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

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Introduction

- Silicon sensors 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 dedicated 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 measurements
From LHC to HL-LHC

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

**LHC / HL-LHC Plan**

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**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 upgrade are:

- Radiation Tolerance. ⇒ Flip from p-on-n to n-on-p sensors, 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 closely spaced strip sensors
- **PS modules** Two very closely spaced 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 ($50 \times 50 \ \mu m$),($100 \times 25 \ \mu m$)
**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 biasing

- **PS-s sensors**
  - 6″ wafers
  - n-on-p sensors
  - Float-zone technique
  - Active thickness 290 um
  - AC coupled with Poly-silicon biasing

- **PS-p sensors**
  - 6″ wafers
  - n-on-p sensors
  - Float-zone technique
  - Active thickness 290 um
  - DC coupled
  - Biased with punch-through structures

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Figure: Design of the 2S, PS-s and PS-p wafers

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¹GDS files made by Institute of High Energy Physics (HEPHY), Austria
Sensor and process quality control

- **25 sensor wafer**

- **PSs sensor wafer**

- **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 can be measured.

- **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
- Rochester

**PQC centers**
- Brown
- Demokritos
- Hephy
- Perugia

**IT centers**
- KIT
- Brown
PQC measurements: 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 and a switching matrix

- Each Half Moon contain 2 sets of 4 flutes in each side. They are separated 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 with a LabView program
  - A probe card and switching matrix is used for automatization of the measurements 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 $t_{ox} = C_{ox}/\varepsilon A$

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Example of measurements: Diodes

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

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

**IV Measurements:**
- Current value at 600V ($< 2.5 \, nA/mm^3$)
- Check for breakdown voltage
Example of measurements: Gate controlled diode

- GCD is used to investigate the surface current and the number of interface traps
- Consisting of comb-shaped Diode with n+ strips, intertwined with comb-shaped MOS.

Parameters measured with this device:
- Surface current $I_{surf} = I_{depl} - I_{inv}$
- Surface recombination velocity $S_0 \propto I_{surf}$
- Interface trap density $D_{it} \propto S_0$
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 good
  - Uniform measurements between different batches
  - Good agreement between the PQC centers