Comparison of X-ray radiation damage for different oxide types in HGCAL silicon sensors prototypes

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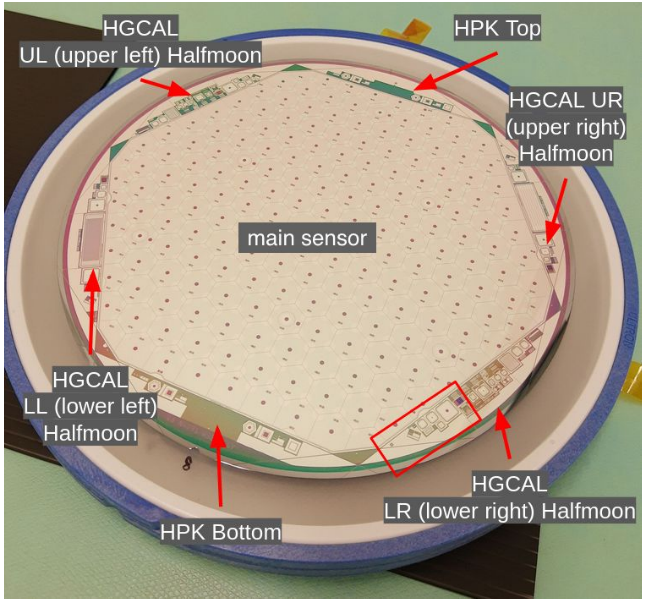
on behalf of the CMS collaboration

Motivation and history

- HGCAL silicon sensors produced by Hamamatsu (HPK)
  - First 8-inch p-type sensors used in a particle detector
  - Radiation hardness qualification needed for bulk and **oxide**
    - Oxide radiation hardness important for cell isolation

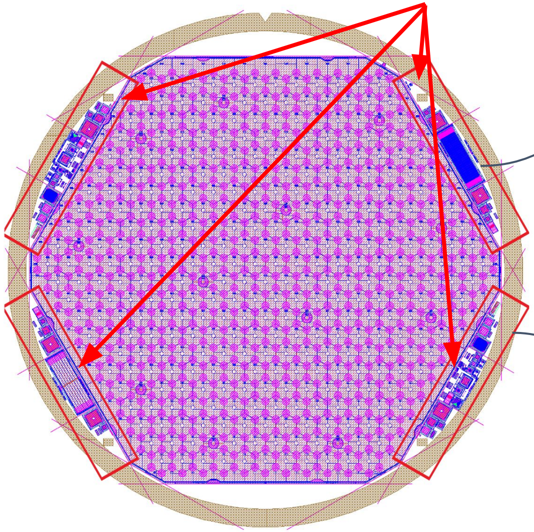
- In the 8-inch prototype phase (2018–2022), HPK provided amongst others **10 oxide variants**
  - First prototypes **had -5V** flat band voltage (V_{fb})
  - HGCAL wished to mimik **CMS outer tracker** sensors which are well established in terms of radiation hardness, with **V_{fb}=-2V**
  - HGCAL production started using so-called Type C with V_{fb}=-2V, (best performance among provided oxide variants)
  - In parallel to production start in 2023, HPK proposed **Type C'** (more similar to tracker sensors, also in terms of p-stop resistance)
  - **Fast track qualification** needed of new oxide variant to be relevant for production

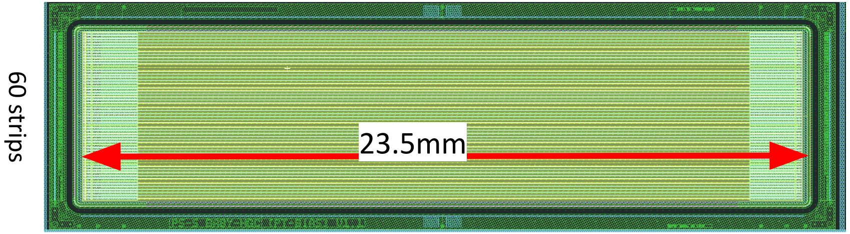


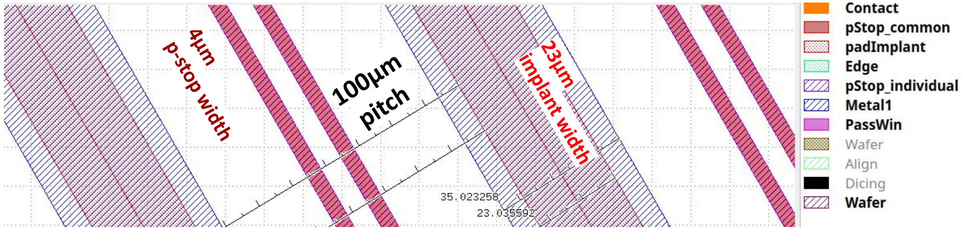
Sensor design

HGCAL sensor

Half moons with test structures

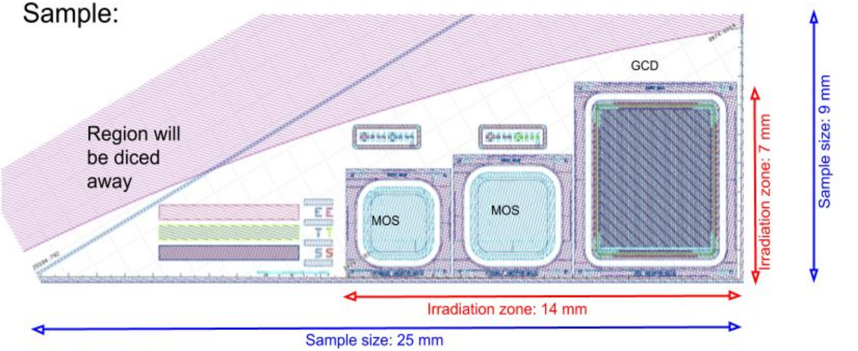






Strip sensors

Sample:



MOS

Sensor variants

HGCAL 8-inch:

	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	

*MOSFET measurements indicate higher p-stop concentration in Type C' than in Type C

HGCAL 8-inch:

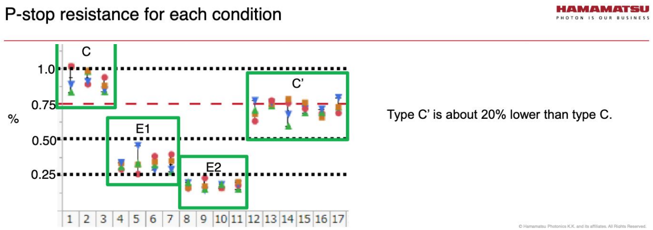
- 300µm float zone (FZ), V_{dep} = ~270V

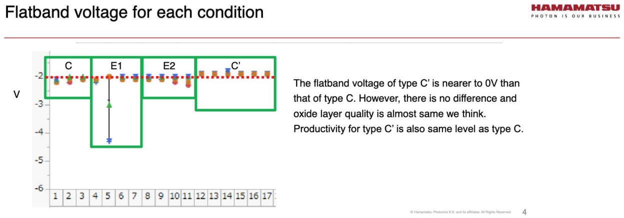
HGCAL 6-inch:

- 320µm physical thickness, 290µm active thickness, deep diffused float zone (dd-FZ)

CMS outer tracker (6-inch):

- Sample from PS-s wafer from the pre-production (series S15569-01)
- 320µm physical thickness, 290µm active thickness, deep diffused float zone (dd-FZ)



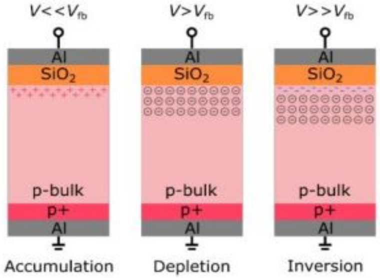


Sample irradiation in ObeliX (CERN)

- Effect of **trapped charge**:
  1. Increase in $V_{flatband}$ in MOS
  2. Increase in **surface current** in GCD

- Measurement **procedure:**
  - X-ray irradiation and in-situ measurements at <1% relative humidity and -20 °C
    → **Crucial to control annealing**
  - Dose rate = **14 kGy/h**
  - One of the two MOS biased with +10 V in order to study the radiation damage in the presence of an **electric field**

MOS



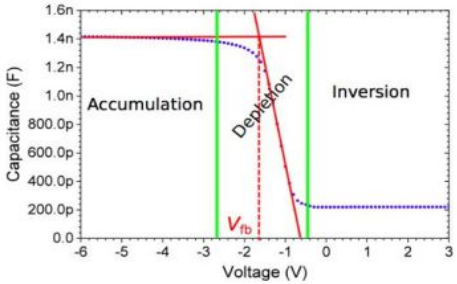
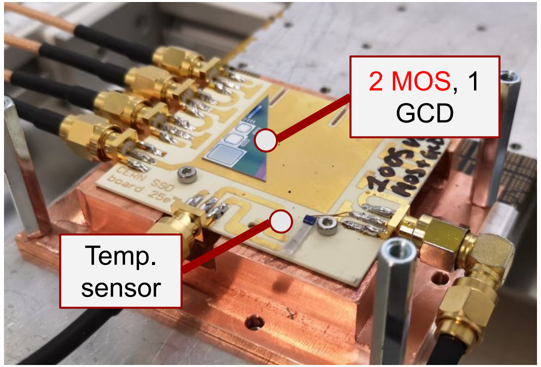
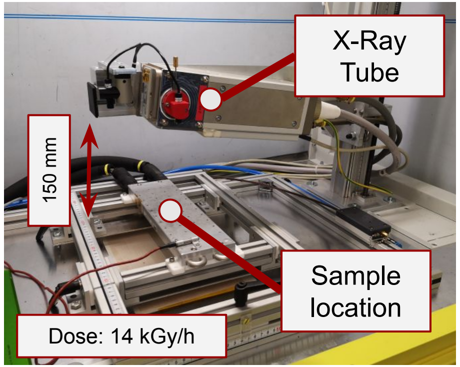
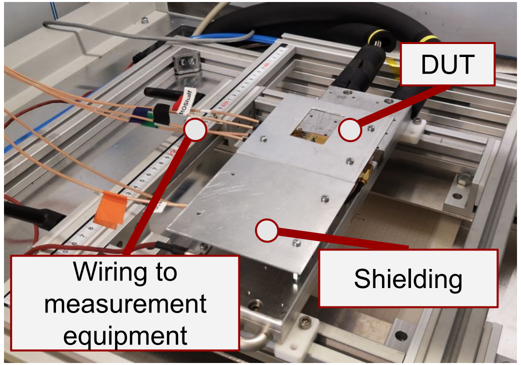


Illustration by V. Hinger (HEPHY)





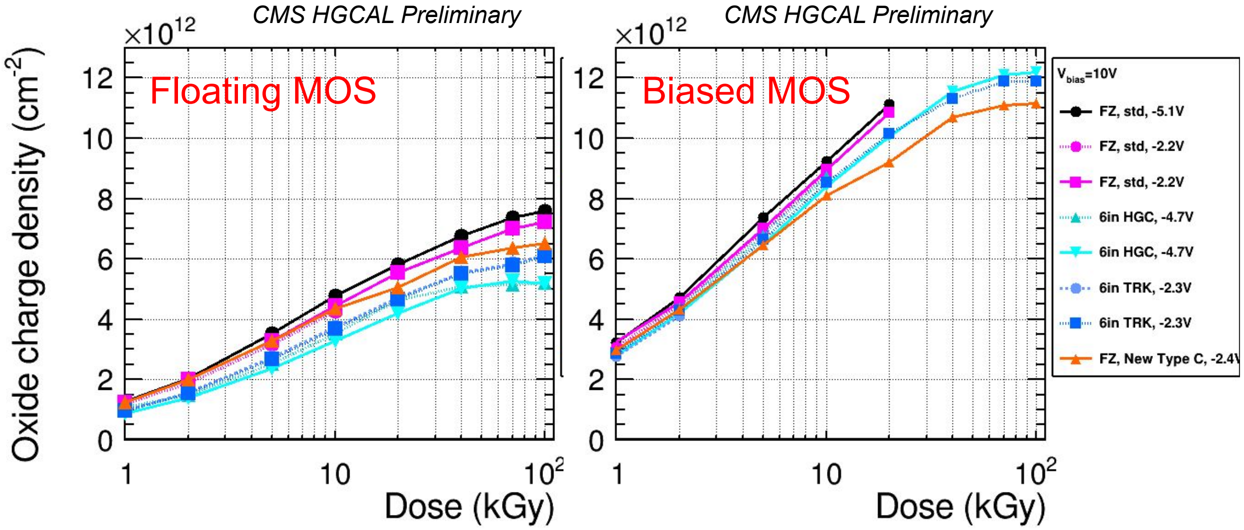


Comparison to benchmark sensors: MOS

- Convert $V_{flatband}$ into oxide charge density

$$N_{oxide} = \frac{C_{oxide}}{qA_{gate}}(\phi_{ms} - V_{FB})$$

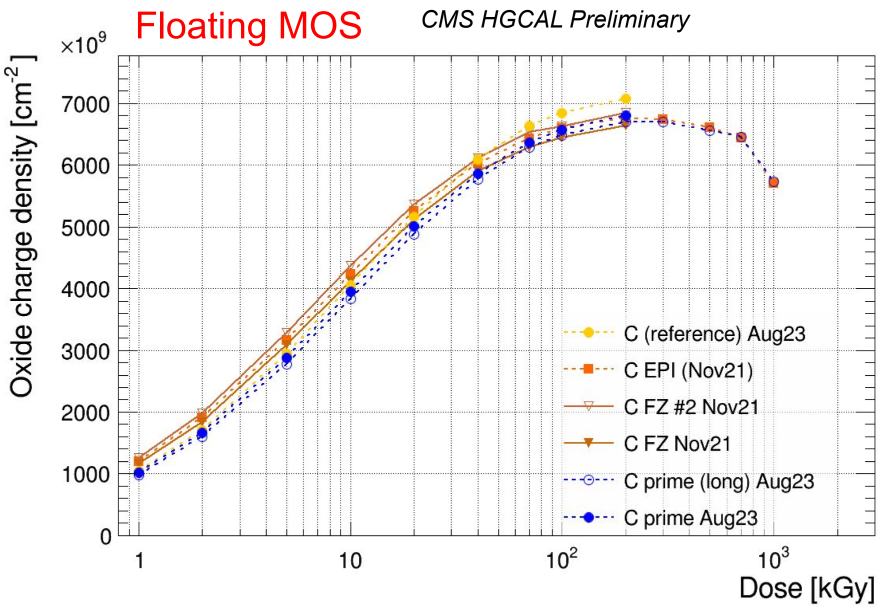
- Type C compared to HGCAL 6'' prototypes and CMS outer tracker (benchmarks), obtained with the same procedure

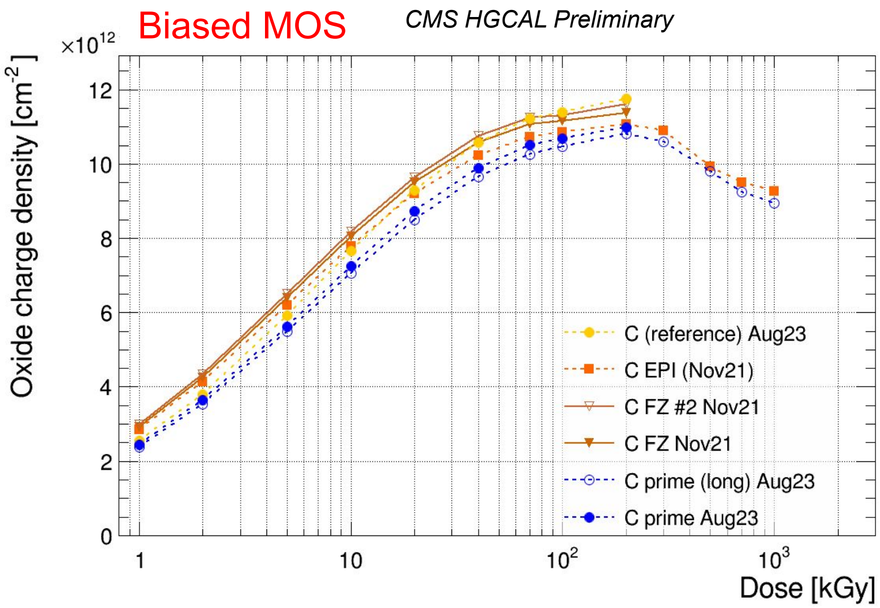


- Comparable performance and trend in the absence of electric field
- Type C performs better in the presence of an electric field

-> In both cases, better performance compared to V_{fb} = -5V prototypes

MOS results for type C-prime (Aug ‘23)

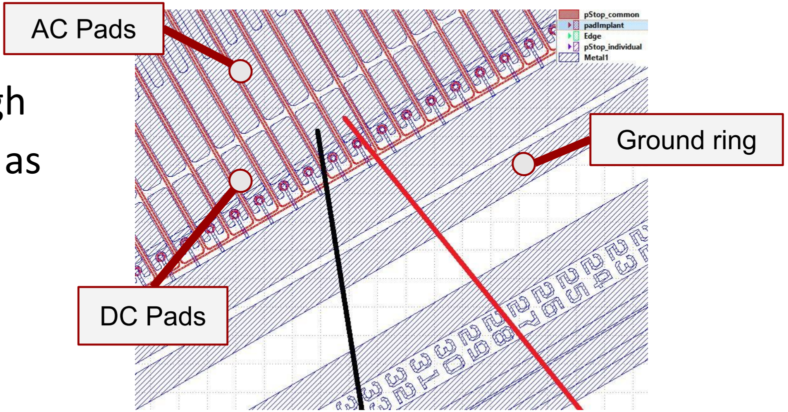


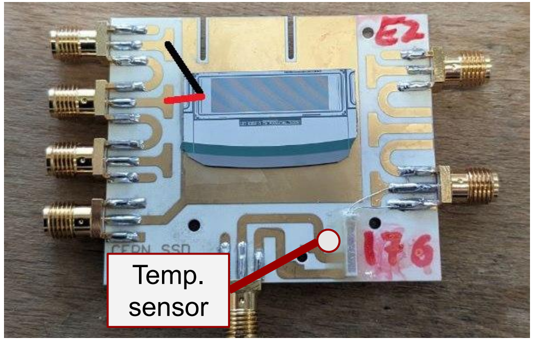


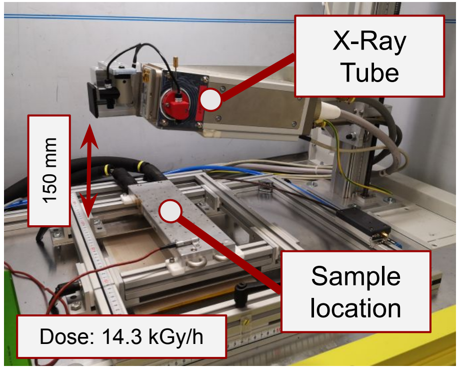
- Differences between **Type C’** and **Type C** within the experimental resolution (around 5%)
- This motivates the need to perform complementary studies with **micro-strips**

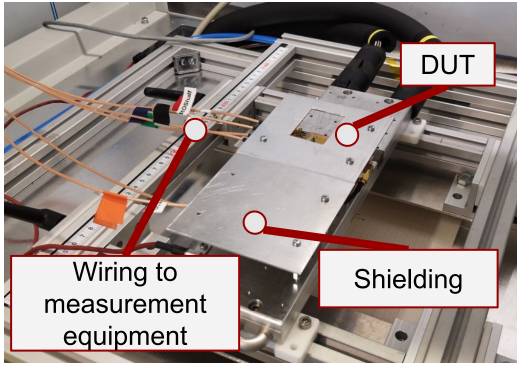
Interstrip C and R with micro-strips sensors

- Wire bonding of 2 neighbour strips
- Strips biased via bias ring, connected via punch-through
- X-ray irradiation and in-situ measurements performed as for MOS
- Measurements
  - Interstrip resistance and capacitance



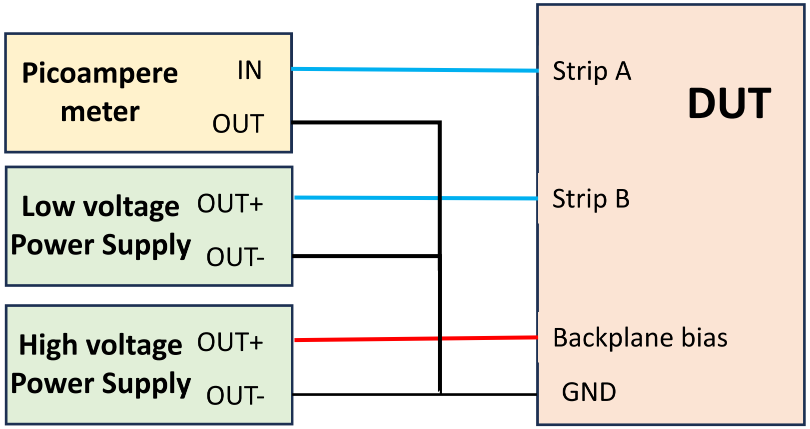




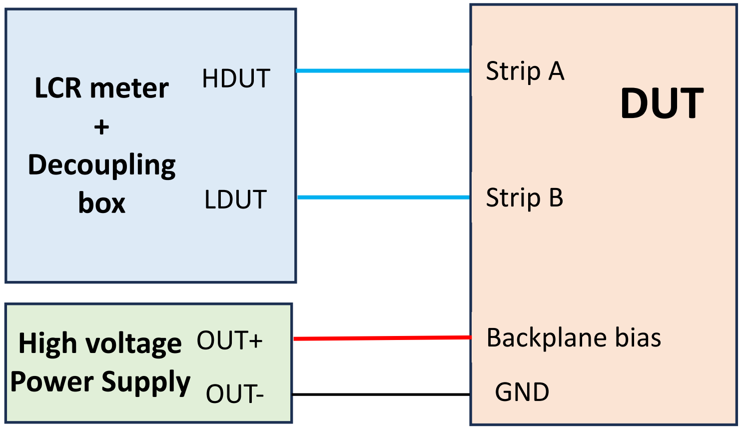


Inter-strip measurement circuits

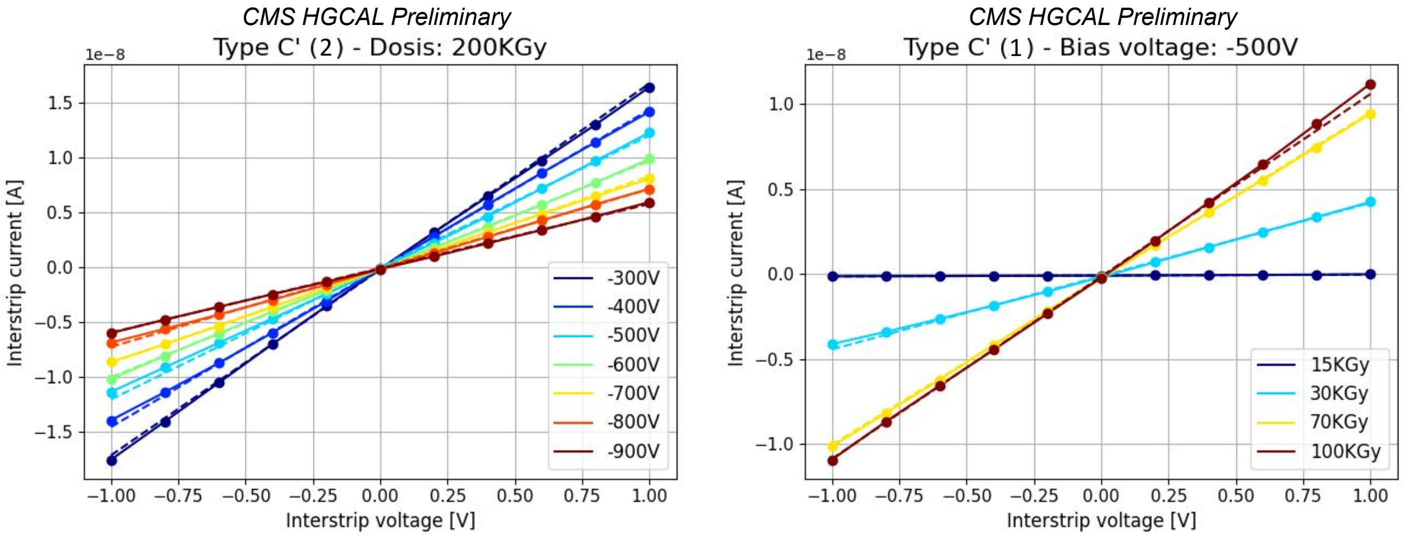
Inter-strip resistance



Inter-strip capacitance



Interstrip-R extraction from IV



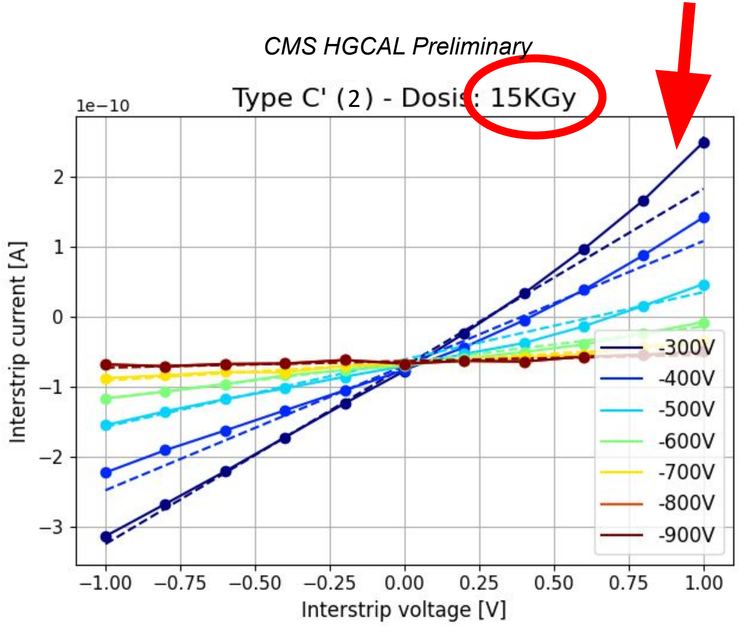
Linear fit:

R_{int} = inverse of the slope

I_{leak} = intercept

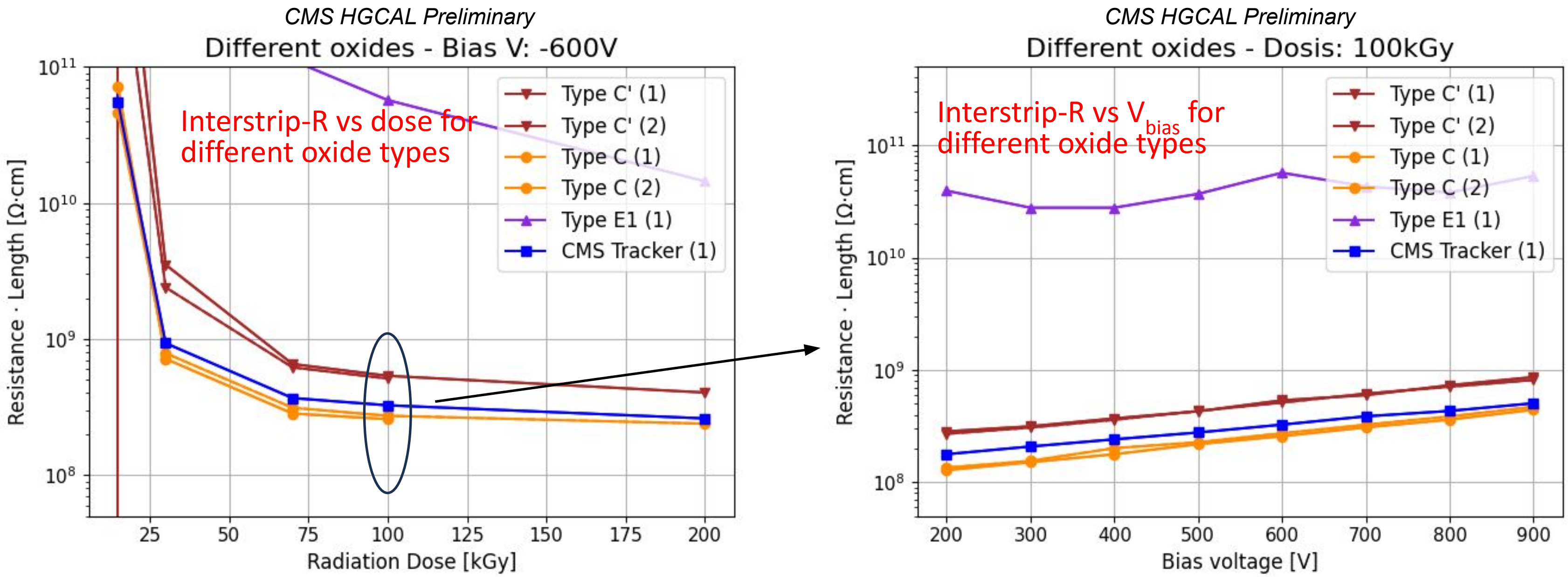
Interstrip current vs interstrip voltage curves for a C-prime 300µm sensor using a fixed radiation dose and different bias voltages (left) and fixed bias voltage and different radiation doses (right). The dashed line corresponds to the linear fit.

Interstrip-R extraction from IV



For small irradiation doses (and low bias voltages) we observe that the behaviour is not linear
-> we will adopt an ad-hoc solution for this, or discard the dose point

Results: Interstrip-R vs dose and vs V_{bias}



- Around **x2 higher R** for **Type C’** when compare to **Type C** in line with **higher initial p-stop** concentration
- Around **x100 higher R** for **Type E1** due to the **higher concentration of p-stops**

Trends vs dose and V are **similar between type C and C’** => no clear preference between the two

Summary

- **Goal**: Identify best oxide process for HGCAL production silicon sensors
- Investigation of **oxide radiation damage** as a function of the absorbed dose
- In-situ measurement procedure allows to obtain **excellent reproducibility** of the result

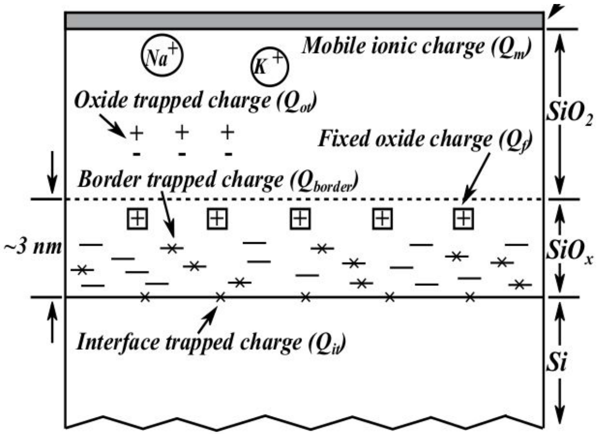
- Comparison of production process candidates **Type C** and **Type C’**
  - MOS irradiation (floating and biased)
    - No clear difference
  - Inter-strip resistance
    - Not directly comparable because of different p-stop
    - Same rate of degradation as a function of the dose -> no clear preference

- Production of HGCAL silicon sensors had started with **Type C** before the studies were completed
- No practical advantage to moving to **Type C’** from **Type C**, considering
  - More extensive qualification of **Type C** at HPK and in CMS (e.g. pre-production)
  - Decided to stick to **Type C** for the rest of the HGCAL production
- **Type C’** interesting candidate for future silicon detector projects using 8-inch p-type sensors

BACKUP

Effect of SiO_2 damage on interstrip properties

- Radiation damage in silicon oxide creates charge accumulation in border region + recombination current at the Si-SiO_2 interface
- This favours the formation of an electron accumulation layer (n) that degrades the isolation properties between neighbouring cells (n+ implants)
  - partially mitigated by dedicated p-stop implants
- These effects can be studied using dedicated test structures with MOS and micro-strip sensors (see next slides)



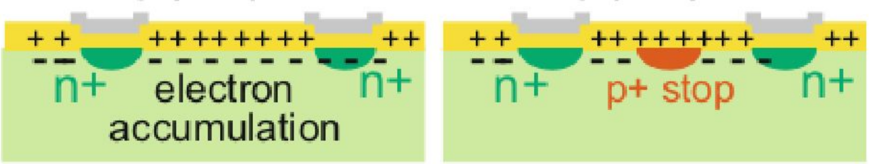
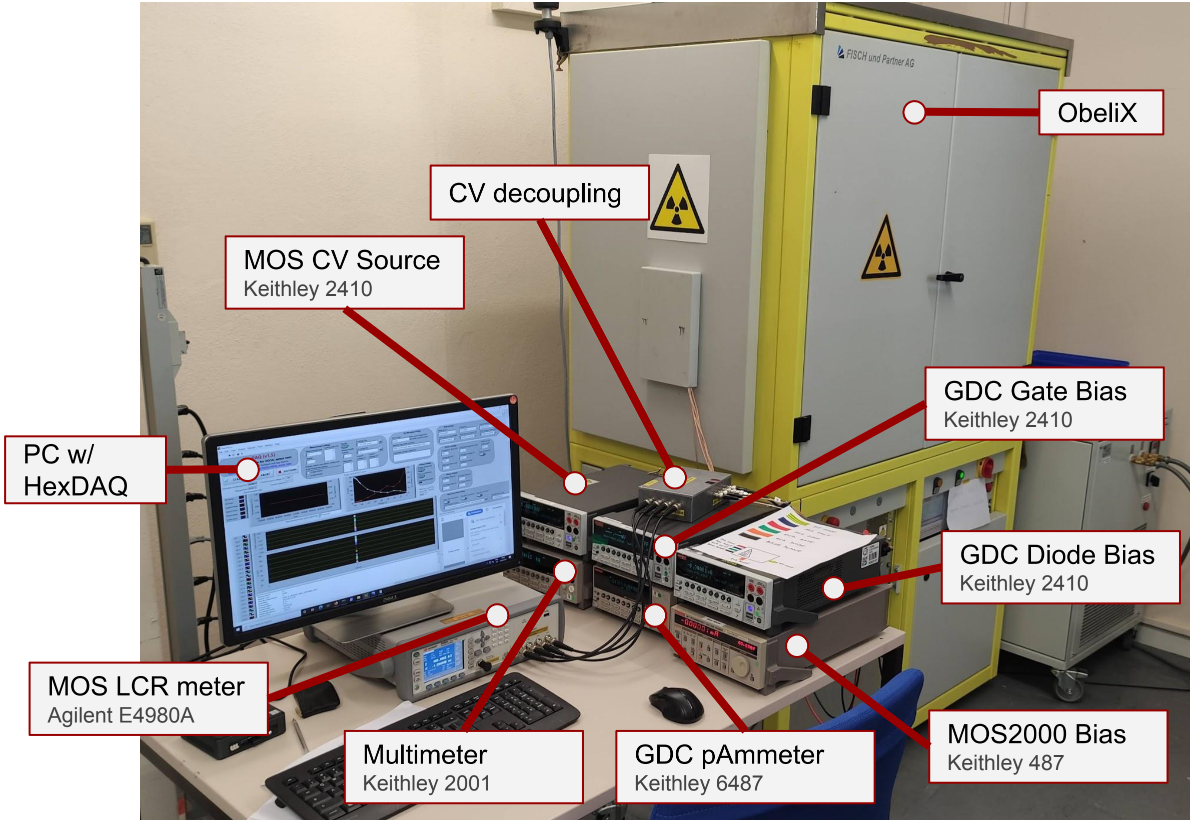


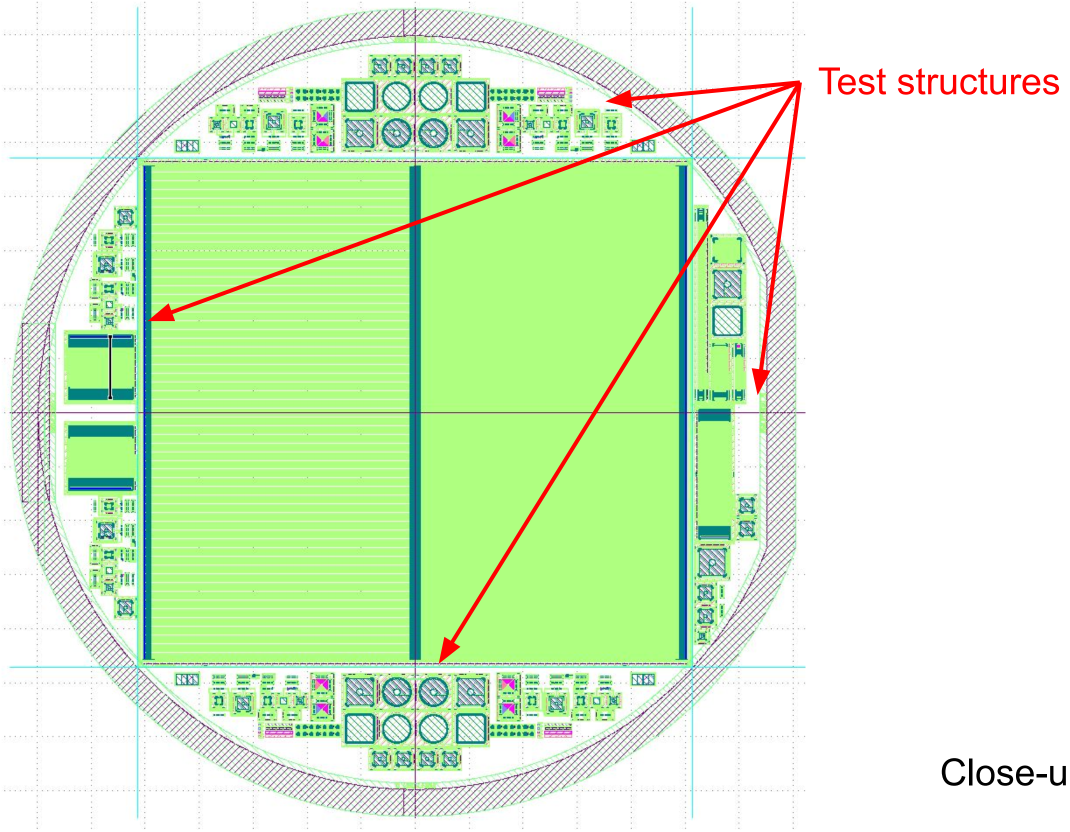
Illustration by Jan-Ole Müller-Gosewisch (KIT)

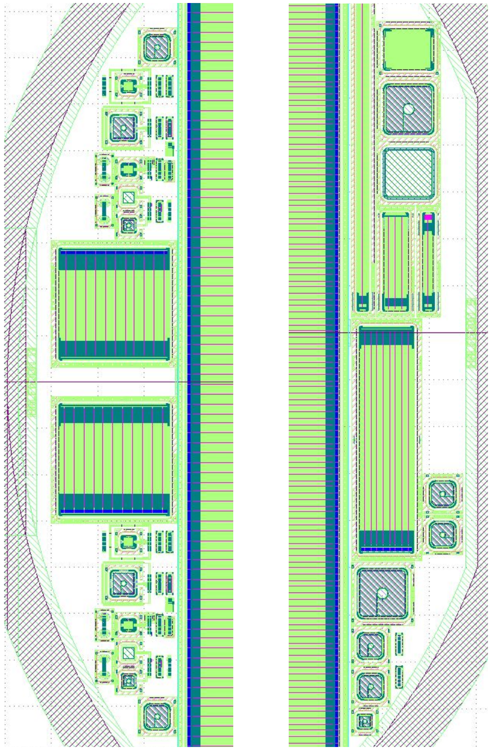
As a function of the absorbed dose, we therefore expect a degradation of the isolation between neighbouring strips, and an increase in the accumulated charge in the SiO_2

The X-ray setup @ ObeliX



CMS Outer tracker wafer and test structures

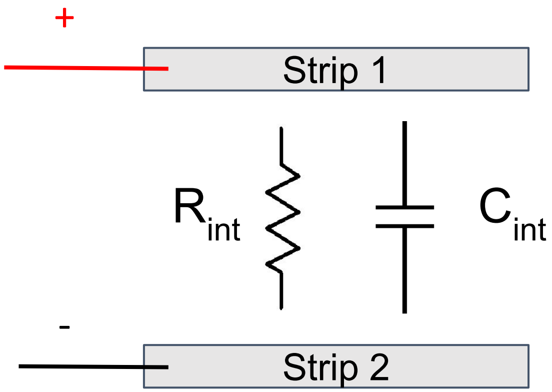




Close-up view

Definition of interstrip variables

Interstrip Resistance (R_{int}) and Capacitance (C_{int})



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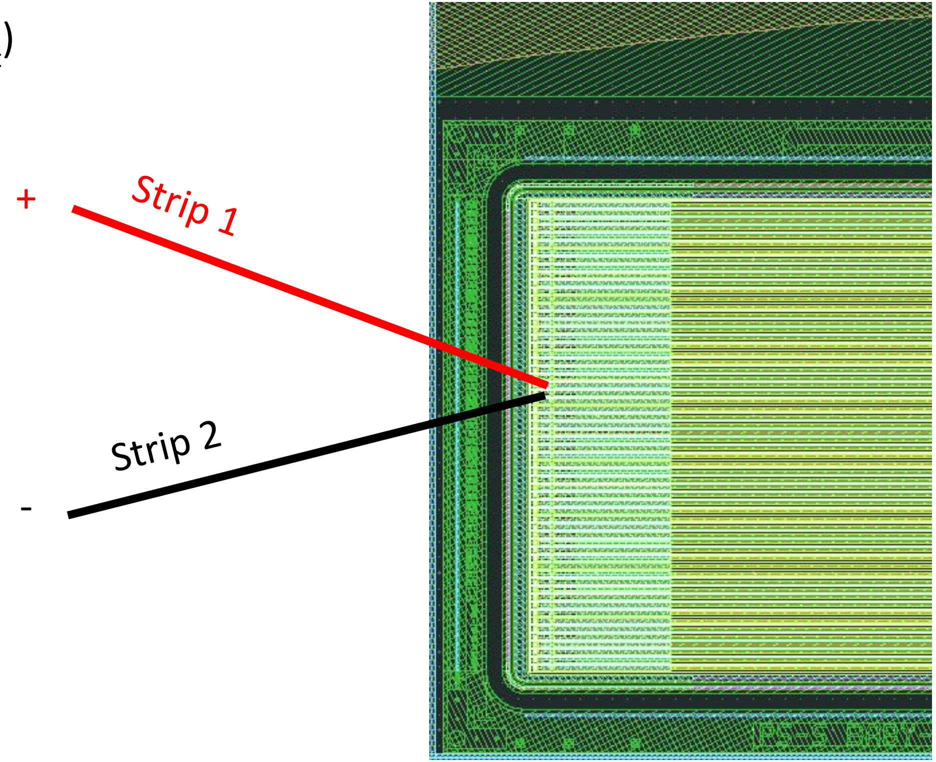
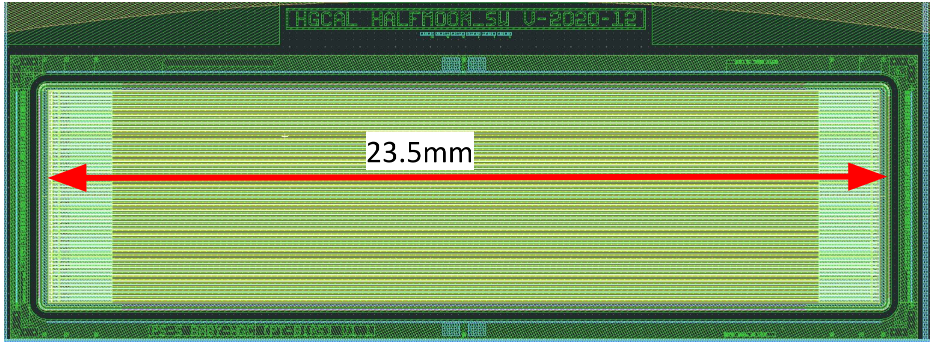
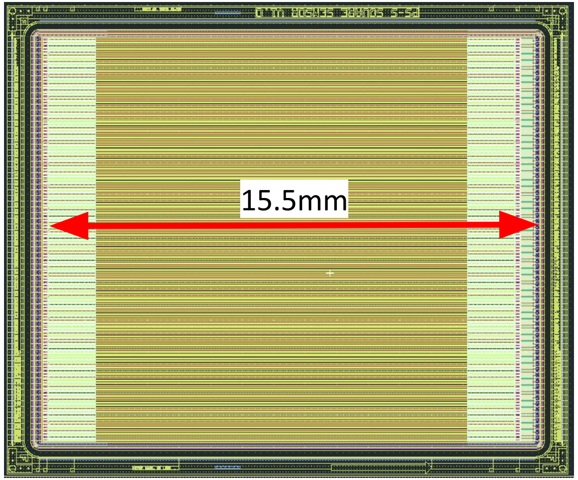


Geometry and normalization

HGCAL tracker-like strip sensor:
100µm pitch, ~23.5mm strip length, 60 strips



Tracker strip sensor test structure
100µm pitch, ~15.5mm strip length, 128 strips

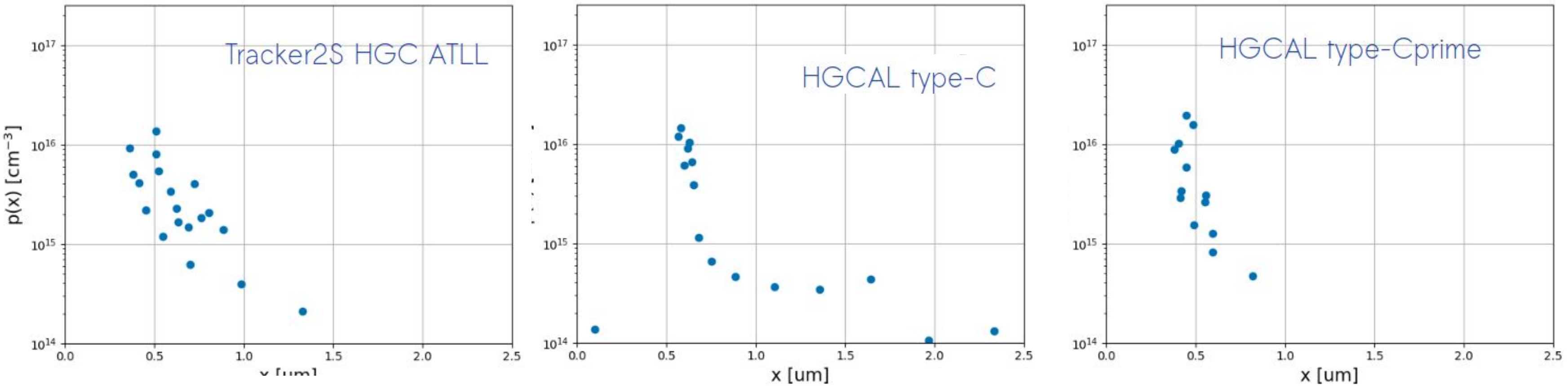


· Current flow is **perpendicular** to strip length

· Geometric normalization of results by accounting only for the **strip length**:

- Resistance · Length
- Capacitance / Length

P-stop concentration



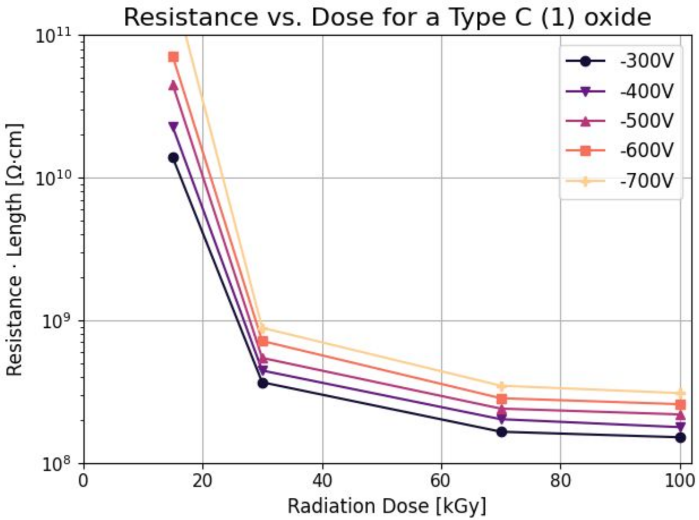
P-stop studies conducted by Thomas Bergauer, Suman Chatterjee, Marko Dragicevic, Kostas Damanakis, Ioannis Kopsalis, Veronika Kraus (HEPHY)

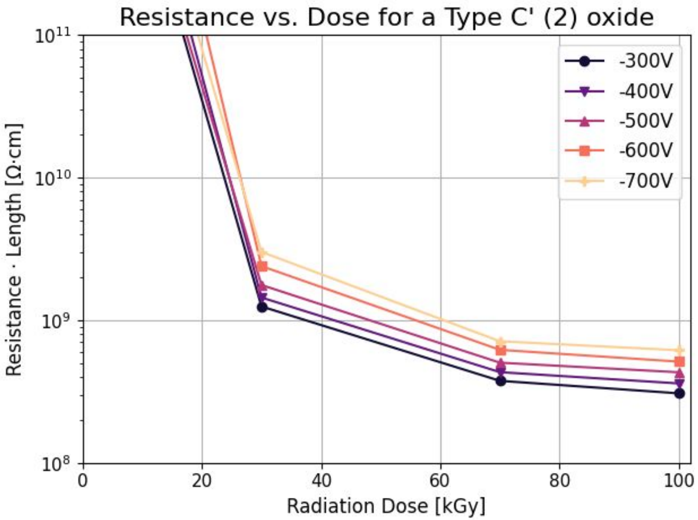
- **Higher** doping concentration observed for **Type C'** compared to **Type C**
- Slightly smaller concentration for **CMS Tracker** than for **Type C'**

Expected results: ↑ **p-strop** concentration ⇒ ↑ **Resistance**

Preliminary results: Interstrip-R vs dose (vs V_{bias})

CMS HGCAL Preliminary

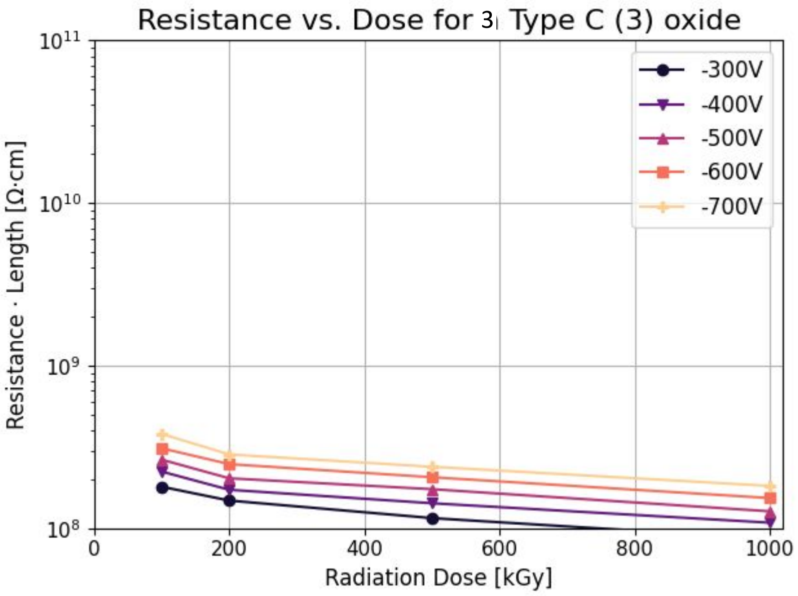


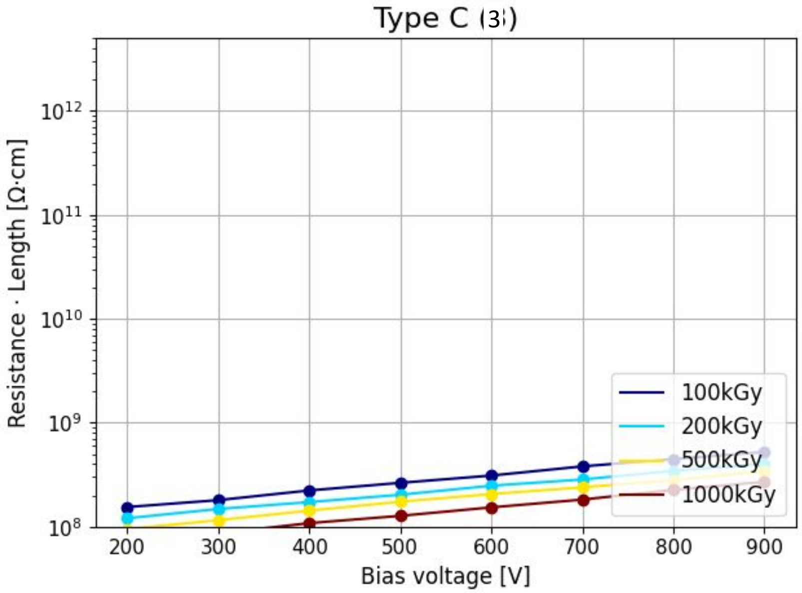


Interstrip resistance vs radiation dose for type C (left) and C-prime (right) 300µm sensor using different bias voltages above full depletion

Interstrip-R: Long irradiation up to 1MGy

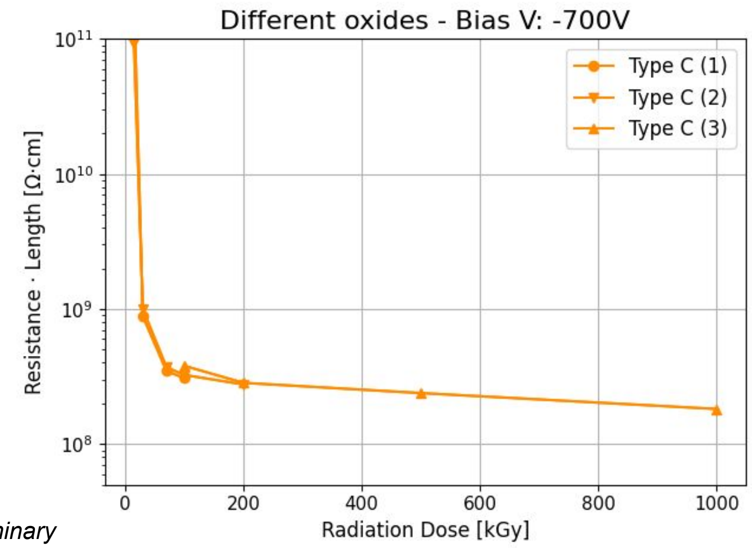
CMS HGCAL Preliminary





- Measured R_{int} well above the 10^8 Ω benchmark for V_{bias} > 400 V at 1 MGy

Interstrip-R: Long irradiation up to 1MGy



CMS HGCAL Preliminary

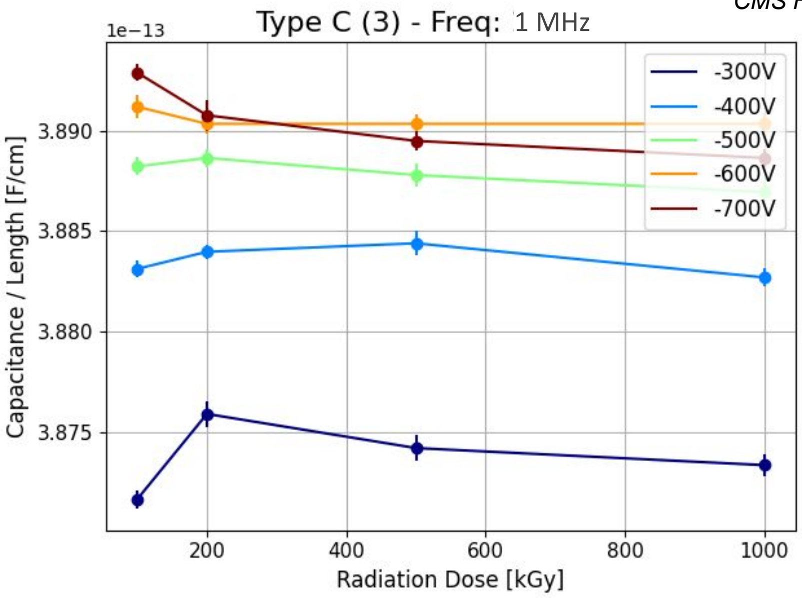
Attention:
Different dose rates used (24.3kGy/h for 1MGy vs 14.3kGy/h)

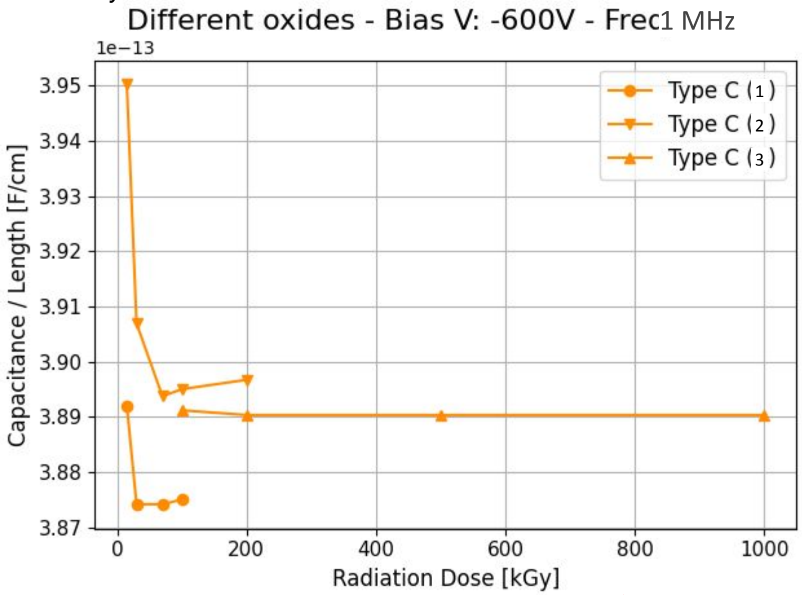
See slide 8

- Measured R_{int} well above the 10^8 Ω benchmark for V_{bias} > 400 V at 1 MGy

Interstrip-C: Long irradiation up to 1MGy

CMS HGCAL Preliminary

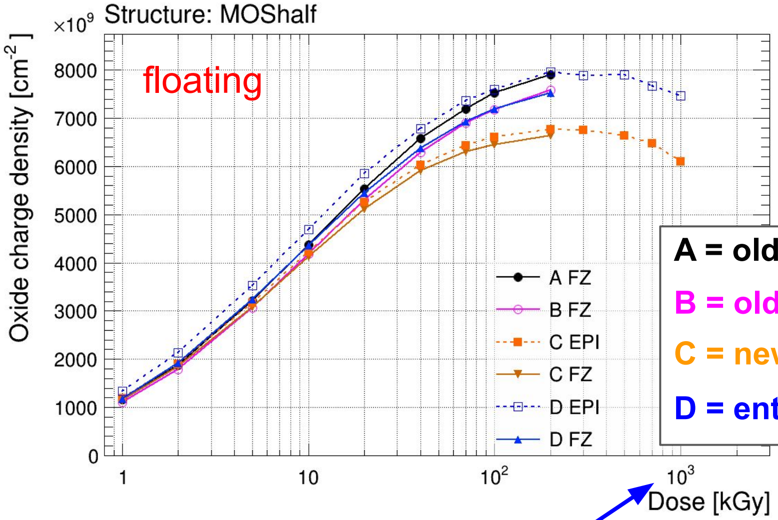




Attention: Different dose rates used (24.3kGy/h for 1MGy vs 14.3kGy/h)
See slide 8

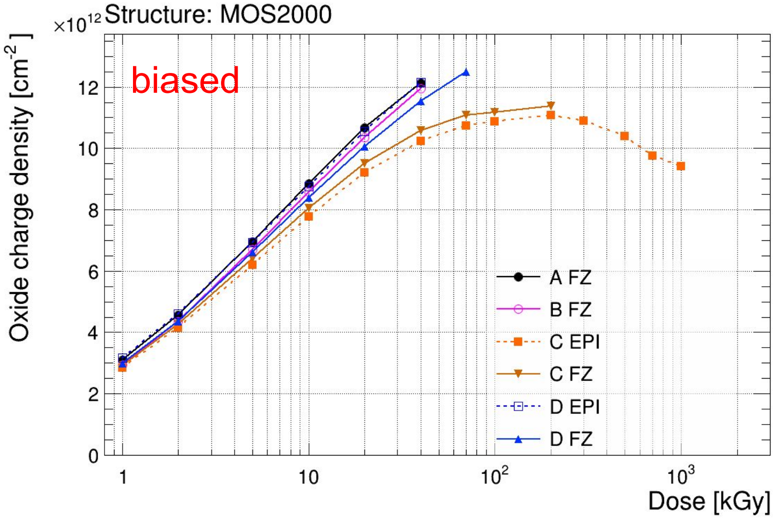
- Measured C_{int} almost constant for large values of radiation dose (**no degradation observed**)
- Consistent results within 1% between short and long irradiation campaigns

MOS: Results for new types A-D



CMS HGCAL Preliminary

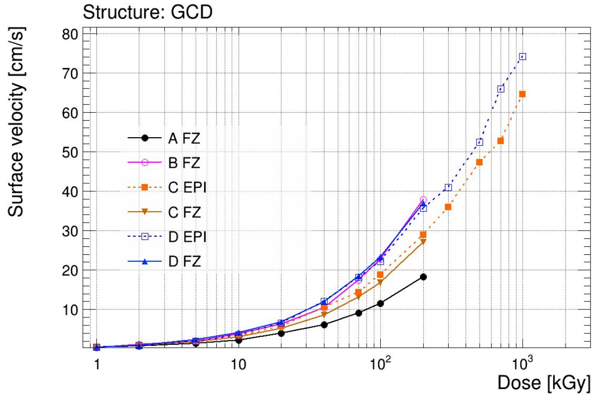
A = old STD -5V
B = old STD -2V
C = new type C
D = entirely new type



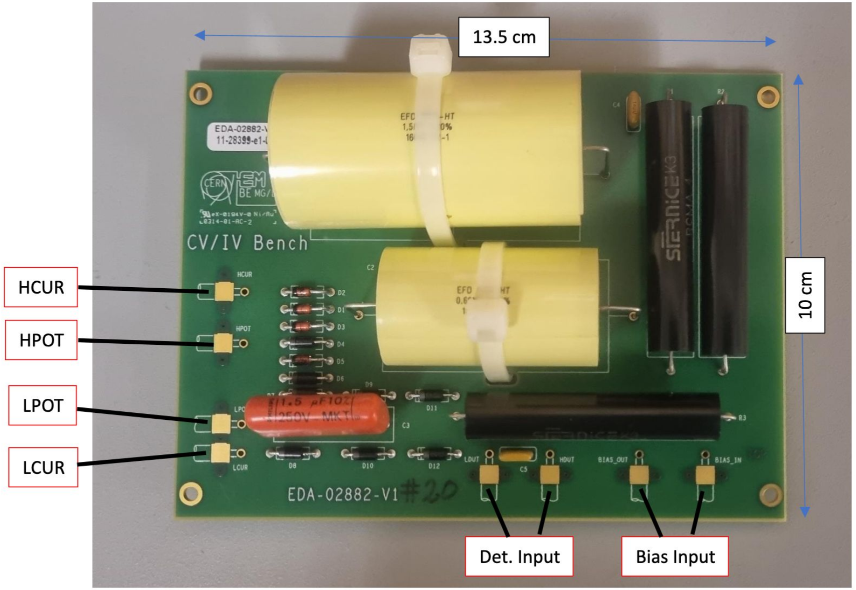
EPI material irradiated up to 1MGy (expected dose in forward region of the calorimeter at the end of HL-LHC)

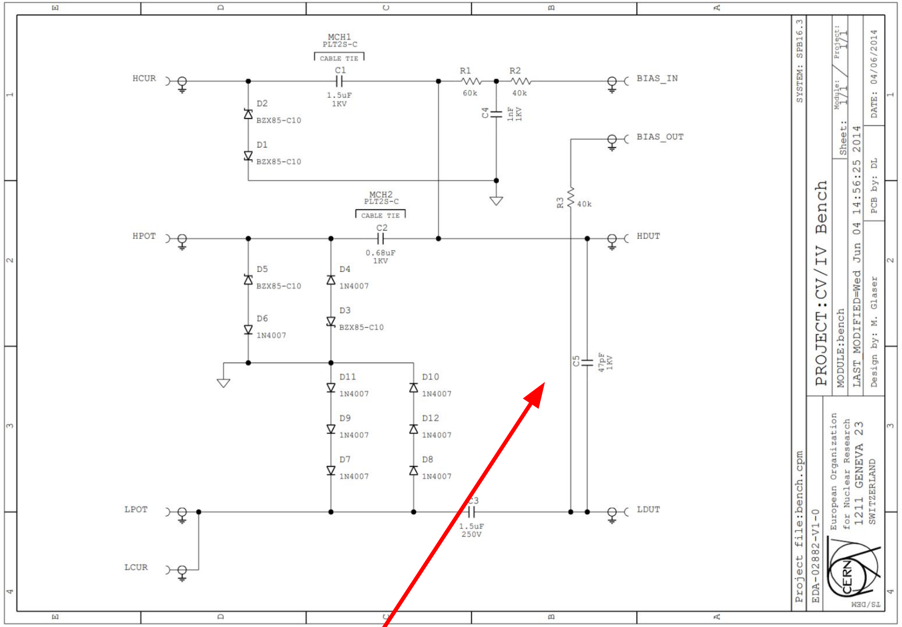
confirmed preference for new type C -> currently being used by HPK for sensors production

-> new variant called C-prime recently provided by HPK



Open correction for C_{int}

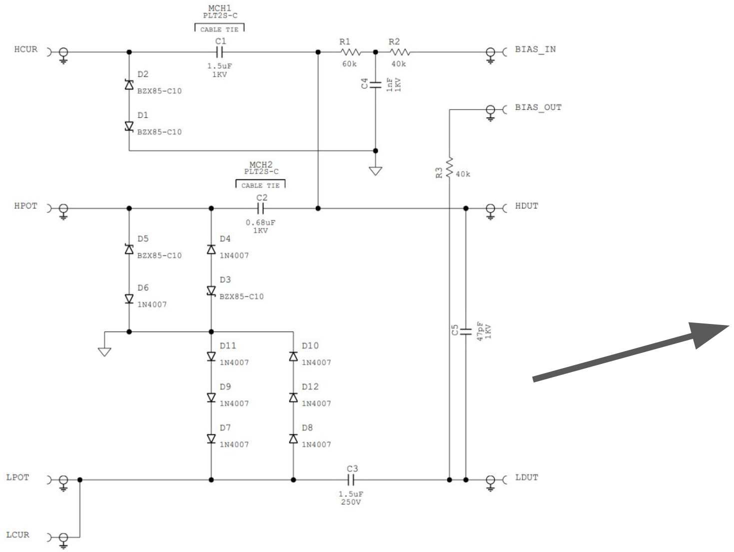


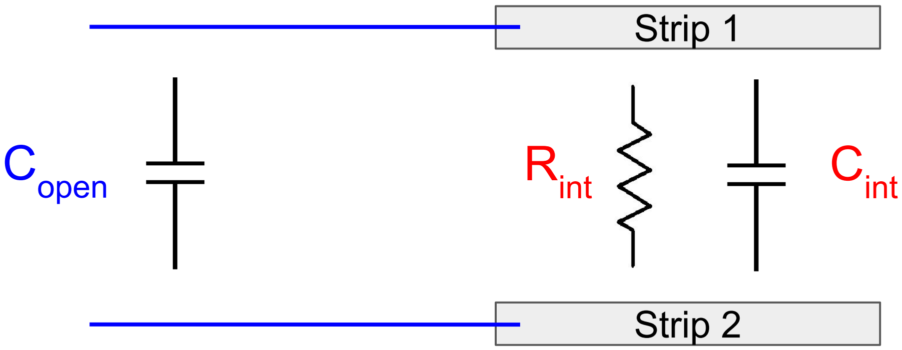


Open capacitance driven by C_5 = 47 pF in decoupling box connected to LCR meter

Open correction for C_{int}

$C_{corr} = C_{meas} - C_{open}$





- Measured C_{open} = 49.7 pF (consistent with C_5 = 47 pF of design sheet)
- Simplified correction $C_{corr} = C_{meas} - C_{open}$
- Open correction derived for each LCR frequency

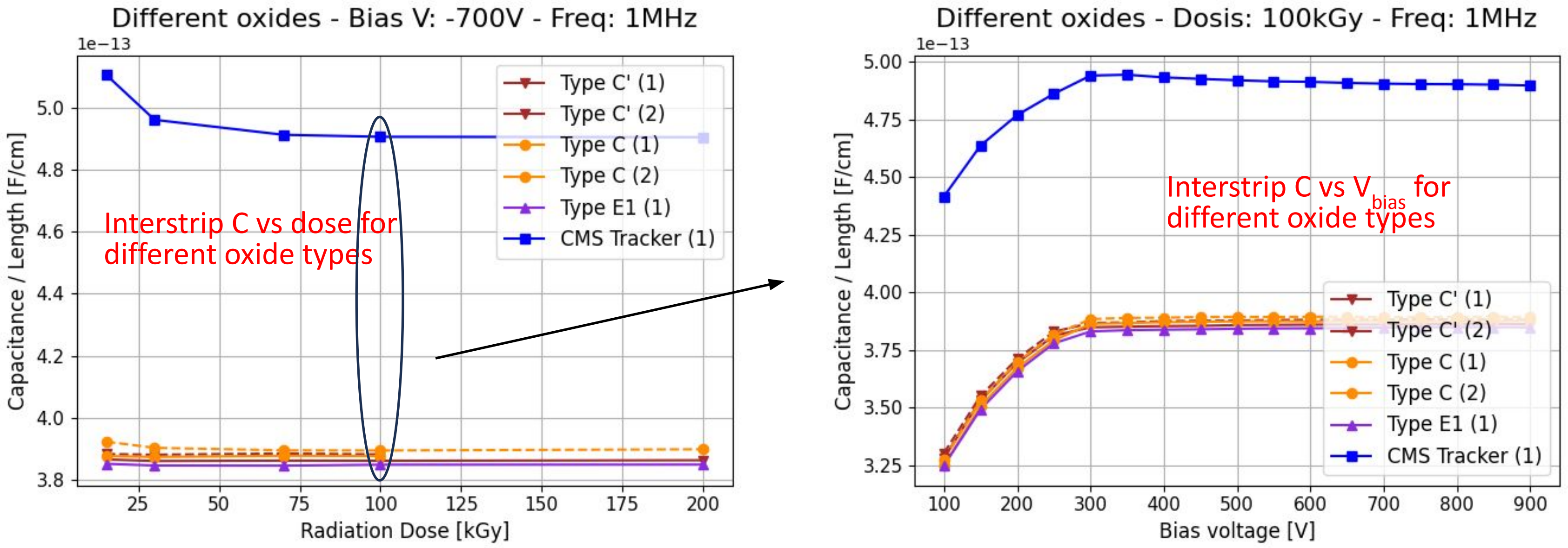
Matteo Defranchis (CERN)

Summary including CMS Tracker

Comparison of production process candidates Type C, **Type C’ and CMS tracker**

- MOS irradiation (floating and biased)
  - **Comparable results** in **MOS** measurements for all oxides
- Inter-strip resistance
  - **Slightly higher inter-strip resistance for Type C’** compared to Type C**. CMS tracker** very similar to Type C**.**
- Inter-strip capacitance
  - **Lower inter-strip capacitance in type C and C’** compared to **CMS tracker sensors**

Results: Interstrip-C vs dose and vs V_{bias}



- **Same performance of Type C, C' and E1** (differences **smaller than 1%**, which is the same order of magnitude of the measurement reproducibility)

- **CMS Tracker** offered a capacitance around **30% larger**

Samples of strip sensors

	Copies	Maximum dose [kGy]	Comment
Type C	”(1), (2)” “(3)”	200@14.3kGy/h 1000@24.3kGy/h	Production sensors so far
Type C’	“(1), (2)”	200@14.3kGy/h	Proposed by HPK, closer to tracker, higher p-stop concentration than Type C
Type E1	“(1)”	200@14.3kGy/h	Type C with 2.5x p-stop concentration
CMS outer tracker	“(1)”	200@14.3kGy/h	

HGCAL:

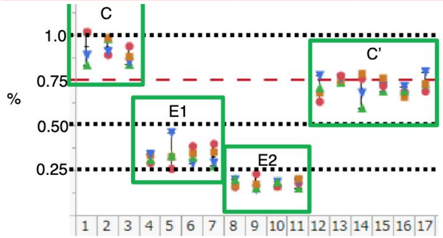
- all 300µm float zone (FZ), V_{dep} = ~270V

CMS outer tracker:

- Sample from PS-s wafer from the pre-production (series S15569-01)
- 320µm physical thickness, 290µm active thickness, deep diffused float zone (dd-FZ)

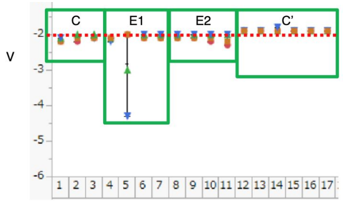
230314 300µm		Vfb	p-stop	oxide quality improvement	p-stop concentration	comment
	A	-5V	common	STD	STD	not improved Vfb & STD condition (for ref.)
	B	-2V	common	STD	STD	improved Vfb with special masking method
	C	-2V	common	thermal condition change	STD	(for ref.) production condition
	C'	-2V	common	thermal 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	

P-stop resistance for each condition



Type C’ is about 20% lower than type C.

Flatband voltage for each condition



The flatband voltage of type C’ is nearer to 0V than that of type C. However, there is no difference and oxide layer quality is almost same we think. Productivity for type C’ is also same level as type C.