Process quality control (PQC) of silicon sensors for the Phase-2 upgrade of the CMS Tracker

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Research & Innovation

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Introduction

- Silicon sesnors before they are installed in the high energy experiments must have a substantial quality, in order to cope with the higher luminosity of HL-LHC.
- CMS has developed a quality assurance plan to make sure that all the components meet the specifications and to monitor the production procedure of the sensors.
- Process quality control is contacted to deticated test structures produced in the same wafer as the silicon sensors that will be used in the experiment.
- Together with the Sensor Quality control consist of the two main procedures of the quality assurance of the sensors.

1. The phase 2 upgrade of CMS Tracker
2. Sensor and process quality control
3. Examples of experimental measurments

From LHC to HL-LHC

- Phase-I: (2018-2020), Double the designed Luminosity:$2 \cdot 10^{34} cm^{-2} s^{-1}$, Integrated Luminosity: 300 fb^{-1} at Run 3.
- Phase-II: (2024-2026) , Luminosity:$5 \cdot 10^{34} cm^{-2} s^{-1}$, 300 fb^{-1} per year 3000 fb^{-1} for 10 years of operation

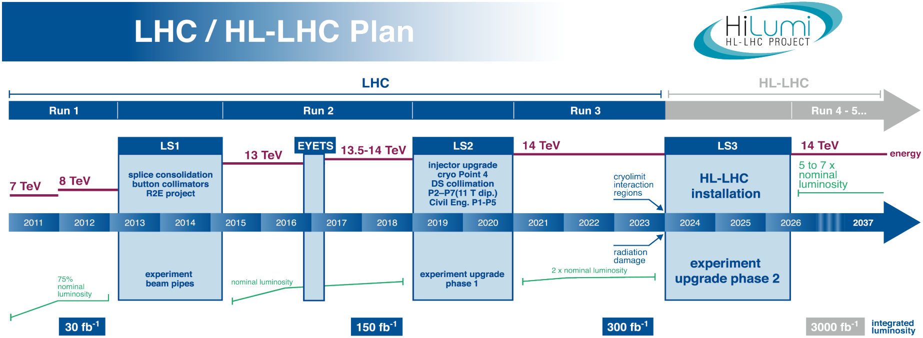
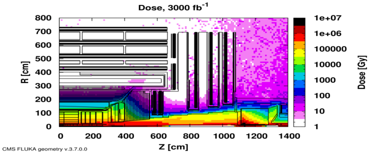
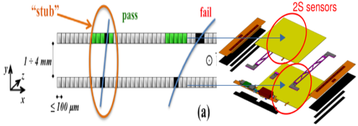


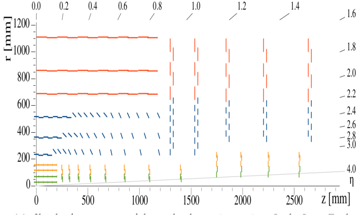
Figure: *HL-LHC upgrade schedule.*

Phase-2 upgrade of CMS Tracker

- Due to high number of pile-up events and radiation levels a major upgrade of the CMS experiment is needed. Three of the most important requirements for the CMS Tracker are:
  - Radiation Tolerance. ⇒ Flip from p-on-n to n-on-p, Oxygen-rich substrates
  - High Pile up ⇒ Increase granularity.
    - Increased number of sensors
    - Increased segmentation to each sensor.
  - Improve CMS trigger system ⇒ Contribution of CMS Tracker at Level-1 Trigger.
    - Discrimination of low p_T events at module level at bunch crossing rate.
    - Reduce data volume.
    - Keeping the most interesting events for physics studies.
- Outer Tracker:
  - 2S modules Two very closed spaced strip sensors
  - PS modules Two very closed sensors. One with macro-pixels (PS-p) and one with strips (PS-s)
- Inner Tracker:
  - Pixel modules Pixel very thin detectors with two pixel geometries $(50x50)$,$(100x25)$







Outer Tracker sensors

Outer Tracker will encompass 200 m^2
Consisting of 24000 sensors
Two different modules with three different sensors

- 2S sensors
  - $6''$ wafers
  - n-on-p sensors
  - Float-zone technique
  - Active thickness 290 um
  - AC coupled with Poly-silicon biased
- PS-s sensors
  - $6''$ wafers
  - n-on-p sensors
  - Float-zone technique
  - Active thickness 290 um
  - AC coupled with Poly-silicon biased
- PS-p sensors
  - $6''$ wafers
  - n-on-p sensors
  - Float-zone technique
  - Active thickness 290 um
  - DC coupled
  - Biased with punch-through structures

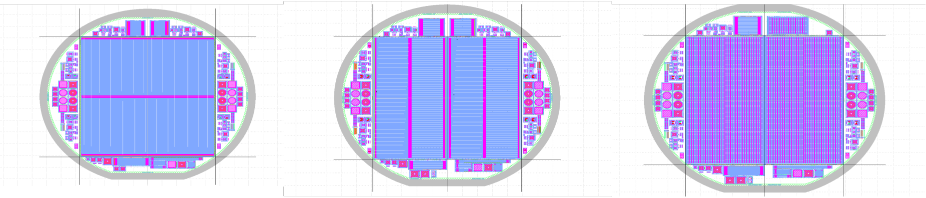


Figure: *Design of the 2S, PS-s and PS-p wafers* [1]

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[1] GDS files made by Institute of High Energy Physics (HEPHY), Austria

Sensor and process quality control

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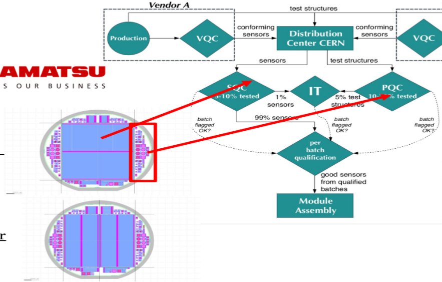
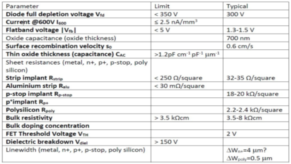
- 2S sensor wafer
- PSs sensor wafer



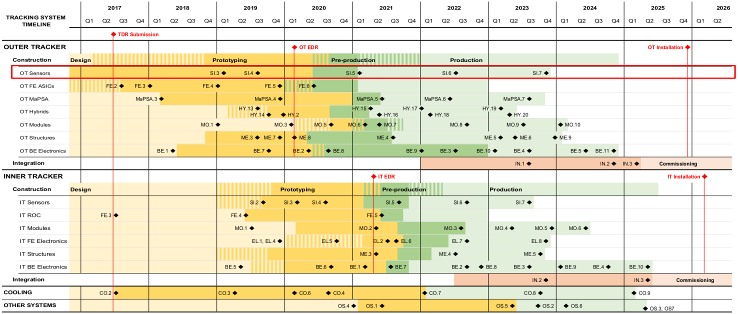


Parameter	Limit	Typical
Diode full depletion voltage V_{fd}	< 350 V	300 V
Current @600V I_{600}	≤ 2.5 nA/mm^3	
Flatband voltage $\lvert V_{fb} \rvert$	< 5 V	1.3-1.5 V
Oxide capacitance (oxide thickness)		700 nm
Surface recombination velocity s_0		0.6 cm/s
Thin oxide thickness (capacitance) C_{AC}	>1.2pF cm^{-1} pF^{-1} µm^{-1}	
Sheet resistances (metal, n+, p+, p-stop, poly silicon) **Strip implant R_{strip}**	< 250 Ω/square	32-35 Ω/square
Aluminium strip R_{alu}	< 30 mΩ/square	
p-stop implant $R_{p\text{-}stop}$		18-20 kΩ/square
p$^+$implant R_{p+}		
Polysilicon R_{poly}		2.2-2.4 kΩ/square
Bulk resistivity	> 3.5 kΩcm	3.5-8 kΩcm
Bulk doping concentration		
FET Threshold Voltage V_{TH}		2 V
Dielectric breakdown V_{diel}	> 150 V	
Linewidth (metal, n+, p+, p-stop, poly silicon)		ΔW_{n+}=4 µm? ΔW_{poly}=0.5 µm

- Sensor quality control
  - Direct measurement of subset of sensors which will be made into modules
  - Directly verify that HPK is producing sensors within our specs
  - Takes a lot of time. Less samples in the same batch.
- Irradiation tests
  - Irradiate mini sensors and test structures from same wafer as diced sensors
  - Verify that the silicon will behave within spec after expected radiation doses of HL-LHC
- Process quality control
  - Measurement of test structures located on the same wafer constructed with the same properties as the main sensors, utilizing the empty space on the edges of the wafers.
  - Verify silicon quality without the need to handle sensors
  - Takes less time. More samples in the same batch can be measured

QA centers

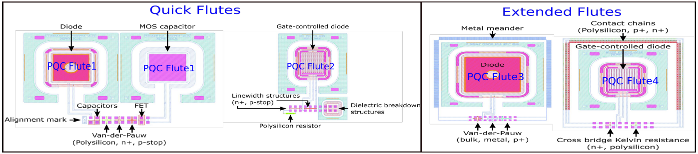
- SQC centers
  - Brown
  - Delhi
  - Hephy
  - KIT
  - NCP
  - Rochecter
- PQC centers
  - Brown
  - Demokritos
  - Hephy
  - Perugia
- IT centers
  - KIT
  - Brown



PQC mesurments: Flute structures

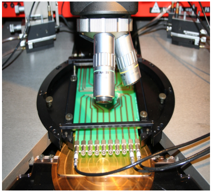
- Test structures that are arranged around an array of 20 contact pads, called ”flute”
    - Automated measurements by using a 20 needle probe card

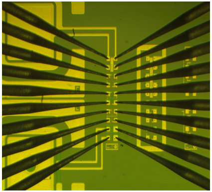
- Each Half Moon contain 2 sets of 4 flutes in each side. They are seperated in
    - Quick Flutes (Quick evaluation of most important parameters. Takes about 30 min)
        - Flute 1: MOS, VDP (P-stop, n+, Poly), FET
        - Flute 2: GCD, Rpoly, Diel Breakdown, Linewidth(n+, p-stop)
    - Extended Flutes (Providing additional parameters. Performed in a smaller number of wafers. Takes about 50 min)
        - Flute 3: Diodes Half, VDP(Bulk, Edge(p+), Metal(Al))
        - Flute 4: GCD05, CBKR(n+, Poly)
    - Additional flute and standard test structures to be contacted with needles.

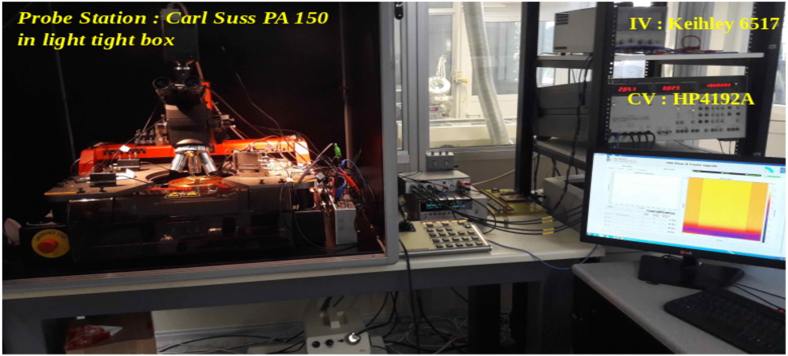


Experimental setup

- Electrical characterization setup consisting of:
  - Probe Station: Karl Suss PA 150
  - CV: HP4092A
  - IV: Keithley 6517A
  - IV: Keithley 2410A
  - The whole setup is controlled witha a LabView program
  - A probe card and switching matrix is used for automatization of the measurments on the flute structures

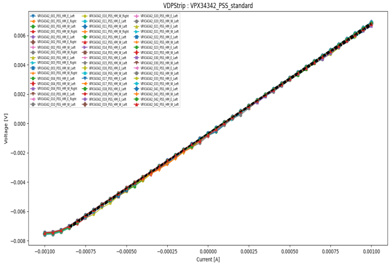


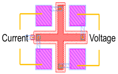




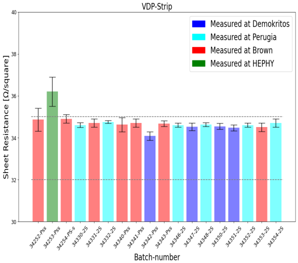
Example of measurements: Van der Pauw cross structures

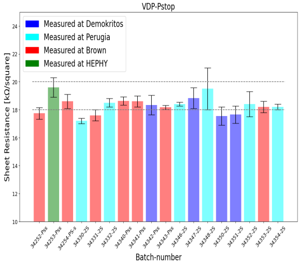
- Van Der Pauw (VDP) test structures are used to measure the resistance of thin films (Al, n+, p-stop, Edge)
- A current source is applied in two contacts. The voltage difference is measured to the other two contacts

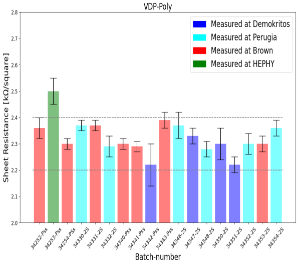




$$R_{sh} = \frac{\pi}{ln(2)} \frac{V}{I}$$

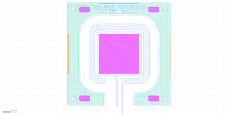


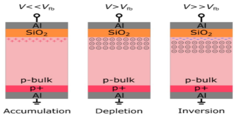


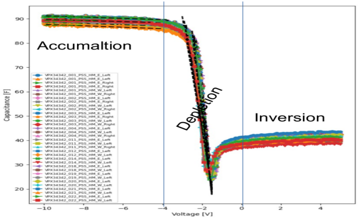


Example of measurements: MOS capacitors

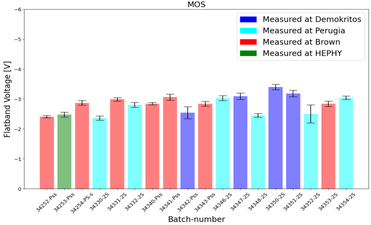
- MOS capacitor is the most useful device in the study of semiconductor surfaces and interfaces.

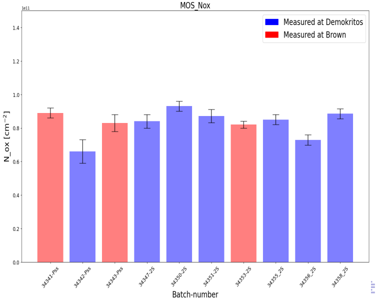






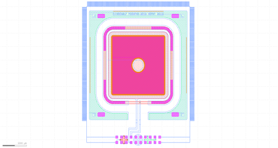
- Parameters measured with this device:
  - Flatband voltage $V_{fb} = \phi_{Al} - \phi_{Si}$
    - Ideal case: $V_{fb} = 0$
    - Non ideal: $V_{fb} \propto N_{ox}$
  - Fixed oxide charge concentration N_{ox}
  - Oxide capacitance C_{ox}
  - Oxide thickness $t_{ox} = C_{ox}/\varepsilon A$

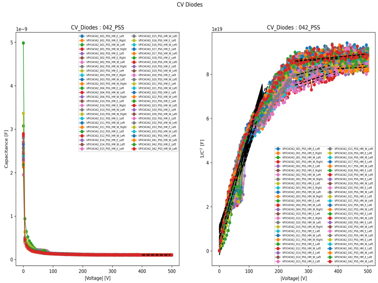




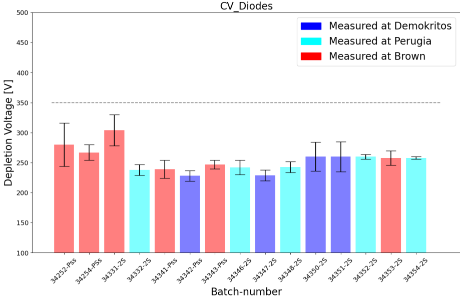
Example of measurements: Diodes

- Diodes are used in order to study of the bulk properties. The standard type of measurements are IV and CV measurments:





- CV Measurments:
  - Full depletion Voltage V_{fd}
  - Doping concentration N_{sub}
  - Bulk resistivity $\rho > 3.5k\Omega cm$



- IV Measurments:
  - Current value at 600V ($< 2.5nA/mm^3$)
  - Check for breadown voltage

Conclusion

- The Process Quality Control (PQC) aims to monitor the stability of the sensor fabrication process.
- We are moving into a mass production period with all the PQC centers ready for this phase.
- All the batches that were tested so far were qualified as qood
  - Uniform measurements between different batches
  - Good agreement between the PQC centers