Studies of surface radiation damage with CMS HGCAL test diodes

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4th DRD3 week on Solid State Detectors R&D
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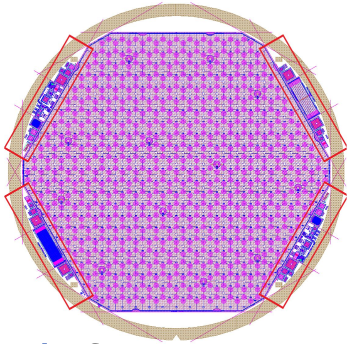
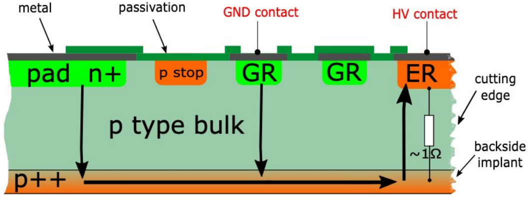
E. Fialova et al, “Novel method to assess the electromagnetic radiation damage using HGCAL silicon sensors”,
10.1088/1748-0221/20/07/C07061

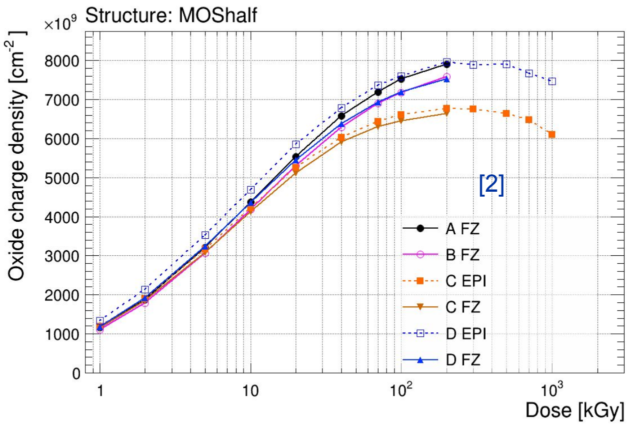
CMS HGCAL - Si sensors





Figures by Peter Paulitsch

- **High Granularity Calorimeter (HGCAL)**: forward sampling calorimeter for HL phase 2 of the LHC [1]
- HGCAL will feature 8'' hexagonal *n*-on-*p* type Si sensors (Hamamatsu)
- Test structures printed on the cutted edges from the circular wafer, used to perform destructive tests
- **X-ray irradiation:** studies of EM radiation damage in **SiO_2**
- Preproduction phase multiple oxide variants
- Based on the MOS measurements oxide **Type C** was selected for production [2]

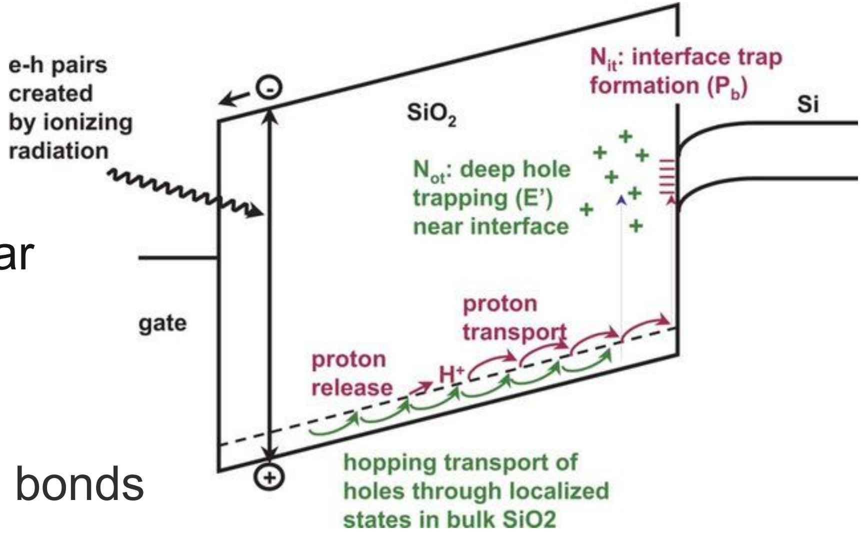


[1]CMS collaboration, The Phase-2 Upgrade of the CMS Endcap Calorimeter.

[2]Matteo Defranchis, "Characterisation of the silicon oxide quality in CMS HGCAL sensor prototypes", presentation at the TRENTO workshop

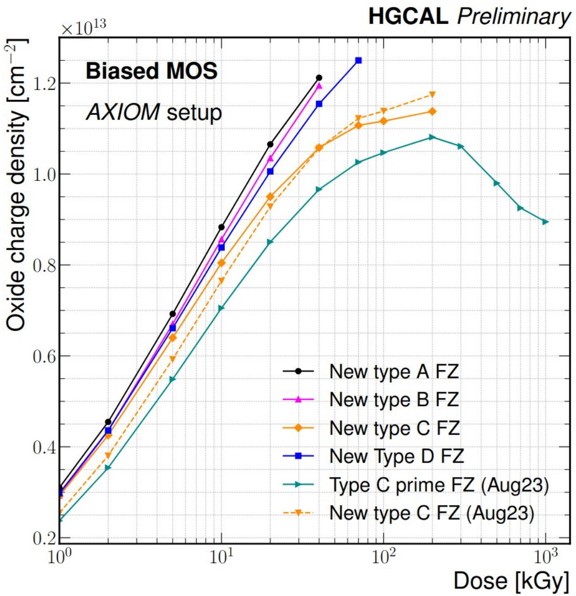
Surface damage from electromagnetic radiation

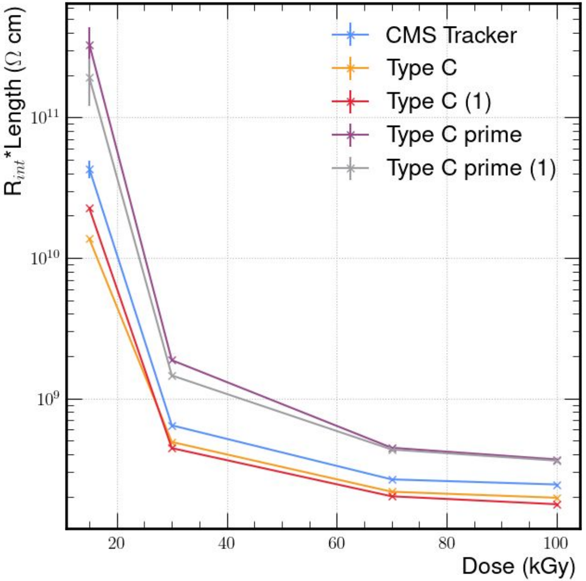
- EM radiation -> e/h pairs in the SiO_2 layer, fraction recombines
- Electrons collected at the electrodes
- Holes slowly diffuse -> can be trapped near the Si/SiO_2 interface
- **Oxygen vacancies**: trapping centers for holes -> **positive oxide charge N_{ox}**
- **Interface traps N_{it}** (**P_b centers**): dangling bonds formed at the Si/SiO_2 interface
- Number of N_{ox} and N_{it} depends on dose, electric field, annealing time and temperature, crystal orientation, and oxide quality



Motivation: interstrip resistance and MOS measurements

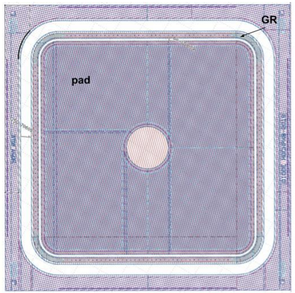
- **Type C prime** oxide: possibly higher quality than Type C
- Measurements of **interstrip resistance (R_{int})** with strip test structures [4]
- Results show no clear preference between different oxide variants due to the difference in *p*-stop concentration
- Need for a new method



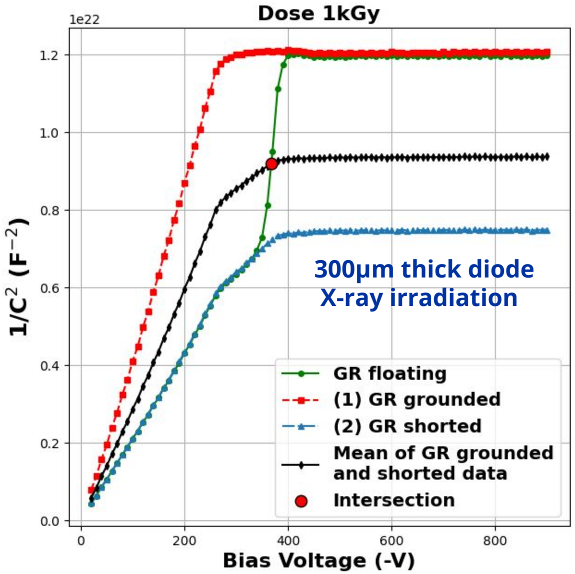


[4]Pablo Alvarez Domínguez, "Comparison of X-ray radiation damage for different oxide types in HGCAL silicon sensors prototypes", presentation at the DRD3 Workshop

Interpad isolation - $V_{th,iso}$



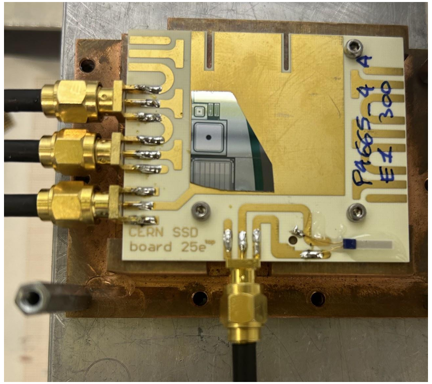
- **Threshold voltage of inter-electrode isolation ($V_{th,iso}$)**: voltage when the *n*+-electrodes become electrically isolated by the influence of applied reverse biased voltage [5]
- Investigation of regions without isolation implants between *n*+-electrodes : **diode pad + guard ring**
- **Better oxide quality -> lower $V_{th,iso}$**

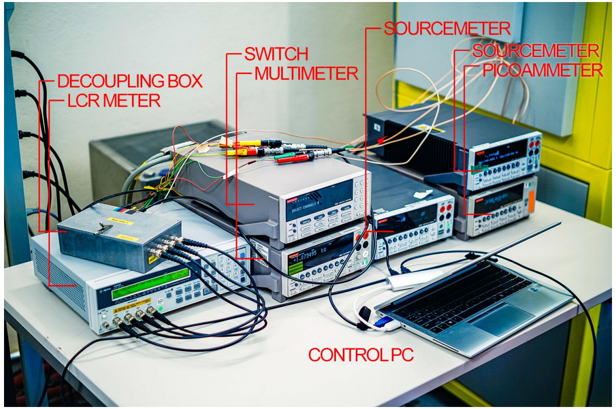


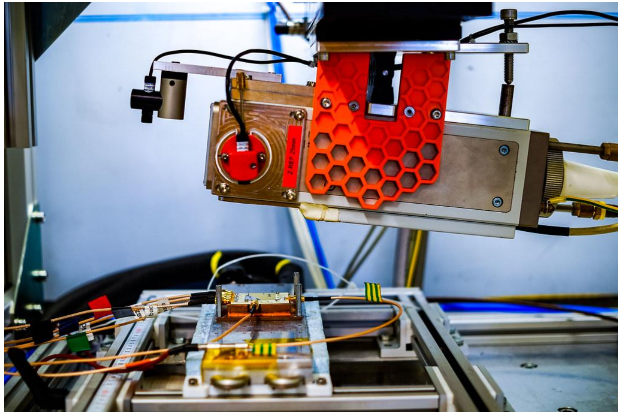
[5] Timo Peltola, "A method to observe field-region oxide charge and inter-electrode isolation from *CV*-characteristics of *n*-on-*p* devices"

X-ray irradiation at CERN

- ObeliX X-ray irradiation system (EP-ESE-ME group)[6]
- Irradiation and measurements at -20°C -> **to avoid annealing**
- Fully automated measurement setup
- Fixed dose rate for all dose steps:
  24.6kGy/h for CV and R_{int}, and 13.1kGy/h for IV measurements



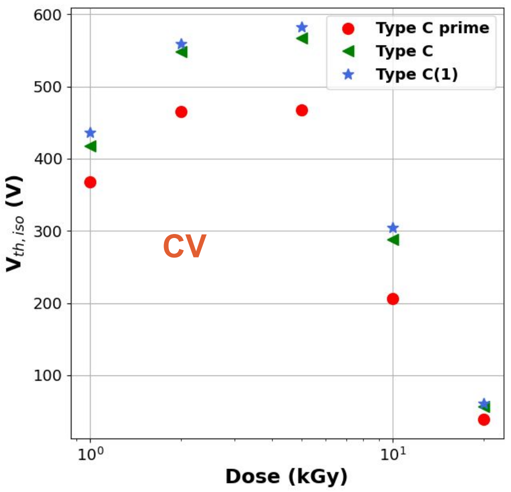


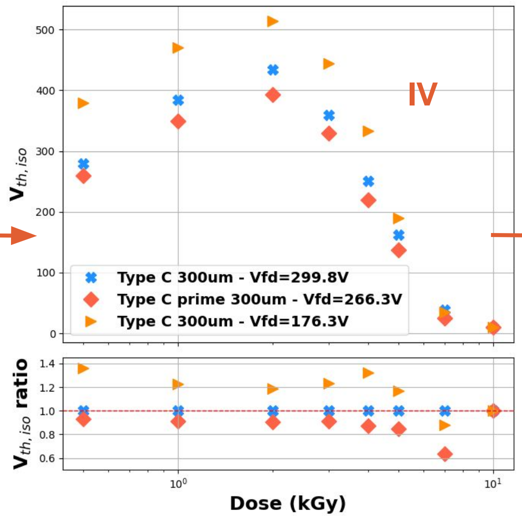


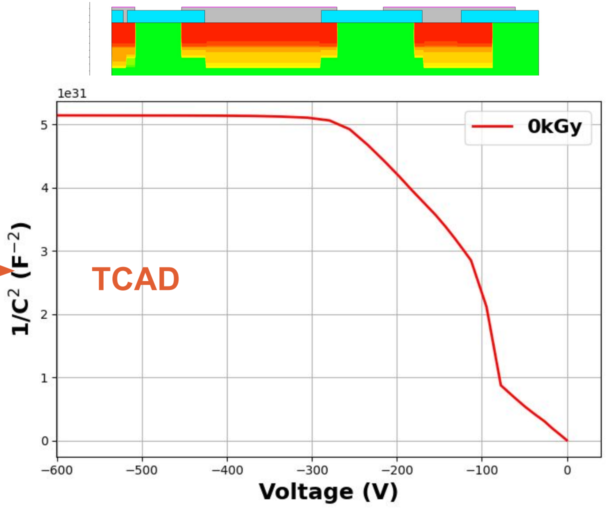
[6] https://ep-ese-me-xray.web.cern.ch/ObeliX/

$V_{th,iso}$ measurements: how the story went

- **Initial approach**: **CV measurements** (GR floating, grounded, and shorted)
- Further investigations-> $V_{th,iso}$ extraction from **IV measurements**
- For full understanding -> **TCAD simulations**

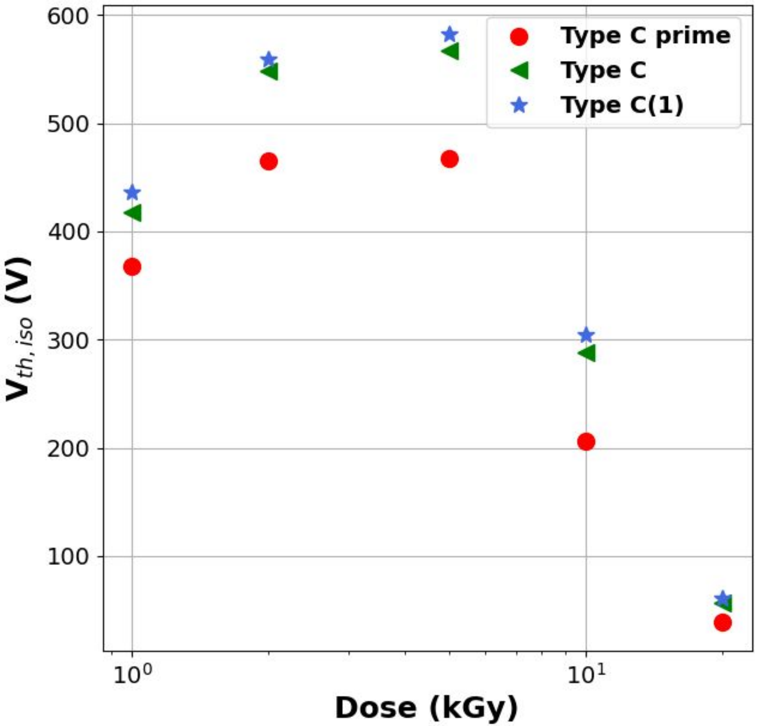






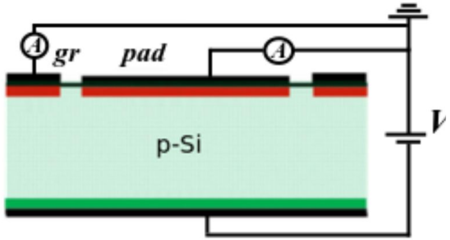
$V_{th,iso}$: CV measurements

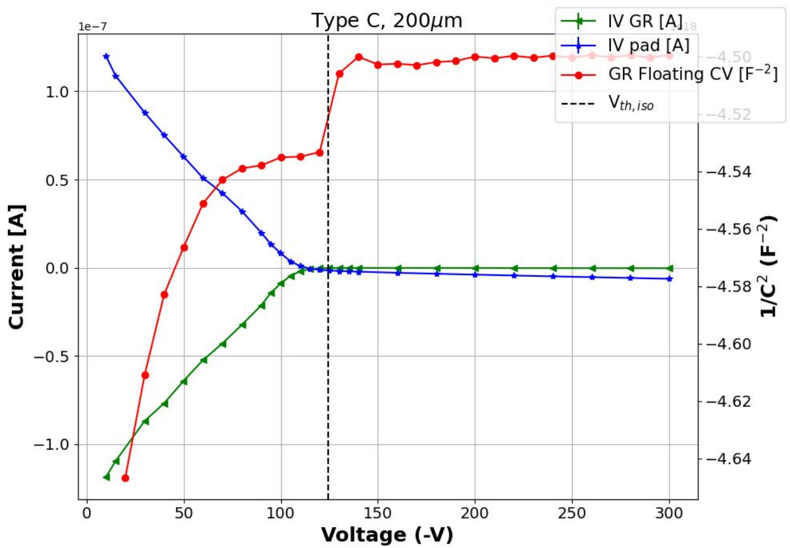
- **Motivation:** method to compare **Type C** and **C prime** oxide
- **C prime lower $V_{th,iso}$**
- Unexpected dependence of $V_{th,iso}$ on dose: **decrease in $V_{th,iso}$** after a peak at 5kGy
- Possible issue: capture and emission rate of $N_{it,acc/don}$ dependent on frequency -> **interpad resistance R_{int}** measurements
- Reproducibility below ≤ 3%



$V_{th,iso}$ - IV measurements

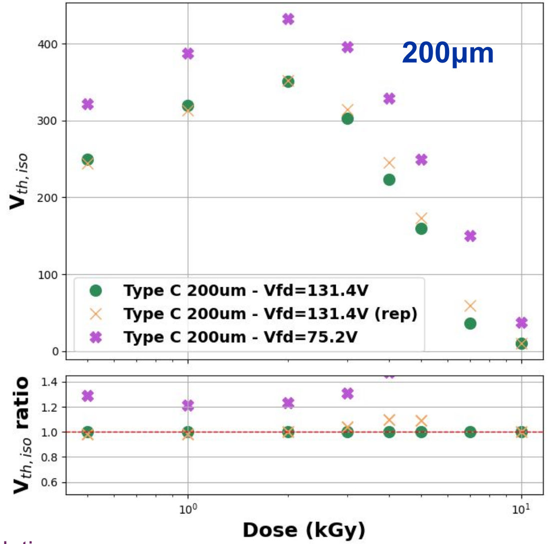
- Robust method to confirm previous results: biasing the backplane and measuring the currents separately from the pad and guard ring
- Point where two curves meet corresponds to $V_{th,iso}$

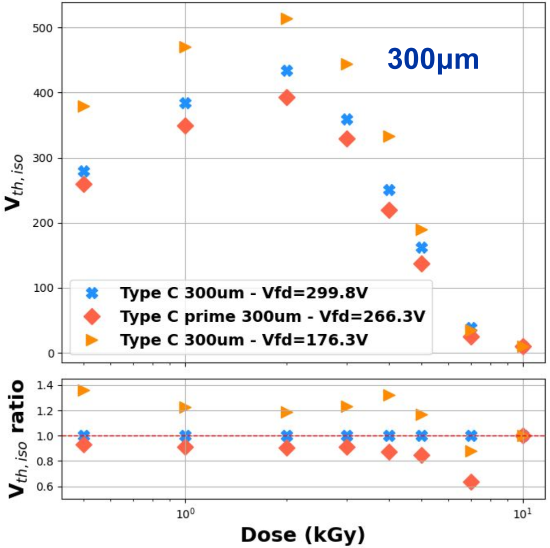




$V_{th,iso}$ - IV measurements

- Type C prime oxide - **lower $V_{th,iso}$** , same as CV results (300um samples)
- New observation: bulk properties before irradiation (V_{fd}) influence the surface properties after irradiation
- Deliberate selection of samples with extreme V_{fd} values [7]
- Results reproducible within less than 10% (200um samples)





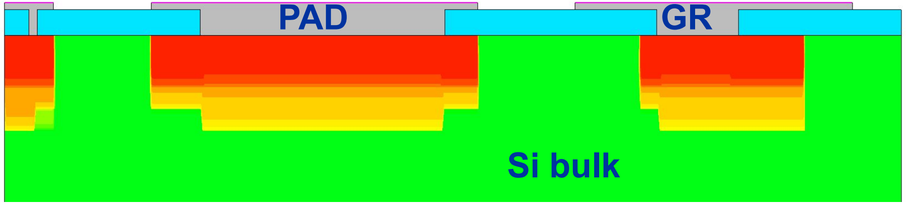
[7]Timo Peltola, Understanding CV-results of test diodes & MOSCAPs of HGCAL production sensors by TCAD simulations

Remaining question

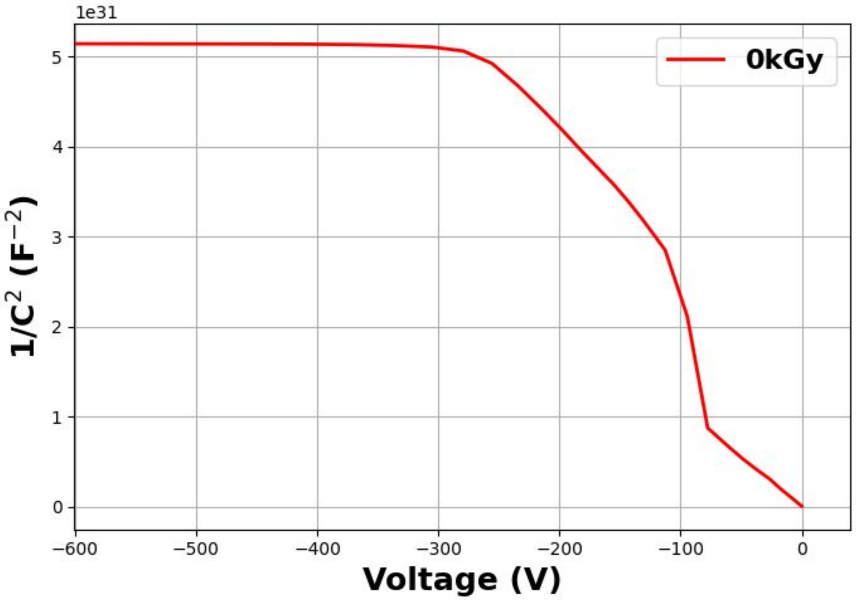
- **Why does $V_{th,iso}$ decrease after a certain dose?**
  - Possible explanation: **difference in the introduction rate of donor-like and acceptor-like interface traps ($N_{it,acc}$ vs $N_{it,don}$)[6]**
- Investigation using Synopsys TCAD simulations

[6]G. Borghello, “Ionizing radiation effects in nanoscale CMOS technologies exposed to ultra-high doses”

TCAD simulations



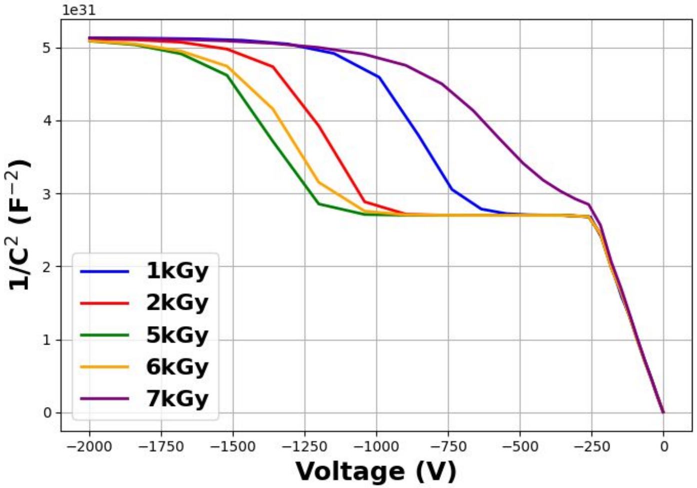
- 2D diode simulation of the CV measurements
- Surface radiation damage simulation: **Perugia model [7]**
- Model differentiates between N_{ox}, $D_{it,acc}$, and $D_{it,don}$ to describe surface radiation damage

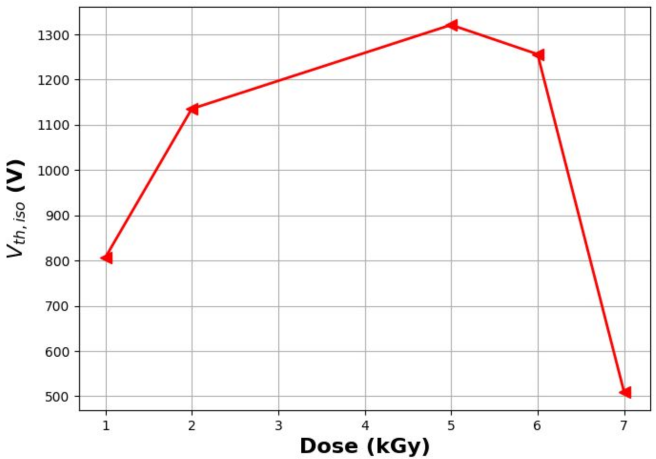


[7] Arianna Morozzi, "TCAD Modeling of Surface Radiation Damage Effects: A State-Of-The-Art Review"

TCAD simulations

- Simulations predict higher $V_{th,iso}$ values than measurements -> model not tuned for these structures
- **Decrease in $V_{th,iso}$**
- **Parameters set to arbitrary values:** model needs parameter tuning (MOS, GCD) -> comparison with measurements
- Improvement compare to the previous simulations, where $V_{th,iso}$ only increased with dose
- $D_{it,acc}$ has a major impact on the $V_{th,iso}$





Conclusions

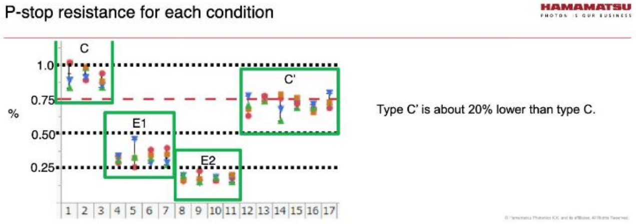
- Type **C prime** shows **lower $V_{th,iso}$** -> preferable oxide for future uses
- $V_{th,iso}$ peaks between 2-5 kGy, followed by sharp decrease at higher doses, likely due to the **difference in introduction rate of $N_{it,don}$ vs $N_{it,acc}$**
- Correlation between the bulk properties before irradiation and surface properties after irradiation
- **CV-based extraction** shows the **best reproducibility** -> recommended method for $V_{th,iso}$ estimation
- TCAD simulations confirm the influence of introduction rate of acceptor and donor-like interface traps on $V_{th,iso}$

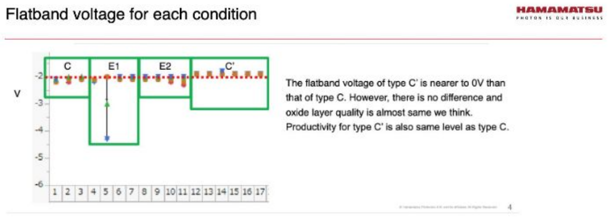
Backup

Oxide variants

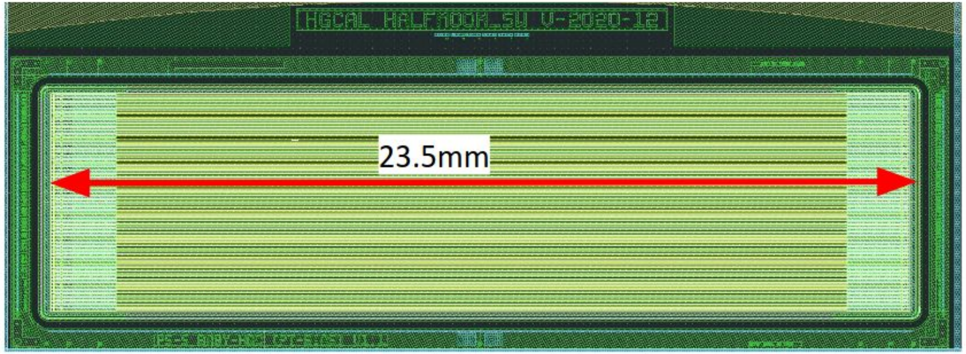
	Vfb	p-stop	oxide quality improvement	p-stop concentration	comment
A	-5V	common	STD	STD	not improved Vfb & STD condition (for ref.)
B	-2V	common	STD	STD	improved Vfb with special masking method
C	-2V	common	thermal condition change	STD	(for ref.) production condition
C'	-2V	common	thermal condition change	STD	more close to 6" line than type C
D	-2V	common	combination of B and C	STD	CMS required condition
E1	-2V	common	thermal condition change	x2.5	conbination C and p-stop concentration
E2	-2V	common	thermal condition change	x5.0	

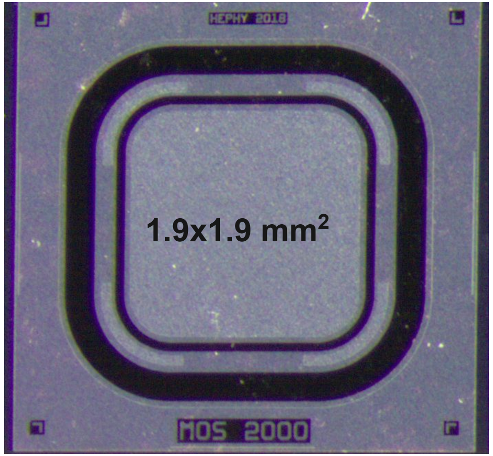
- 300μm float zone, V_{dep}≃270V
- MOSFET measurements indicate **higher *p*-stop concentration** for Type C prime than for Type C

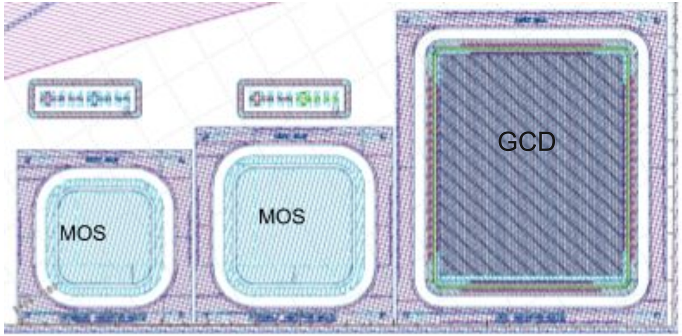




Test structures

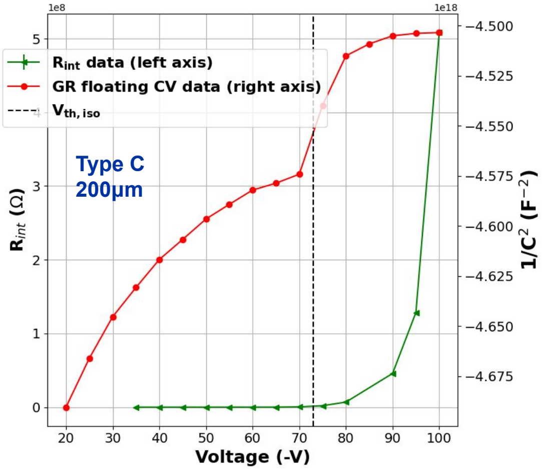


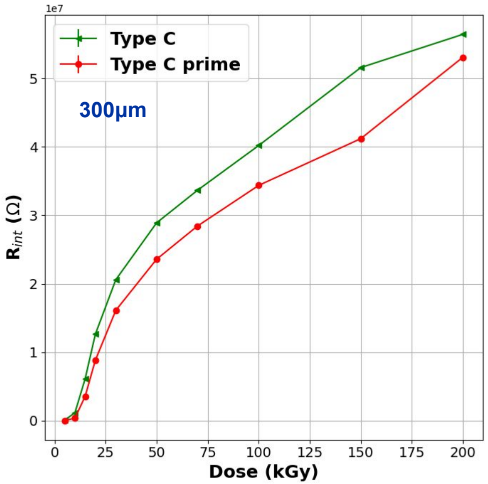


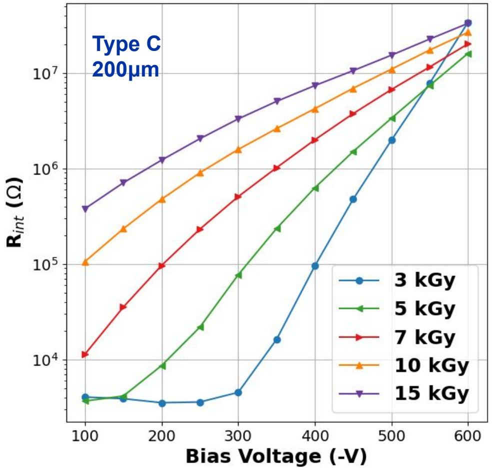


R_{int} measurements

- Interstrip-like measurements with **diode pad** and **GR** (no *p*-stop, but different geometry)
- **R_{int} increases with dose**, contrary to previous measurements with strips
- Increase in R_{int} corresponds to the $V_{th,iso}$
- Possible correlation between **increase in R_{int} and decrease in $V_{th,iso}$** with increasing dose







$V_{th,iso}$ estimation from the IV measurements

- $V_{th,iso}$ estimated using the RMS of the difference of the GR and pad current
- The RMS is computed over a sliding window of 5 voltage points
- $V_{th,iso}$ is computed as:
  $\Delta I(V_{th,iso}) = \Delta I_{min} + 0.01^{*} (\Delta I_{max} - \Delta I_{min})$