Measurements of Total Ionizing Dose Effects in TPSCo 65 nm and Influence of NMOS Bulk Bias

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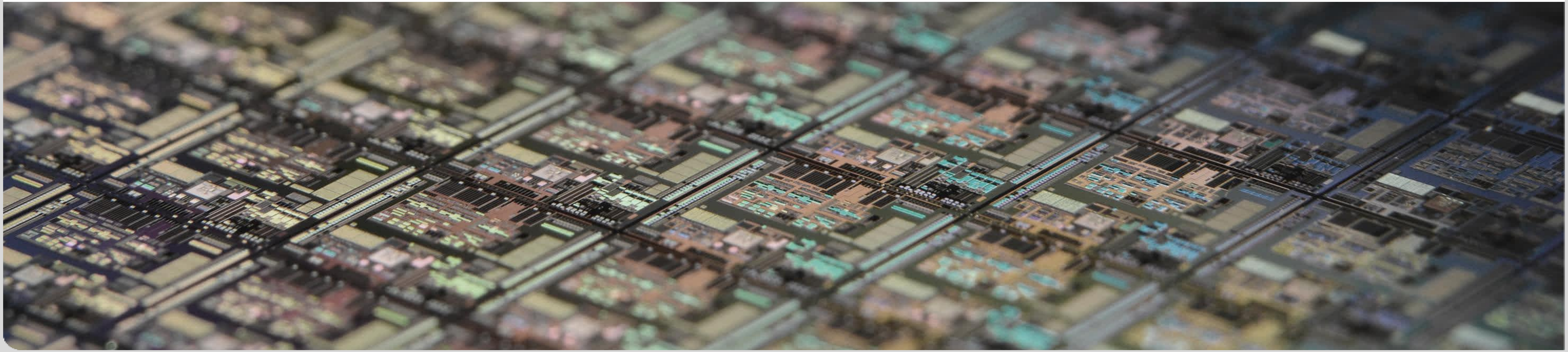
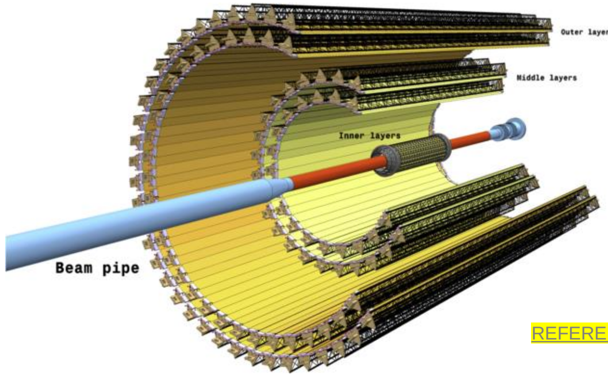
EP-ESE-EME



Context

- **CERN EP R&D WP1.2**
  - First candidate chosen **TPSCo 65 nm ISC technology**
  - Develop new monolithic pixel sensors for CERN experiments (i.e. ALICE ITS3)



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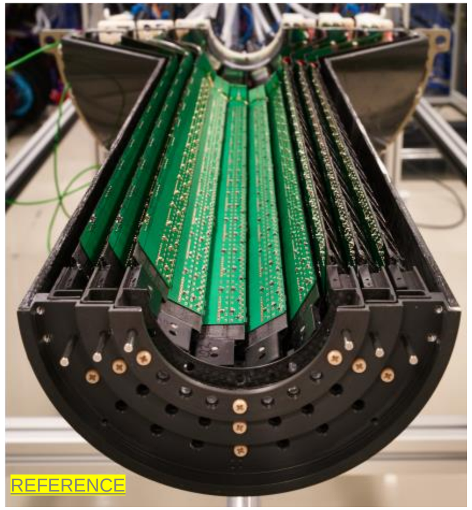

ALICE ITS2 UPGRADE

Inner detector with polygonal shape

REFERENCE

ALICE ITS3 UPGRADE *IN PROGRESS*

Inner detector with fully cylindrical shape

Context

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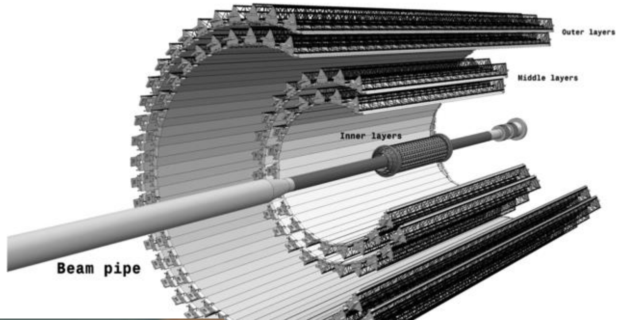
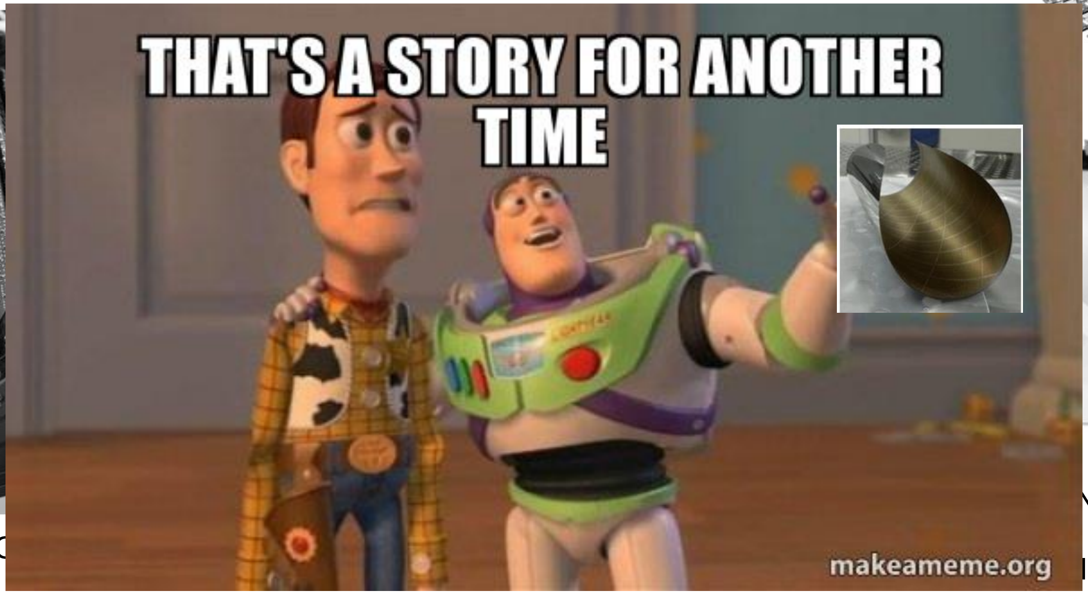
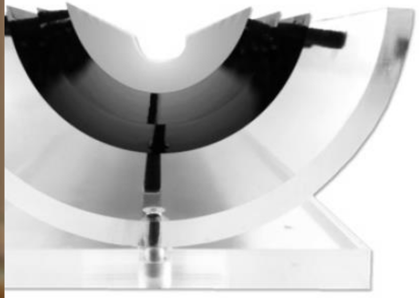


ALICE ITS2 UPC

Inner detector with polygonal shape



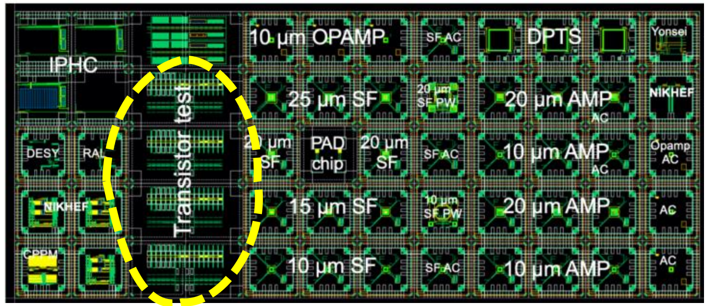


N PROGRESS*

lindrical shape

Expected Total Ionazing Dose (TID) of 1 Grad SiO_2

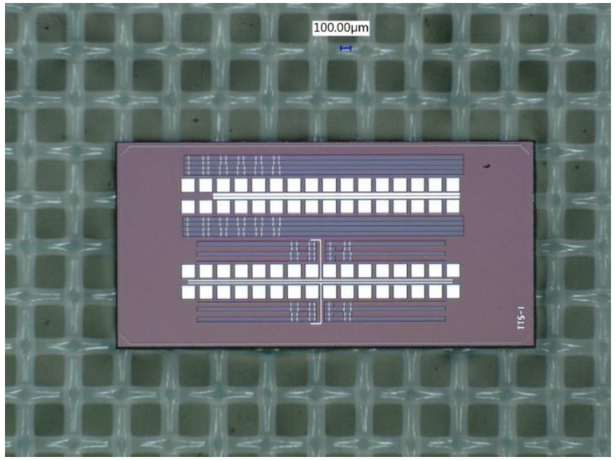
TPSCo 65 nm transistors characterization



Layout submitted with TTS

- **Objective: to offer a preliminary characterization of this technology to the designers**
  - TTS (Transistor Test Structures): for process verification
  - TTS chips contain arrays with different transistor sizes from this technology

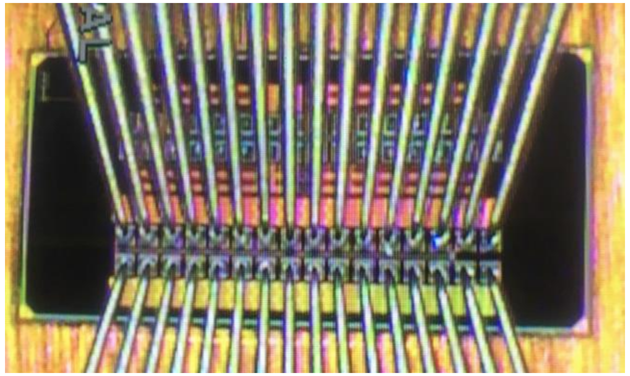
They came back from the foundry!



TTS1 with 1.2 V core transistors

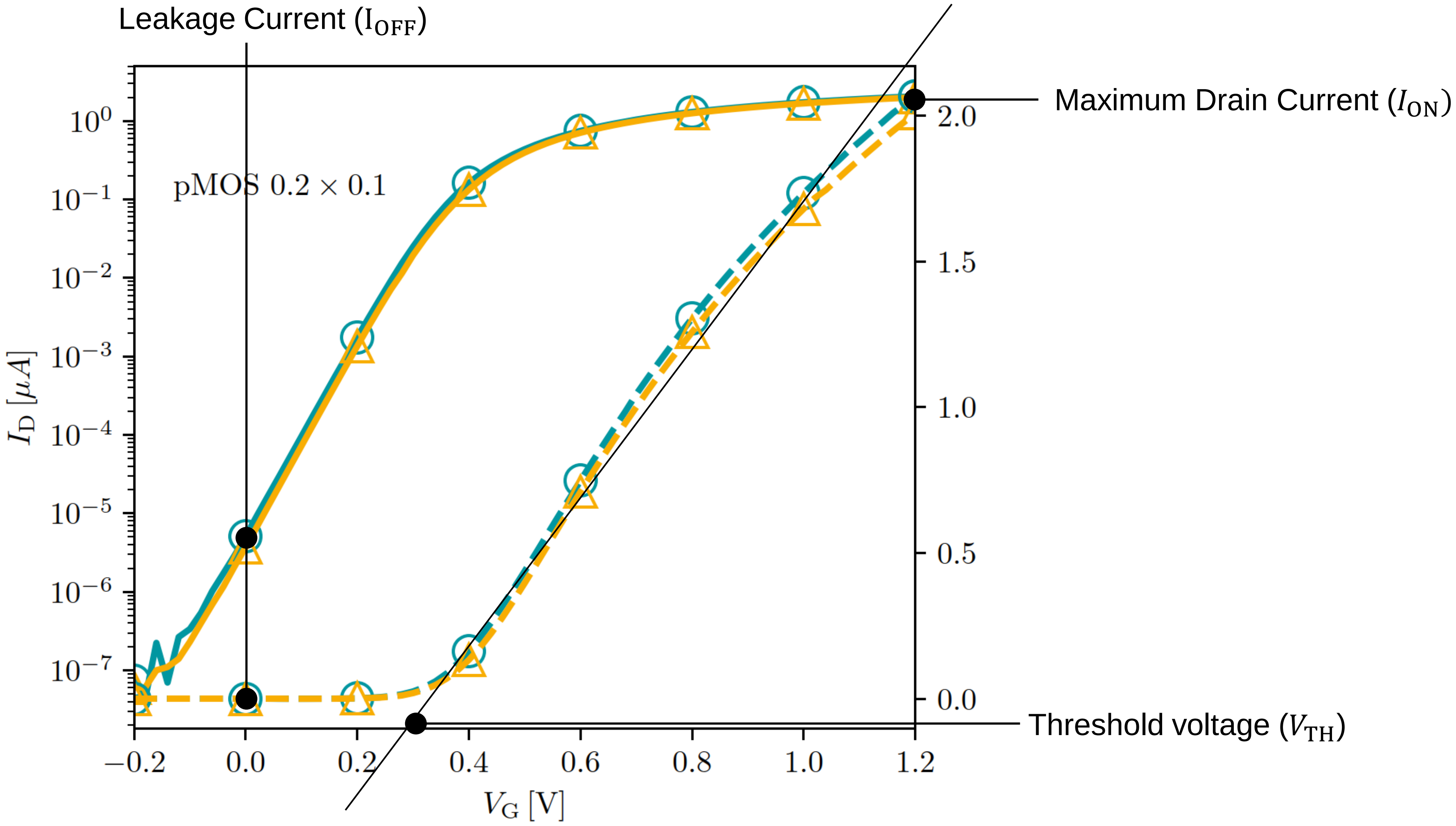
Probing station

Needles connected to the TTS pads



Now we can bias gate, source, drain and bulk, and we can measure!

The I_D vs. V_G measurements: Definition of I_{ON}, V_{TH}, I_{OFF}

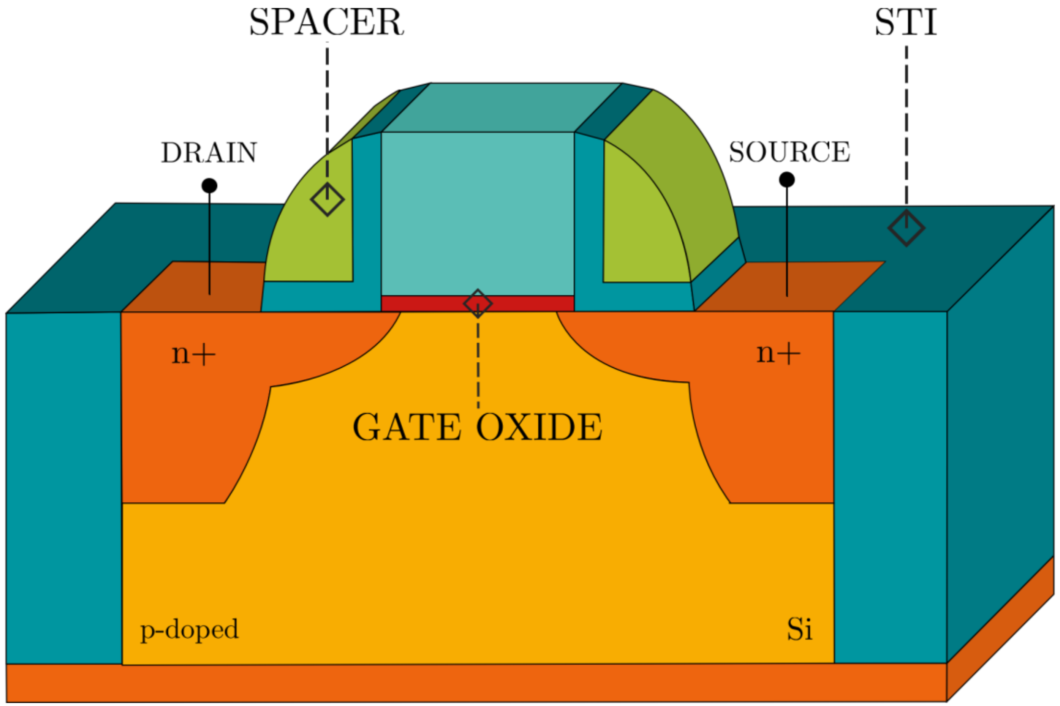


RESULTS FROM IRRADIATION MEASUREMENTS

Why irradiating the transistors?

Main known radiation-induced effects in modern planar CMOS technologies:

- **RISCE (Radiation-Induced Short Channel Effects):** Due to positive charges accumulating at the **spacers**
- **RINCE (Radiation-Induced Narrow Effects):** Due to positive charges accumulating at the **Shallow Trench Isolation (STI)**
- **Radiation-Induced Leakage Current:** Due to positive charges accumulating at the **STI of the nMOS** during OFF state

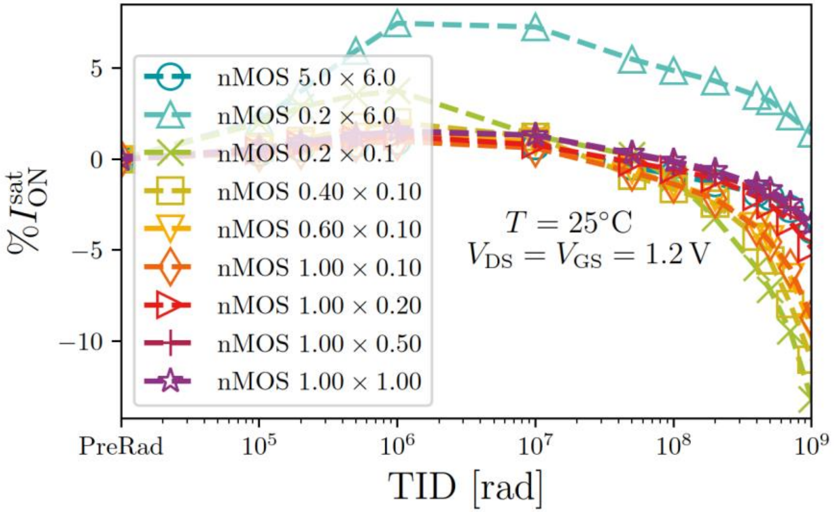


Expected Total Ionazing Dose (TID) of 1 Grad SiO_2

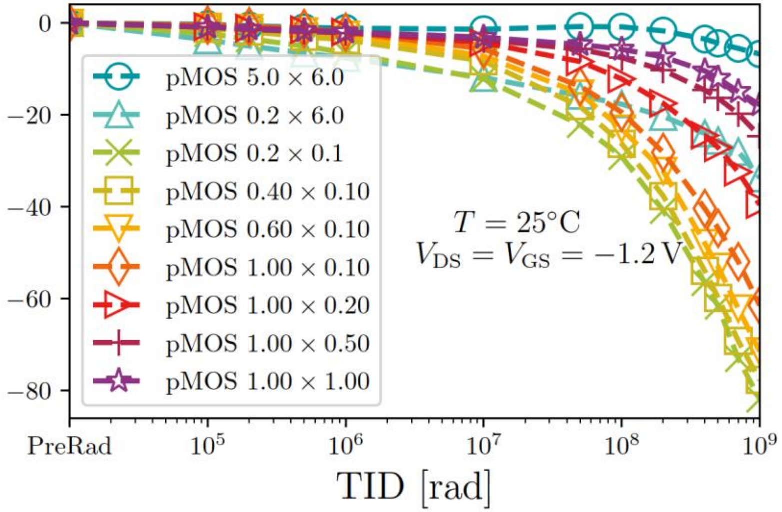
We need to make sure that TPSCo 65 nm behaves like previous 65 nm technologies from other manufacturers

Measurements up to 1 Grad TID (SiO_2): I_{ON} Degradation

nMOS



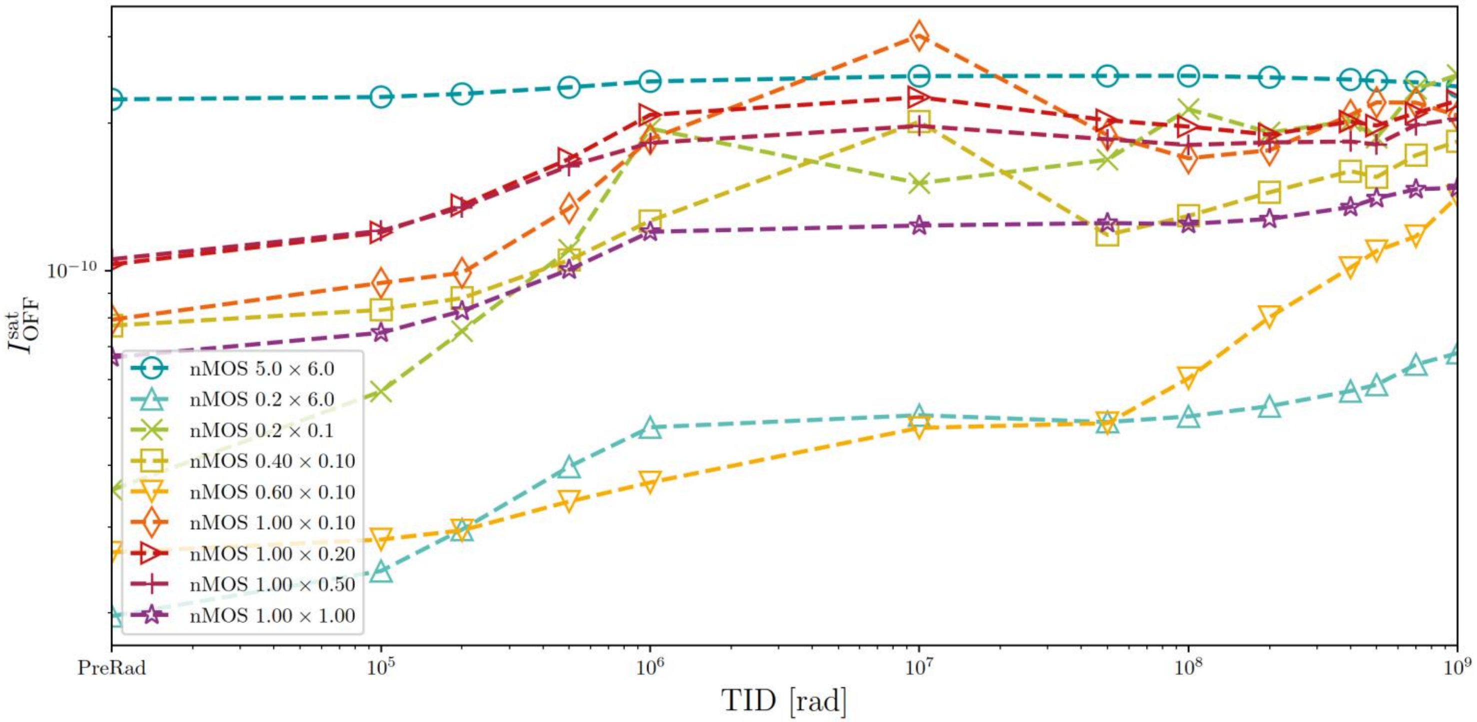
pMOS



✓ This degradation is comparable with other 65 nm technologies

- Up to **80% drop of I_{ON}^{sat}** delivered by the pMOS. Channel length dependence
- Up to **15% degradation of I_{ON}^{sat}** of the nMOS

Measurements up to 1 Grad TID (SiO_2): Radiation Induced Leakage Current



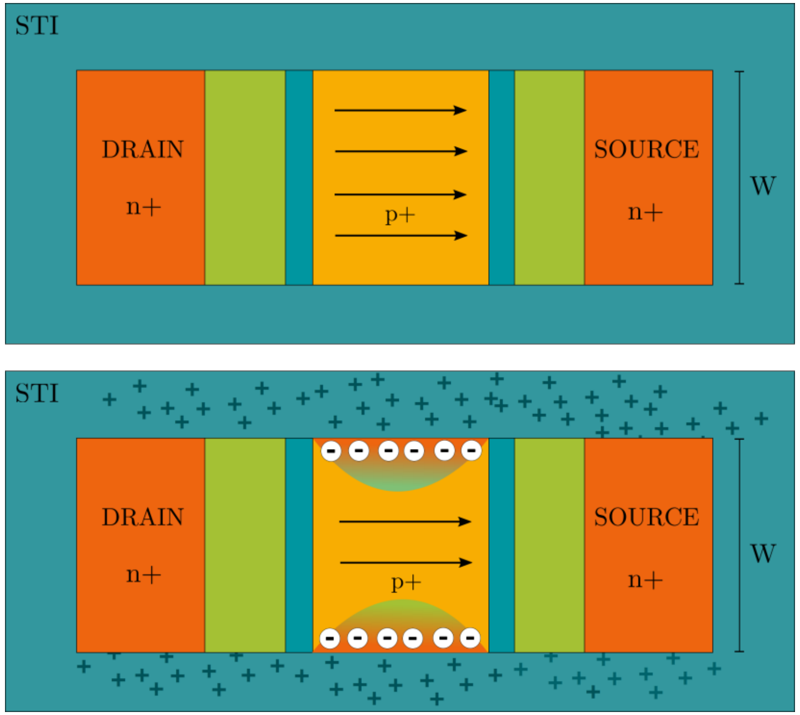
- ✓ Robustness of this node regarding radiation-induced leakage current. I_{OFF}^{sat} increase below one order of magnitude

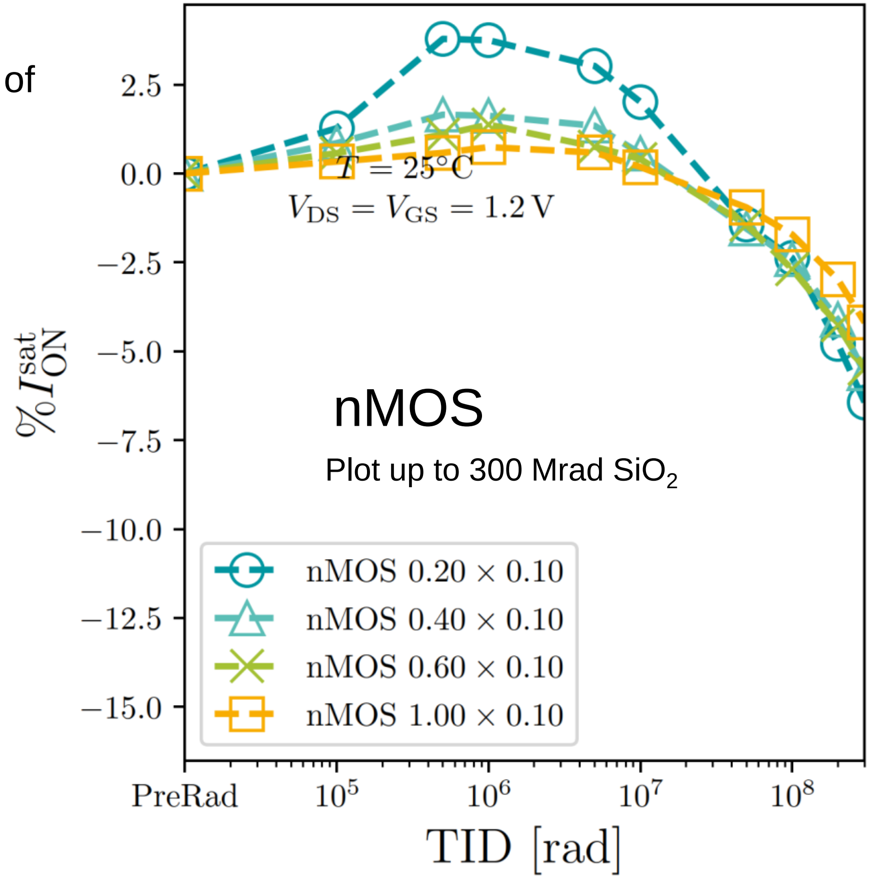
Radiation-Induced Narrow Channel Effects (RINCE): nMOS

1. Beginning of irradiation: positive charges accumulate at the STI lowering V_{TH} and increasing $I_{\mathrm{ON}}^{\mathrm{sat}}$.
2. Increasing TID, negative charges accumulate at STI/Si compensating the effect of trapped holes and degrading $I_{\mathrm{ON}}^{\mathrm{sat}}$

Before irradiation

During irradiation





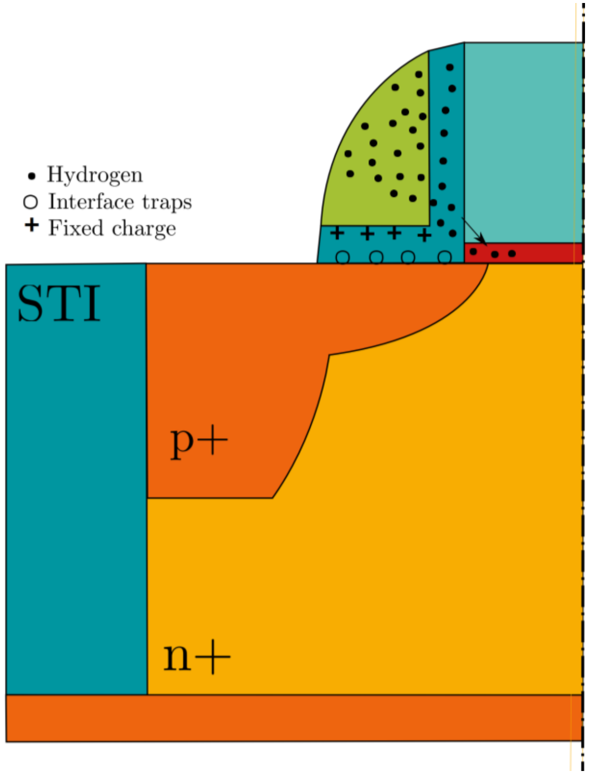
nMOS

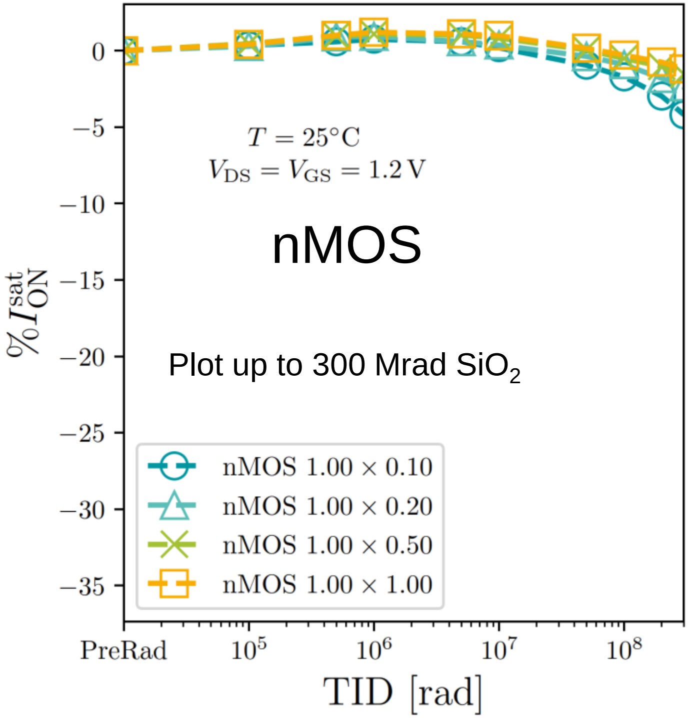
Plot up to 300 Mrad SiO_2

Radiation-Induced Short Channel Effects (RISCE)

RISCE is characterized by:

1. During irradiation: increase of series resistance on the sides of the channel
2. During annealing: V_{TH} shift due to the transport of H+ ion in the gate oxide

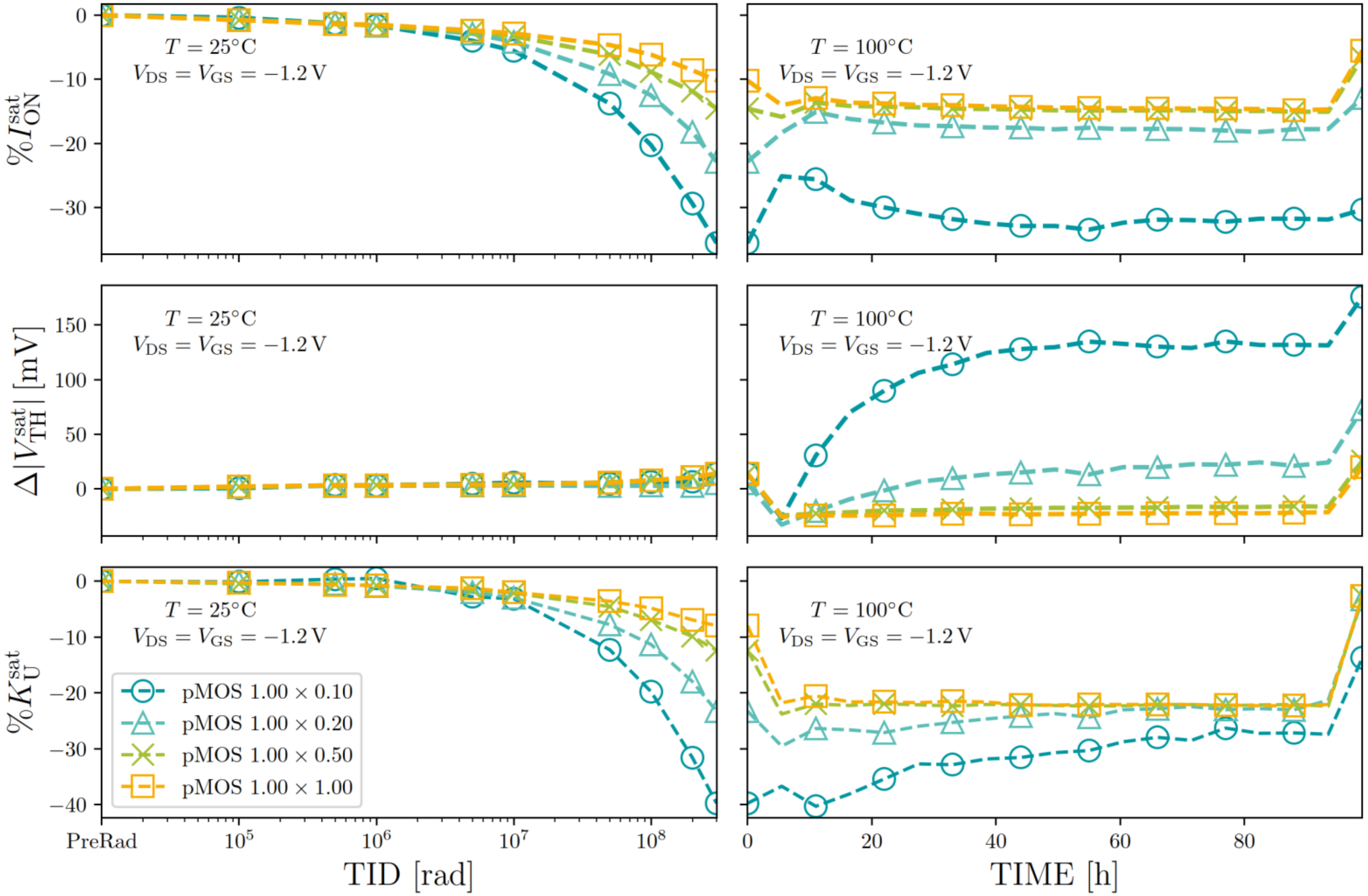




Plot up to 300 Mrad SiO_2

Radiation-Induced Short Channel Effects (RISCE): pMOS

Plot up to 300 Mrad SiO_2

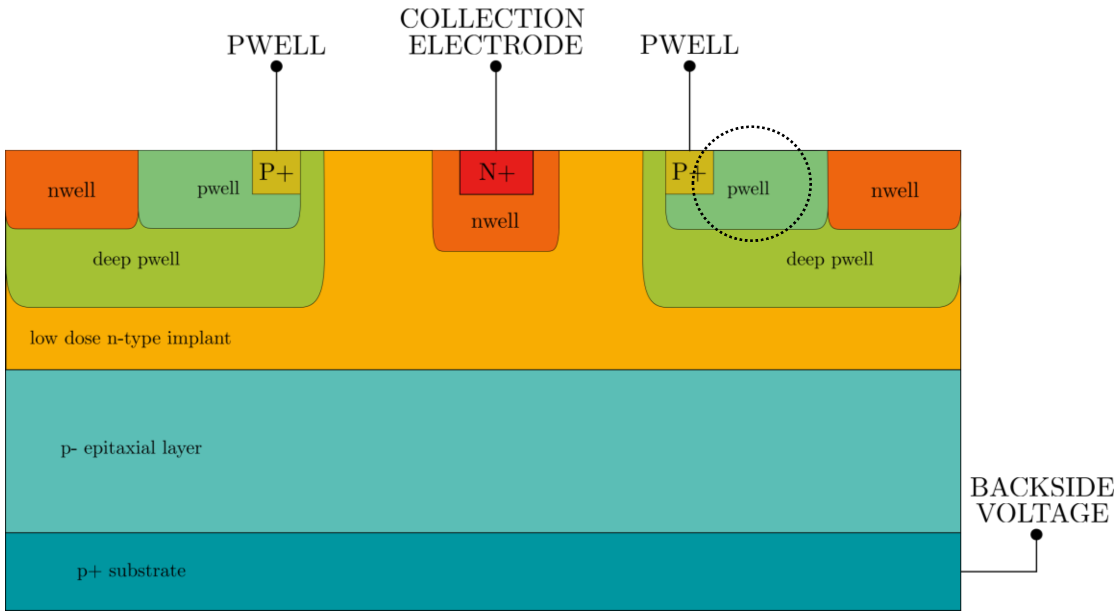


Last points after annealing at room temperature

$$K_{\mu} = \frac{\mu_{\mathrm{n}} C_{\mathrm{OX}}}{2} \frac{W}{L}$$

RESULTS FROM NMOS BULK BIAS MEASUREMENTS

Why nMOS Bulk Bias?



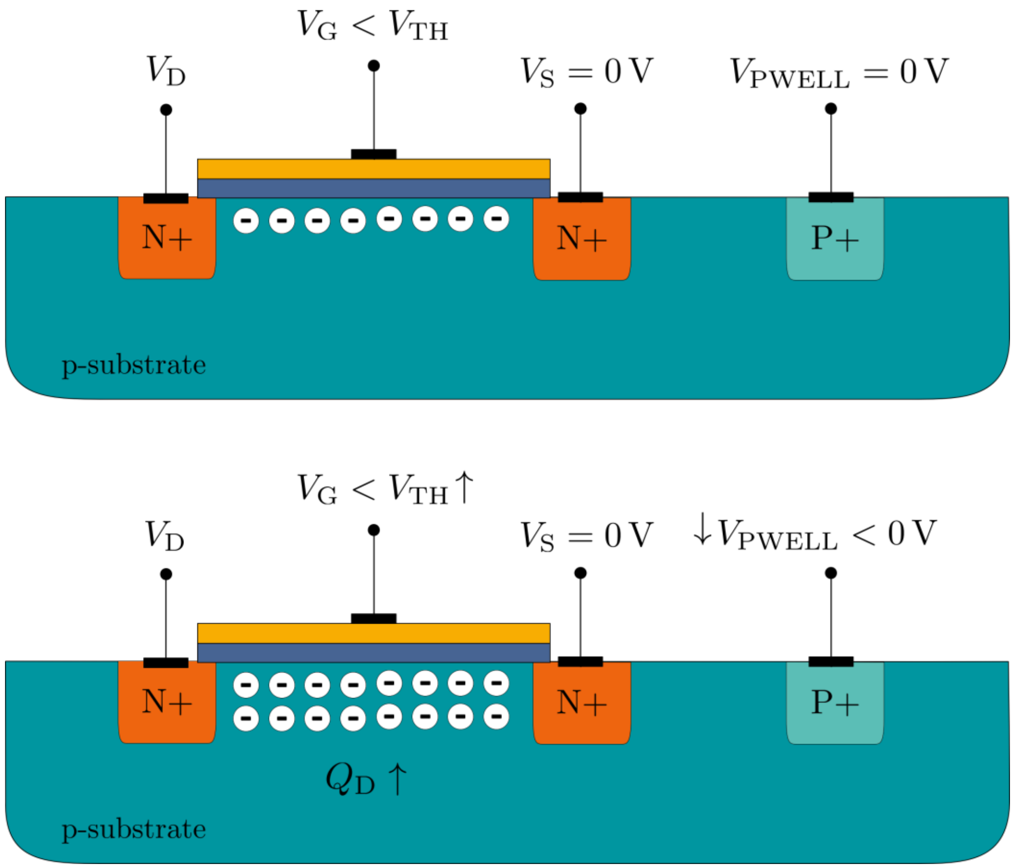
- nMOS on the pixel matrix have their bulk (PWELL) and substrate (BACKSIDE VOLTAGE) biased down to -6 V
- This allows to enhance the depletion and the detection but **there is a side consequence** → **BODY EFFECT**
- This study aims to analyse the behaviour of nMOS transistors at an unusual operating point at which the models provided by the foundry are not longer valid.

The Body Effect

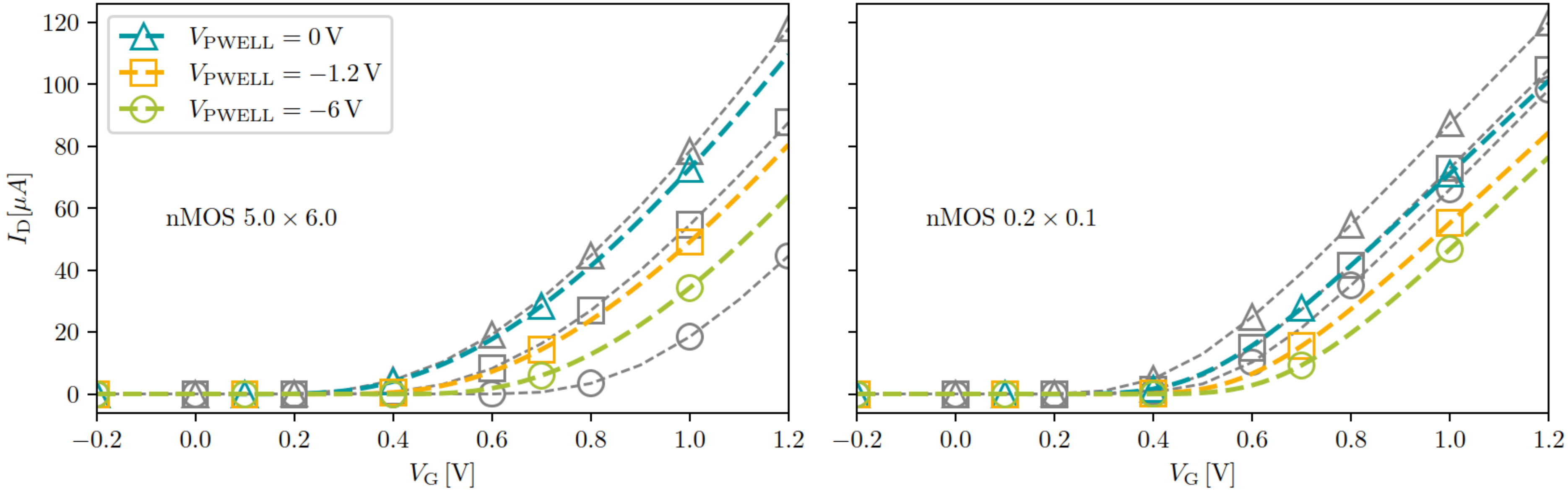
- As $V_{\mathrm{PWELL}} < 0\ \mathrm{V}$, the depletion region becomes wider → charge at the depletion region (Q_{d}) increases
- The charge at the gate must mirror Q_{d} to create inversion layer
- V_{TH} increases following Q_{d}:

$$\mathrm{V}_{TH} = V_{TH0} + \gamma \left(\sqrt{2\,\phi_F + V_{SPWELL}} - \sqrt{|2\,\phi_F|} \right)$$

- V_{G} increases to create inversion layer



Measurements at Different Biases and Comparison with Simulation



1. Measurements of nMOS transistors with V_{PWELL} = -6 V show an **increase of the nominal V_{TH} of ~260 mV** together with a **~40% drop of I_{ON}^{sat}**
2. ***V_{TH}* shift is overestimated for maximum size** devices and **underestimated for minimum size devices**
3. In both cases **not accurate at large reverse biases**

Conclusion

✓ Irradiation response like other 65 nm technologies from other manufacturers

- Up to 1 Grad (SiO_2): max. ~15% I_{ON}^{sat} drop for nMOS and max. ~80% I_{ON}^{sat} drop for pMOS
- Up to 300 Mrad (SiO_2) and subsequent 100°C annealing: presence of RISCE and RINCE. V_{TH} shift of 200 mV and $K_{\mathrm{U}}^{\mathrm{sat}}$ recovery after annealing at 25°C
- Radiation Induced Leakage Current increase less than one order of magnitude

‼ Large negative bulk biases induce an important body effect

- Simulation with TYP corner not accurate at large reverse biases (error w.r.t. the simulation reaches ~160 mV)
- Measurements of nMOS transistors with V_{PWELL} = -6 V show an increase of the nominal V_{TH} of ~260 mV

THANK YOU!

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Definition of $\%I_{\mathrm{ON}}$, V_{TH}, $\mathrm{I_{OFF}}$, K_{μ}

Variation of Maximum Drain Current ($\%I_{\mathrm{ON}}$)	$\%I_{\mathrm{ON}}(TID) = 100\,\frac{I_{\mathrm{ON}}(TID) - I_{\mathrm{ON}}(TID = 0\ \mathrm{rad})}{I_{\mathrm{ON}}(TID = 0\ \mathrm{rad})}$
Threshold voltage (V_{TH})	Defined as necessary V_{GS} to create conducting channel between drain and source. Extracted from IDVG measurements using linear extrapolation method
Leakage Current ($\mathrm{I_{OFF}}$)	Defined as the measured I_{D} current when $V_{\mathrm{G}} = 0\ \mathrm{V}$ (transistor OFF) and $V_{\mathrm{DS}} > 0$
Transconductance (K_{μ}) *in saturation*	$K_{\mu} = \frac{\mu_{\mathrm{n}} C_{\mathrm{OX}}}{2} \frac{W}{L}$ Extracted from IDVG measurements as the derivative of $\sqrt{I_{\mathrm{D}}^{\mathrm{sat}}}$