Measurements and Simulations of Surface Radiation Damage Effects on IFX and HPK Test Structures

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15TH VIENNA CONFERENCE ON INSTRUMENTATION

Outline

- **Motivations**
- **Experimental measurements (X-rays irradiations)**
  - Different test-structures (MOS capacitors, Gated Diodes, Interstrip resistance test structures)
  - Different providers (HPK, IFX) and processes
- **TCAD Simulation Results**
- **Model validation: comparison between simulation findings and experimental data**
- **Conclusions and future developments**

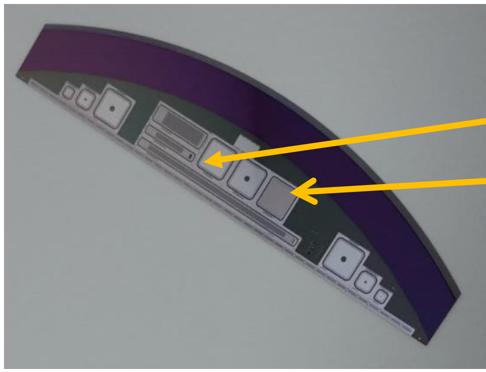
Motivations and goals

- Study the effects of surface damage on silicon devices at high doses (HL-LHC operation greater than 50 Mrad for Outer Tracker and 1 Grad for Inner Tracker).
- Surface damage can strongly influence the breakdown, the inter-electrode isolation, the dark current and the charge collection efficiency of the sensor.
- Extension of the predictive capability of the past "University of Perugia" numerical TCAD model to these very high doses:
  - Physically-grounded parametrization,
  - Keep low the number of traps (e.g. avoiding fitting),
  - No over-specific modelling (e. g. device and technology independent)
  - Deep understanding of physical device behavior.
- Extraction from simple test structures of relevant parameters to be included within the model
- Validation of the new modeling scheme through comparison with measurements of different test structures manufactured by different vendors with different processes before and after irradiation.

Test structures IFX and HPK

IFX

HPK



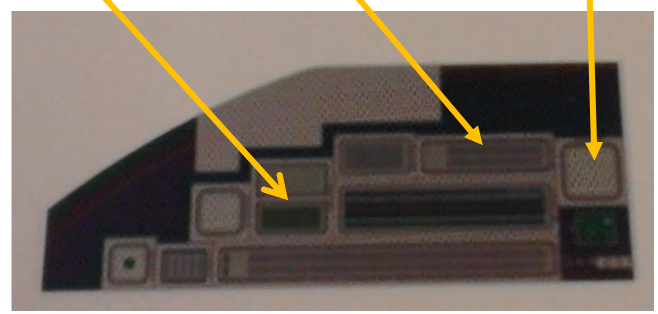
MOS capacitor

Gated-diode

Cap-TS for Rint

MOS capacitor

Gated-diode



- MOS capacitors
- 1 gated diode (called GCD)
- Strip structures for Rint measurements

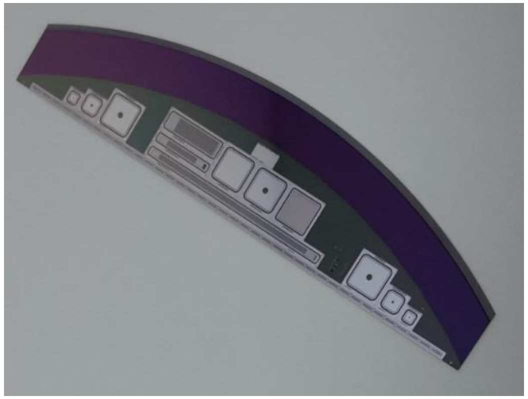
√ Measurement Campaign: X-ray irradiation

- carried out in Padova (IT). Dose rate 0.8 Mrad/hour
- doses range: 0.05 ÷ 100 Mrad(SiO_2)
- Measurements after irradiation / annealing 80°C 10 min.

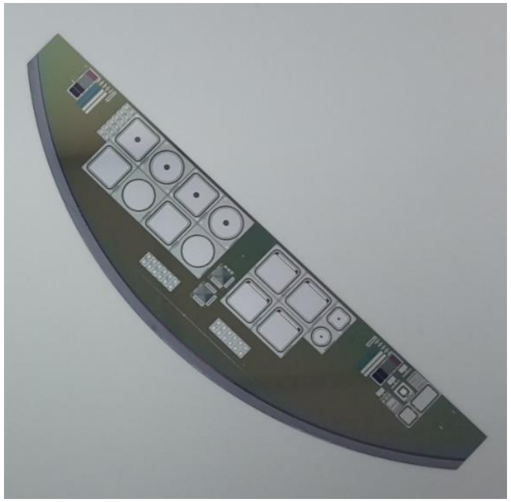
IFX devices

1st campaign 0.05-20 Mrad
IFX 8-inch 2S run
MOS
GCD
Rint

2nd campaign
IFX 8-inch 2S run
MOS



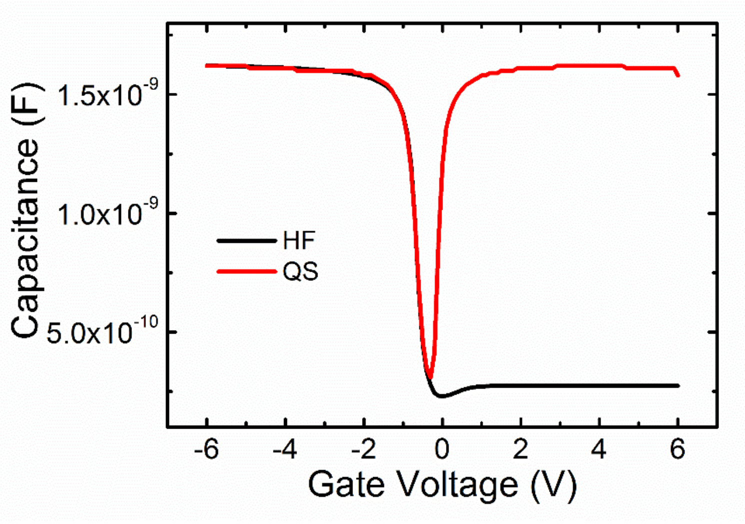
2nd campaign
IFX 6-inch PS-S run
MOS
FET



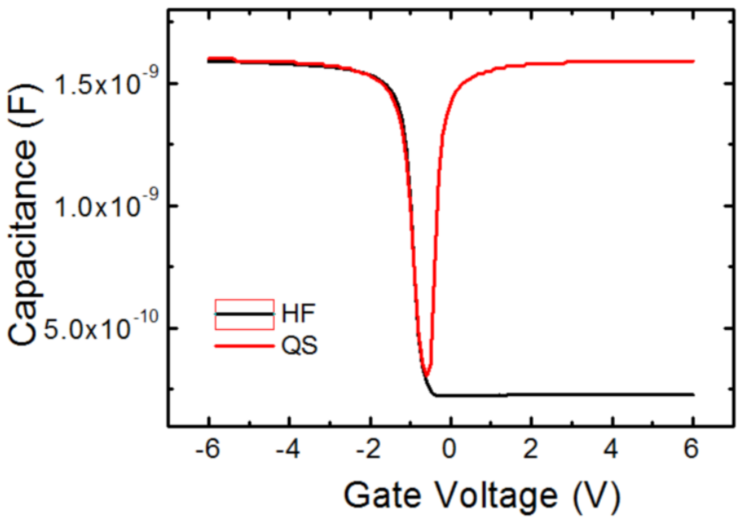
MOS Capacitors: measurements

- *p*-type substrate.
- HF measurements at 100 kHz with a small signal amplitude of 25 mV.
- The QS characteristics were measured with delay times of 0.5 s using a voltage step of 100 mV.
- Effective oxide charge density N_{EFF} obtained from V_{FB} measurements.
- Unbiased devices during the irradiation steps. Dry N flux during measurements.

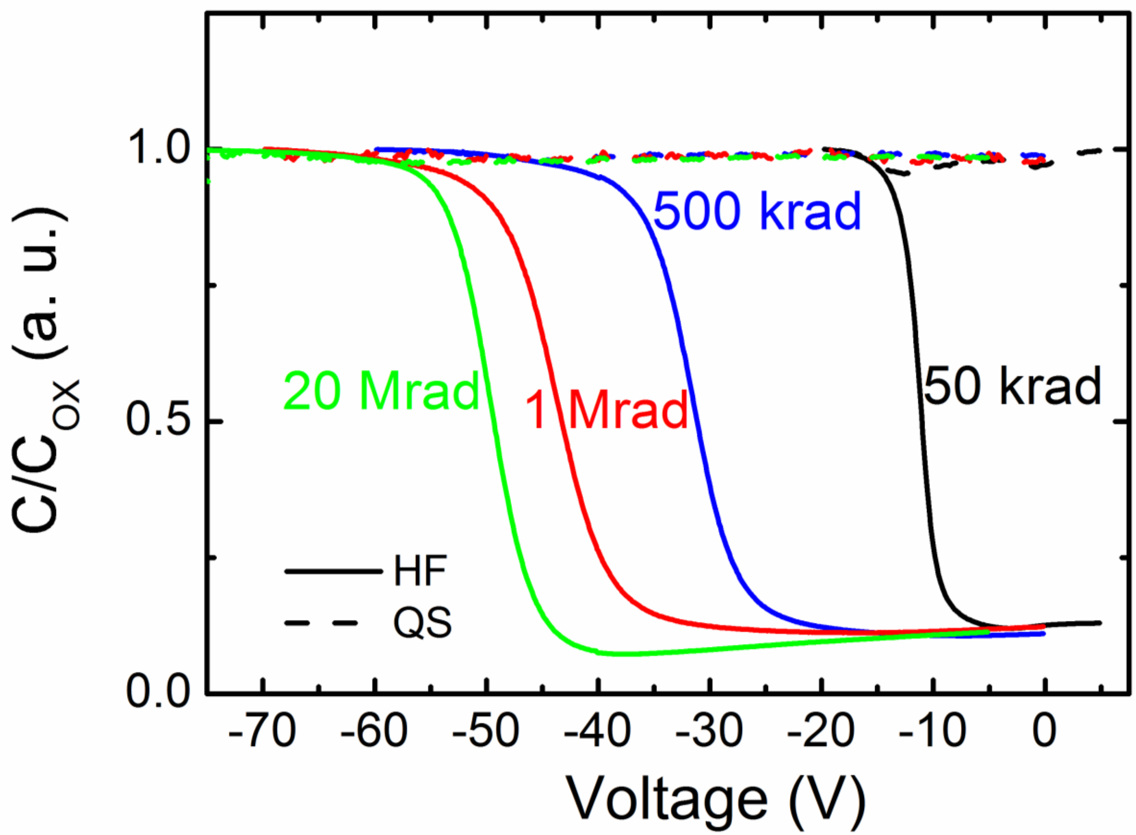
IFX PS-S



IFX 2S

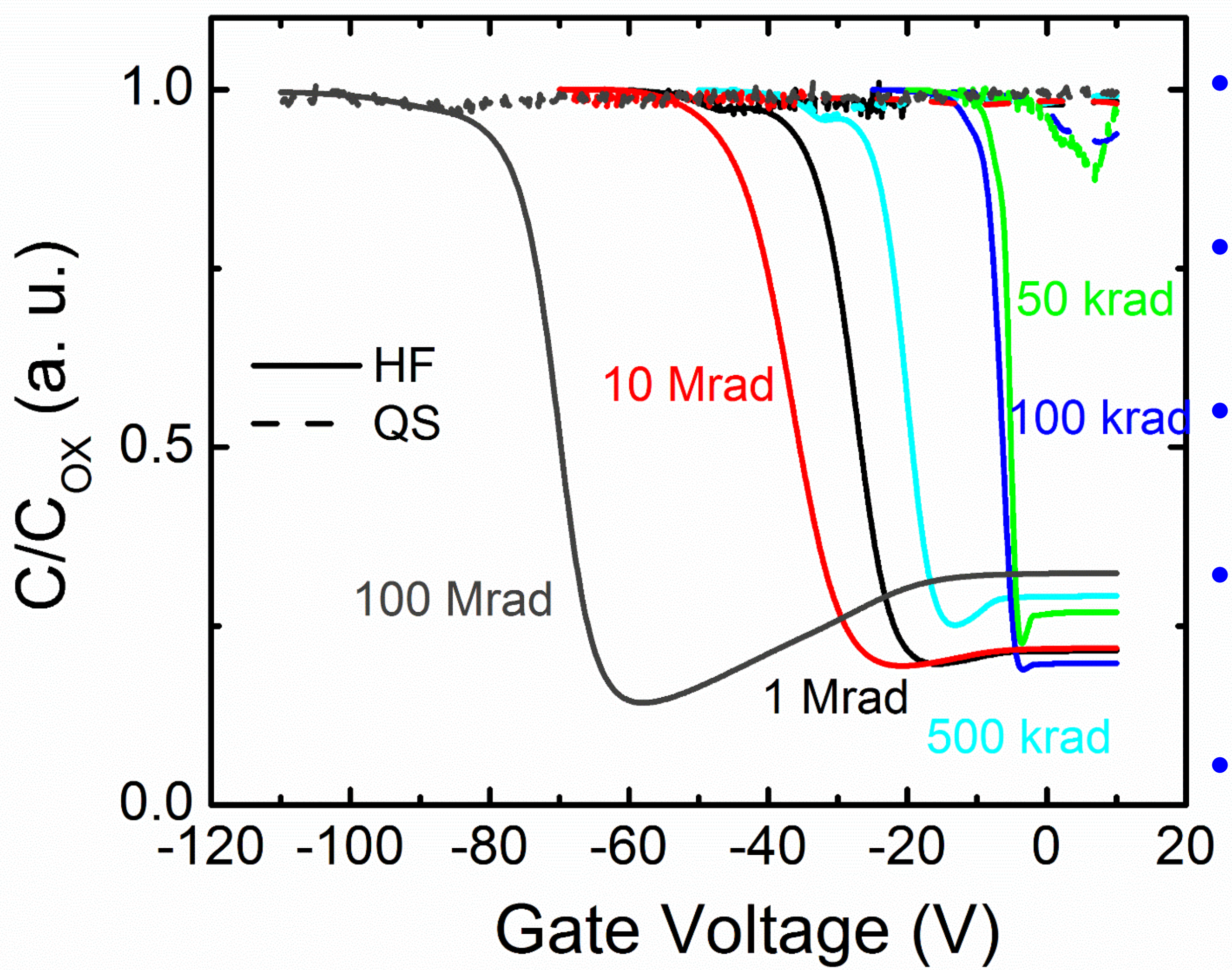


IFX 2S MOS CV Measurements after X-ray



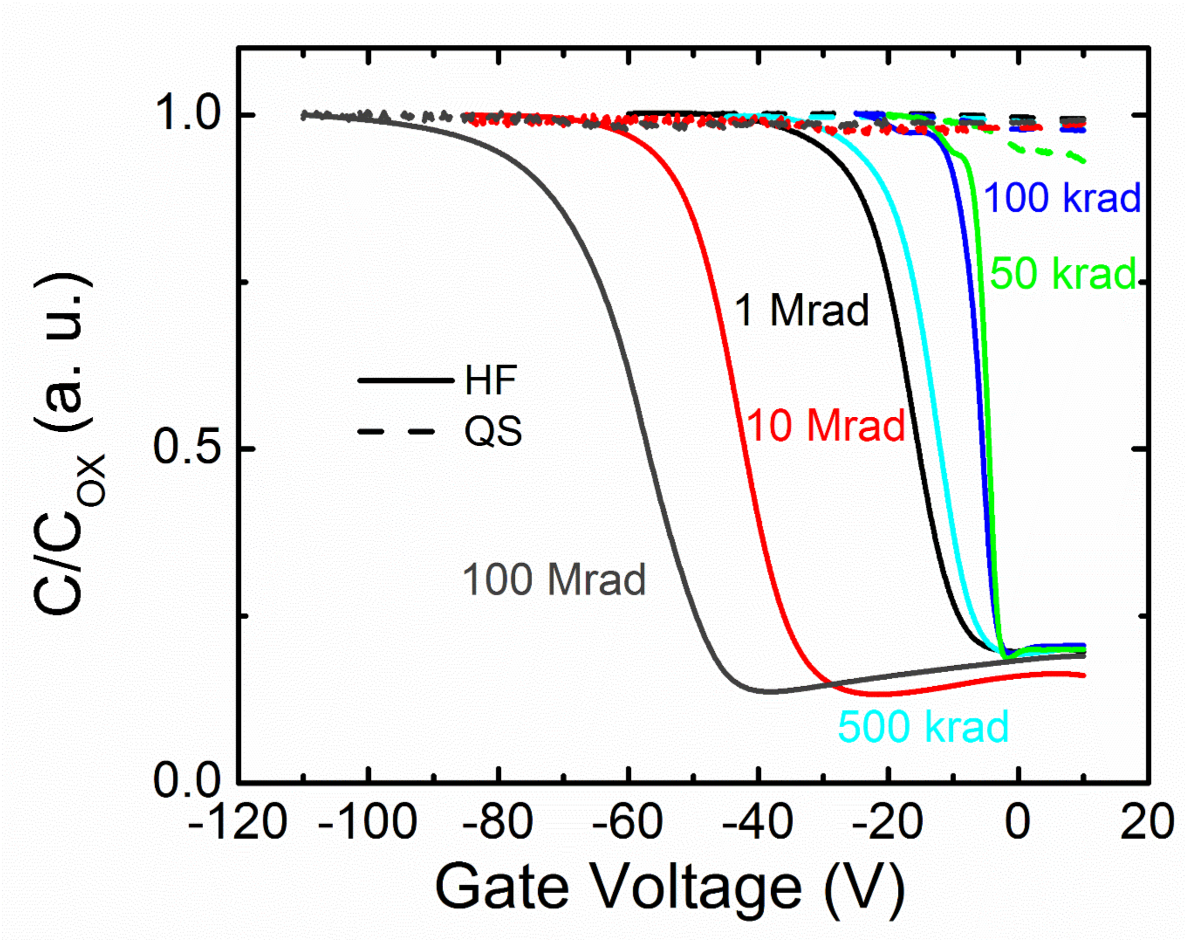
- $V_{FB} \cong -10$ V at 50 krad
- $V_{FB} \cong -17$ V at 100 krad (not shown in this figure)
- $V_{FB} \cong -30$ V at 500 krad
- $V_{FB} \cong -42$ V at 1 Mrad
- $V_{FB} \cong -50$ V at 10-20 Mrad

IFX 2S MOS CV after X-ray 2nd campaign



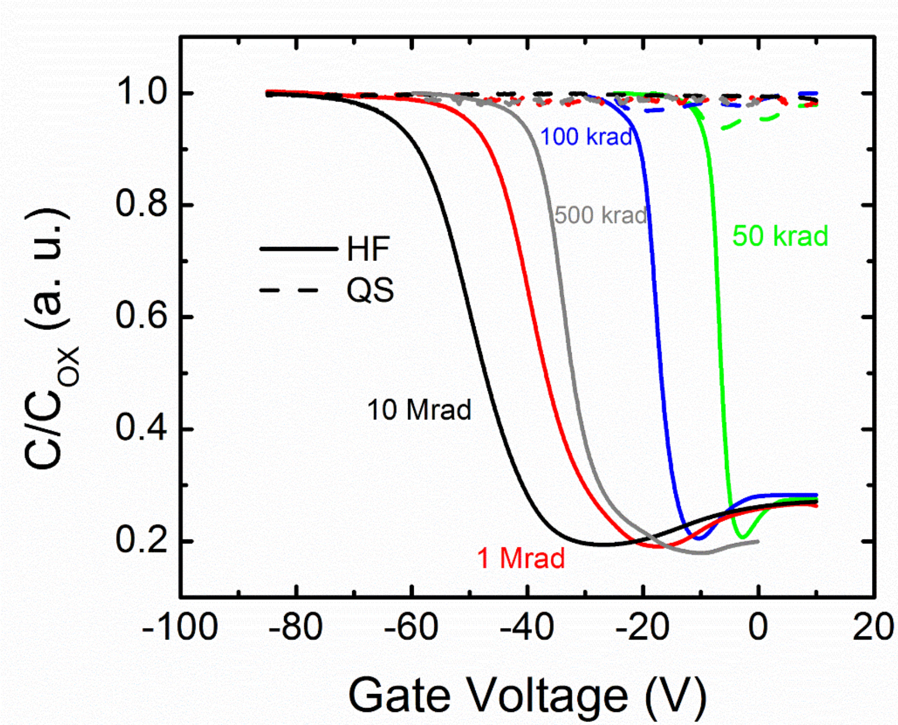
- $V_{FB} \cong$ -5 V at 50 krad
- $V_{FB} \cong$ -7 V at 100 krad
- $V_{FB} \cong$ -18 V at 500 krad
- $V_{FB} \cong$-23 V at 1 Mrad
- $V_{FB} \cong$-35 V at 10 Mrad
- $V_{FB} \cong$-65 V at 100 Mrad

IFX PS-S CV after X-rays

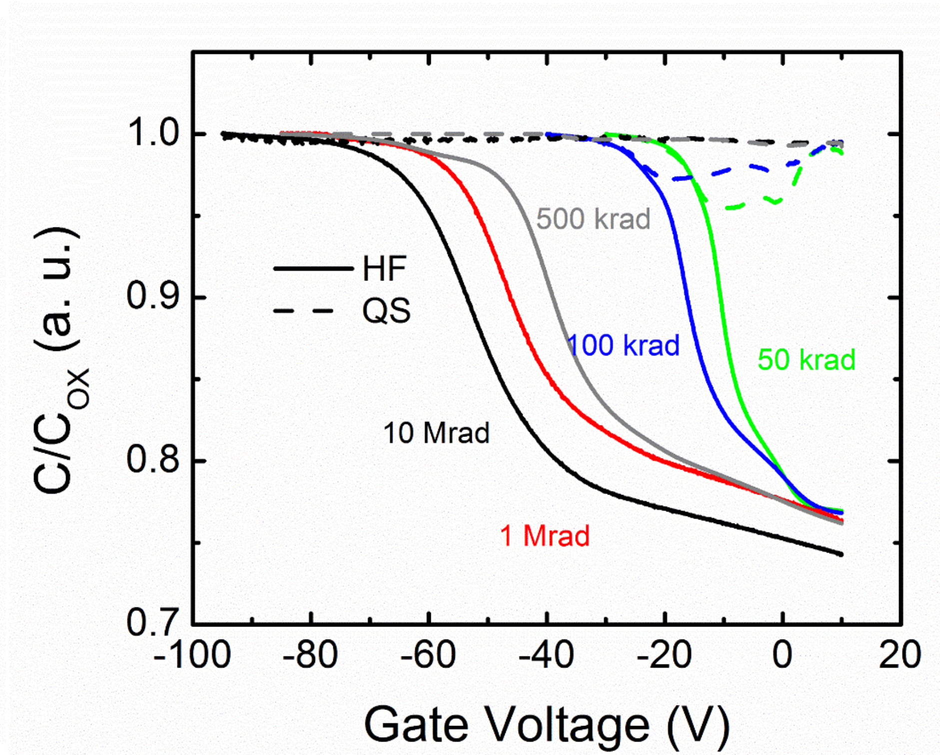


- $V_{FB} \cong$ -4 V at 50 krad
- $V_{FB} \cong$ -5 V at 100 krad
- $V_{FB} \cong$ -11 V at 500 krad
- $V_{FB} \cong$-15 V at 1 Mrad
- $V_{FB} \cong$-40 V at 10 Mrad
- $V_{FB} \cong$-55 V at 100 Mrad

HPK CV after X-rays



Process p-stop (no implant under the oxide)

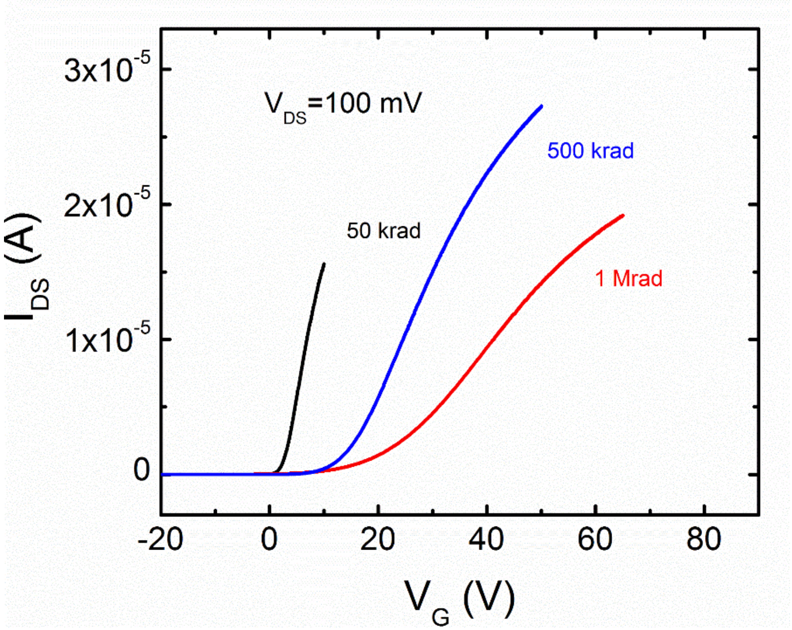


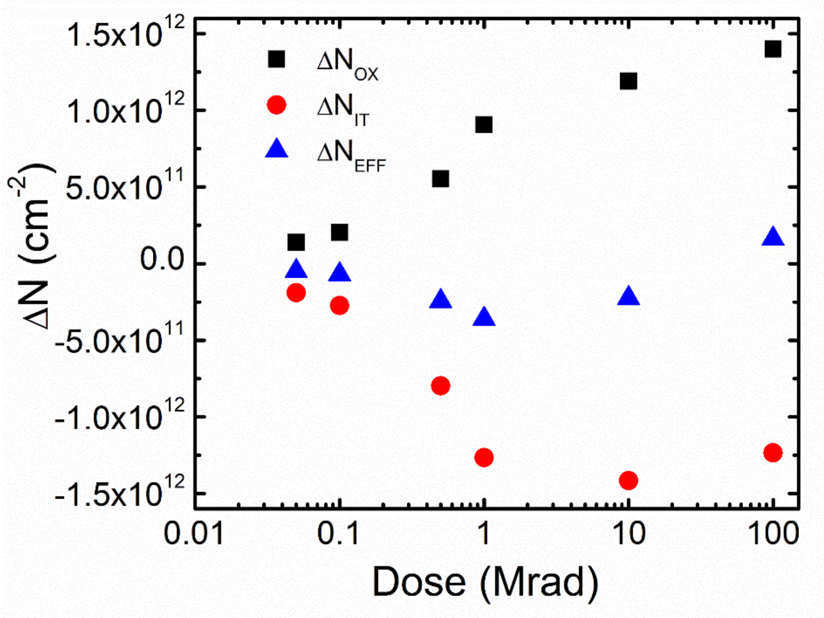
P-spray

IFX - MOSFETs

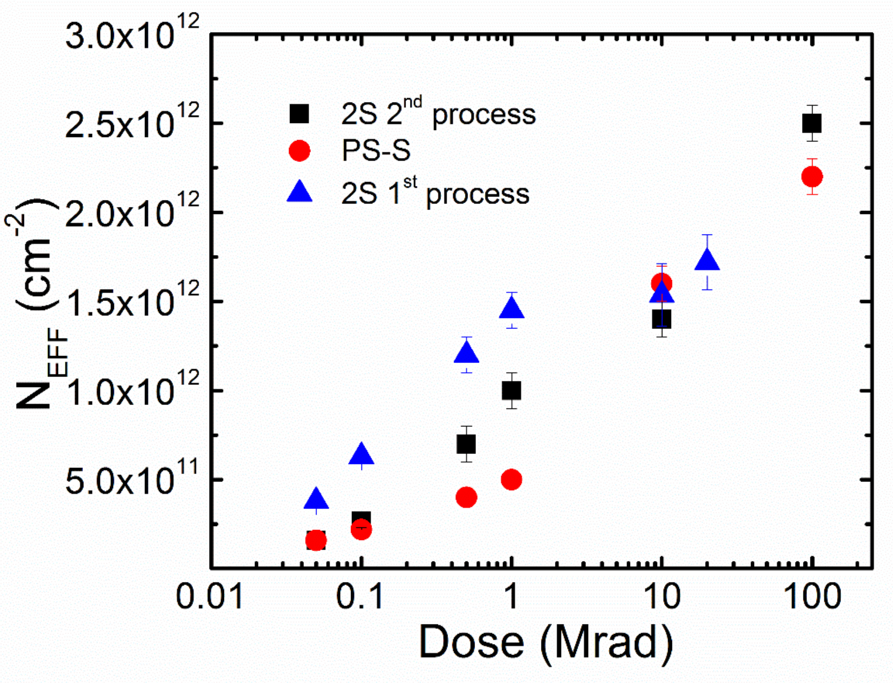
- V_{th} = -0.1 (unirradiated)
- Unbiased devices during the irradiation steps
- Radiation → interface traps (N_{IT}) + trapped-oxide (N_{OX}) → V_{th} shift (ΔV_{th}).
- ΔV_{th} is separated into a contribution due to N_{IT} and due to $N_{OX,}$ from I_{DS}-V_{GS} of MOSFET (method proposed in McWorther Applied Physics Letters 48, 133 (1986))

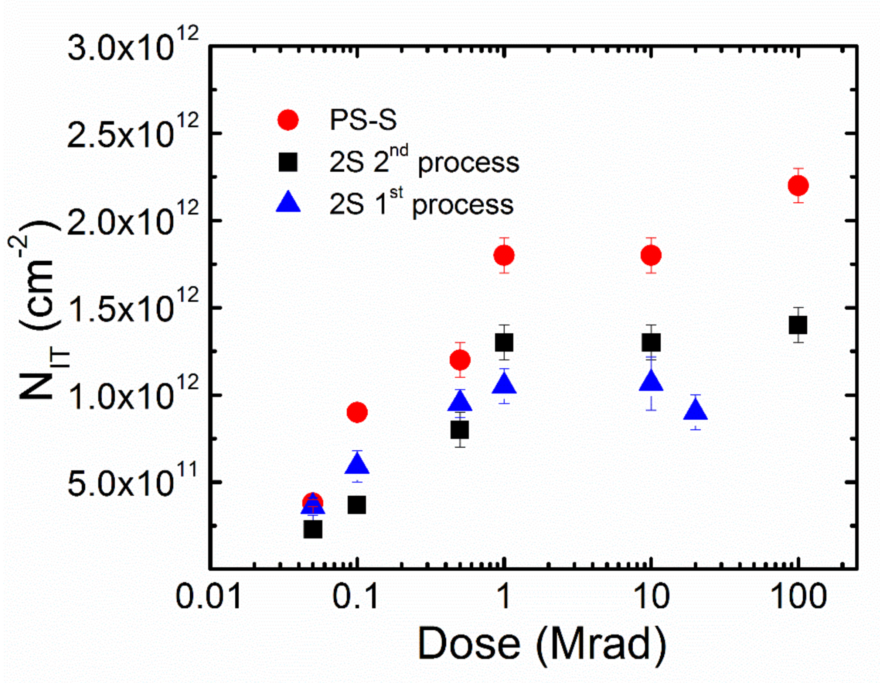
$$\Delta V_{th} = \Delta V_{N_{it}} + \Delta V_{N_{ox}}$$





IFX p-type Summary of measurements





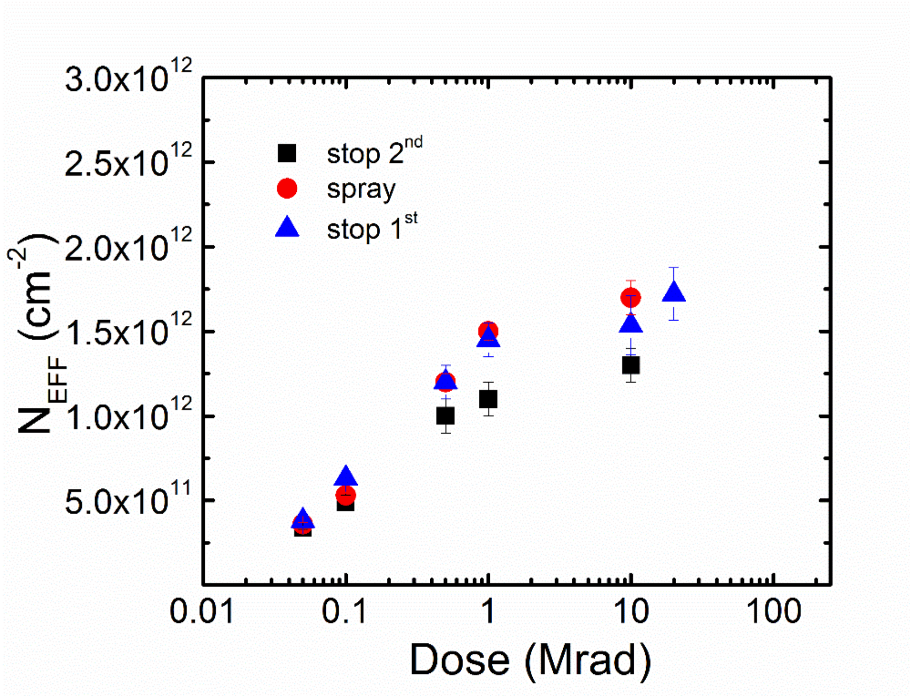
For N_{EFF} :

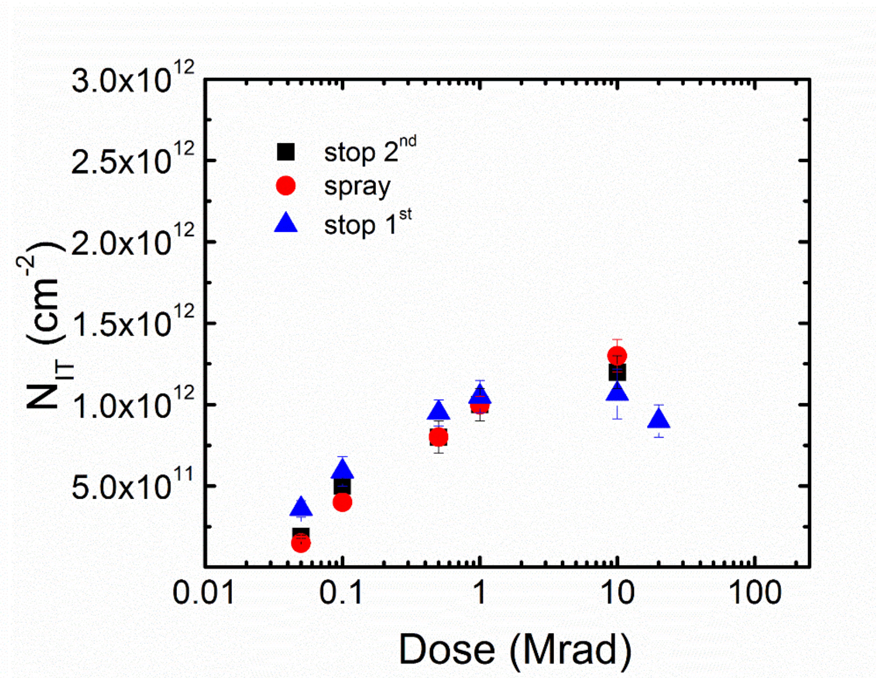
Differences among the three processes at low doses.

At high doses similar results.

PS-S has higher interface traps

HPK p-type Summary of measurements



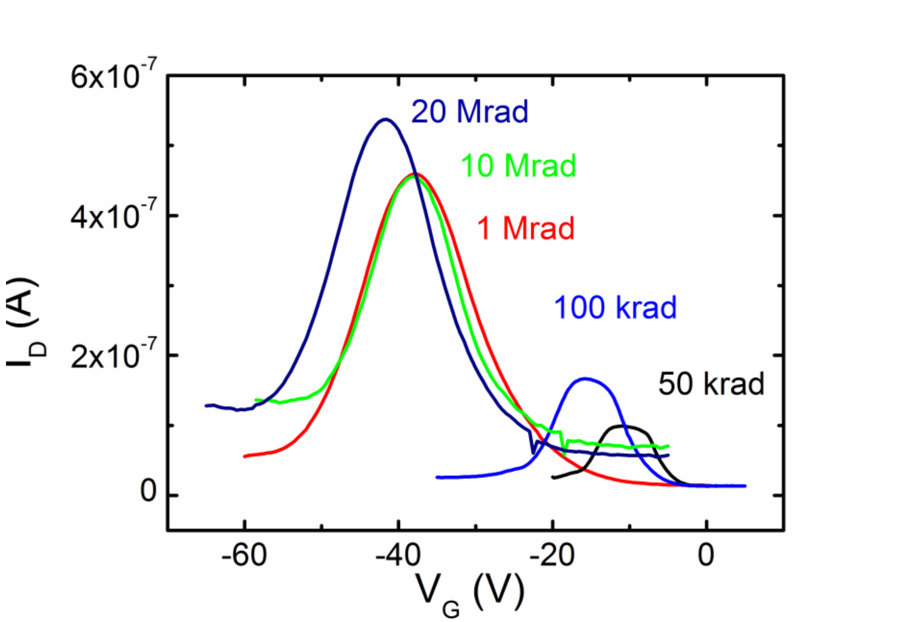


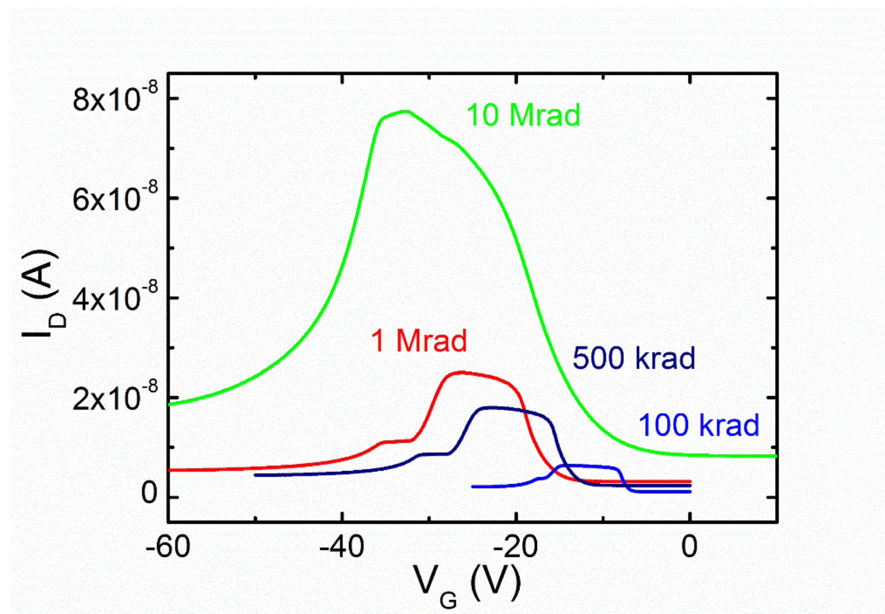
As expected very similar values for HPK devices

IFX and HPK p-type GCD after X-ray irradiation

IFX

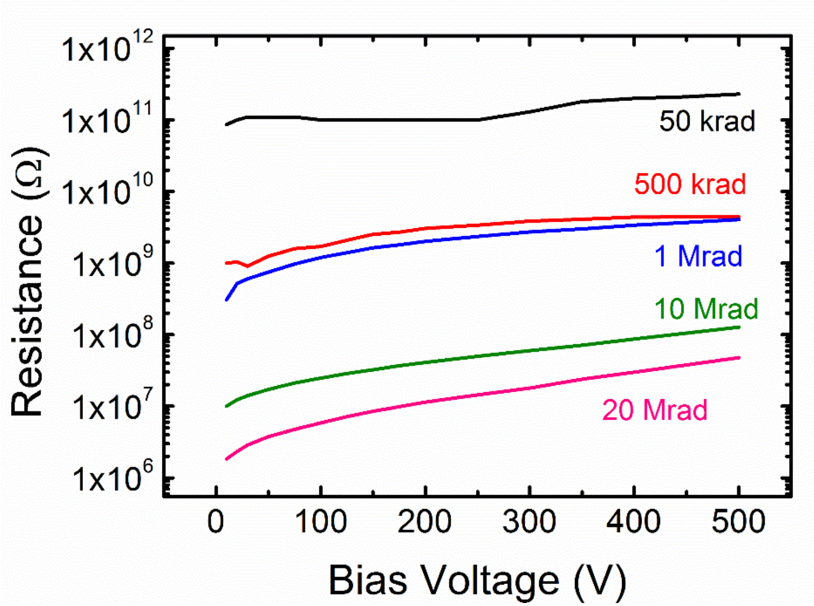
HPK



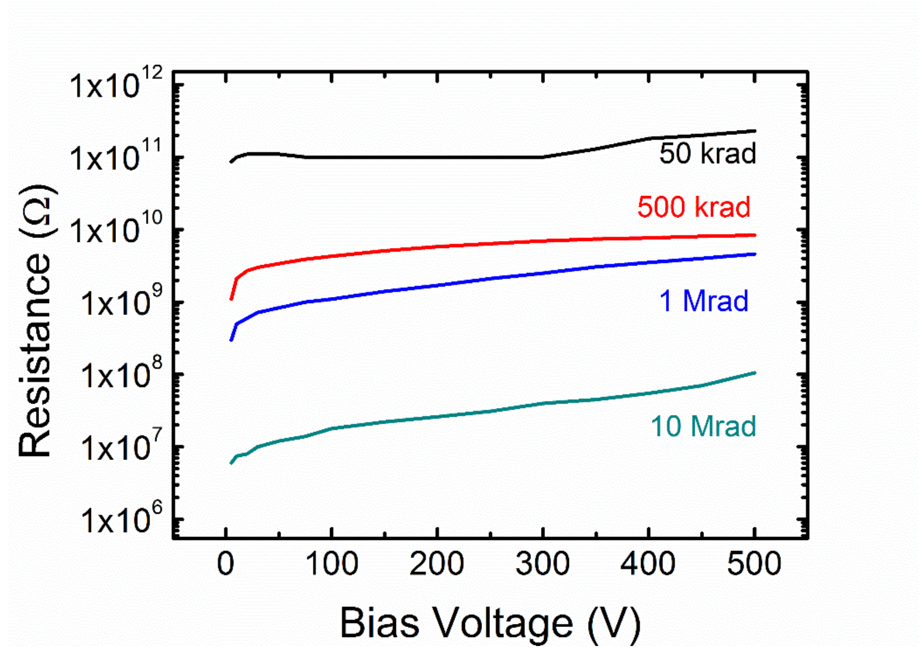


- Annealing 80°C 10 min
- Surface velocity s_0 evaluated as a function of the dose
- Area 11.71 mm^2 Area 6.14 mm^2

Interstrip resistance after X-ray irradiation



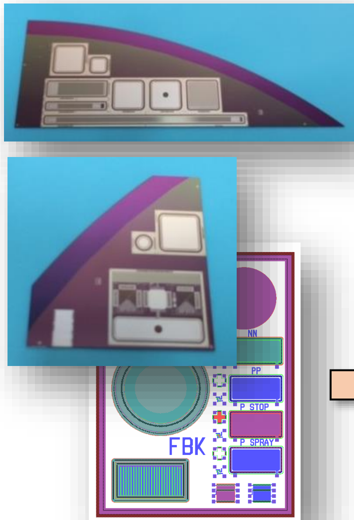
P-stop 1st campaign



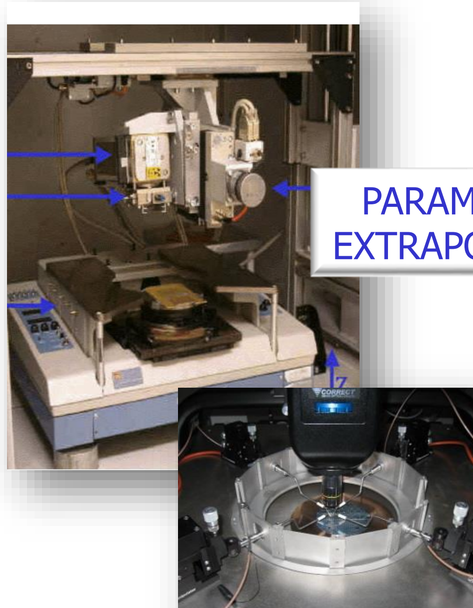
P-stop 2nd campaign

Interstrip resistance values are similar between the two campaigns

New “University of Perugia” model

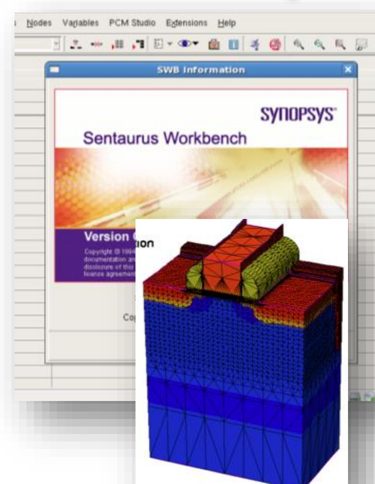


TEST STRUCTURE MEASUREMENTS



PARAMETERS EXTRAPOLATION

MODEL

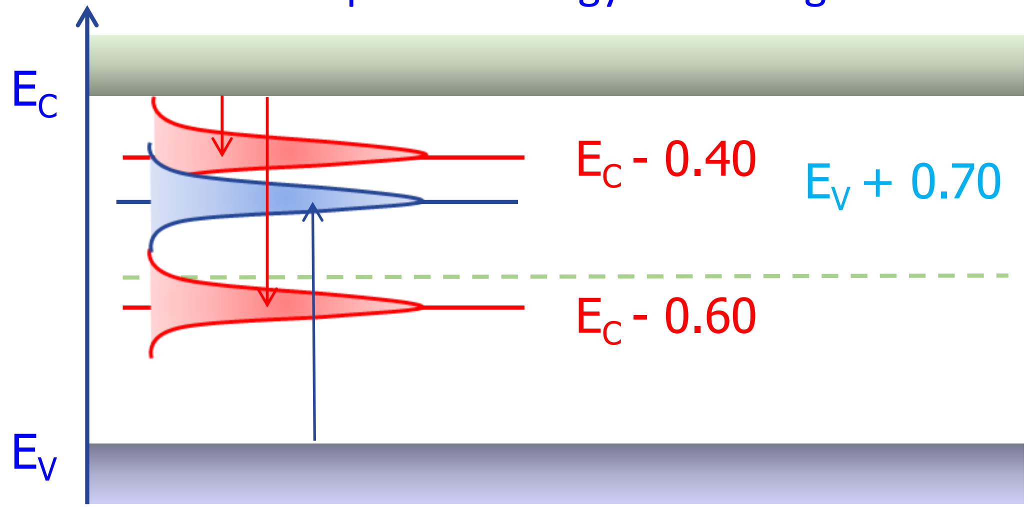


MODEL VALIDATION

DETECTOR OPTIMIZATION

Surface Damage Model: Gaussian

- Interface trap state energy modelling

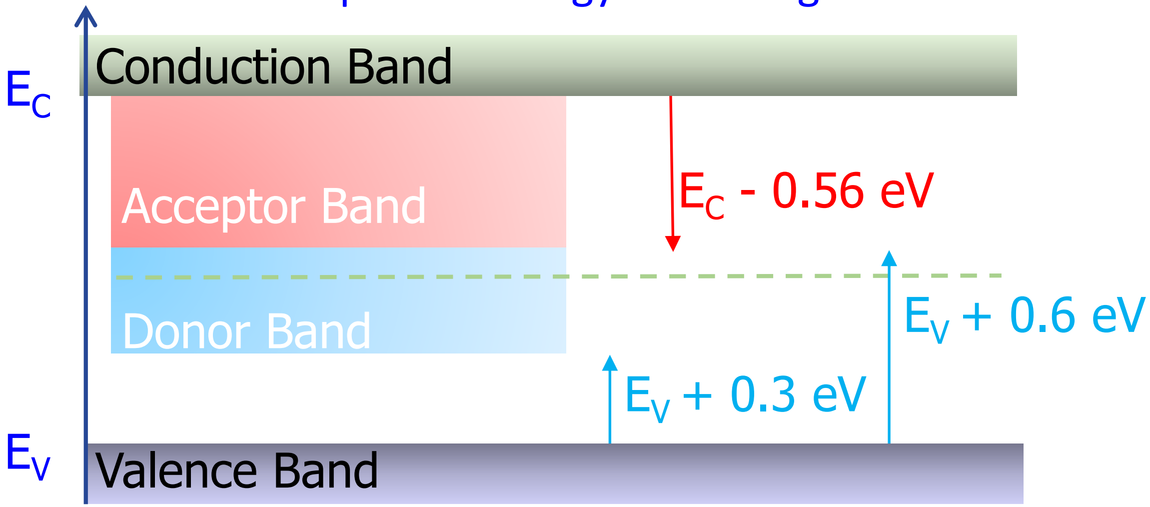


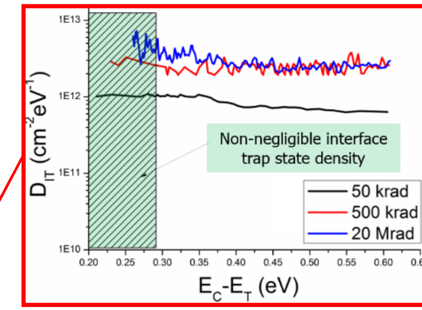
Type	Peak Energy (eV)	Density (cm^{-2})	σ (eV)
Acceptor	$E_C - 0.40$	40% of acceptor N_{IT} [1] ($N_{IT}=M \cdot N_{OX}$)	0.07
Acceptor	$E_C - 0.60$	60% of acceptor N_{IT} [1] ($N_{IT}=M \cdot N_{OX}$)	0.07
Donor	$E_V + 0.70$	100% of donor N_{IT} ($N_{IT}=M \cdot N_{OX}$)	0.07

F. Moscatelli et al., *Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC*, IEEE Transactions on Nuclear Science, 2017, Vol. 64, Issue: 8, 2259 - 2267

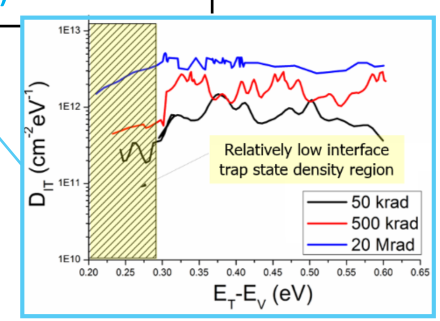
Surface Damage Model: Uniform Bands

- Interface trap state energy modelling



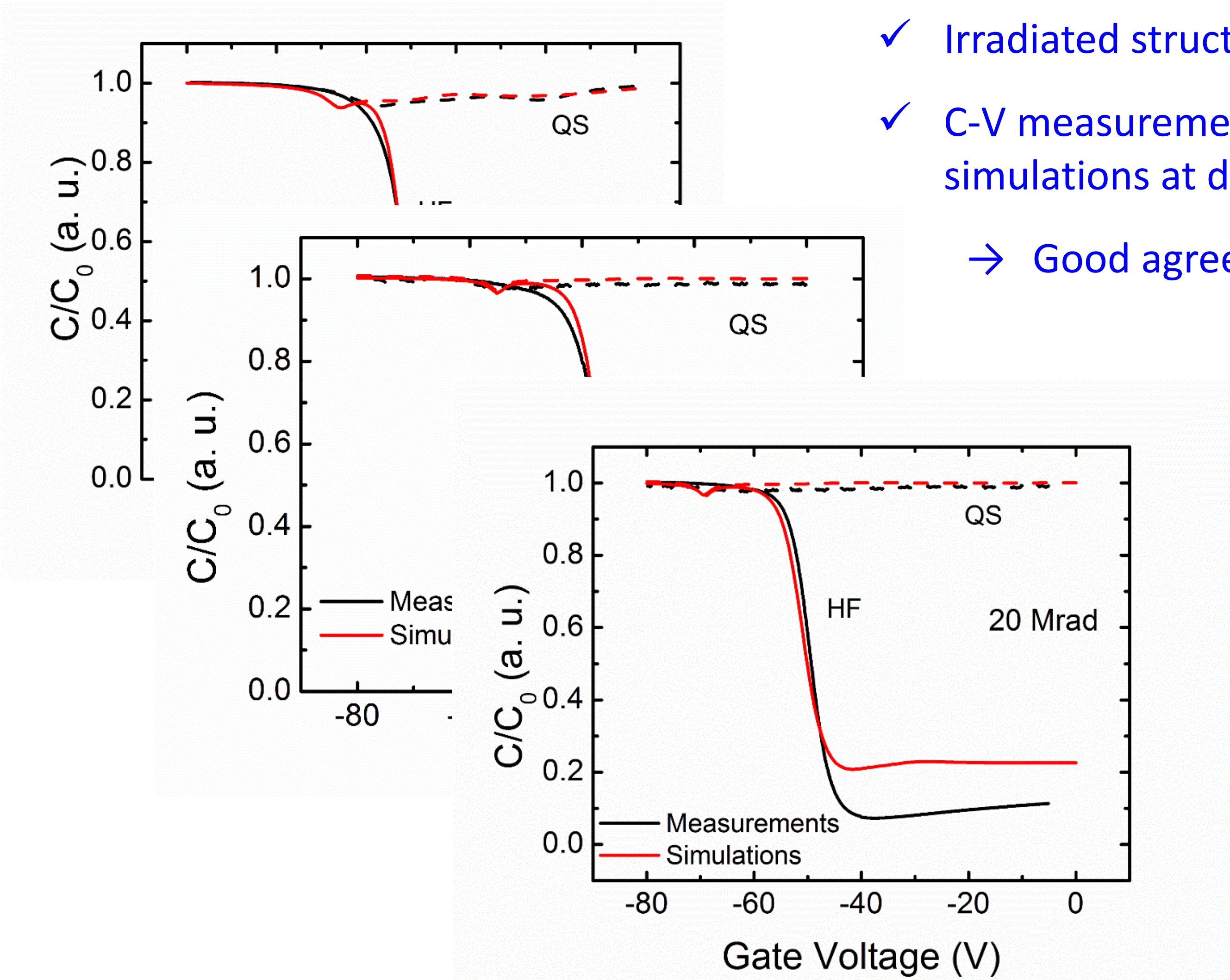


Type	Energy (eV)	Band width (eV)	Concentration (cm^{-2})
Acceptor	$E_C \leq E_T \leq E_C$-0.56	0.56	Dit = Dit(Φ)
Donor	E_V+0.3 $\leq E_T \leq E_V$+0.6	0.30	Dit = Dit(Φ)



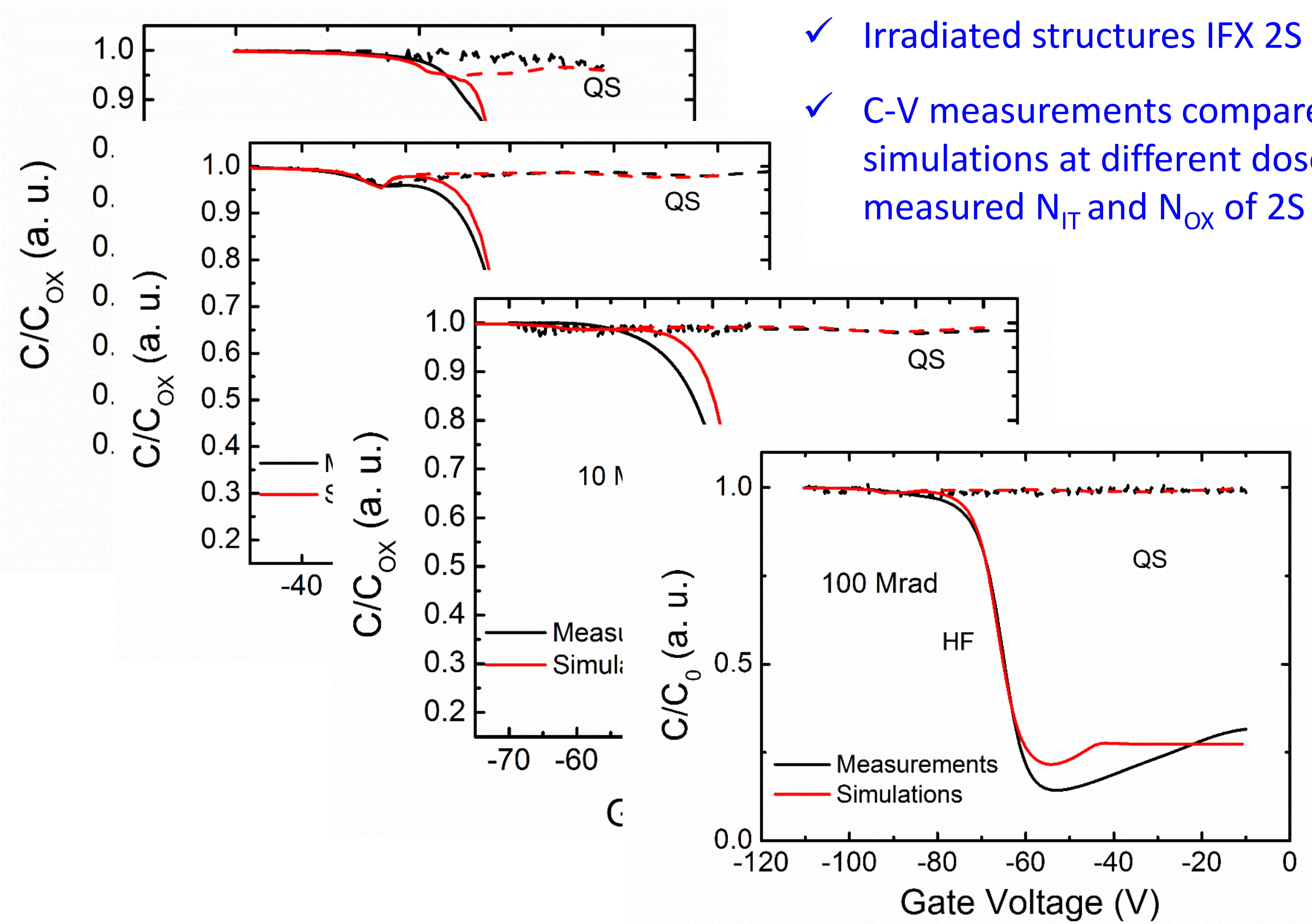
F. Moscatelli et al: "Analysis of surface radiation damage effects at HL-LHC fluences: Comparison of different technology options", NIMA https://doi.org/10.1016/j.nima.2018.07.081

IFX 2S MOS capacitors: simulations



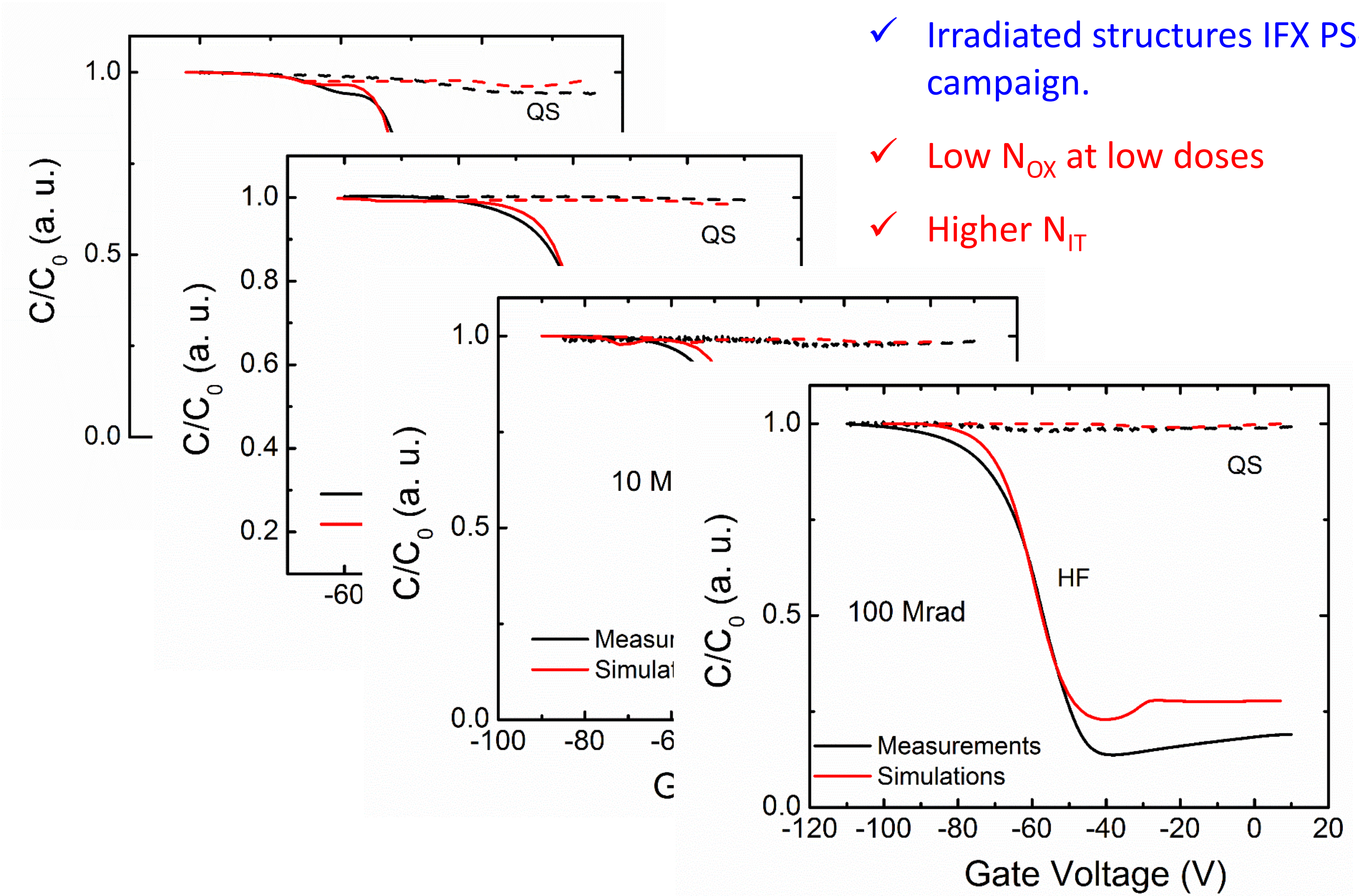
- ✓ Irradiated structures IFX 2S 1st campaign.
- ✓ C-V measurements compared to simulations at different doses.
  - → Good agreement for IFX devices!

IFX 2S 2nd campaign MOS capacitors



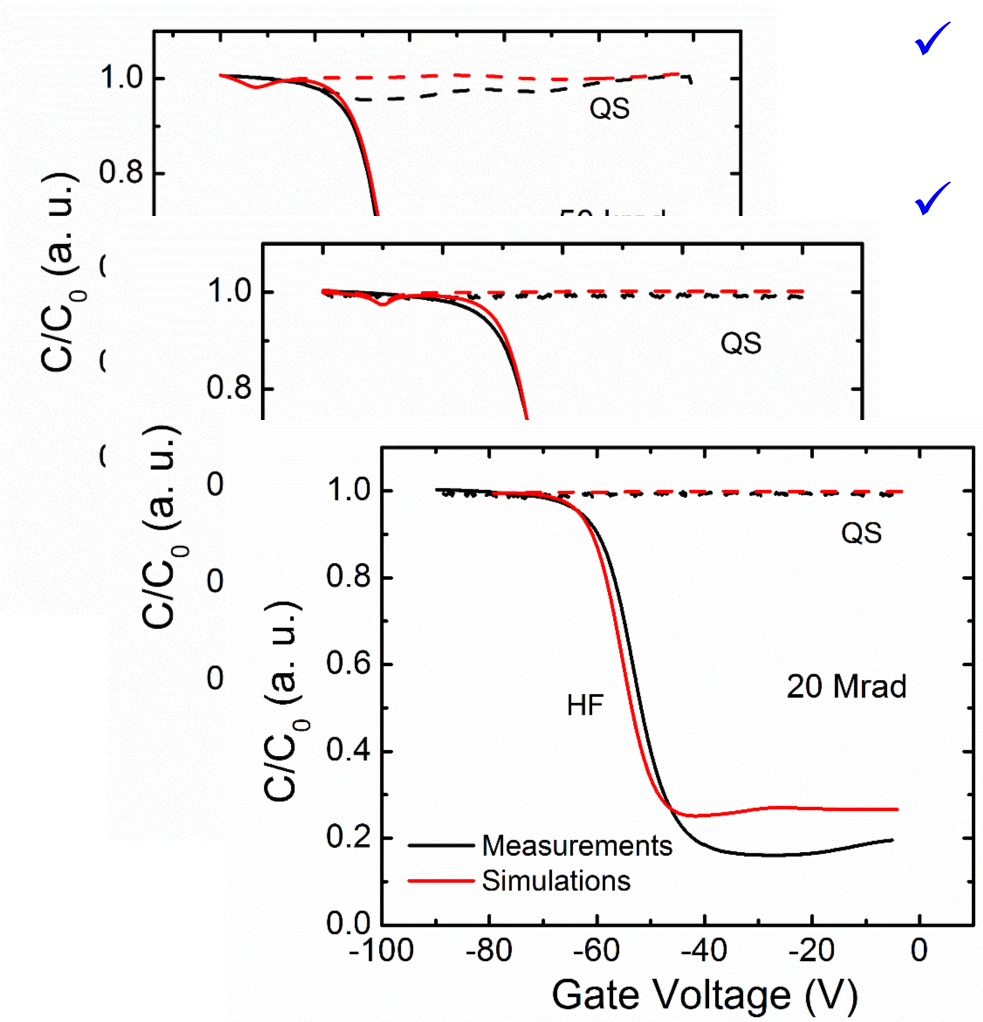
- ✓ Irradiated structures IFX 2S 2nd campaign.
- ✓ C-V measurements compared to simulations at different doses with measured N_{IT} and N_{OX} of 2S wafer.

IFX PS-S MOS capacitors



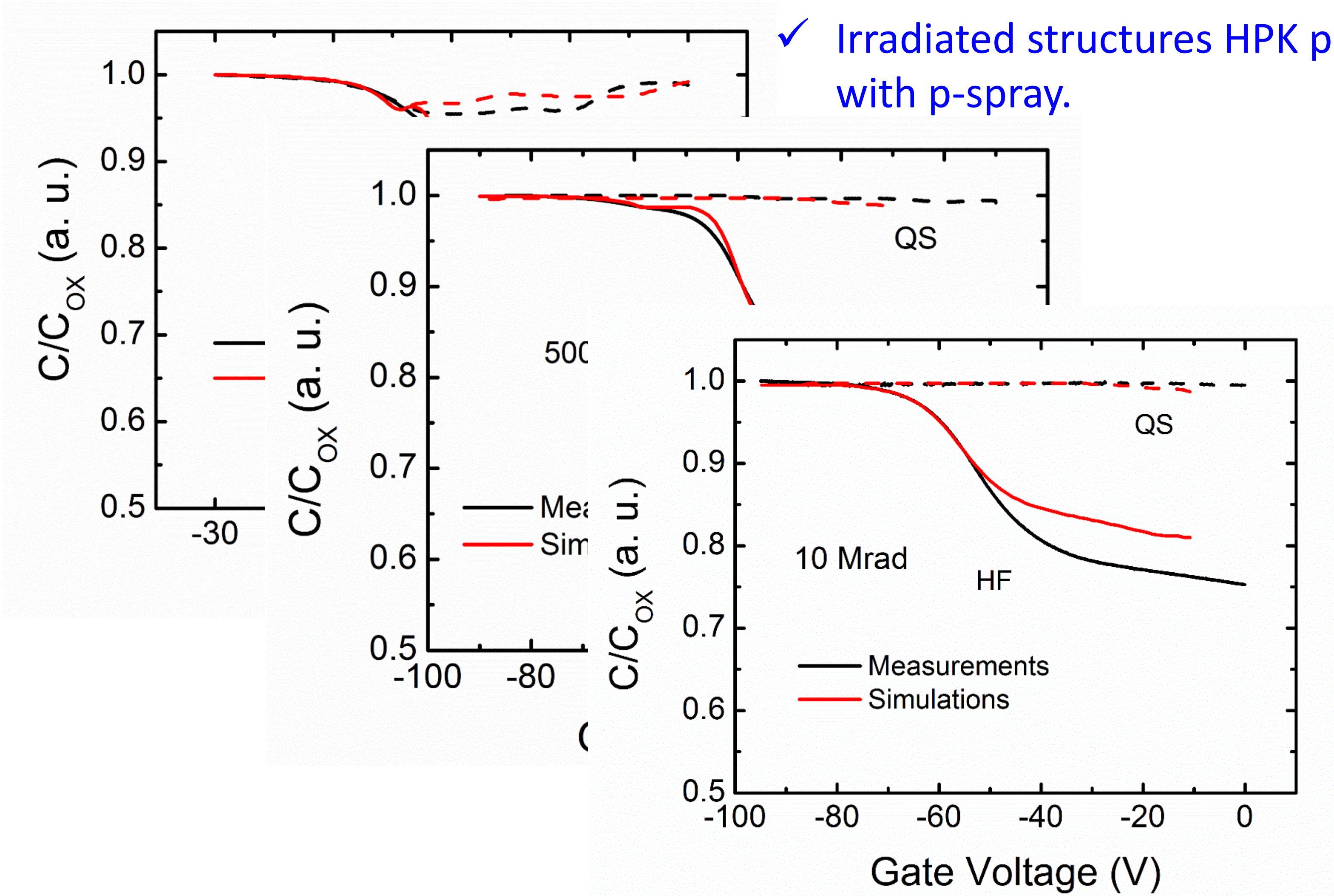
- ✓ Irradiated structures IFX PS-S 2nd campaign.
- ✓ Low N_{OX} at low doses
- ✓ Higher N_{IT}

HPK p-type MOS capacitors: simulations



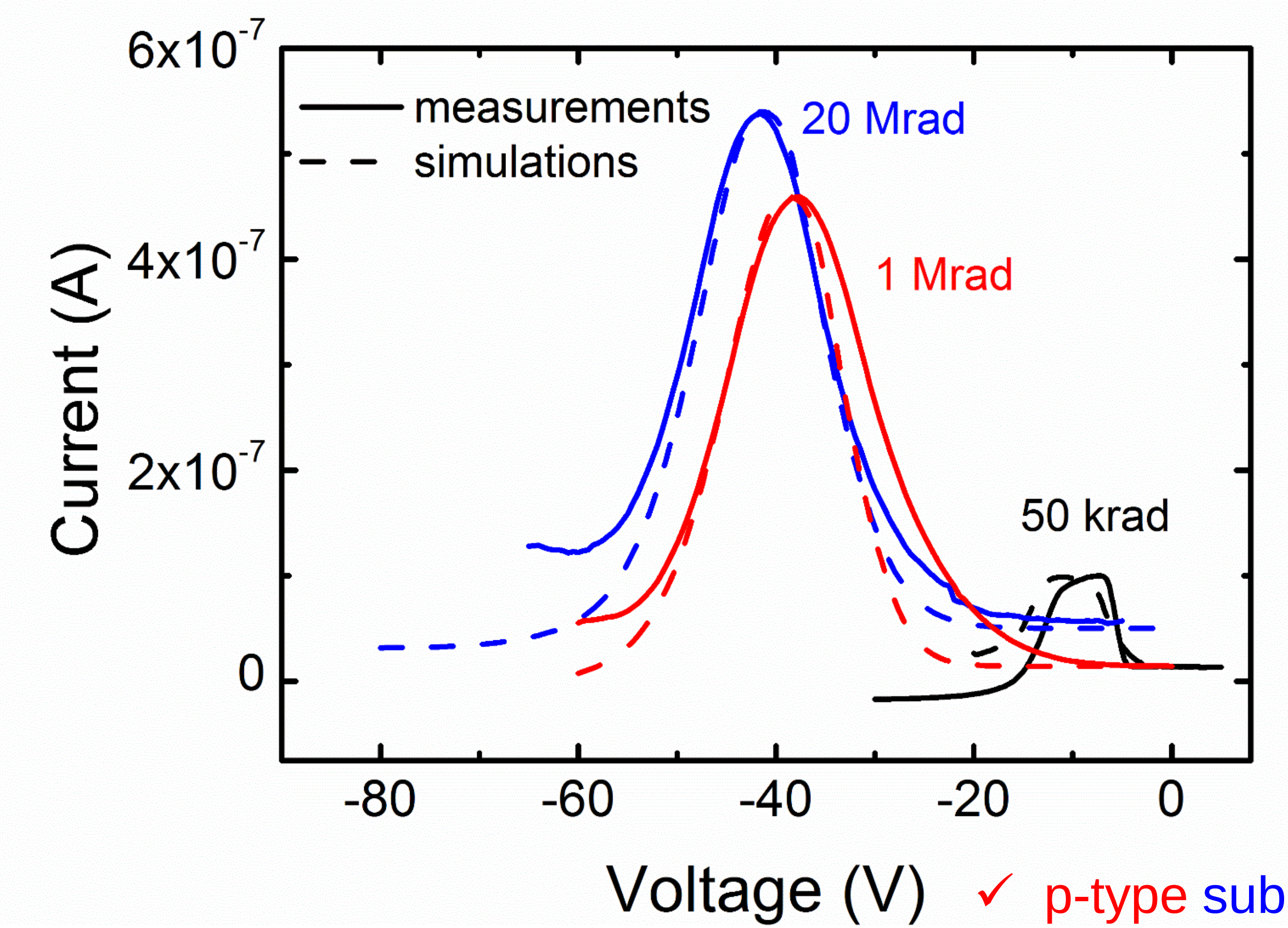
- ✓ Irradiated structures HPK p-type without p-spray.
- ✓ C-V measurements compared to simulations at different doses.
  - → Using the same model with measured N_{OX} and N_{IT} good agreement between simulation and experimental data

HPK MOS capacitors with p-spray: simulations



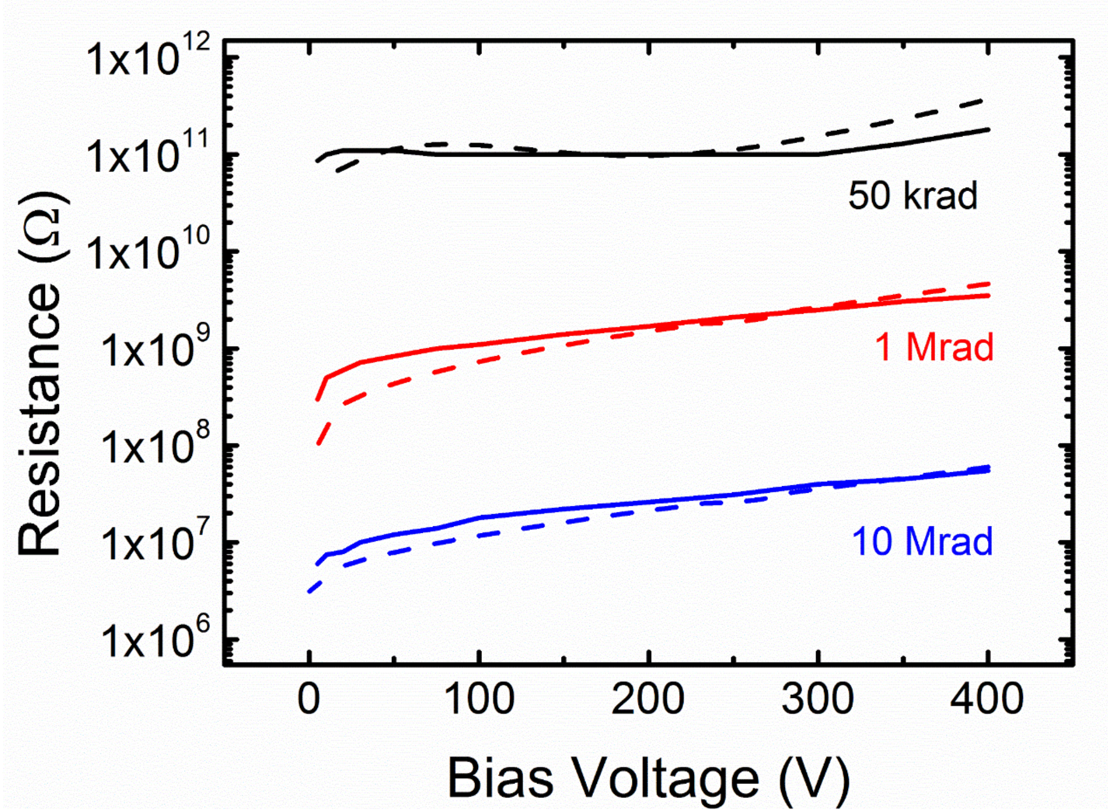
- ✓ Irradiated structures HPK p-type with p-spray.

Gated diodes



- ✓ p-type substrate
- ✓ Irradiated structures IFX p-type.

Interstrip resistance HPK



Good agreement using the same model used to simulate MOS capacitors

Conclusions

- ✓ Extensive measurements campaign on 5 different IFX and HPK n-on-p test structures before and after irradiation with X-rays.

- ✓ Surface radiation damage effects have been deeply investigated aiming at the extraction of the most relevant parameters:
  - ✓ cross-check of N_{OX}, N_{IT}, D_{IT} evaluated by different methodologies from different test structures, for different vendors (HPK and IFX) and different processes.

- ✓ Development of the radiation damage modelling scheme, suitable for commercial TCAD tools (e.g. Synopsys Sentaurus), with a good agreement between measurements and simulations

- ✓ Application to the analysis and optimization of different classes of silicon detectors to be used in the future HEP experiments.

Future developments

- ✓ Bias the IFX and HPK devices during X-rays irradiation
- ✓ Irradiate new HPK batches FZ290 and thFZ240
- ✓ Irradiate test structures first with X-rays and then with neutrons to combine surface and bulk damage

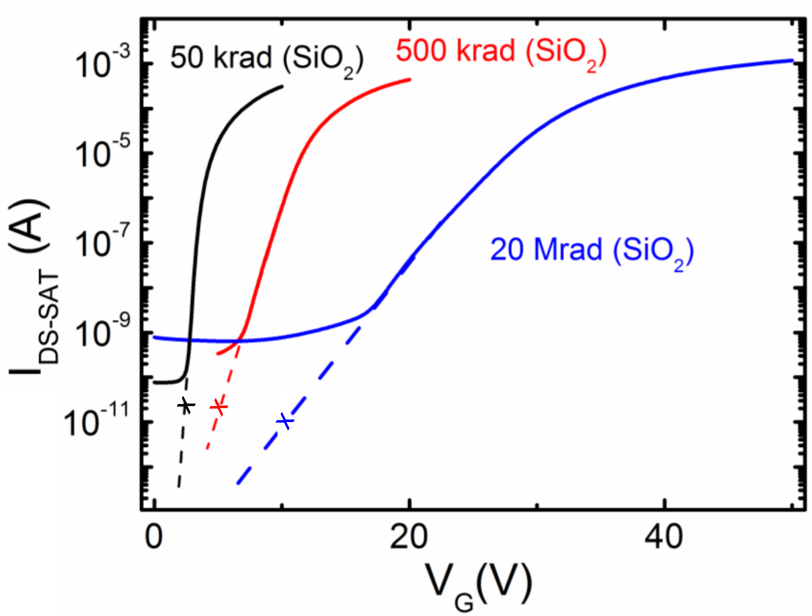
Backup slides

FBK - MOSFETs

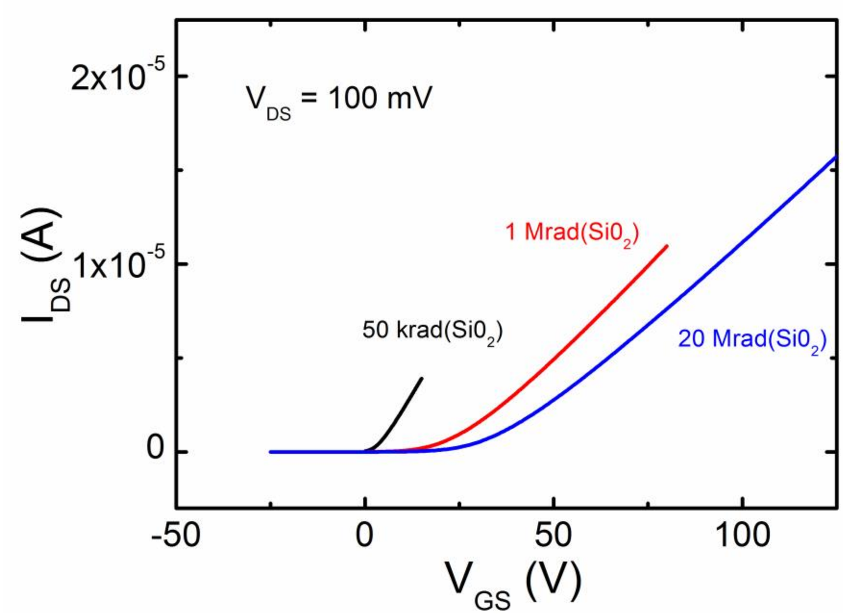
- V_{th} = -0.8 ÷ 0.1 V (unirradiated)
- Unbiased devices during the irradiation steps
- Radiation → interface traps (N_{IT}) + trapped-oxide (N_{OX}) → V_{th} shift (ΔV_{th}).
- ΔV_{th} is separated into a contribution due to N_{IT} and due to $N_{OX,}$ from I_{DS}-V_{GS} of MOSFET (method proposed in McWorther Applied Physics Letters 48, 133 (1986))

$$\Delta V_{th} = \Delta V_{N_{it}} + \Delta V_{N_{ox}}$$

pMOSFET

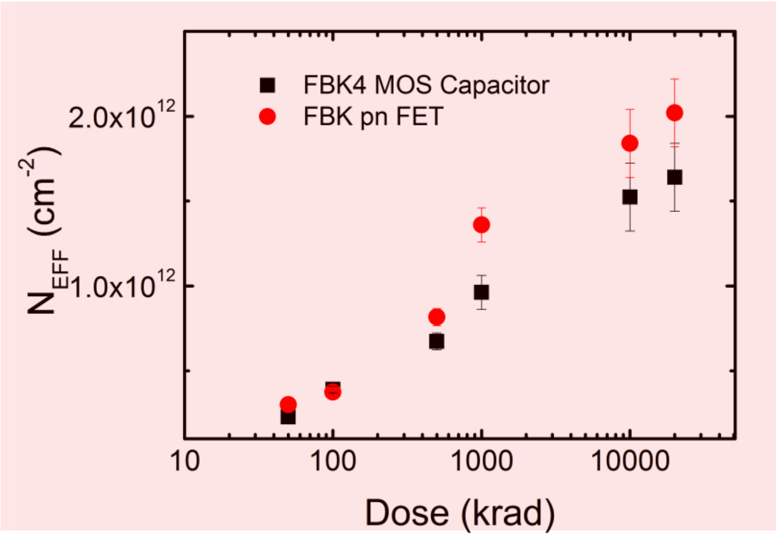


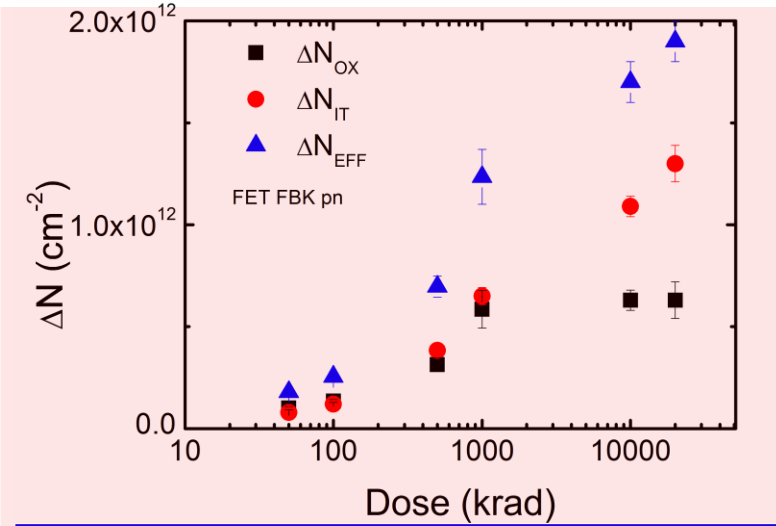
nMOSFET



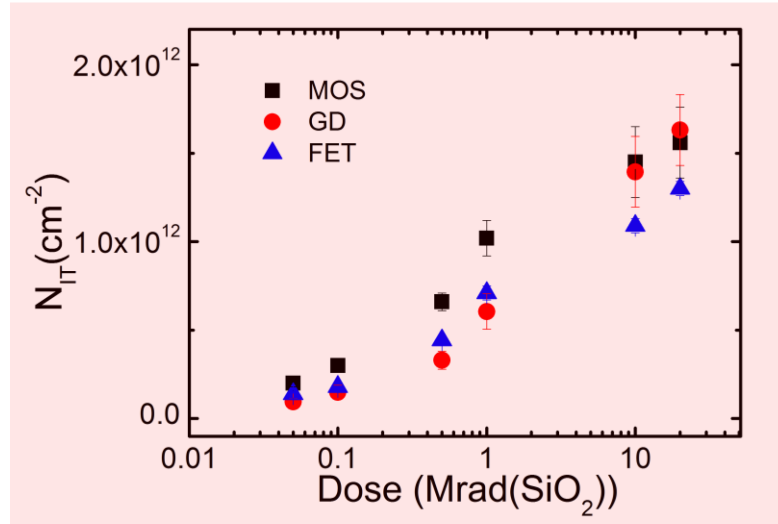
FBK Summary of measurements – p-type

Effective oxide charge density (N_{EFF})





Integrated interface trap density (N_{IT})

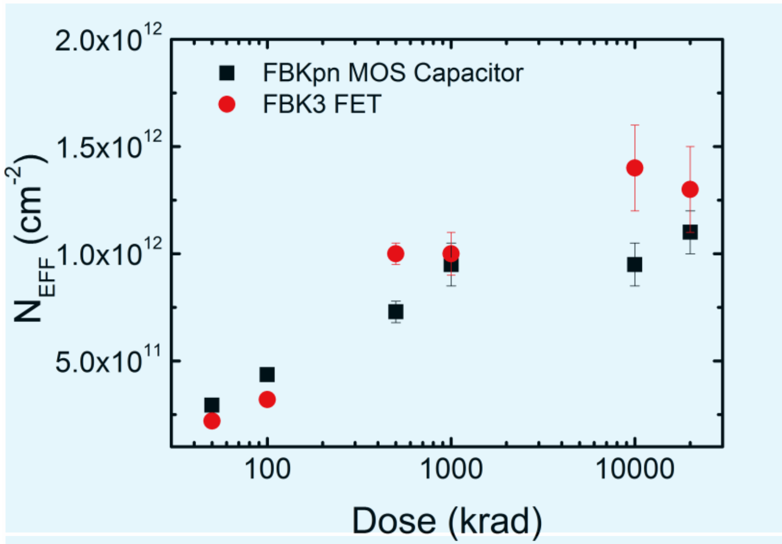


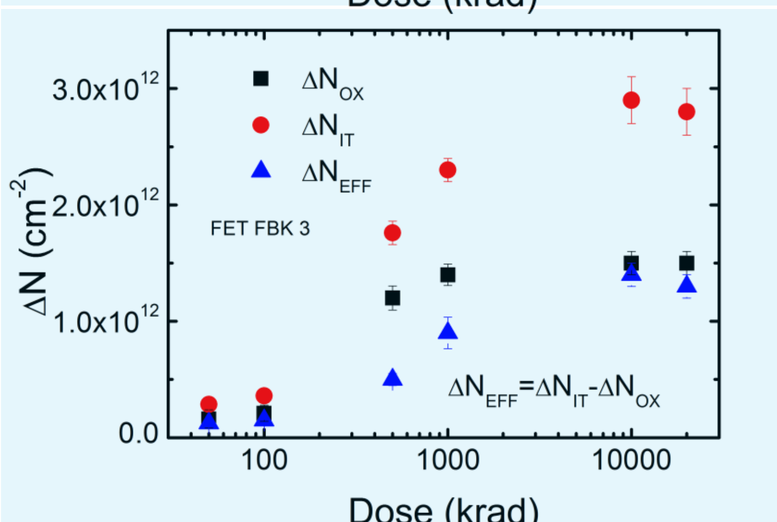
Describe the Donor trap state characterisics

as INPUT PARAMETERS to the TCAD tool

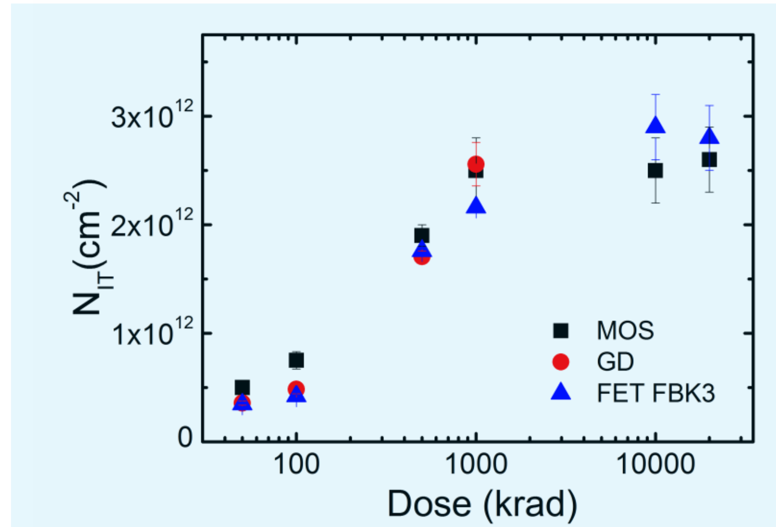
FBK Summary of measurements – n-type

Effective oxide charge density (N_{EFF})





Integrated interface trap density (N_{IT})



Describe the Acceptor trap state characterisics

as INPUT PARAMETERS to the TCAD tool

Two different irradiation conditions: without/with biasing the devices.