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

Panagiotis Assiouras
on behalf of the CMS collaboration

National Center of Scientific Research Demokritos
Institute of Nuclear and Particle Physics
Detector Instrumentation Laboratory

17th Trento Workshop on Advanced
Silicon Radiation Detectors

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: (2019-2021), Double the designed Luminosity: $2 \cdot 10^{34}\ cm^{-2}s^{-1}$, Integrated Luminosity: $300\ fb^{-1}$ at Run 3.
- Phase-II: (2025-2027) , Luminosity: $5 \cdot 10^{34} cm^{-2}s^{-1}$, $300\ fb^{-1}$ per year $3000\ fb^{-1}$ for 10 years of operation

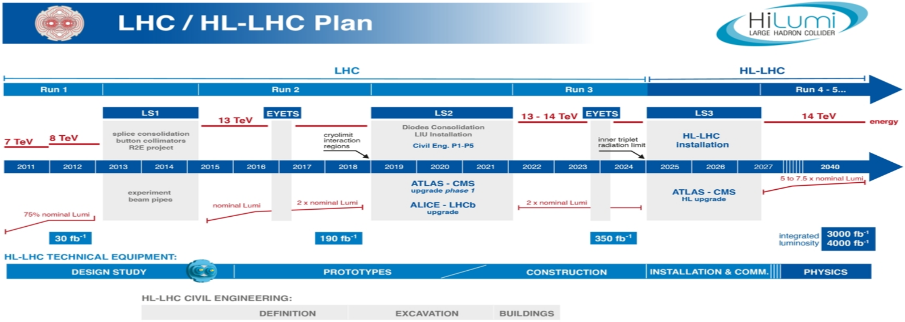
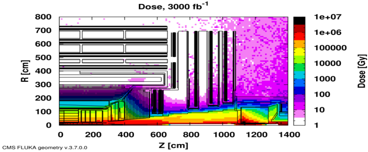
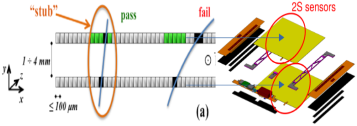


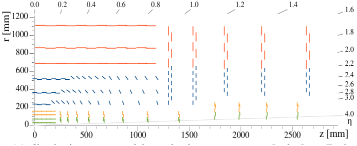
Figure: HL-LHC upgrade schedule.

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 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 ($p_T < 2$ GeV) 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 $(50x50\ \mu m)$,$(100x25\ \mu m)$







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

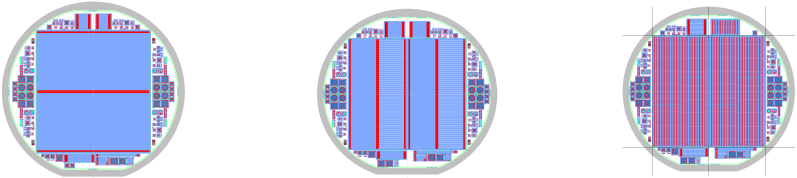
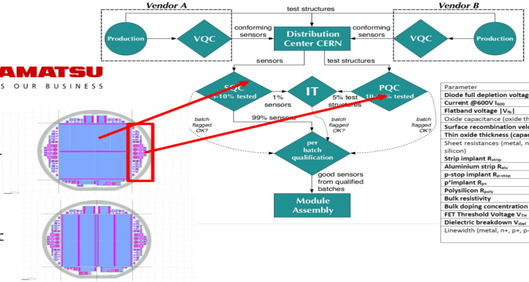


Figure: Design of the 2S, PS-s and PS-p wafers [1]

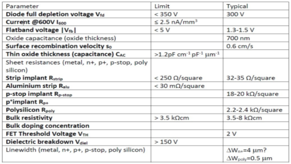
---

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

Sensor and process quality control



- 2S sensor wafer
- PSs sensor wafer

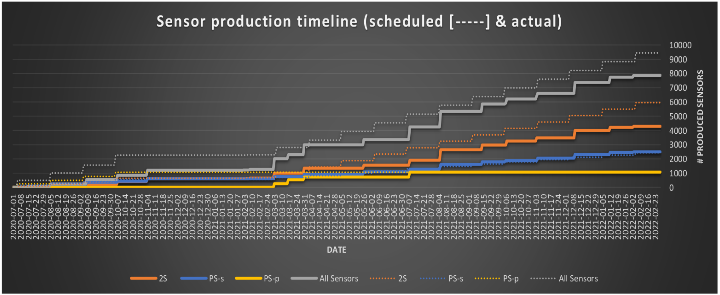


Parameter	Limit	Typical
Diode full depletion voltage V_{fd}	< 350 V	300 V
Current @600V I_{600}	≤ 2.5 nA/mm^3	
Flatband voltage $\|V_{fb}\|$	< 5 V	1.3-1.5 V
Oxide capacitance (oxide thickness)		700 nm
Surface recombination velocity s_0		0.6 cm/s
Thin oxide thickness (capacitance) C_{AC}	>1.2pF cm^{-1} 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 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

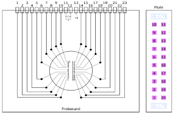
QA centers

- SQC centers
  - Brown University (USA)
  - University of Delhi (India)
  - Institute of High Energy Physics in Vienna (Austria)
  - Karlsruhe Institute of Technology (Germany)
  - NCP (Pakistan)
  - Rochester Institute of Tech- nology (USA)
- PQC centers
  - Brown University (USA)
  - NCSR ”Demokritos”(Greece)
  - Institute of High Energy Physics in Vienna (Austria)
  - INFN Perugia (Italy)
- IT centers
  - Karlsruhe Institute of Technology (Germany)
  - Brown University (USA)
- Sensor production started since summer of 2020 and will run until the mid 2024.
- More than 5000 wafers (> 20 %) have been tested so far.

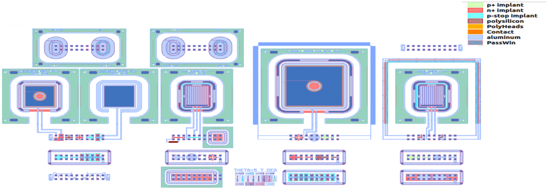


PQC mesurments: Flute structures

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

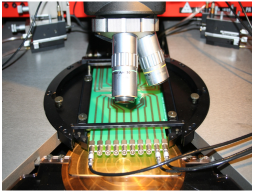


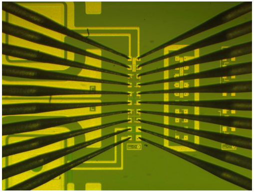
- Each Half Moon contains 2 sets of 4 flutes in each side. They are seperated in
  - Quick Flutes (Quick evaluation of most important parameters. Takes about 30 min)
    - Flute 1: MOS, Van der Pauw structures (P-stop, n+, Poly), FET
    - Flute 2: GCD, Rpoly, Diel Breakdown, Linewidth(n+, p-stop)
  - 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, Cross bridge kelvin resistances (n+, Poly)
  - Additional flute and standard test structures to be contacted with needles.

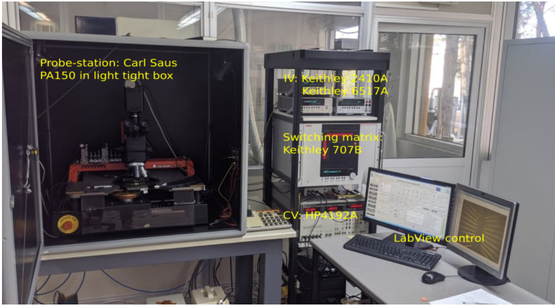


Experimental setup at NCSR “DEMOKRITOS” lab

- 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 automated of the measurements on the flute structures
- Enviromental conditions are constantly monitored:
    - Relative humidity < 30 % RH
    - Temperature fixed at 20 ^{o}C

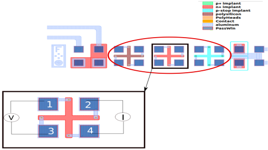




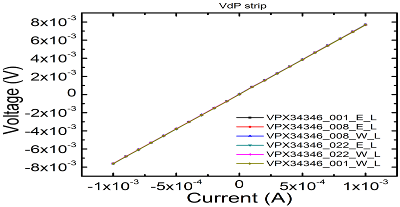


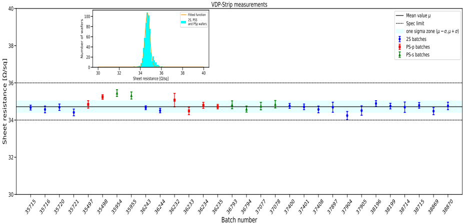
Van der Pauw cross structures

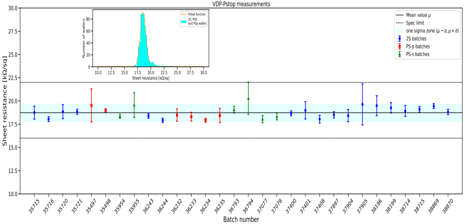
- Van Der Pauw (VDP) test structures are used to measure the resistance of thin films (Al, n+, p-stop, Edge)
- A current source is applied in two contacts. The voltage difference is measured to the other two contacts

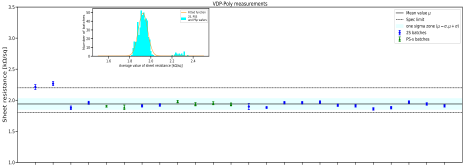


$$R_{sh} = \frac{\pi}{ln(2)}\frac{V}{I}$$



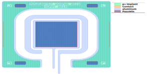




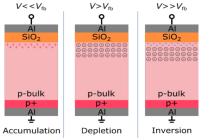


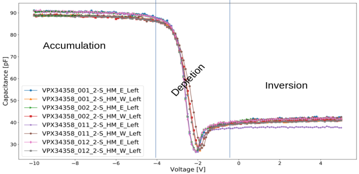
Metal Oxide Semiconductor capacitors (MOS)

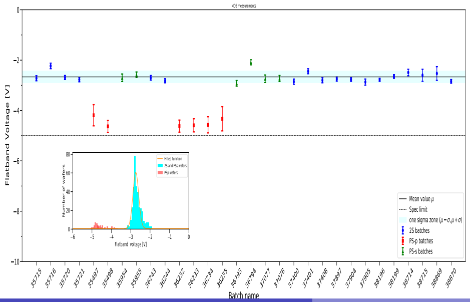
- MOS capacitor is the most useful device in the study of semiconductor surfaces and interfaces.

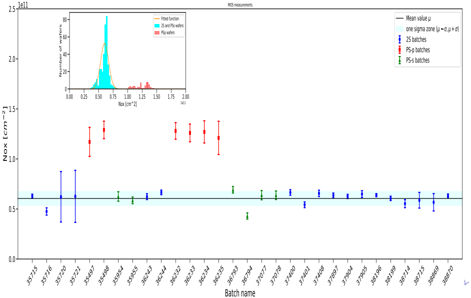


- Parameters measured with this device:
  - Flatband voltage $V_{fb} = \phi_{Al} - \phi_{Si}$
    - Ideal case: $V_{fb} = 0$
    - Non ideal: $V_{fb} \propto N_{ox}$
  - Fixed oxide charge concentration N_{ox}
  - Oxide capacitance C_{ox}
  - Oxide thickness $t_{ox} = C_{ox}/\varepsilon_{Si} A$



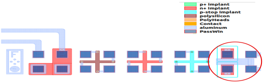




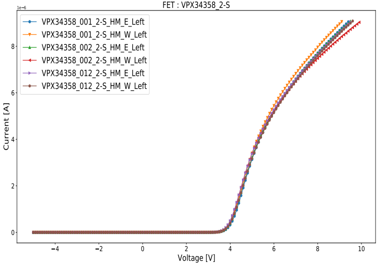


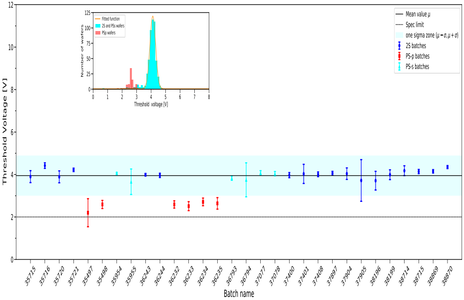
Field effect transistors

- Field-Effect Transistor (FET) test structures can be used to qualitatively determine the strip isolation quality and inter-strip resistance.



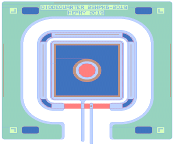
- The FET inter-channel region replicates the sensor inter-channel region:
    - The distance between the source and drain is equal the distance of two neighboring strips.
    - P-stop implants encircle source and drain with exactly the same properties as the sensor (the n+ implant distance, the p-stop layout, the p-stop doping).
- FET threshold voltage is sensitive to variations of p-stop and inter-channel properties and it can provide an evaluation of the p-stop quality.





Diodes

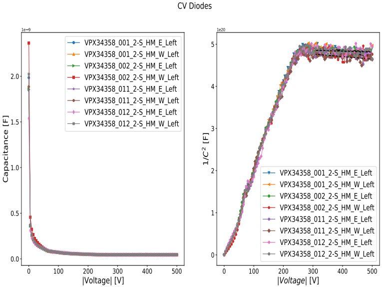
- Diodes are used in order to study of the bulk properties. The standard type of measurements are IV and CV measurments:

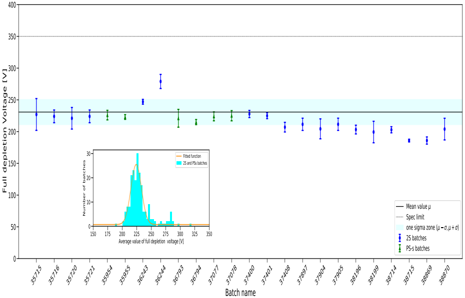


- CV Measurments:
  - Full depletion Voltage V_{fd}
  - Doping concentration N_{sub}
  - Bulk resistivity $\rho > 2.7\ k\Omega cm$

$$\rho = \frac{d^2}{2\epsilon_0 \epsilon_{Si} \mu_h V_{fd}}$$

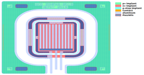
- IV Measurments:
  - Current value at 600V ($< 2.5\ nA/mm^3$)
  - Check for breadown voltage

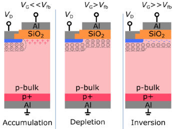


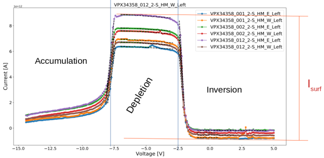


Gate controlled diodes

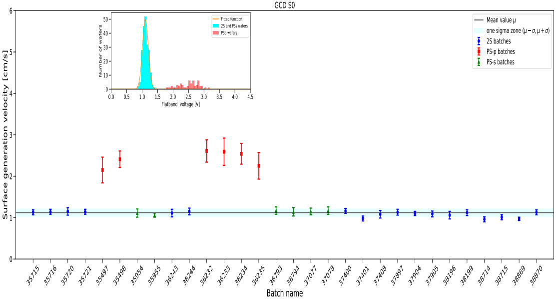
- GCDs are used to investigate the surface current and the number of interface traps
- Consisting of comb-shaped Diode with n+ strips, intertwined with comb-shaped MOS.





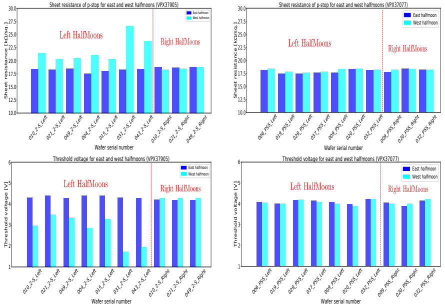


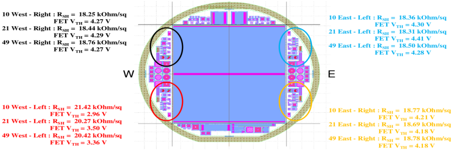
- Parameters measured with this device:
  - Surface current $I_{surf} = I_{depl} - I_{inv}$
  - Surface recombination velocity $S_0 \propto I_{surf}$
  - Interface trap density $D_{it} \propto S_0$



P-stop in-homogeneity

- n-on-p sensors are sensitive to the p-stop doping (implant dose and profiles). P-stop is responsible of the isolation of the strips.
- V_{th} and p-stop resistivity give a qualitative evaluation of the inter-strip isolation.
- Non-uniform measurements has been observed between East and West half-moons regarding the sheet resistance and threshold voltage.
    - Significant large non-uniformity across the wafer shows that there are instabilities in the process which has to be checked and monitored continuously.
- No interstrip resistance issues observed on the sensors from wafers with lower threshold voltages.
    - This indicates that the p-stop is still good enough or that this non-uniformity issue affects mostly the periphery.
- There are no indications that this would limit the lifetime of the sensors.
- Irradiation tests on these samples is on-going



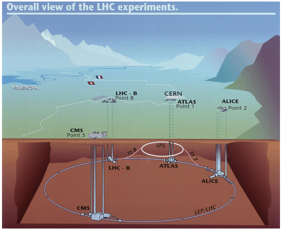


Conclusion

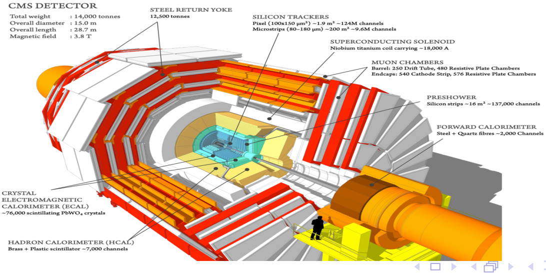
- The Process Quality Control (PQC) aims to monitor the stability of the sensor fabrication process.
- Delivered sensors by HPK show very good quality so far!
- All the batches that were tested so far were qualified as qood
  - Uniform measurements between different batches
  - Good agreement between the PQC centers
- Outer Tracker will be comprised with sensors of high quality for the HL-LHC era!

Backup slides

Compact Muon Solenoid (CMS)

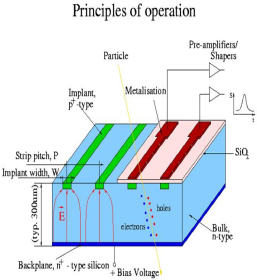


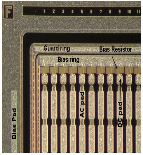
- CMS is one of two large general-purpose particle physics detectors built on the LHC at CERN.
- Consists of 4 sub-detectors:
  - Silicon Tracker
    - Designed to reconstruct the trajectories of high-energy muons, electrons and hadrons. It consists of silicon detectors (micro-strip, micro-pixel)
  - Electromagnetic Calorimeter
    - Designed to measure with high accuracy the energies of electrons and photons.
  - Hadron Calorimeter
    - Designed to measure the energy of hadrons (protons, neutrons, pions and kaons). Additionally it provides indirect measurement of the presence of non-interacting, uncharged particles such as neutrinos.
  - Muon Chambers
    - Designed to identify muons and measure their momenta

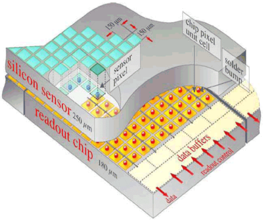


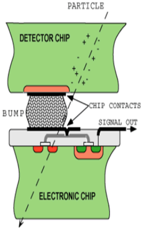
Silicon strip and pixel detectors

- Highly segmented silicon detectors have been used in Particle Physics experiments for nearly 30 years.
- Two commonly used detectors in High Energy Physics experiments are :
  - Micro-strip detectors
    - One surface is segmented in one axis to form strips with regions of p+ (or n+ doping).
    - Forming a 1D matrix of n+p diodes.
    - The trajectory of an incident particle is projected on the strips
    - Detects the passage of ionizing radiation with high spatial resolution, good efficiency and relatively low cost.
  - Hybrid pixel detectors
    - Segmented in two axis to form pixels of p+ (or n+ doping)
    - Forming a 2D matrix of n+p diodes.
    - Connection by “bump bonding”.
    - Every cell is connected to each own processing electronics.
    - Requires more sophisticated readout architecture
    - More robust in radiation damage. Usually placed in the innermost parts of HEP experiments









Polysilicon and punch-through biasing

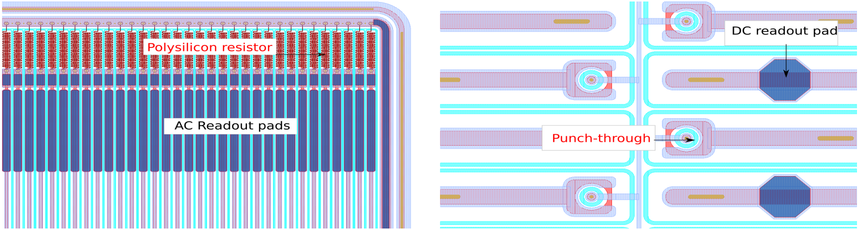
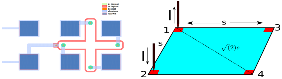


Figure: AC-coupled strip sensor layout with polysilicon bias resistors (left) and DC-coupled macro-pixel sensor layout with punch-through bias (right).

Four point bulk resistivity measurement

- PQC3 flute contains a bulk resistivity cross, for measuring the bulk resistivity.



- For a square like structure in a sample with infinite thickness and surface. The bulk resistivity is given by:

$$\rho_\infty = \frac{2\pi s}{2-\sqrt{2}} \frac{V_{34}}{I_{21}} \tag{1}$$

- where s is the pad spacing.For real wafers where $(t \approx s)$. A correction factor is introduced.

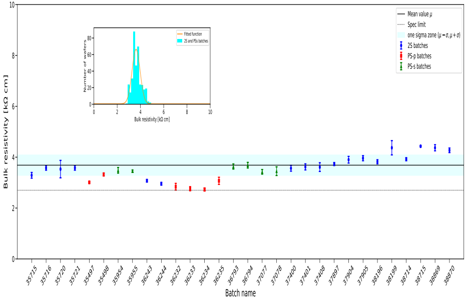
$$\rho = F\rho_\infty \tag{2}$$

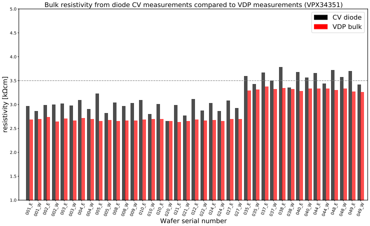
- By performing the image method for a square like structure for a conducting bottom surface. The correction factor is:

$$F = \frac{1}{1 + \frac{4}{2-\sqrt{2}} \sum_{n=1}^{+\infty} (-1)^n \left[\frac{1}{\sqrt{1+(\frac{2nt}{s})^2}} - \frac{1}{\sqrt{2+(\frac{2nt}{s})^2}} \right]} \tag{3}$$

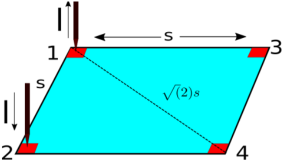
where t is the wafer thickness.

For $t = 290\ \mu m$ and $s = 187\ \mu m$ $F = 1.089$





Bulk resistivity: Extraction of the correction factor



- In the case where s<<t:

$$V_3 = \frac{\rho I}{2\pi}\left(\frac{1}{\sqrt{2}s} - \frac{1}{s}\right)$$

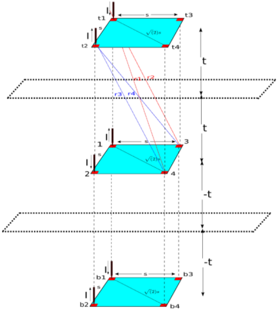
$$V_4 = \frac{\rho I}{2\pi}\left(\frac{1}{\sqrt{2}s} - \frac{1}{s}\right)$$

$$V_{34} = \frac{\rho I}{2\pi s}\left(2 - \sqrt{2}\right)$$

$$\boxed{\rho_\infty = \frac{2\pi s}{2-\sqrt{2}}\frac{V}{I}}$$

- In the case where s~t: By using image method. For n reflections:

$$\begin{aligned} V_{tot} &= V_0 + V_1 + V_2 + \dots .V_n \\ &= \frac{\rho I}{2\pi s}\left(2-\sqrt{2}\right) + \sum_{n=0}^{+\infty}(-1)^n \frac{2\rho I}{\pi s}\left(\frac{1}{\sqrt{((\frac{2nt}{s})^2+1)}} - \frac{1}{\sqrt{((\frac{2nt}{s})^2+2)}}\right)\end{aligned}$$



- Then for resistivity: $\rho = \rho_\infty F$

$$\boxed{F = \frac{1}{1+\frac{4\cdot(-1)^n}{2-\sqrt{2}}\Sigma_{n=1}^{\infty}\left[\frac{1}{\sqrt{1+\left(\frac{2nt}{s}\right)^2}} - \frac{1}{\sqrt{2+\left(\frac{2nt}{s}\right)^2}}\right]}.}$$

For s=187 [μm] and t=290 [μm]: F=1.089