Surface and bulk properties of silicon obtained from quality control test structures for CMS

Thomas Bergauer, Kostas Damanakis, Marko Dragicevic,
Veronika Kraus, Moritz Wiehe

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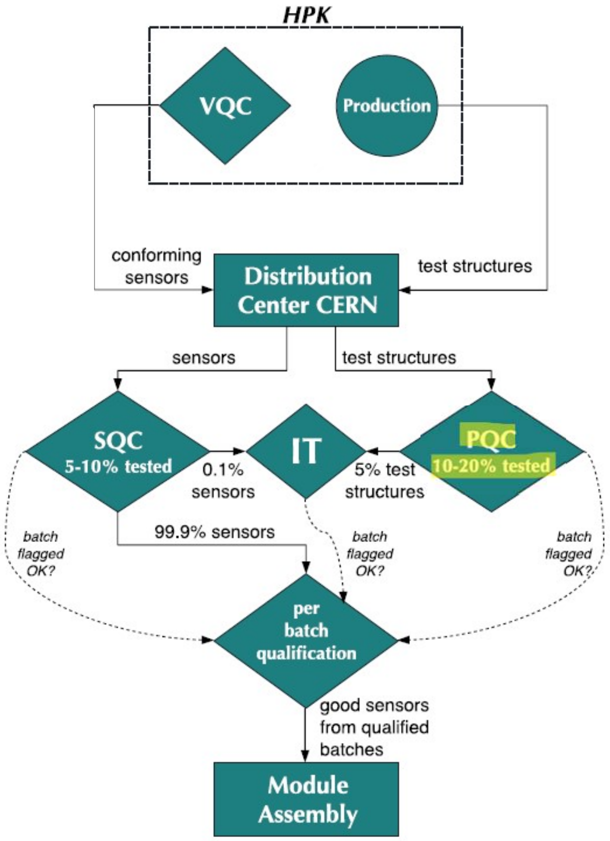
The CMS Phase-2 Upgrade

Motivation for Process Quality Control (PQC): High-Luminosity LHC requires full upgrade of the CMS detector; tracker and calorimeter endcap will be replaced and new silicon sensors incorporated



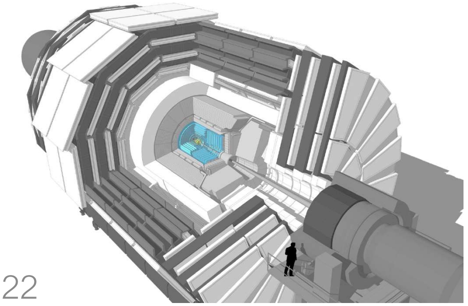
Tracker:

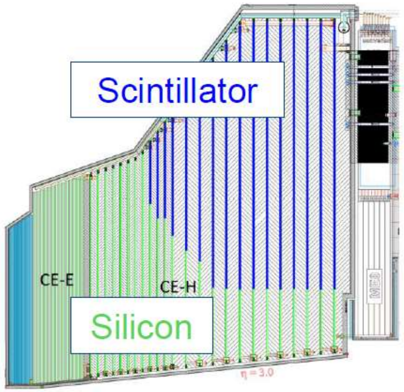
- ~ 200m^2 silicon
- Pixel sensors for inner tracker
- Strip sensors (AC-coupled) and Macropixel sensors (DC-coupled) for outer tracker

High-granularity calorimeter:

- ~ 600m^2 silicon
- DC-coupled pad sensors
- Different wafer thicknesses for regions with different fluences

Fast measurements; Additional parameters accessible



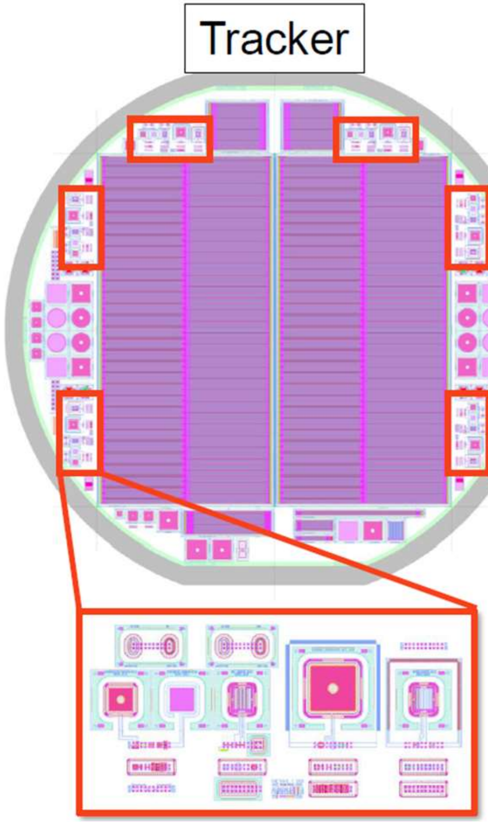


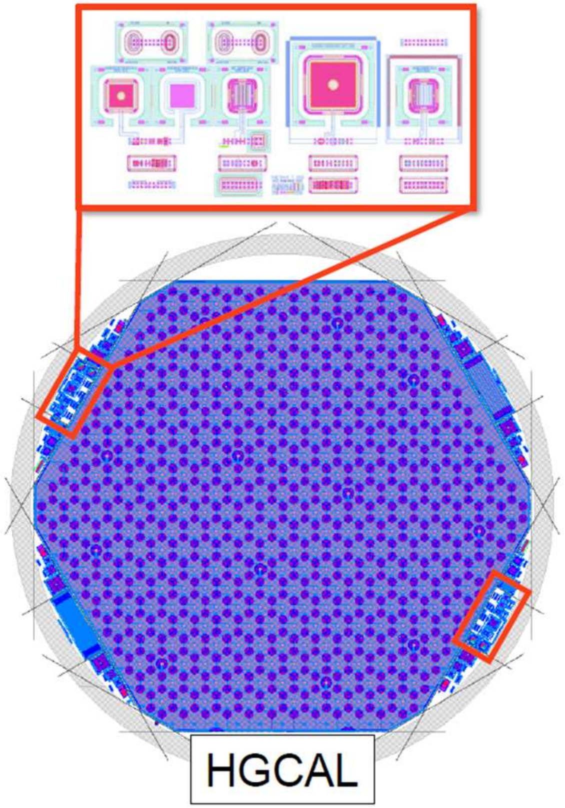
Tracker and HGCAL silicon sensors

- Both Tracker and HGCAL sensors are manufactured on p-type substrate
- Both use p-stop isolation
- Produced by Hamamatsu Photonics K.K
- Tracker: 6'' technology
- HGCAL: 8'' technology

Selected sensor qualification specifications	**Tracker**	**HGCAL**
Substrate resistivity	> 3.5 kΩcm	> 3.0 kΩcm
Physical thickness	320 µm	300 µm
		200 µm
		300 µm
Active thickness	290 µm	300 µm (FZ)
		200 µm (FZ)
		120 µm (epitaxial growth)
Full depletion voltage	< 350 V	300 µm: < 370 V
		200 µm: < 160 V
		120 µm: < 70 V
Types	2S and PS-s strip sensors (AC-coupled); PS-p Macropixel sensors (DC coupled)	LH (low density), HD (high density) and Multi-geometry Wafers (all DC-coupled)

PQC test structure set





- Dedicated structures for each process parameter
- Set of 15 flutes each with access to several different structures:
  - Larger structures (Diodes, MOS and GCD) routed to flute
  - Smaller structures (VdP, CBKR, FET, …) contained “within” flute

Same test structure set on Tracker and HGCAL Wafers!

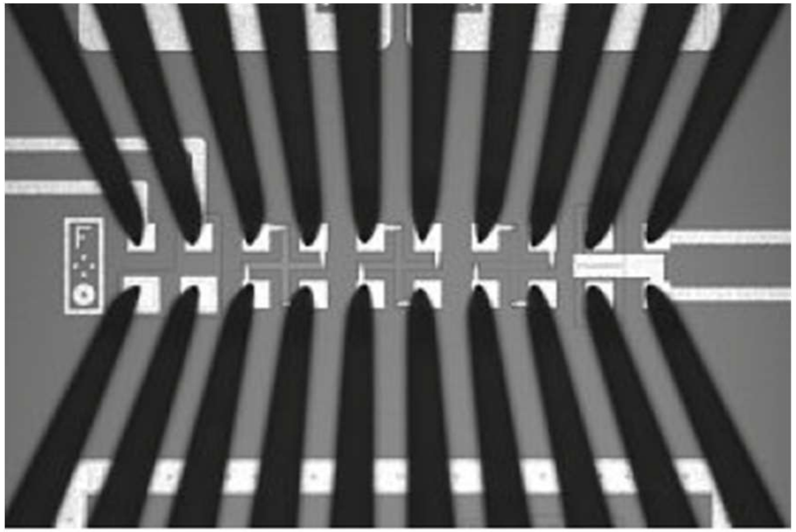
PQC testing method

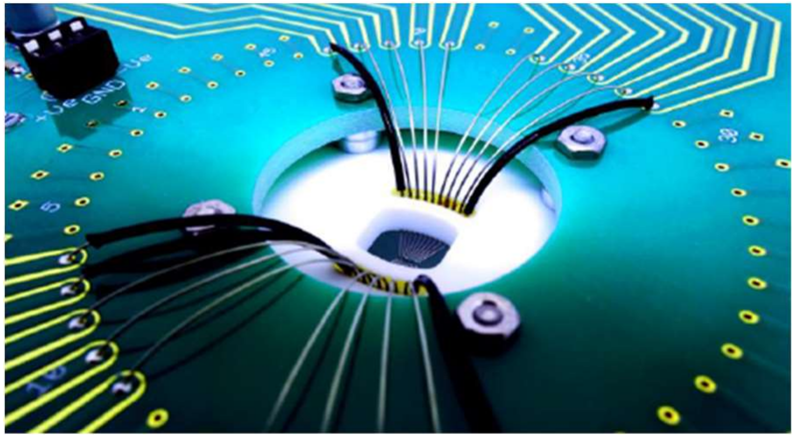
Test structure set on cut-off region of each Wafer

All test structures are accessible using a standardised set of contact pads: **Flute**

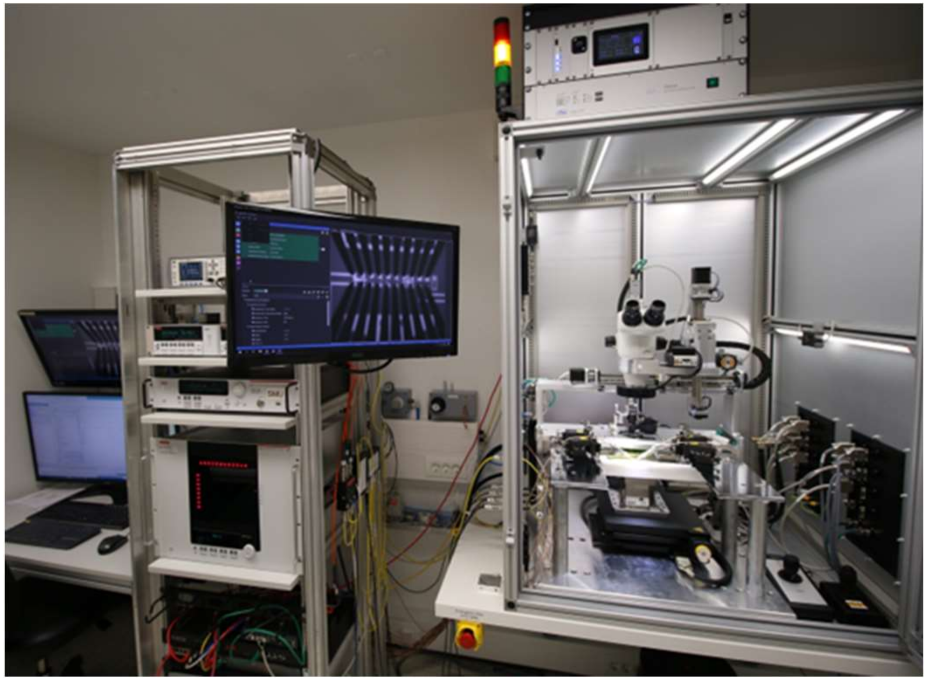
- 2 rows of 10 pads in a 200µm grid
- 100 x 100 pad size

Contacting the flute is best done with a probe card





PQC at HEPHY: Setup

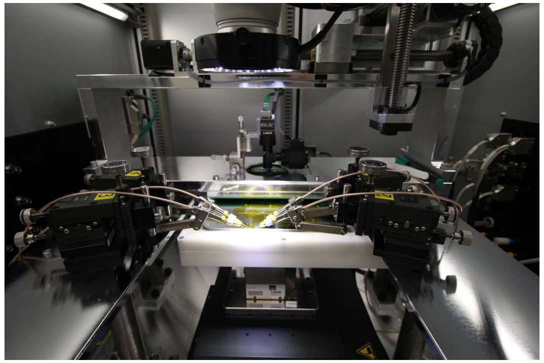


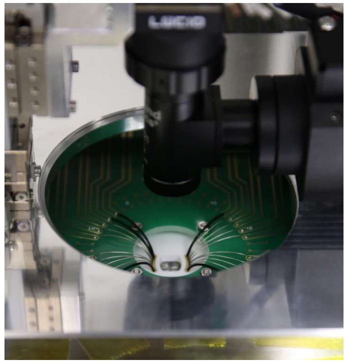
Fully custom built PQC setup:

- Several instruments connected to a switching matrix
- Highly automated measurement process

Instruments:

- SMU: *Keithley 2410*
- Electrometer: *Keithley 6517B*
- LCR Meter: *Keysight 4980A*
- Switching system: *Keithley 7072-HV* matrix cards in a *Keithley 707B* mainframe





PQC at other institutes

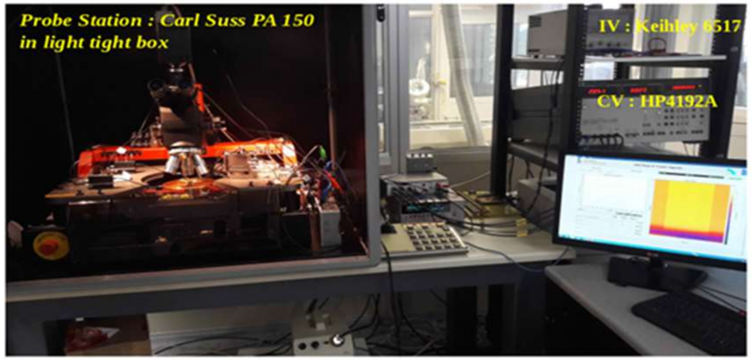
Similar setups for Tracker and HGCAL PQC tests at various other institutes.

Tracker:

- Brown University
- INFN Perugia
- NCSR Demokritos

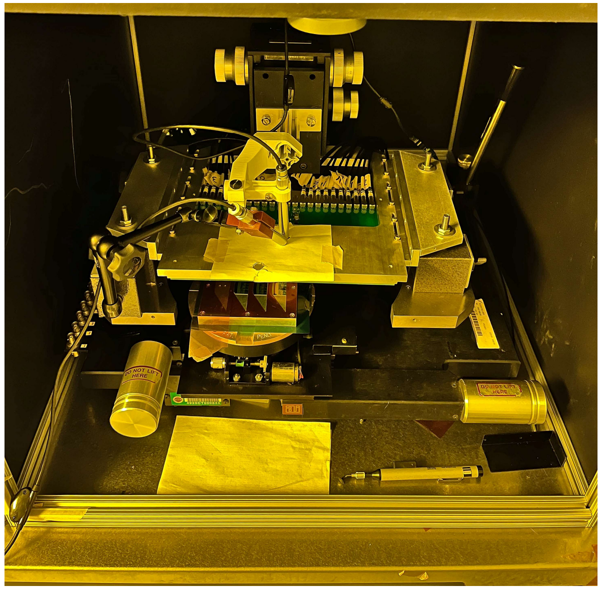
HGCAL:

Florida State University (FSU)

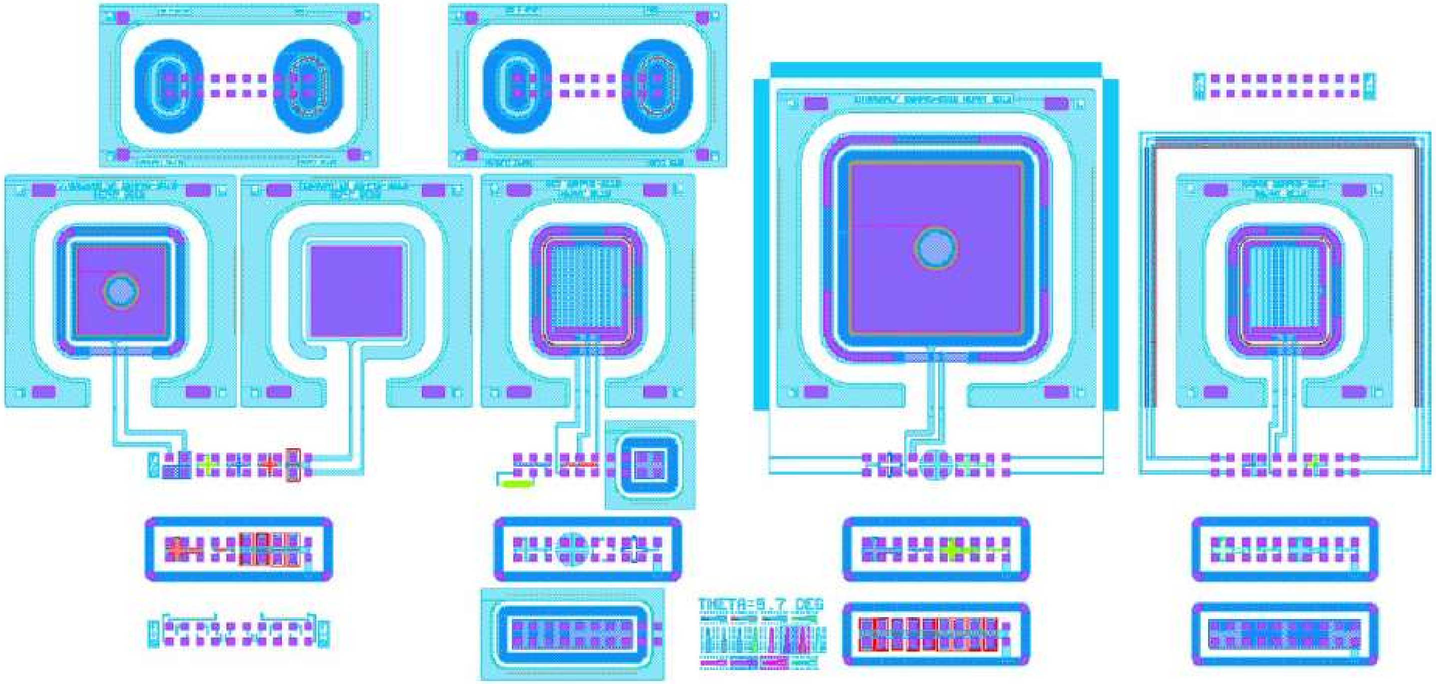


NCSR Demokritos

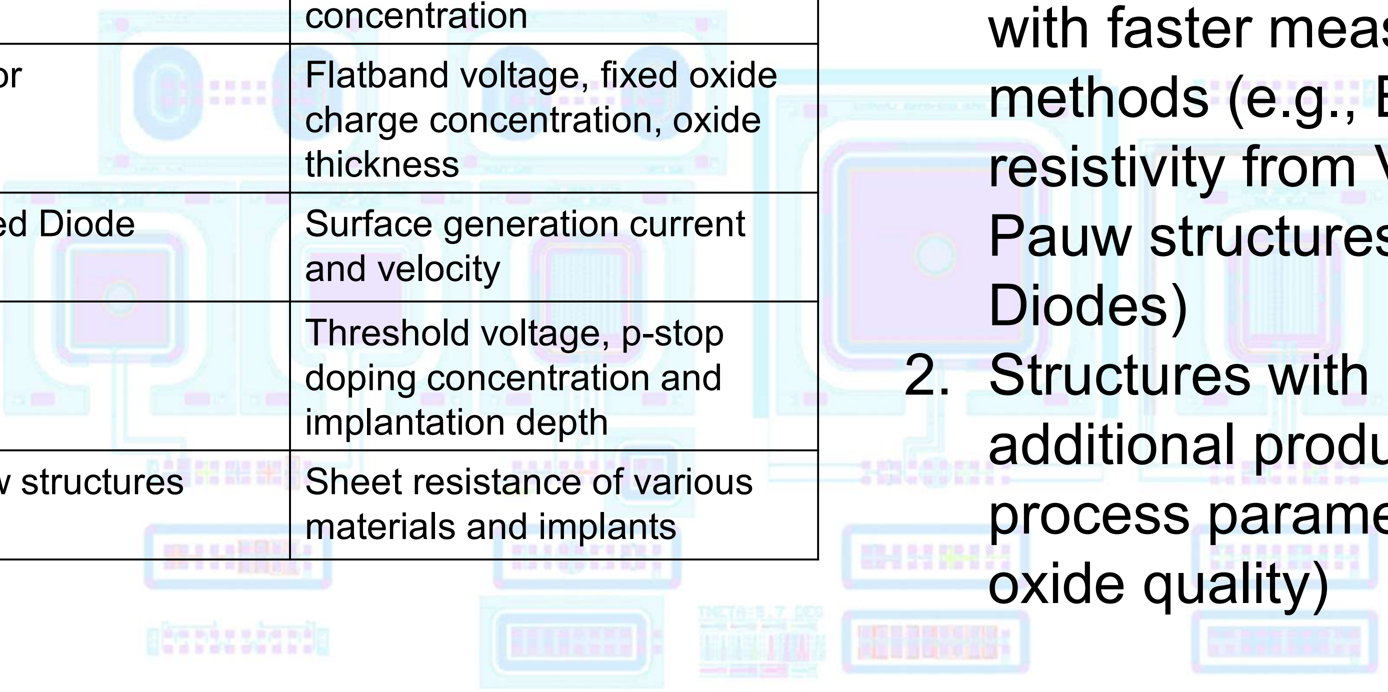
Perugia



Selected PQC test structures and measurements



Overview



Test structure	Accesible process parameters
Diode	Full depletion voltage, bulk resistivity, bulk doping concentration
MOS capacitor	Flatband voltage, fixed oxide charge concentration, oxide thickness
Gate controlled Diode	Surface generation current and velocity
MOSFET	Threshold voltage, p-stop doping concentration and implantation depth
Van-der-Pauw structures	Sheet resistance of various materials and implants

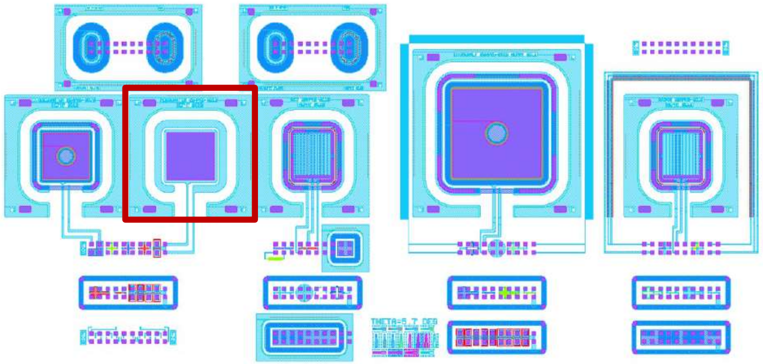
Two types of PQC test structures:

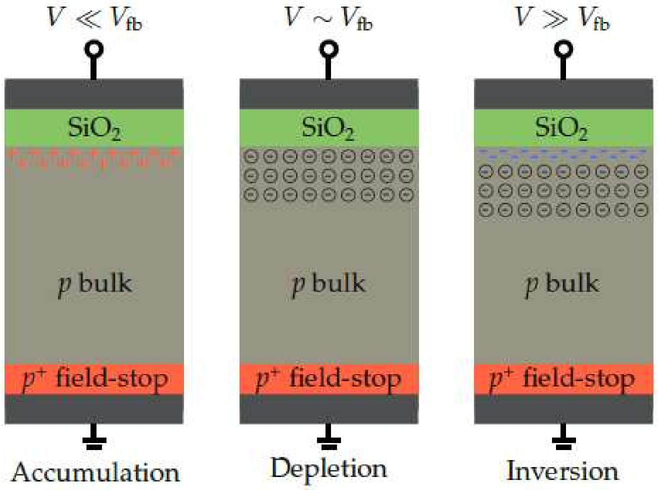
1. Characterization of sensor with faster measurement methods (e.g., Bulk resistivity from Van-der-Pauw structures instead of Diodes)
2. Structures with access to additional production process parameters (e.g., oxide quality)

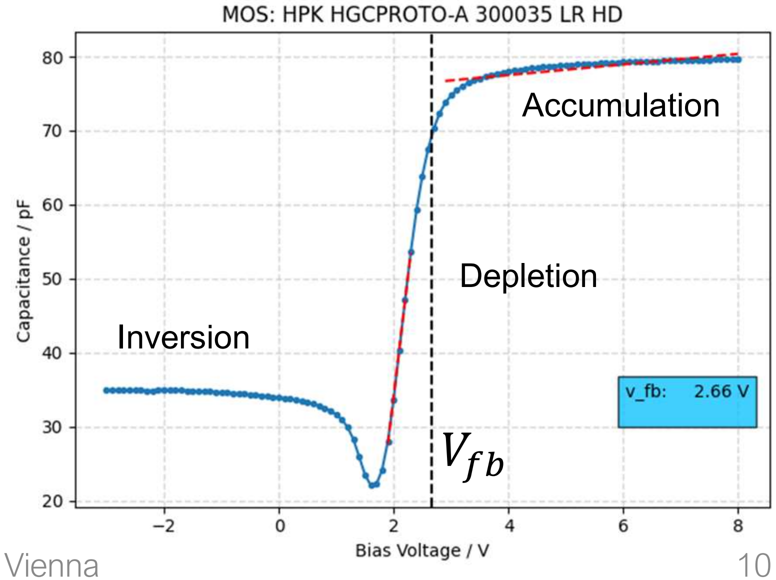
PQC test structure: MOS-Capacitor

Process parameters:

- Oxide charge concentration: $$N_{ox} = \frac{C_{ox}\,(\varphi_{MS} - V_{fb})}{q A_G}$$
- Oxide thickness: $t_{ox} = \varepsilon_{SiO_2} \frac{A_G}{C_{ox}}$
- Flatband voltage V_{fb}







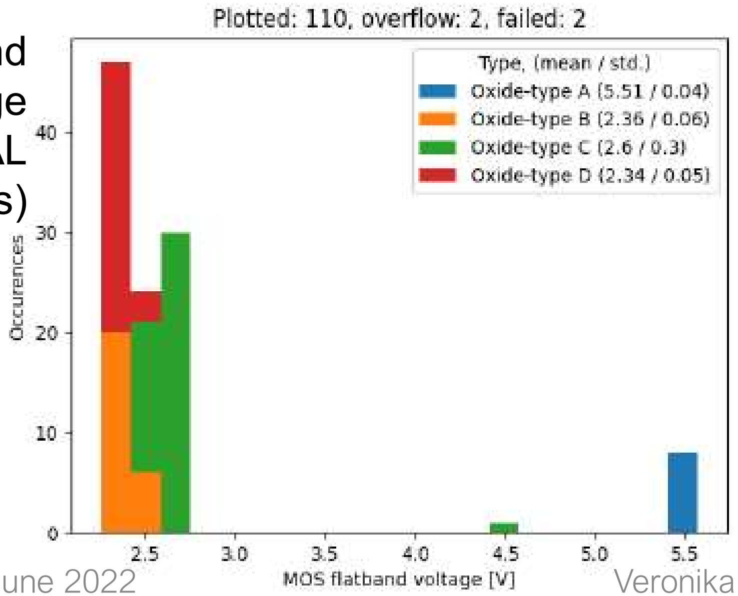
Selected MOS-C results

Oxide Quality and differences between Type A,B,C and D oxide of **HGCAL** test structures determined:

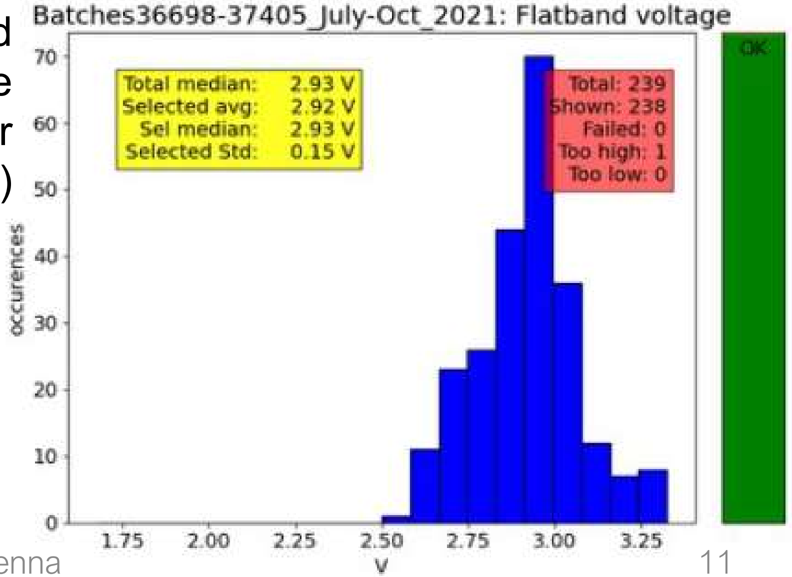
Oxide variants B,C and D show similar behavior, type A rejected. Comparison to **Tracker** (already in production): properties should be similar!

I. *Measurements during sensor development: Establish differences between oxide types/production processes*
II. *Main purpose of PQC: Measurements during production*

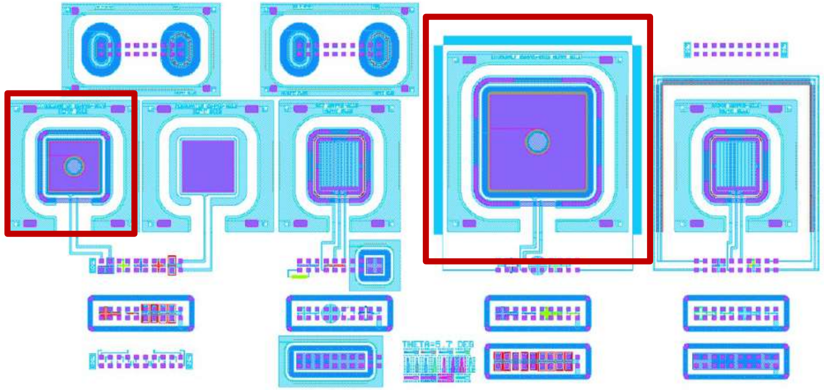
Flatband voltage HGCAL (Prototypes)



Flatband voltage Tracker (Production)

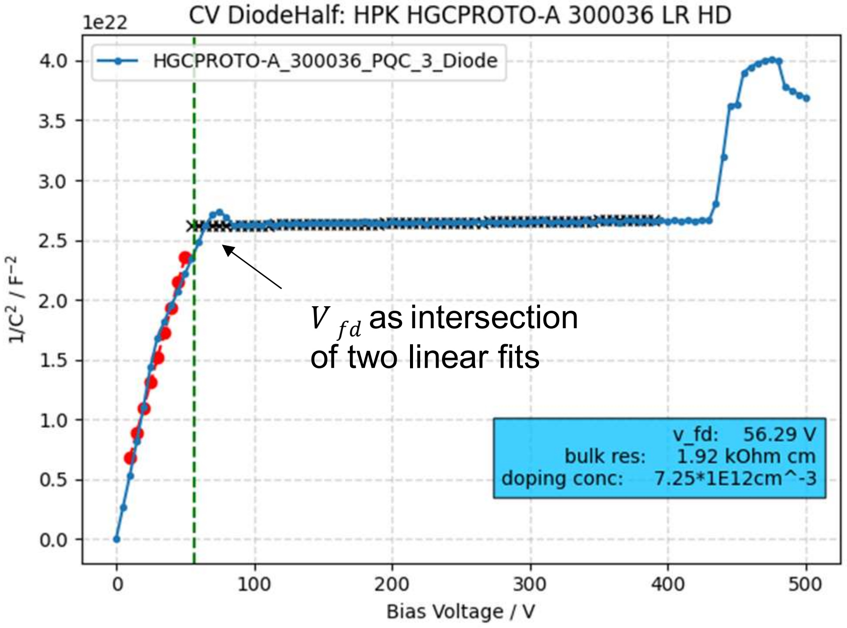


PQC test structure: Diode

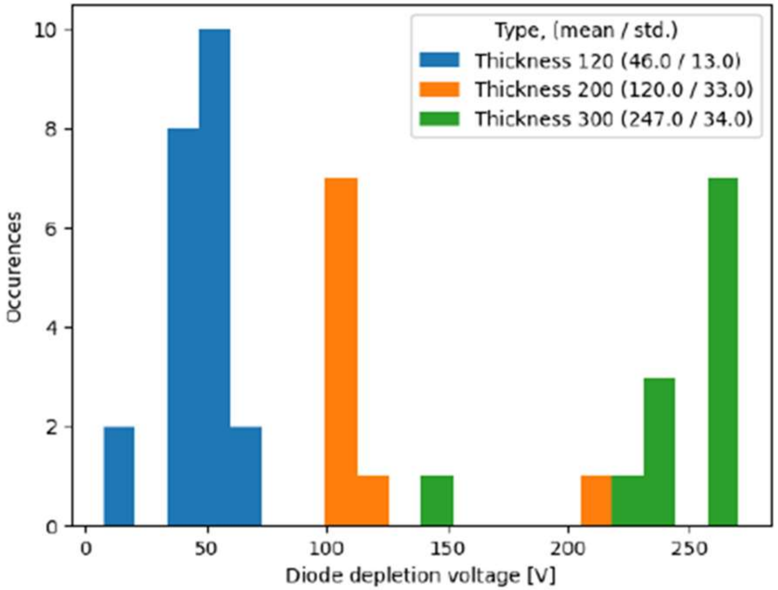


Process parameters:

- Full depletion voltage V_{fd}
- Bulk resistivity
- Bulk carrier concentration



V_{fd} as intersection of two linear fits

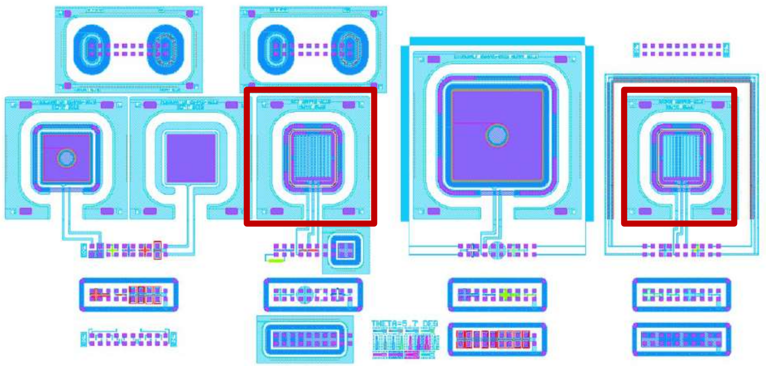


V_{fd} depends on sensor thickness (for similar resistivities of the three types)

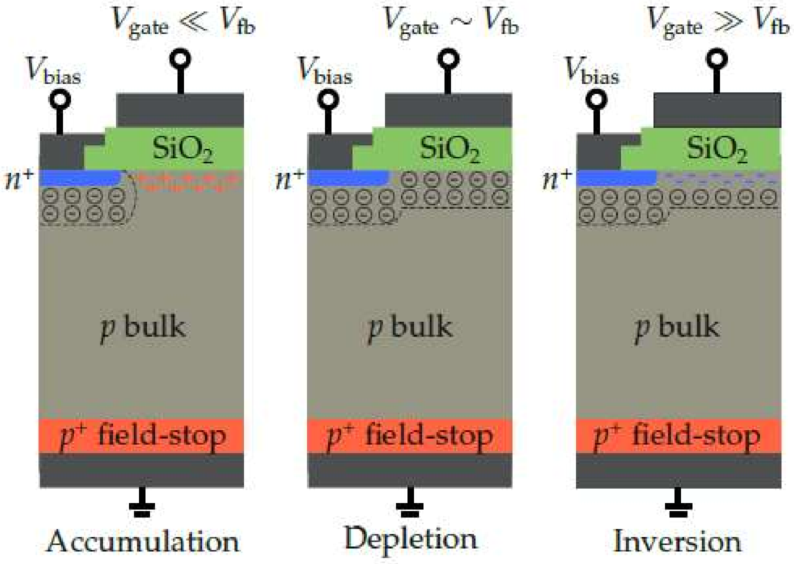
PQC test structure: Gate-Controlled Diode

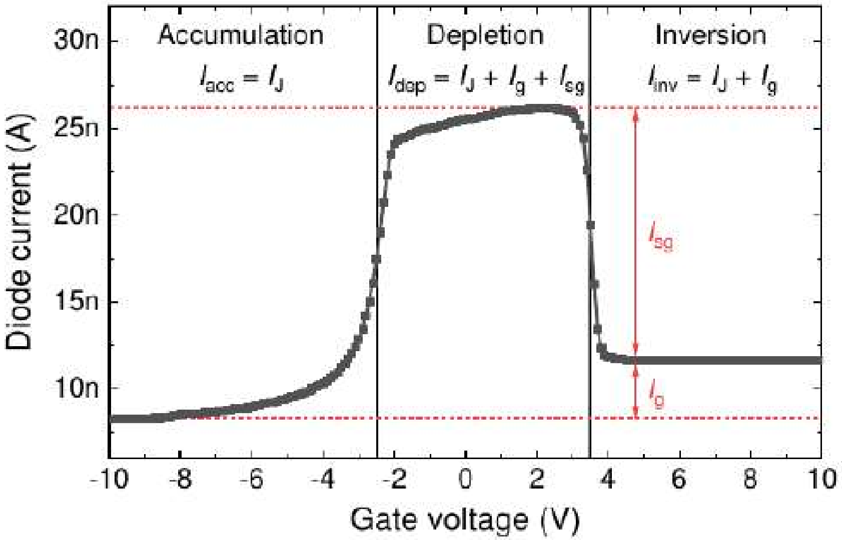
Process parameters:

- Surface current: $I_{sg} = I_{dep} - I_{inv}$
- Surface generation velocity
- Si-SiO$_2$ interface quality
- Interface traps



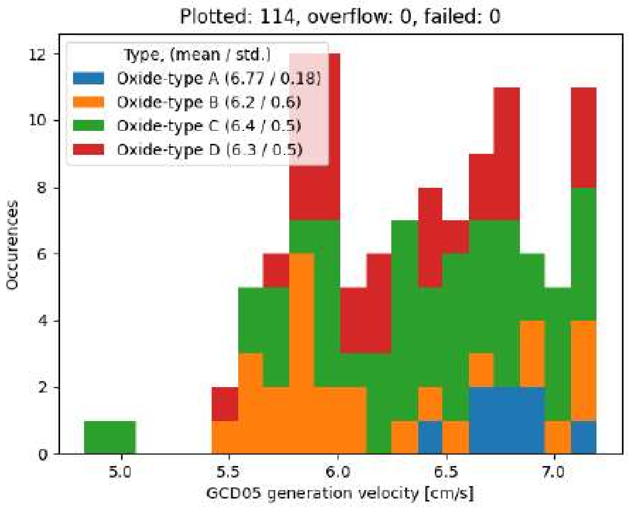
Gate-Controlled Diodes combine properties of a Diode and MOS-C

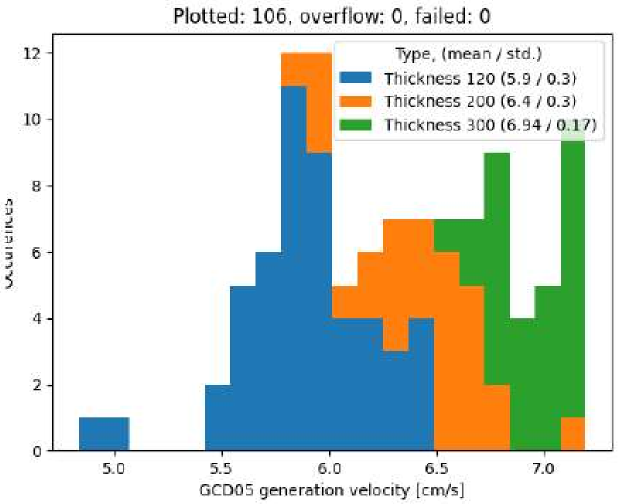




Selected Gate-Controlled Diode (GCD) results

Si-SiO$_2$ interface quality of different oxide types A,B,C, D (left plot) and wafer thicknesses (right plots) of **HGCAL** test structures determined:





Surface generation velocity:

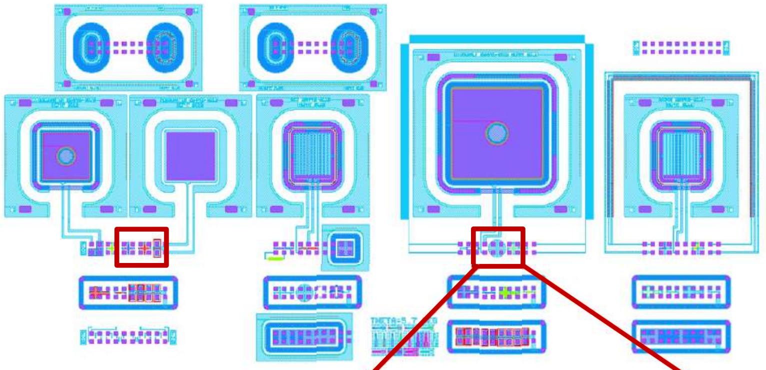
$$s_g = \frac{I_{sg}}{q\, n_i A_G}$$

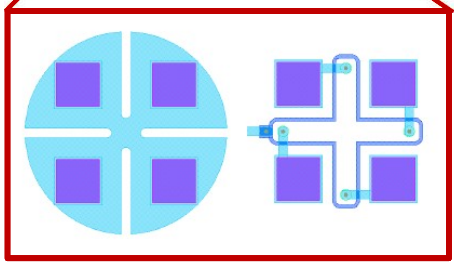
No significant differences between oxide types.

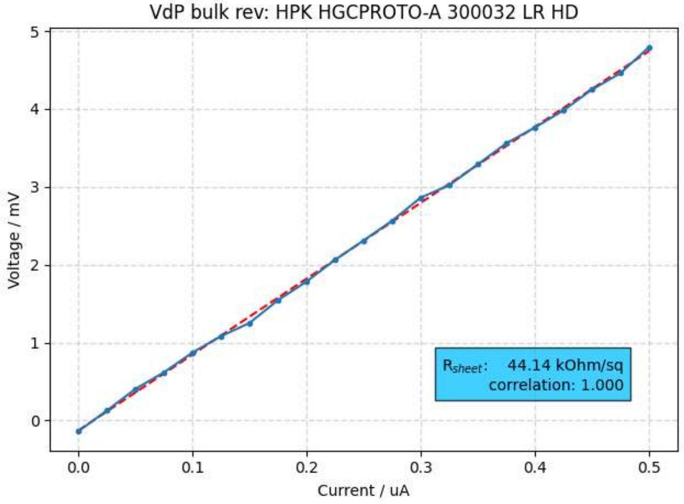
Observation: Dependence of surface generation velocity (and surface current) on sensor thickness.

PQC test structure: Van-der-Pauw structures

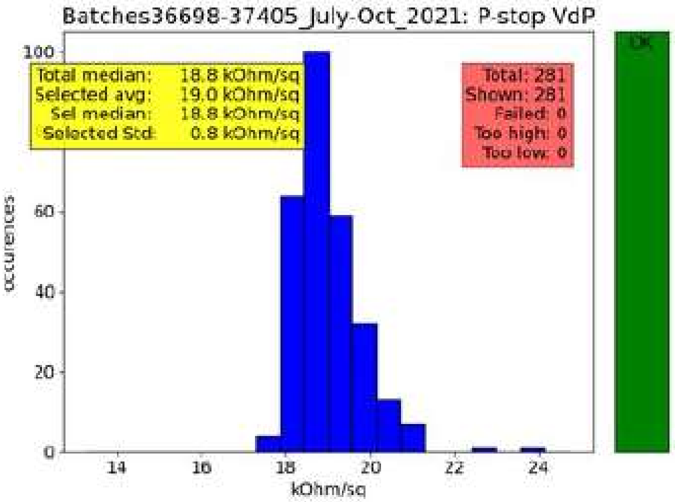
Process parameters: sheet resistance of thin films for different materials and implants (n+, p-stop and p-edge implant layers, metal- and polysilicon layer, bulk material)







Example of bulk VdP measurement

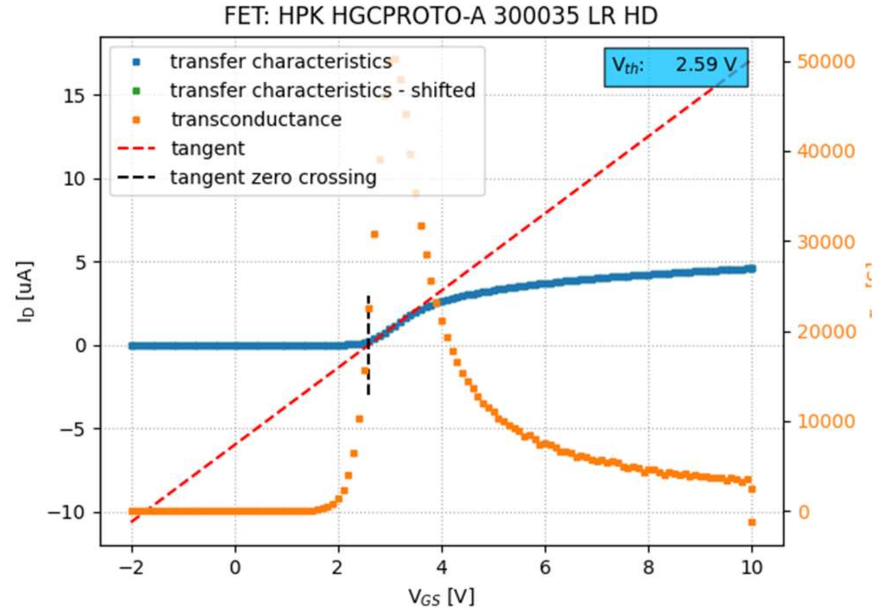


Tracker results of VdP p-stop resistivities

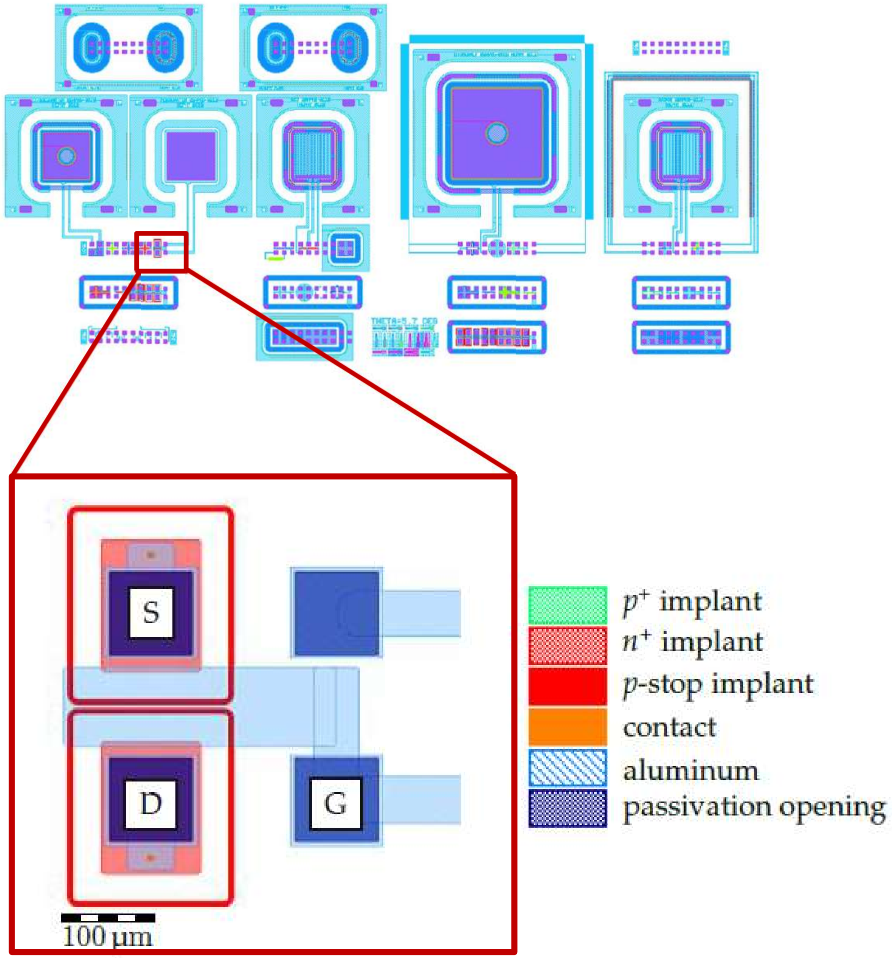
PQC test structure: MOSFET

Process parameters:

- Threshold voltage V_{th}
- p-stop doping concentration
- Inter-channel resistance

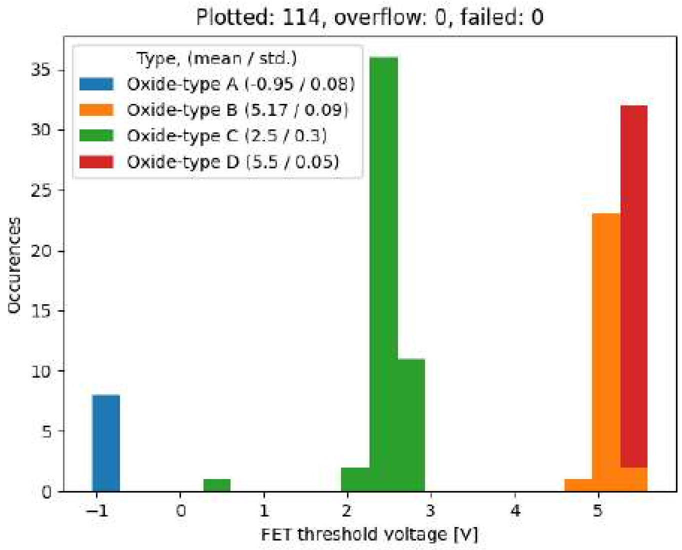


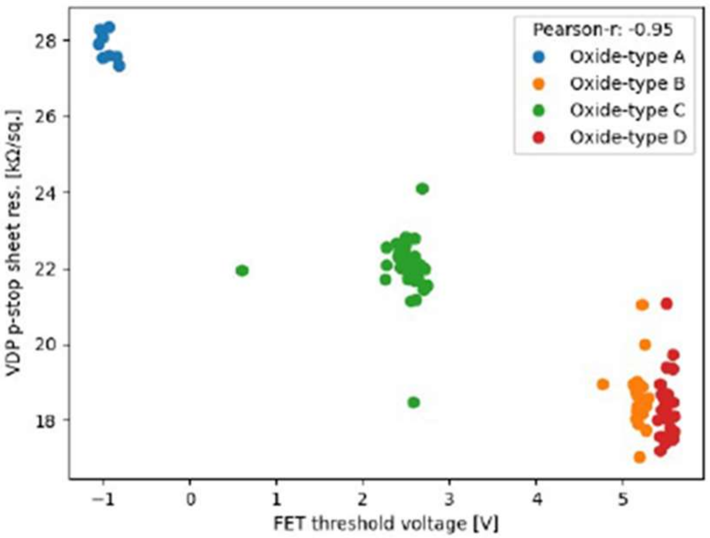
I-V curve
Transconductance (1st derivative)
Lin. extrapolation



Selected MOSFET results

MOSFETs are used to determine inter-channel features (inter-channel resistance, p-stop properties). Measurements of **HGCAL** test structures:



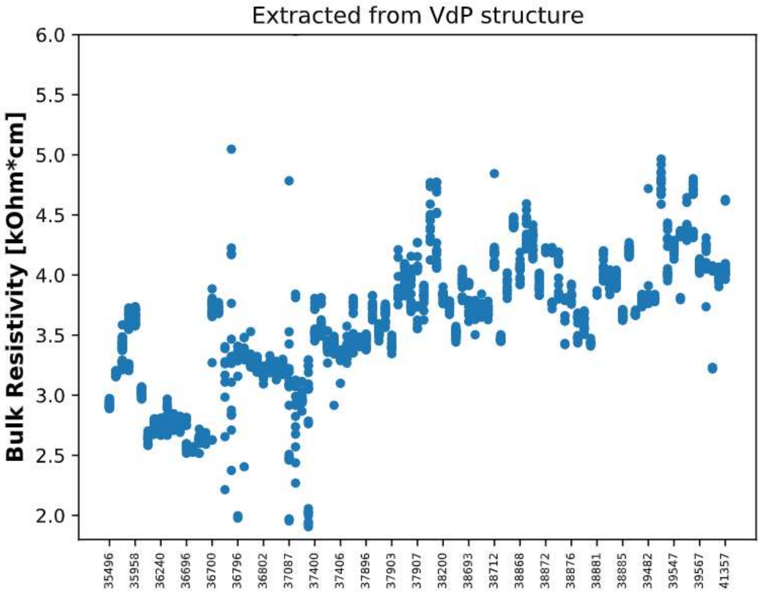


V_{th} is sensitive to the p-stop resistance. Lower p-stop res. → higher V_{th} and therefore better inter-channel isolation

- V_{th}: minimal Gate-Source voltage to obtain a conductive channel between Source and Drain
- FET threshold voltage differs for four oxide types, Type C for final production

Selected VdP results

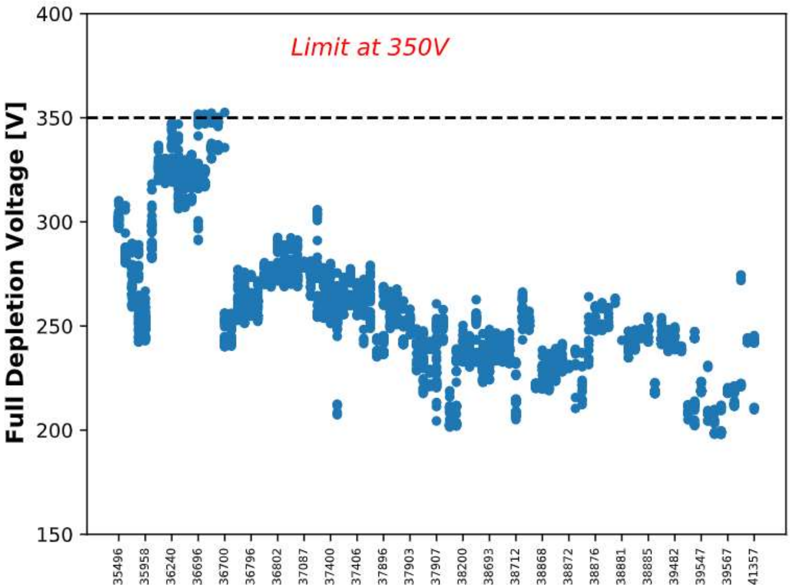
Bulk resistivity of **Tracker** sensors monitored over production time:



791 tested Wafers

⇒ bulk resistivity and full depletion voltage could be improved!

I. *Measurements during sensor development*
II. *Measurements during production: monitor stability of the production process and confirm resulting devices*



Outlook: Neutron irradiated test structures

3 neutron irradiated sensors available for measurements (HGCAL , epi, 120µm):

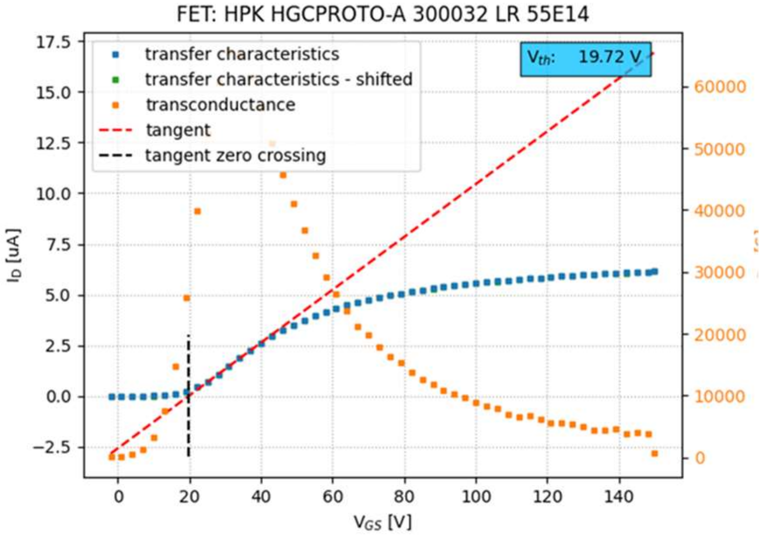
- Proto-A 300012: 1.4E16 neq/cm²
- Proto-A 300009: 1E16 neq/cm²
- Proto-A 300032: 5.5E15 neq/cm²

Annealing before measurement: 80min at 60°C

⇒ PQC method also applicable for irradiated test structures?

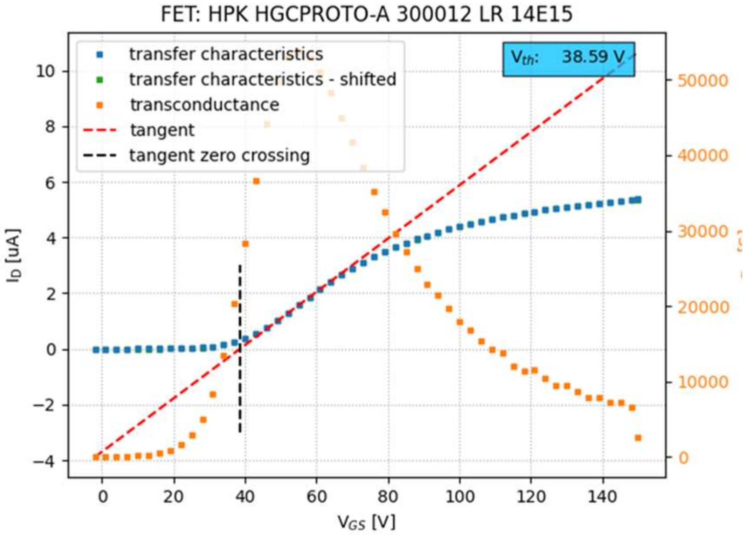
Example 1: Neutron irradiated MOSFET

5.5E15 neq/cm^2



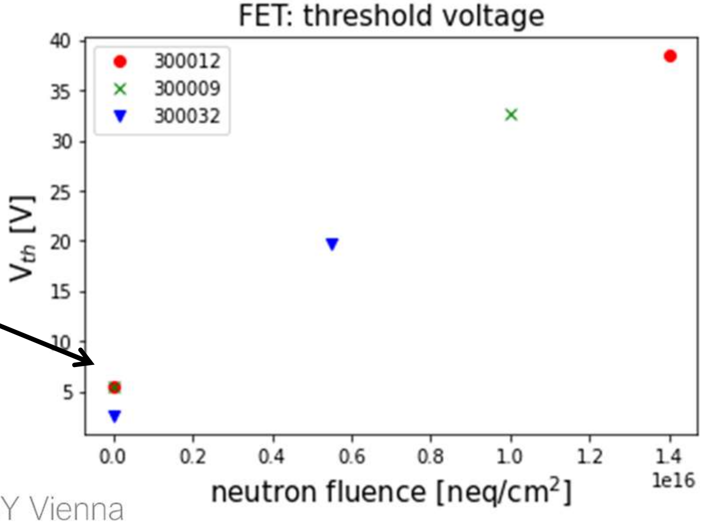
Notice: measurements up to 150V

1.4E16 neq/cm^2

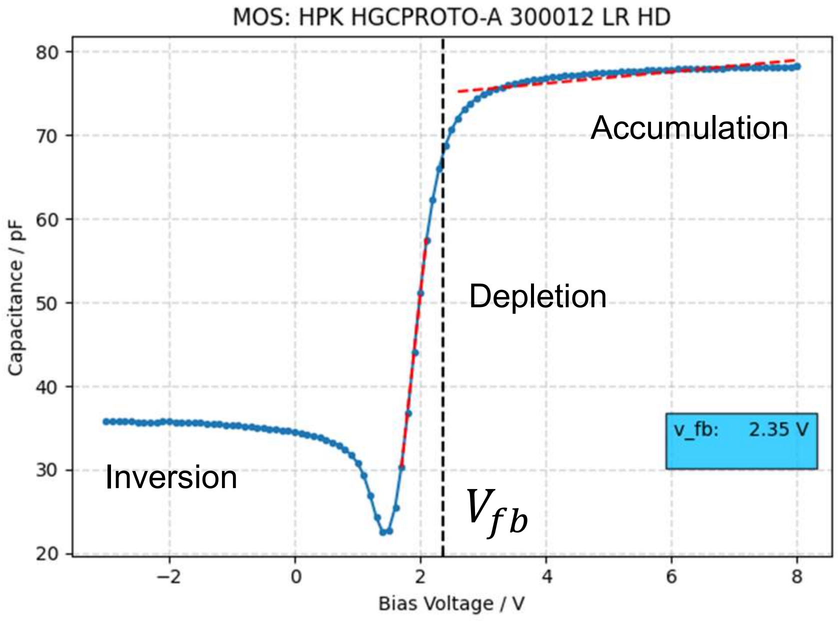


Positive charges generated in oxide
⇒ Increasing FET threshold voltage with higher fluences

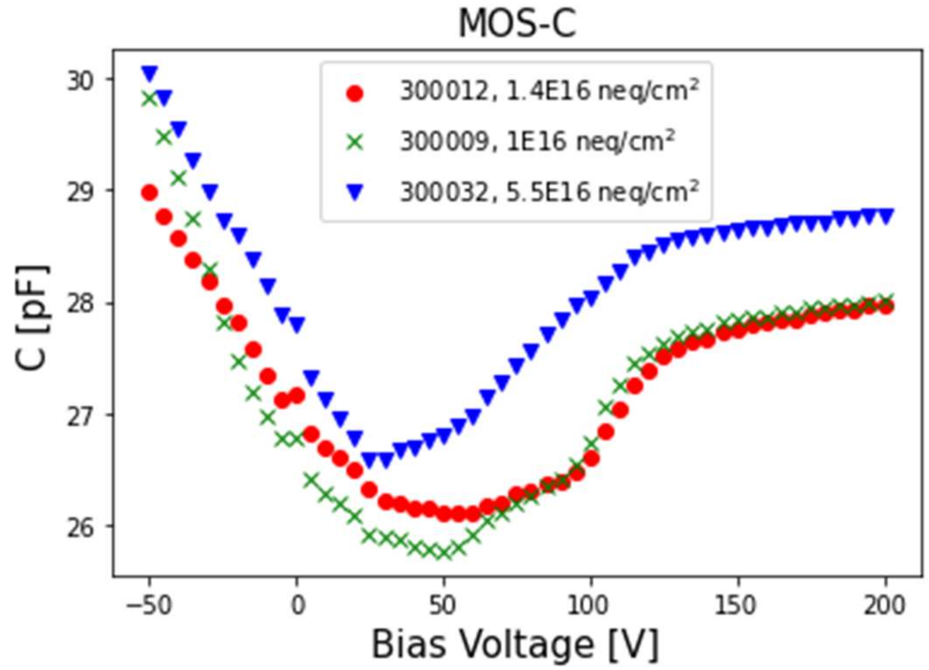
Before irradiation



Example 2: Neutron irradiated MOS-C



Exemplary PQC measurement of not irradiated MOS-C test structure



- Applied voltages increased for irradiated MOS-Cs
- Measurement results not fully understood yet!
- Further plan: investigate frequency dependance

Summary

Process Quality Control establishes a fast method to **test Tracker and HGCAL sensors** for the CMS Phase-2 Upgrade.

- The PQC test method can be used to do **studies in the sensor development phase**.
- The aim of PQC is to **monitor mass production**.

Process parameters get obtained from **dedicated test structures** like MOS-Capacitors, MOSFETs, Diodes and others.

Work in progress: PQC measurements of **irradiated test structures**.

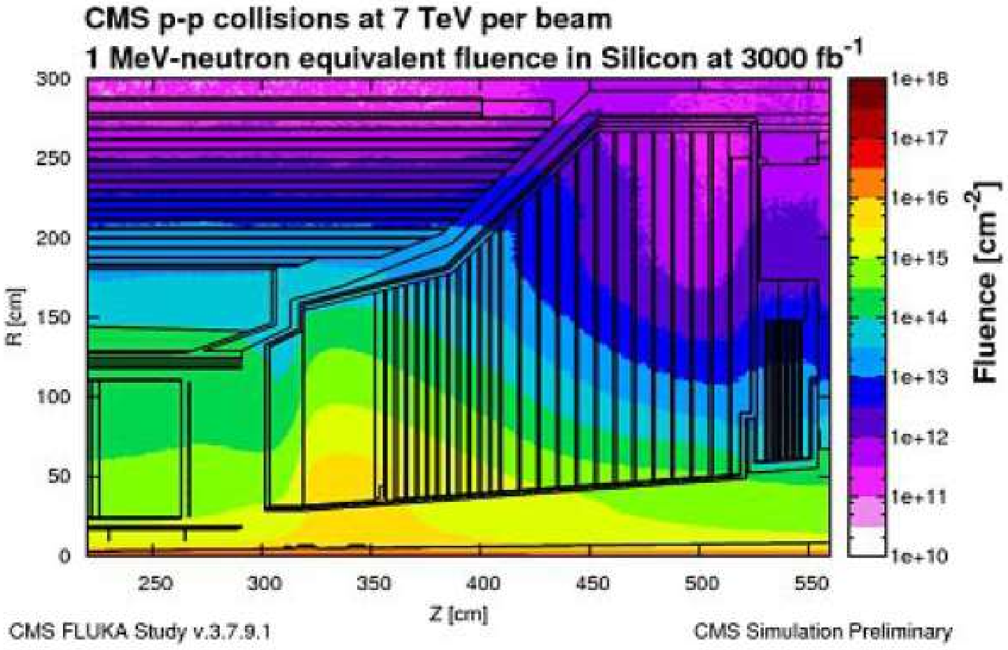
Thanks for your attention!

Thanks to CMS HGCAL and Tracker groups!

Backup

Particle fluences in HGCAL

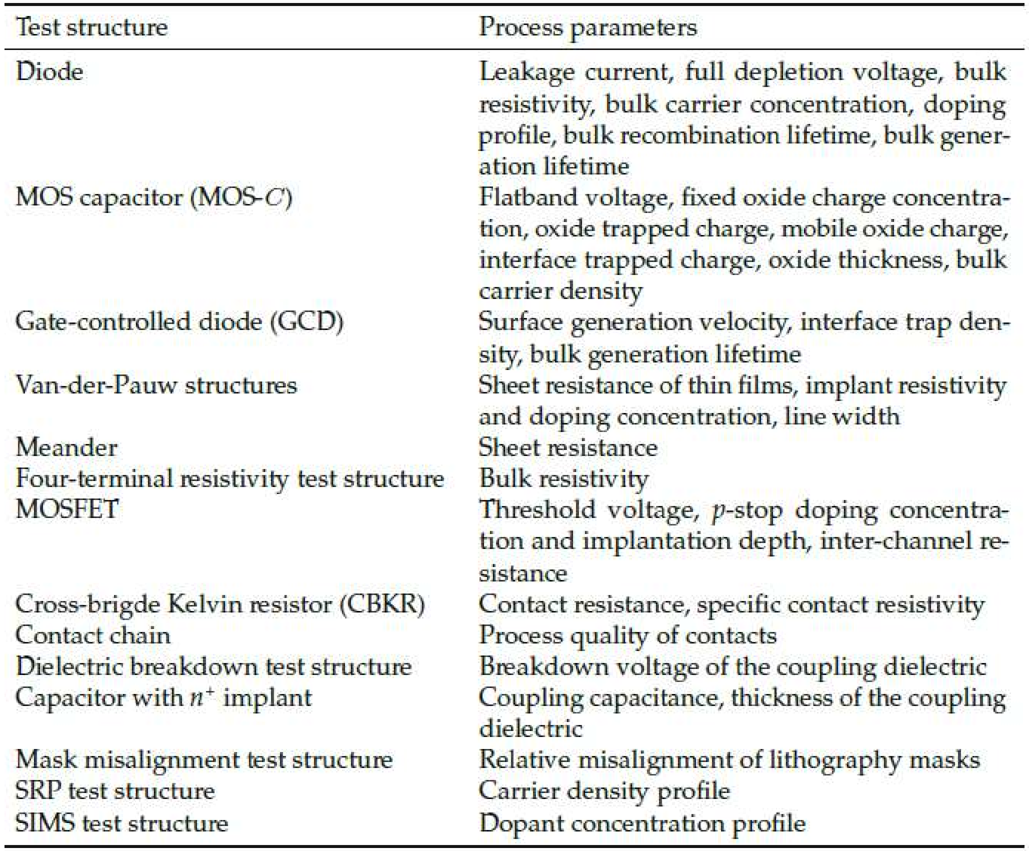
- Electromagnetic compartment of HGCAL uses silicon sensors (high fluence regions)
- Hadronic compartment uses silicon sensors and scintillators
- For regions with different fluences: three different active thicknesses (120µm, 200µm and 300µm) and two different cell granularities (low density and high density)



FLUKA simulation of particle fluence in 1 MeV neq/cm^2 accumulated in HGCAL after an integrated luminosity of 3000 fb^{-1} (from the CMS Collaboration)

Further test structures

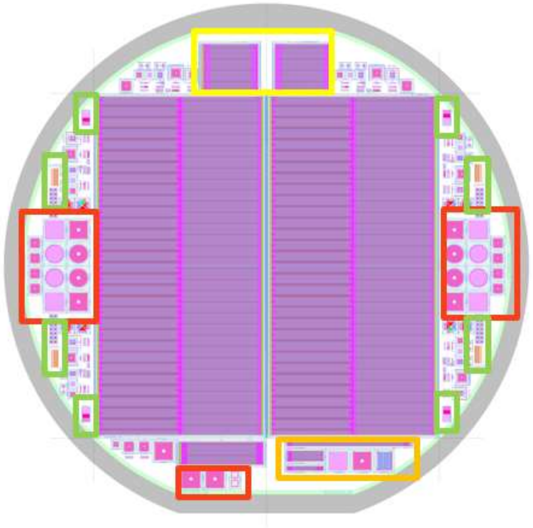
All PCQ test structures:



Test structure	Process parameters
Diode	Leakage current, full depletion voltage, bulk resistivity, bulk carrier concentration, doping profile, bulk recombination lifetime, bulk generation lifetime
MOS capacitor (MOS-*C*)	Flatband voltage, fixed oxide charge concentration, oxide trapped charge, mobile oxide charge, interface trapped charge, oxide thickness, bulk carrier density
Gate-controlled diode (GCD)	Surface generation velocity, interface trap density, bulk generation lifetime
Van-der-Pauw structures	Sheet resistance of thin films, implant resistivity and doping concentration, line width
Meander	Sheet resistance
Four-terminal resistivity test structure	Bulk resistivity
MOSFET	Threshold voltage, p-stop doping concentration and implantation depth, inter-channel resistance
Cross-brigde Kelvin resistor (CBKR)	Contact resistance, specific contact resistivity
Contact chain	Process quality of contacts
Dielectric breakdown test structure	Breakdown voltage of the coupling dielectric
Capacitor with n^+ implant	Coupling capacitance, thickness of the coupling dielectric
Mask misalignment test structure	Relative misalignment of lithography masks
SRP test structure	Carrier density profile
SIMS test structure	Dopant concentration profile

Other test structures on the Wafer:

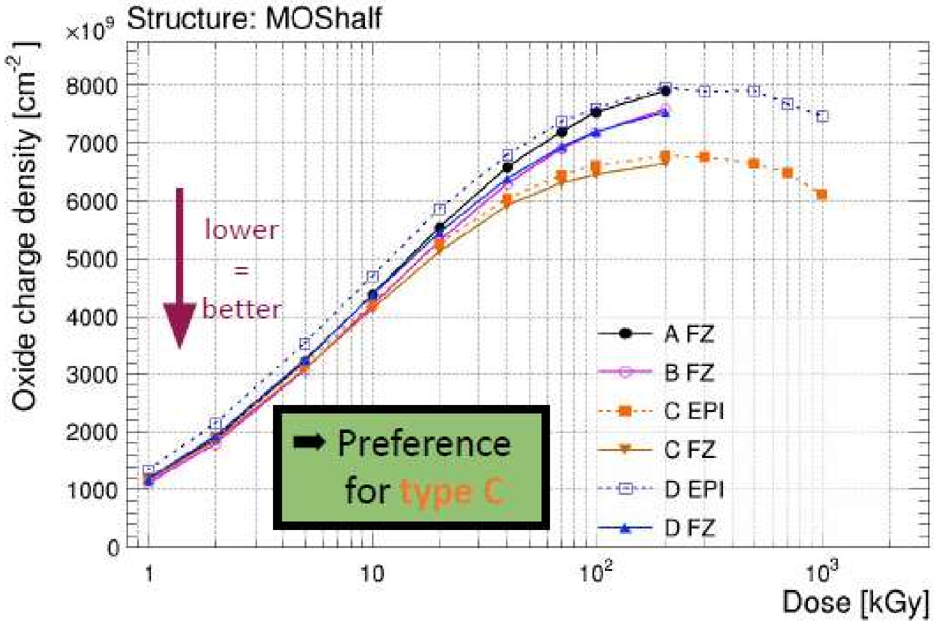
- Diodes and MOS-Cs in various configurations
- Legacy test structures
- Mini sensors
- SIMS, SRP fields ad round FETs



MOS-C measurements: Oxide Types

Four options for the silicon oxide process: A, B, C, D

- **A = old STD -5V** , **B = old STD -2V**, **C = new type C**, **D = entirely new type**
- Properties should be closest to outer tracker sensors in terms of fabrication and characteristics



lower = better

➡ Preference for type C

X-ray irradiation study at CERN

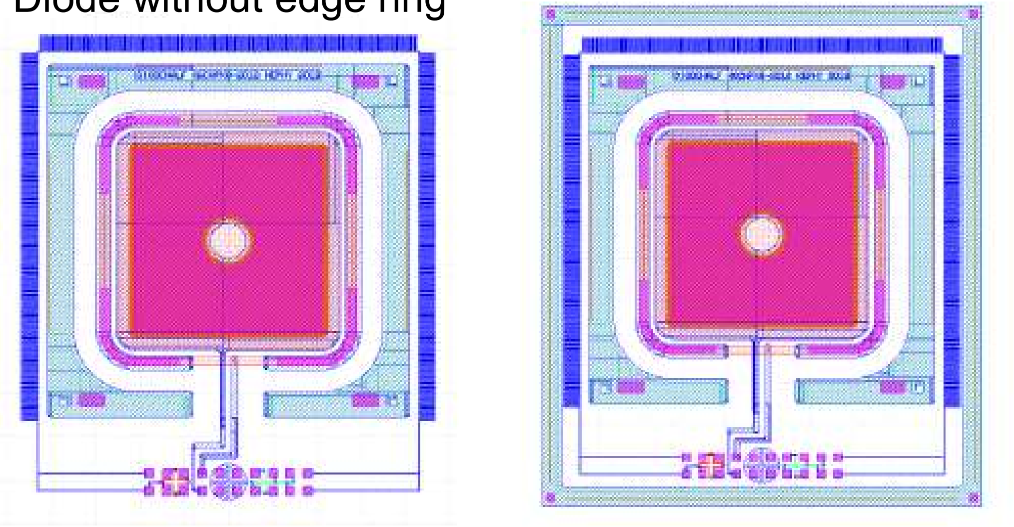
PQC test structure: Diode

Not high voltage stable!
Problems:

- Long rooting necessary
- Open guard ring for connection

⇒ Still reliable up to ~400V!

Alternative on PQC test structure set: Van-der-Pauw Bulk measurements

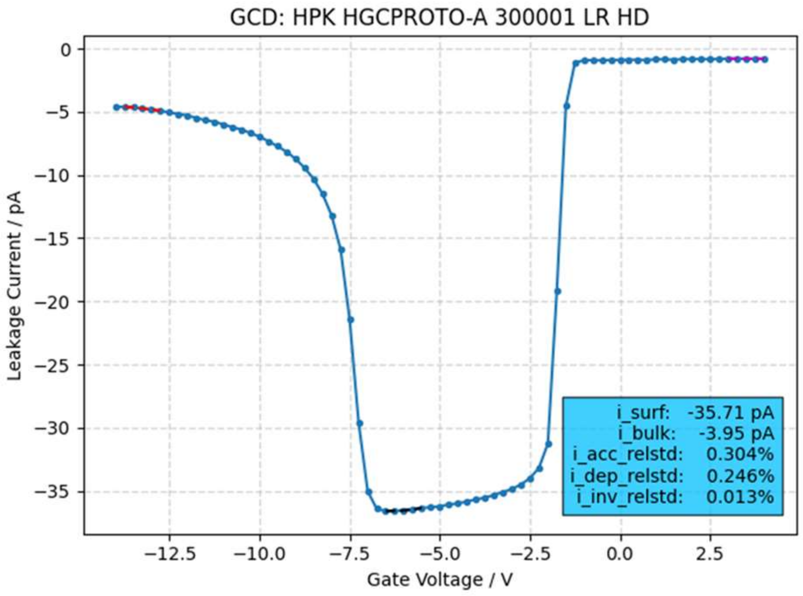

Diode without edge ring

Diode with additional edge ring

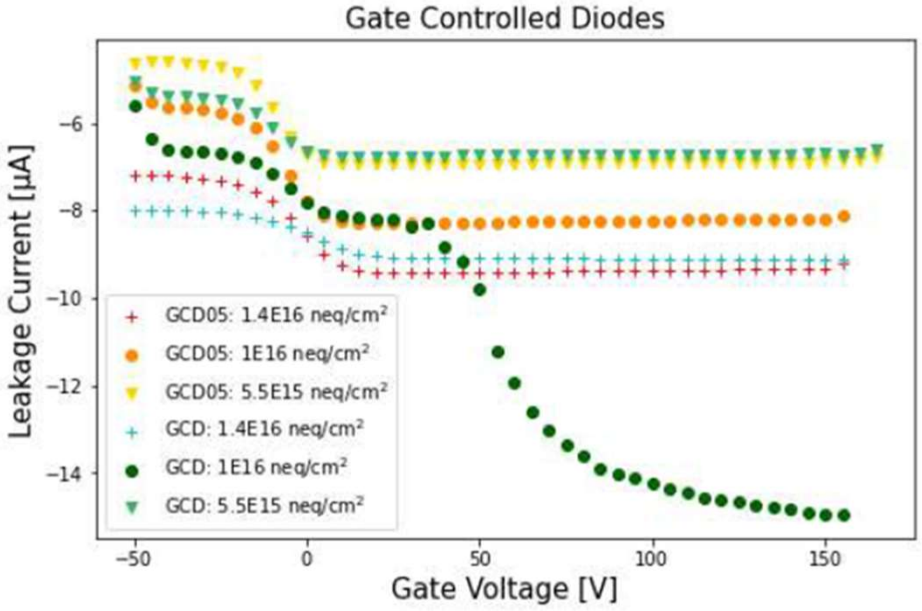
Different diode layouts for two PQC halfmoons: An additional edge-ring was added to the lower-right diode → improvement of IV/CV measurements!

Example 3: Neutron irradiated GCD

PQC test structure set includes two GCDs with equal external dimensions but different gate widths: 50µm (GCD) and 70µm (GCD05)



Exemplary PQC GCD measurement of unirradiated test structure



- Applied voltages increased for irradiated GCDs
- Measurement results not fully understood yet!