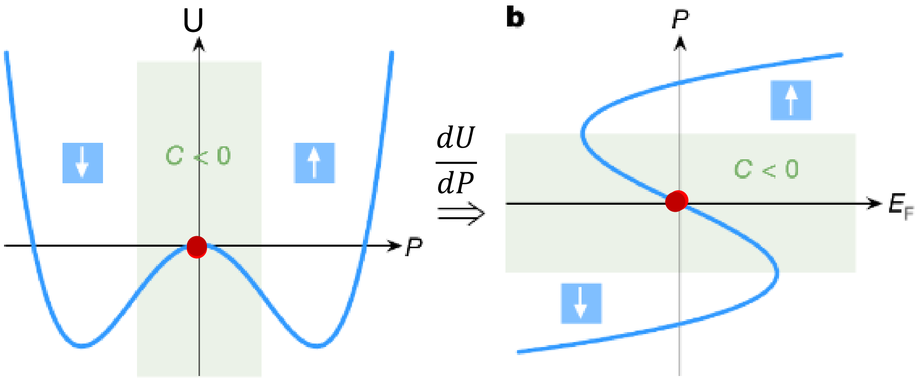




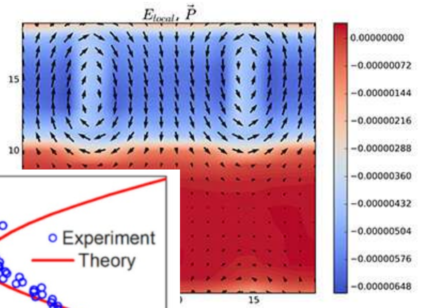
- **Use of negative capacitance to provide voltage amplification for low power nanoscale devices**, S Salahuddin, S Datta, Nano letters 8 (2), 405-410, 2008.
- **Experimental evidence of ferroelectric negative capacitance in nanoscale heterostructures**, AI Khan, D Bhowmik, P Yu, SJ Kim, X Pan, R Ramesh, S Salahuddin, Applied Physics Letters 99 (11), 113501, 2011.
- **Negative capacitance in a ferroelectric capaci**tor, A. I. Khan, K. Chatterjee,B. Wang,S. Drapcho,L. You, Claudy Serrao, S. R. Bakaul, R. Ramesh and S. Salahuddin, Nature Materials 14, 182–186 (2015).
- **Demonstration of Subthrehold Swing Smaller Than 60mV/decade in Fe-FET with P(VDF-TrFE)/SiO2 Gate Stack,** G.A. Salvatore et al., 2008 IEEE International Electron Devices Meeting, DOI: 10.1109/IEDM.2008.4796642.

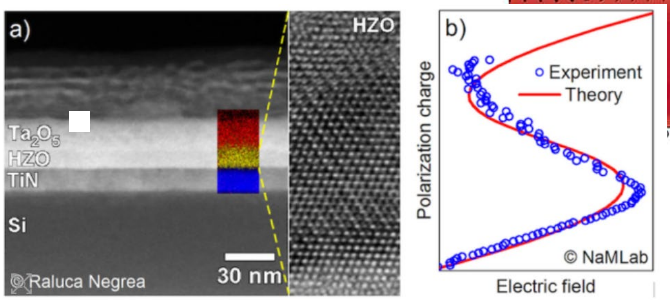
High Energy Physics applications?

Polarization in ferroelectric materials



1° Experimental Evidence

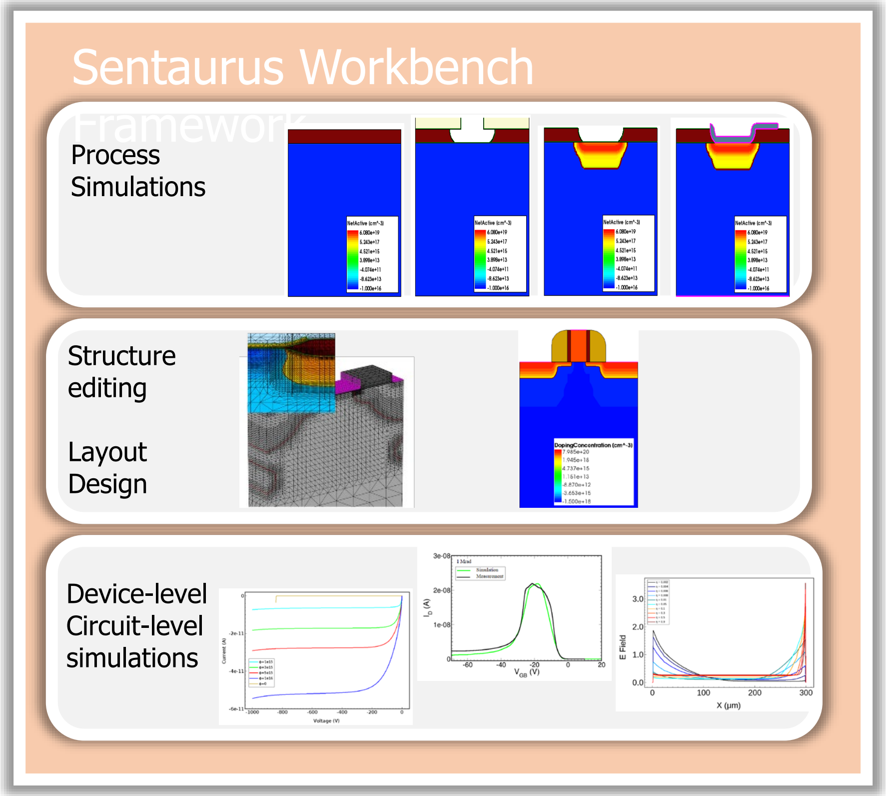




- ✓ Spontaneous polarization
  - → In equilibrium conditions, the ferroelectric material resides in one of the wells.
- ✓ In Landau theory, NC is directly related to the double-well shape of the ferroelectric polarization–energy landscape, which was thought for more than 70 years to be inaccessible to experiments.

[4] M.A. Alam et al., A critical review of recent progress on negative capacitance field-effect transistors, Appl. Phys. Lett. 114, 090401 (2019).
[5] Khan, A., Chatterjee, K., Wang, B. et al. Negative capacitance in a ferroelectric capacitor. Nature Mater 14, 182–186 (2015) doi:10.1038/nmat4148

Technology-CAD modelling approach



- √ State-of-the-art Synopsys© Sentaurus TCAD.
- √ TCAD simulation tools solve fundamental, physical partial differential equations, such as diffusion and transport equations for discretized geometries (finite element meshing).
- √ This deep physical approach gives TCAD simulation predictive accuracy.

$$\nabla \cdot (-\varepsilon_s \nabla \varphi) = q\left(N_D^+ - N_A^- + p - n\right) \quad \text{Poisson}$$

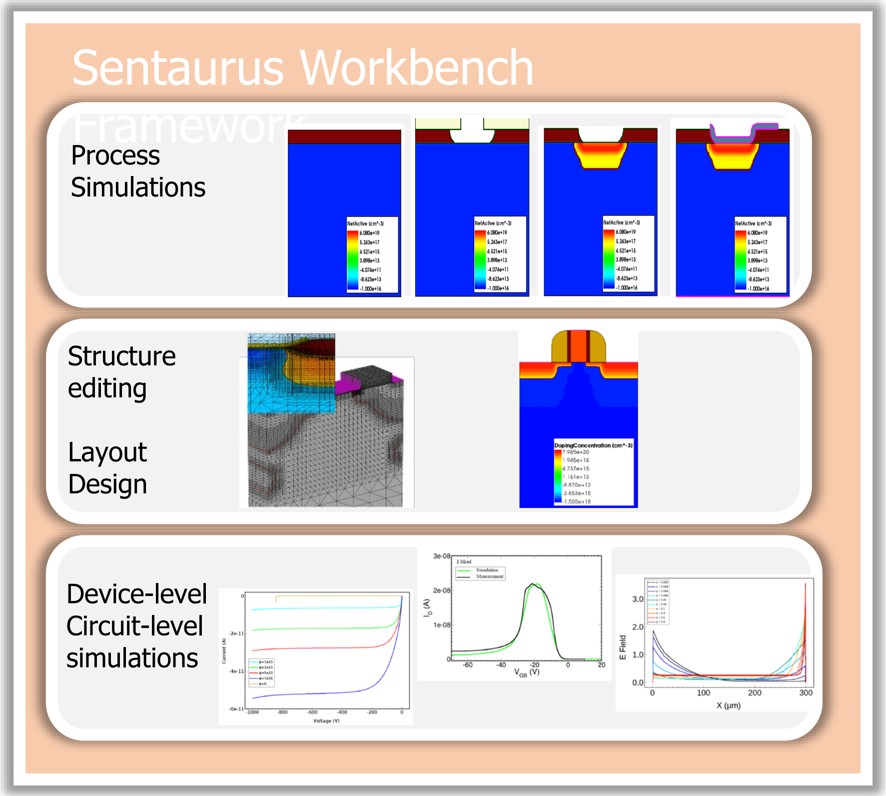
$$\frac{\partial n}{\partial t} - \frac{1}{q} \nabla \cdot \vec{J}_n = G - R \quad \text{Electron continuity}$$

$$\frac{\partial p}{\partial t} + \frac{1}{q} \nabla \cdot \vec{J}_p = G - R \quad \text{Hole continuity}$$

$$\vec{J}_n = -q\mu_n n \nabla \varphi + qD_n \nabla n$$

$$\vec{J}_p = -q\mu_p p \nabla \varphi - qD_p \nabla p$$

Technology-CAD modelling approach



√ State-of-the-art Synopsys© Sentaurus TCAD.

- ❑ Ad-hoc customization of TCAD tools in terms of models and methodology.
- ❑ Implementation of proper physic/electric models which describes ferroelectric materials.
- ❑ Capacitance matching.

INFN Istituto Nazionale di Fisica Nucleare

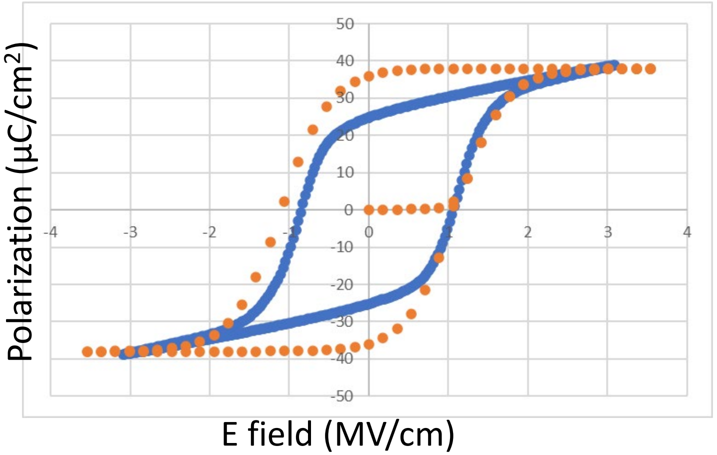
Projects CSN 5

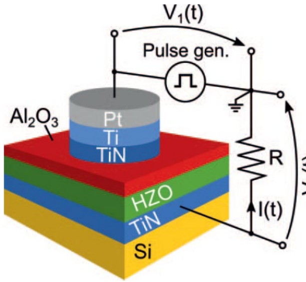
- ✓ CMS (AIDA2020)
- ✓ TIMESPOT
- ✓ 3DSiAM
- ✓ 3Dose
- ✓ 3DSoD

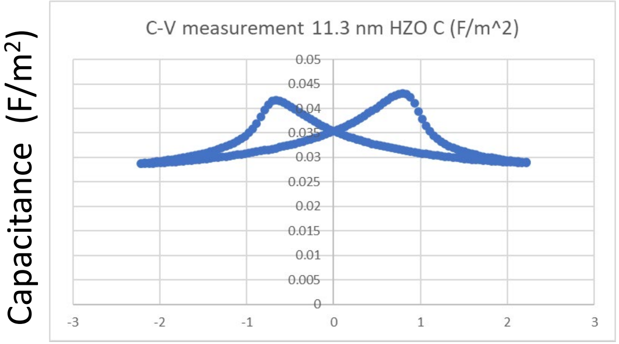
TCAD methodology

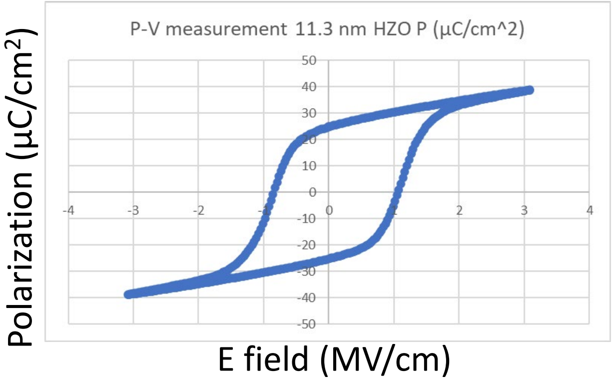
- Simulation inputs:
  - ✓ Preisach-model vs GLK equation
- Simulation outputs:
  - ✓ Polarization vs FEPolarization

Measurements from collaboration with NamLAB

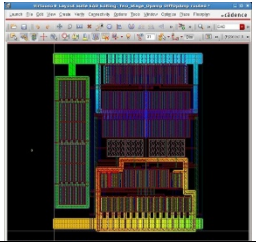


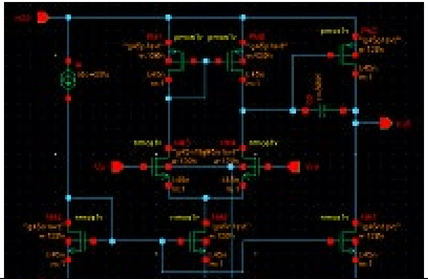


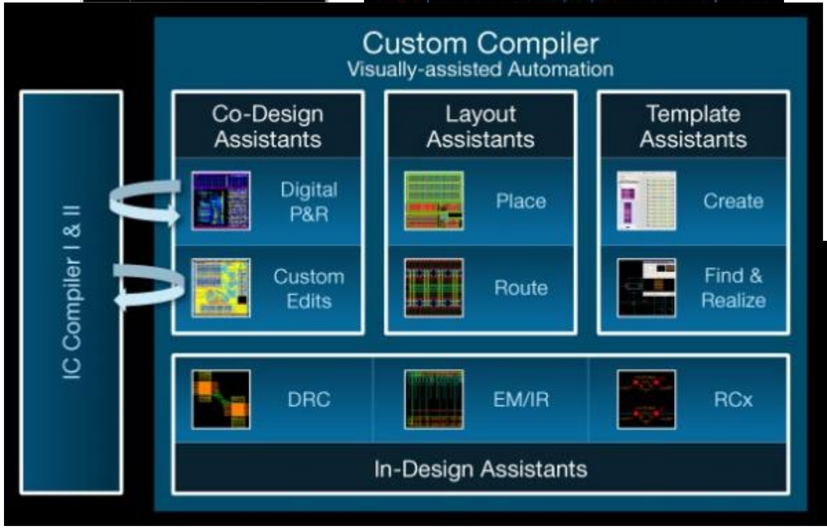


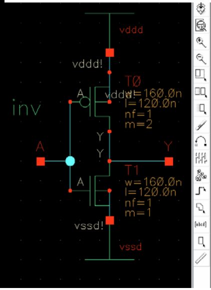


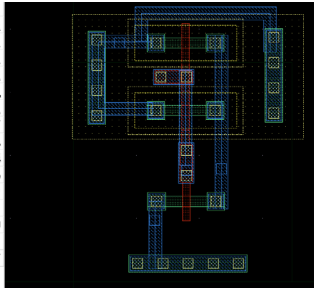
Test structures DESIGN







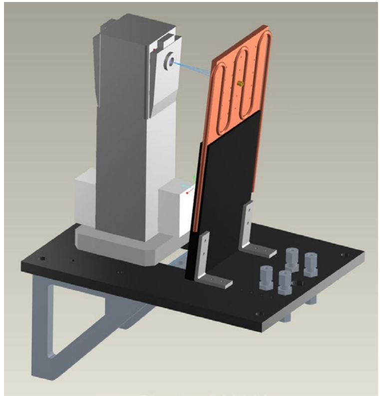


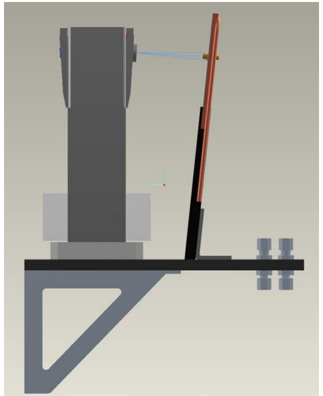


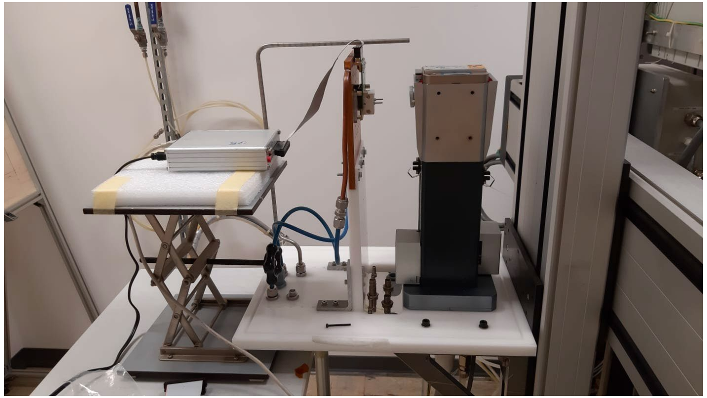
- Design tool:
  Synopsys Custom Compiler.

X-ray facility

- ✓ Irradiation campaign at INFN Genova X-ray facility.
- ✓ Study of the irradiation damage effects of this innovative technology to X-ray irradiation (conventional FETs as reference).
- ✓ X-ray laboratory with precision mechanical support with dry air chamber, cryostat and room temperature/humidity critical issues control.
  Tube with Tungsten cathode. Calibration diode for the absorbed dose by the DUT.
- ✓ Typical dose rate is about 3 Mrad/h in 2 cm^2.

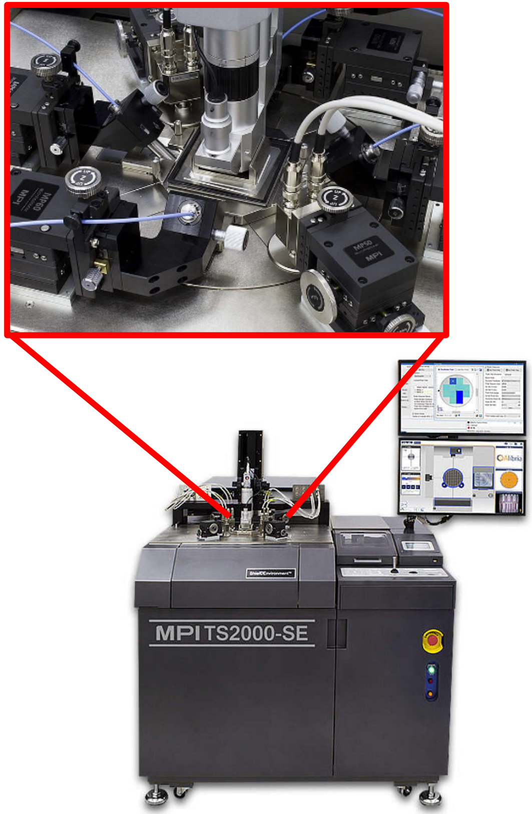






Test structures CHARACTERIZATION

- Test structures characterization at INFN Perugia:
  - ✓ Before X-ray – NC measurements,
  - ✓ after X-ray – radiation damage effects.
- Main analysis:
  - ✓ small-signal analysis measurements,
  - ✓ transient RC measurements (ramp pulse),
  - ✓ (I_D vs V_G) measurements of the subthreshold swing.
- Probe station characteristics:
  - ✓ state-of-the-art MPITS2000 SE semiautomatic with triaxial thermal chuck (-60°C,+200°C), voltage range up to 1 kV, micro-chamber, probe card adapter and 4 probes.



Thanks for the attention!

Negative Capacitance Field Effect Transistors
for the future **H**igh **E**nergy **P**hysics applications

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