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ATLAS ITk

ATLAS ITk Pixel Sensor Characterization for the HL-LHC upgrade

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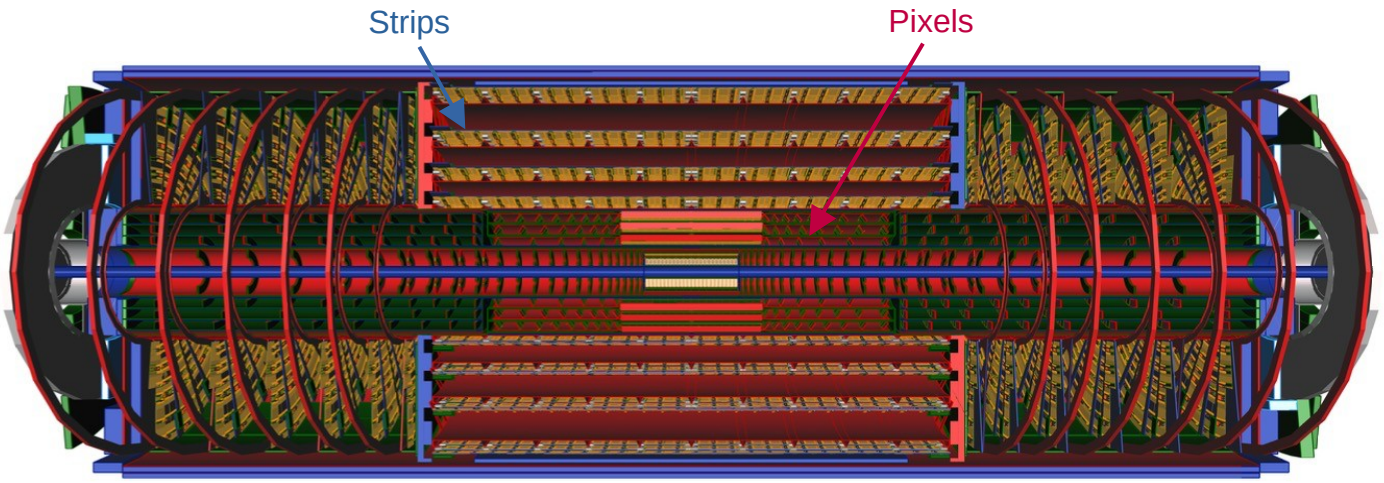
FIS ATLAS

HL-LHC and ATLAS ITk

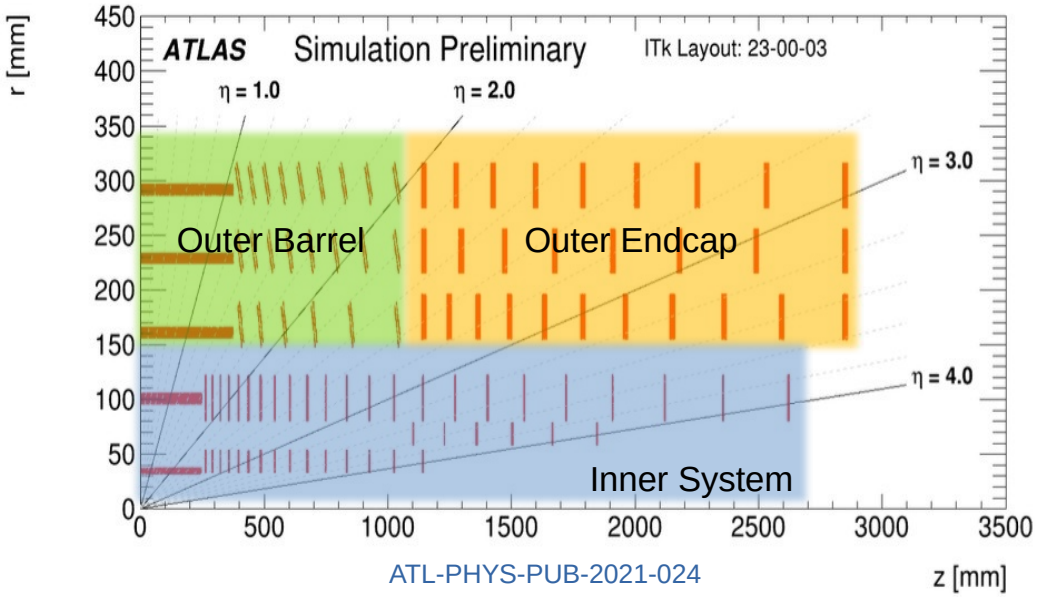
- The High-Luminosity LHC (HL-LHC) is expected to operate with an instantaneous luminosity up to 7.5 x 10^{34} $cm^{-2}s^{-1}$.
  - Expected about 200 inelastic pp collisions per bunch crossing.
- ATLAS aims to accumulate a total data set of 4000 fb^{-1} over 10 years operation.
- A new all-silicon Inner Tracker (ITk) will replace the current Inner Detector.
  - A pixel detector surrounded by a strip detector.
  - Targeting the same or better performance than the current Inner Detector.
  - Increased granularity to maintain occupancy <1%.
  - Lower material budget and increased radiation hardness.



ATL-PHYS-PUB-2021-024

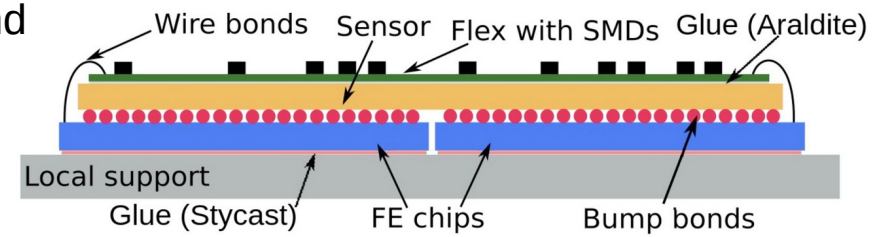
ITk Pixel Layout and Pixel Modules

- ITk Pixel detector:
  - 5 barrel layers and multiple inclined or endcap disks, extending to |η|=4.0.
    - Outer barrel and endcap: n-in-p planar quad modules
    - Inner system (replaceable): 3D triplet modules + n-in-p planar quad modules.
  - ~9400 modules with ~13m^2 active area.
  - Radiation hard,
    - Inner system up to 2 x 10^{16} n_{eq}/cm^2.



ATL-PHYS-PUB-2021-024

- Hybrid pixel module
  - Passive high resistivity silicon sensor + front-end (FE) readout chip fabricated in 65nm CMOS technology.



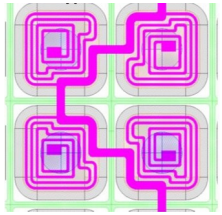
Quad module x-sec.

- Currently in pre-production stage.
  - ~10% sensor production.
  - Sensors and test structures are tested for quality checks and compare with the test results provided by vendors.

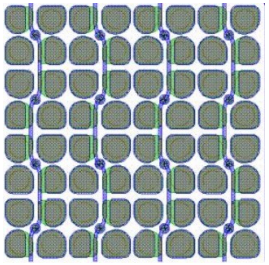
Pixel Sensor

- Planar sensors
  - Outer layers: 150µm thick sensors with pitch size of 50x50µm^2.
  - Inner system L1: 100µm thick sensors with pitch size of 50x50µm^2.
  - Various detailed designs from vendors, requirements defined on performance.
    - Insulation: p-stop vs. p-spray
    - Polysilicon bias or punch-through
    - Guard-ring geometry
- 3D sensors in Inner system L0:
  - 25x100 µm^2 in the barrel.
  - 50x50 µm^2 in the endcap.

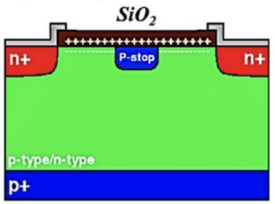
Poly-si bias resistor



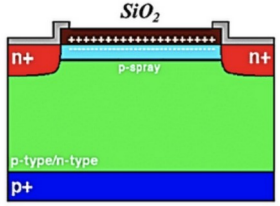
Punch-through bias rail



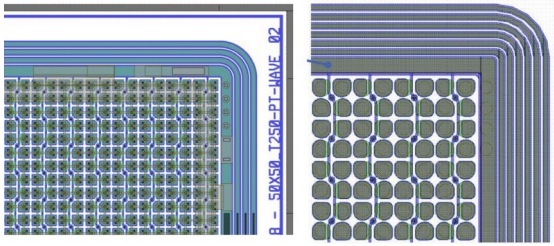
p-stop



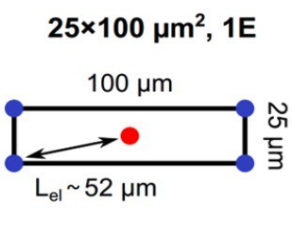
p-spray

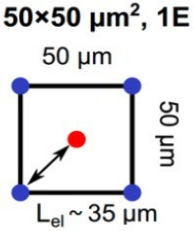


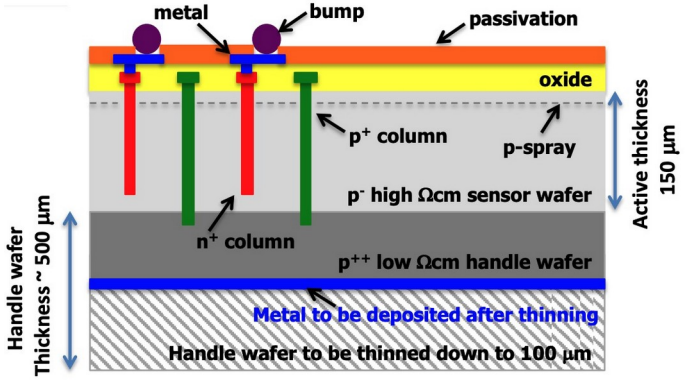
Guard-ring



3D sensors

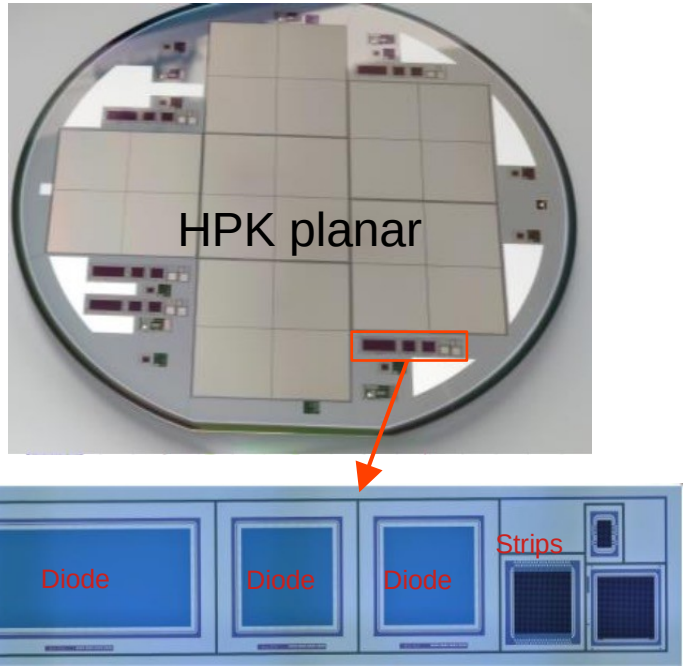


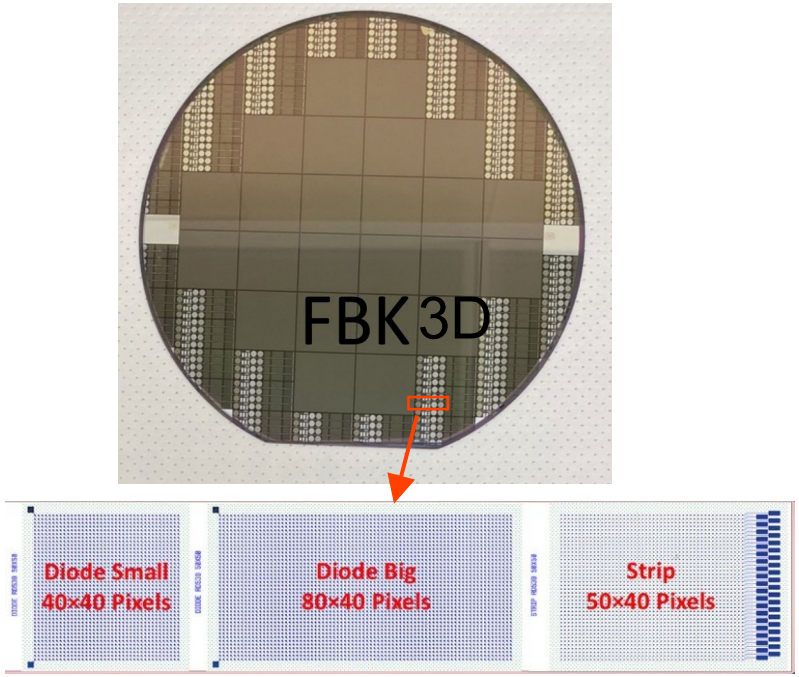




Test Structures

- The wafer holds the sensors and test structures to perform quality checks.
  - Diodes - reproduce the electrode structure of the actual sensors.
  - Strips – pixel implants connected in rows and routed to periphery.
  - Mini sensor matrix, inter-pixel capacitance structures …
  - Leakage current, bulk capacitance, inter-pixel resistance, capacitance etc. are tested (sensor quality assurance)

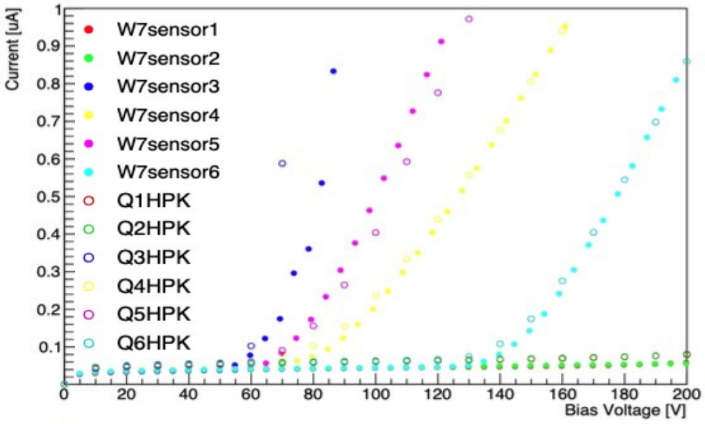


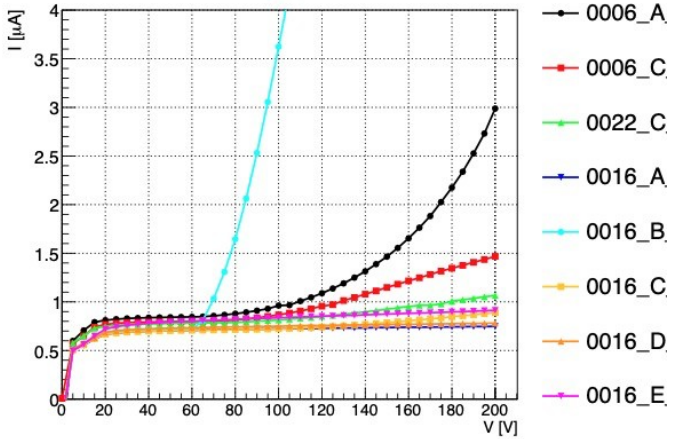


Leakage Current

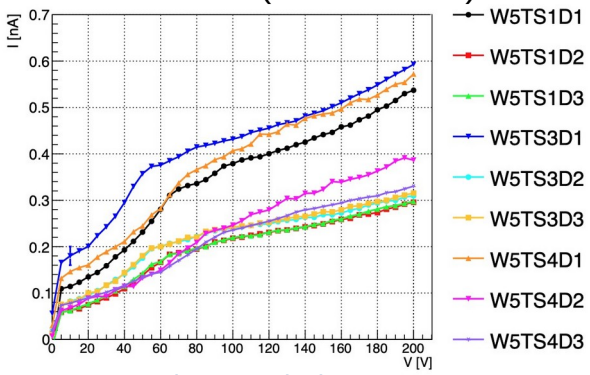
- I-V curves measured on sensors and diodes, before and after irradiation.
  - Un-irradiated tiles measured at (20±2)°C, RH<50%, reverse bias applied up to -200V or until breakdown reached in step of 5V, with a delay time of 2s.

150μm Planar quad sensors (un-irradiated)





HPK diodes (un-irradiated)



Y.Tian etc. Pixel2022

Breakdown voltage (V_{bd}): $\frac{I_{leak}@(V_{bias}+10V)}{I_{leak}@(V_{bias}+5V)} > 1.2$

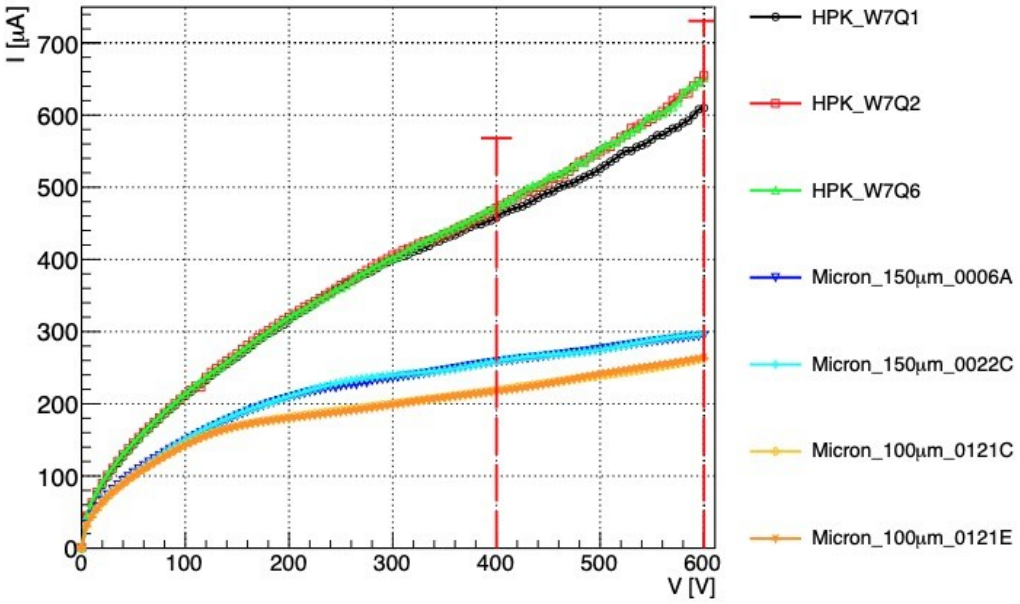
Criteria (un-irradiated quad sensors):

- $V_{bd} > V_{depl} + 70V$
- $I_{leak}@(V_{depl} + 50V) < 0.75\ \mu A/cm^2 \rightarrow 12.2\ \mu A$

Leakage Current

- Some sensors and test structures are irradiated to 5x10^{15} or 2x10^{15} n_{eq}/cm^2 to verify the radiation hardness.
  - Irradiated sensors measured at -25°C, up to -400 (-600) V for 100 (150) µm thick sensors or until breakdown.

Planar quad sensors (irradiated)



Y.Tian etc. Pixel2022

Criteria for 100 (150) µm thick quad sensors irradiated to 5x10^{15} n_{eq}/cm^2:

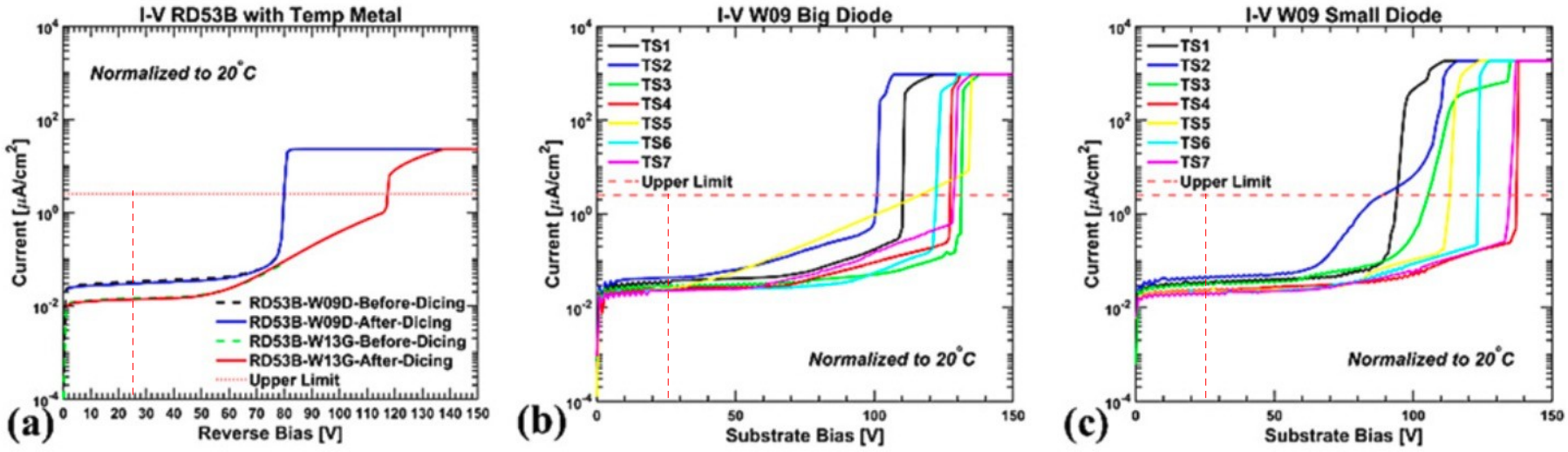
- $I_{leak} < 35\ (45)\ \mu A/cm^2 \rightarrow 570\ (730)\ \mu A$

Leakage Current

FBK 3D: Temporary metal grid is realized on sensors and removed once the electrical tests are complete.

- reverse bias applied up to -100V or until breakdown reached in step of 1V,

50x50 μm^2, with temporary metal, un-irradiated



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Breakdown voltage (V_{bd}): $\frac{I_{leak}@(V_{bias}+2V)}{I_{leak}@(V_{bias\,1}V)} > 2$

Criteria (un-irradiated 3D sensors):

- $V_{bd} > V_{depl} + 20V$
- $I_{leak}@(V_{depl} + 20V) < 2.5\ \mu A/cm^2$

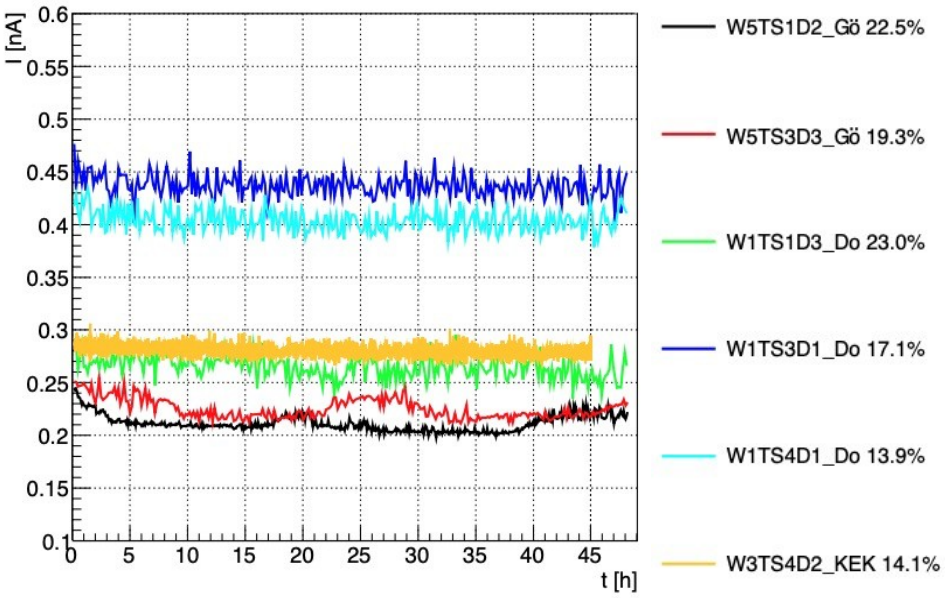
Leakage Stability

- Long-term stability of leakage current is studied by applying a typical operation bias voltage for 48h.

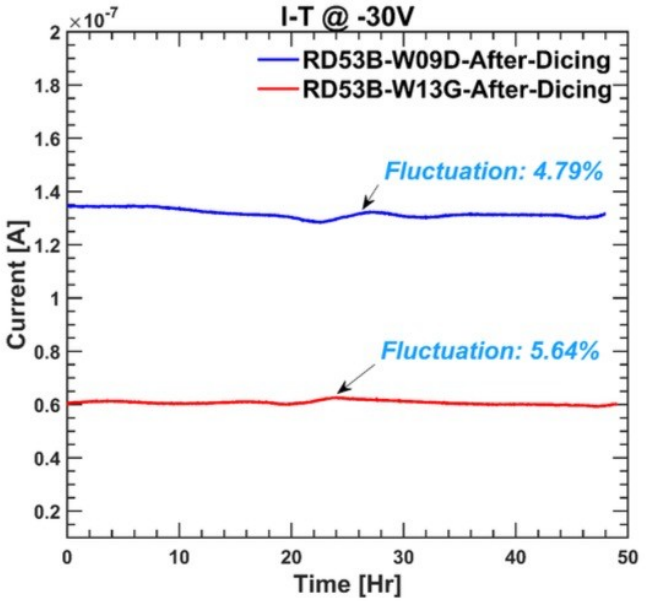
Criteria: $\frac{I_{max}-I_{min}}{I_{average}} < 25\%$

excluding the first 10 minutes after ramping up.

HPK diodes (un-irradiated)



FBK 3D (un-irradiated)

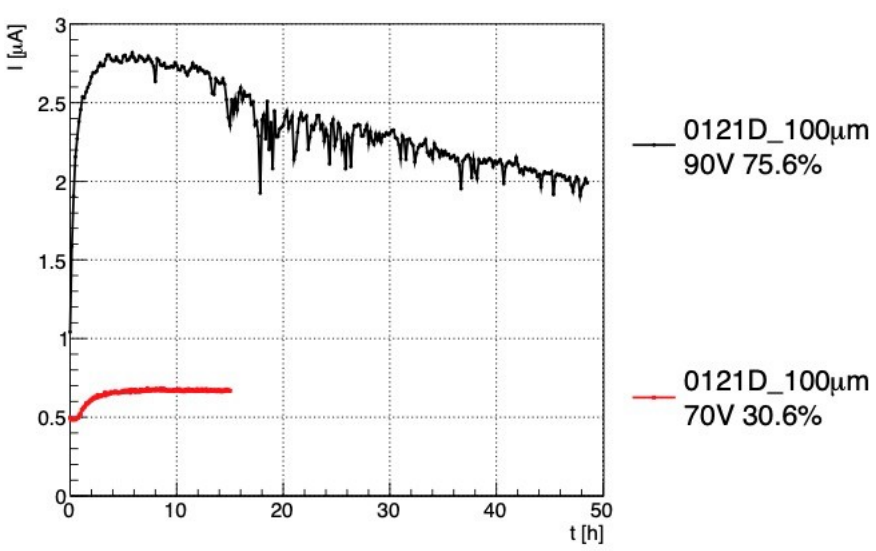


Leakage Stability

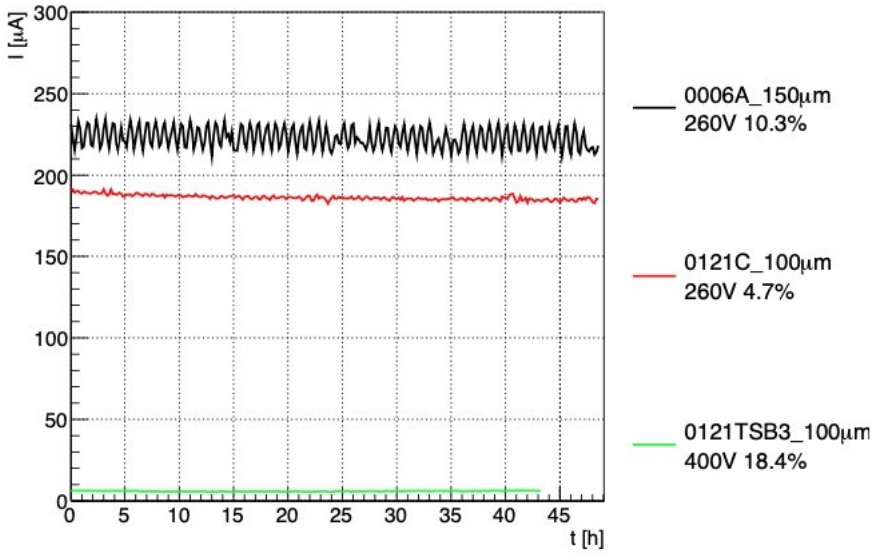
Micron 100 µm thick quad sensor shows unstable I_{leak}.

- Possible surface effect at oxide layer.
- Still in discussion, acceptable for using in detector.
- Stability gets improved after extra baking (125°C for 16h) or after irradiation.
- Statistics is limited.

Unirradiated Micron 100 µm sensor



Irradiated Micron 100 µm sensor



Bulk Capacitance

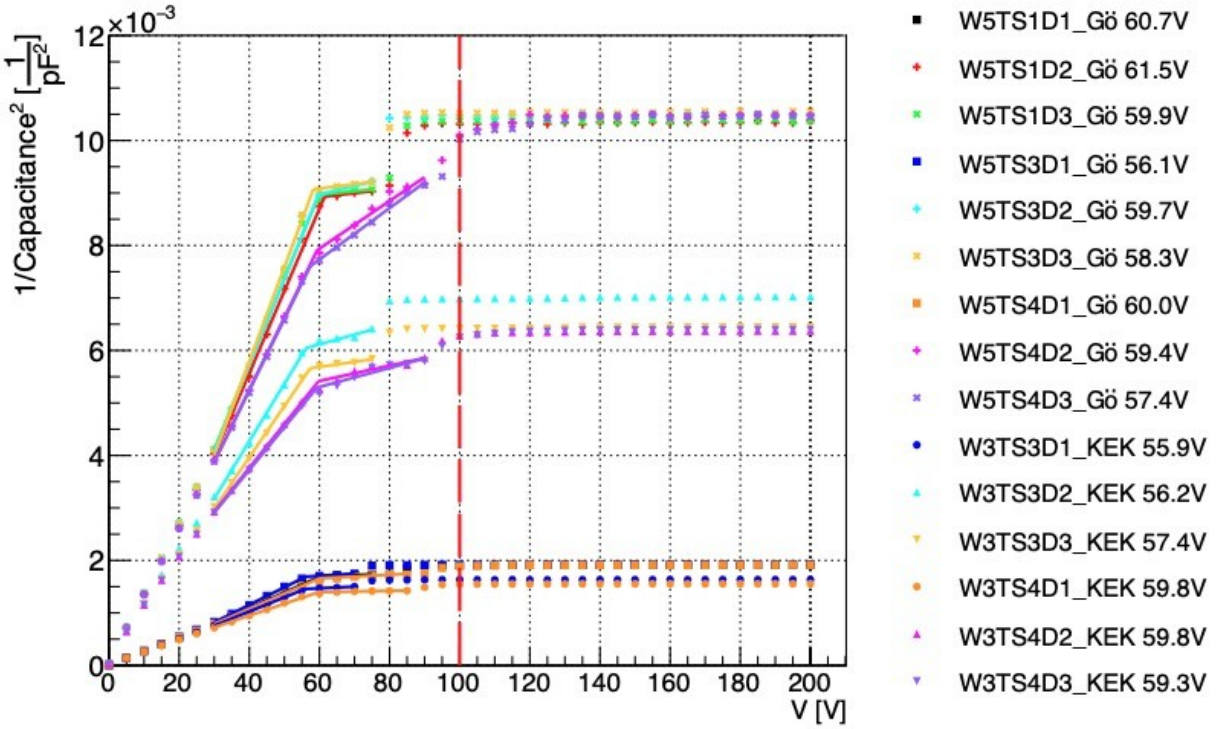
- C-V measurements are performed to determine the full depletion voltage (V_{depl}) of wafer.
  - Measured with a LCR meter coupled to an external voltage source.
  - V_{depl} is obtained from the intersection of linear fits of the ramping and plateau region of $1/C^2$ plot.

Criteria for 100 (150) µm thick quad sensors:

$$V_{depl} < 60\ (100)\ V$$

The second kink in $1/C^2$ plot is due to the depletion at the extra p^+-doped rings around the active area of the diodes.

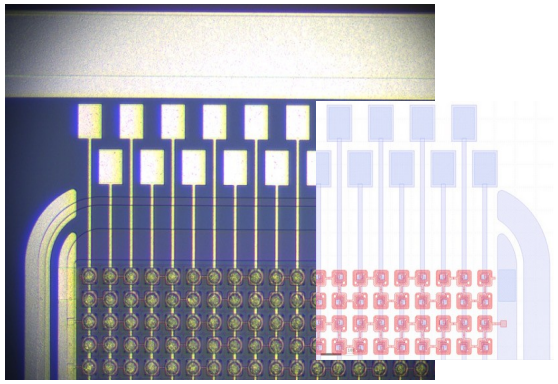
HPK diodes (un-irradiated)



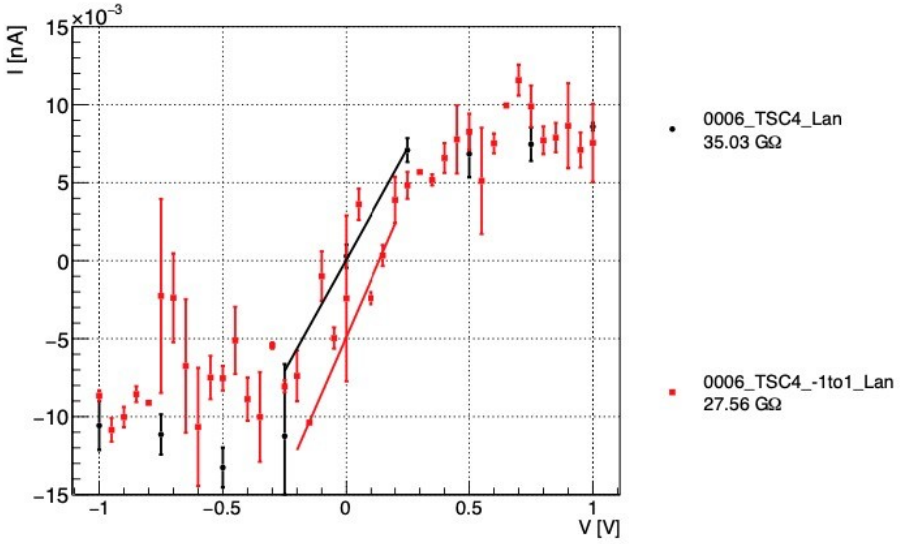
Inter-pixel Resistance

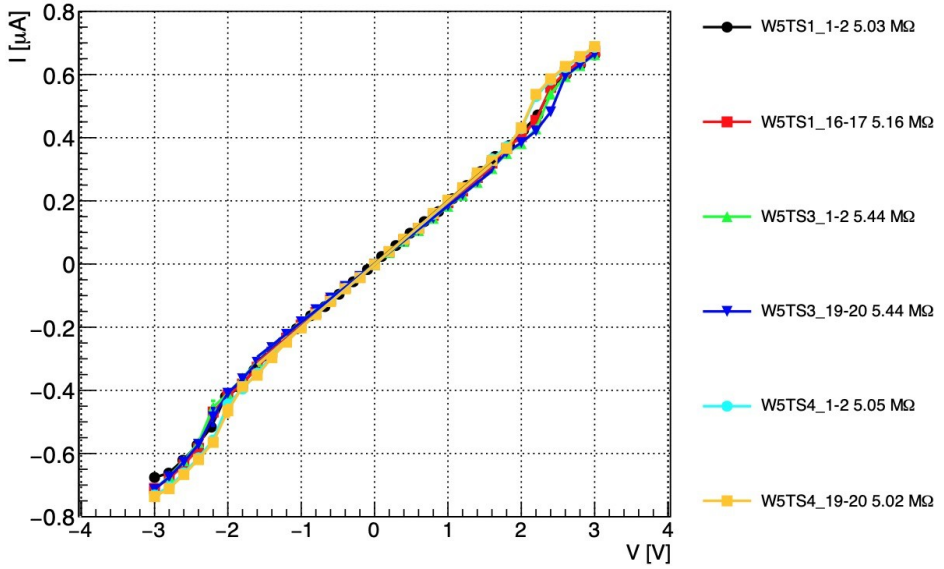
- Inter-pixel resistance was measured to verify the wafer and implantation quality.
  - The resistance is measured by probing the neighboring strips and applying voltage.
  - Specification depends on the bias structures.
    - $R_{interpix}$ > 2 MΩ per pixel cell for poly-Si resistors,
    - otherwise $R_{interpix}$ > 20 MΩ per pixel cell.

HPK strips test structures
(with poly-si bias resistors)



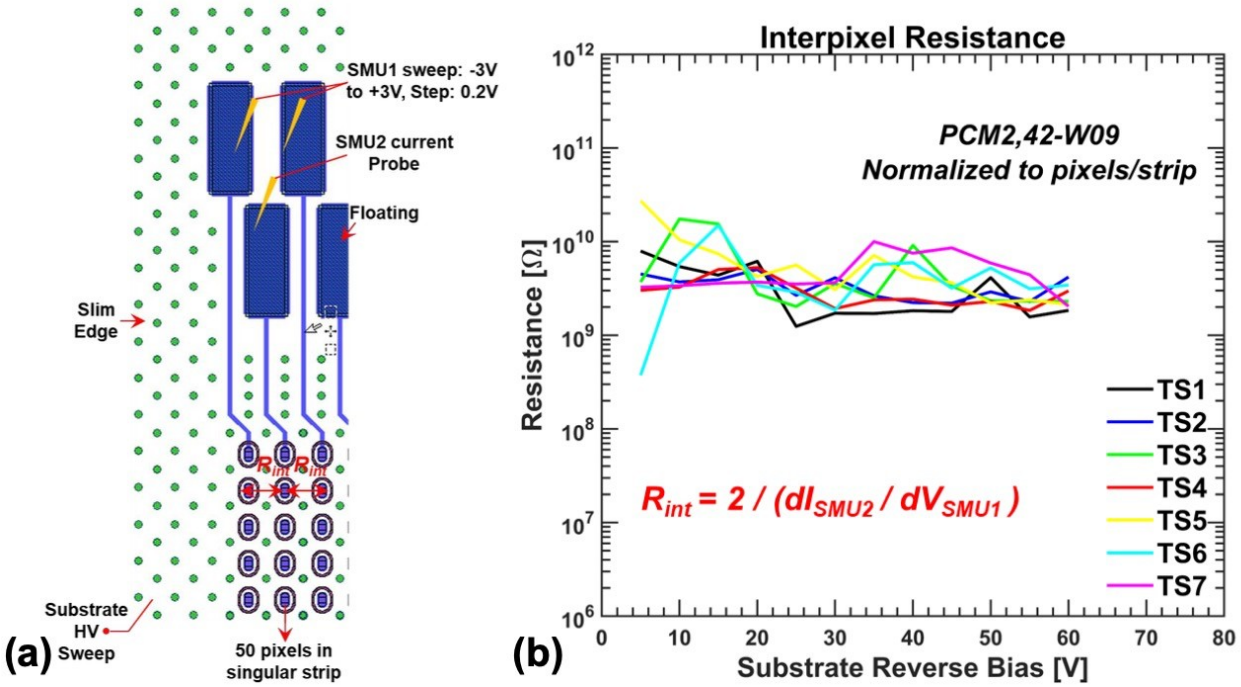
Micron 150μm strips test structures
(with punch-through biasing)





Inter-pixel Resistance

- FBK 3D
  - Two neighboring strips were shorted and a systematic voltage sweep was applied between -3 to 3V.
  - Criteria: $R_{interpix}$ > 1 GΩ per 3D pixel cell
  - Measured $R_{interpix}$ is independent to the reverse bias voltage.



Summary

- A new all-silicon Inner Tracker (ITk) will replace the current Inner Detector in ATLAS for the HL-LHC upgrade. The ITk pixel detector consists of ~9400 hybrid modules with planar n-in-p sensors and 3D sensors.
- ITk pixel project is currently in pre-production, ~10% of sensor production are measured for quality assurance.
- Sensors and test structures from different vendors were measured, both before and after irradiation.
  - Leakage current level and stability, bulk capacitance, inter-pixel resistance were checked and found within the ATLAS ITk pixel sensor specification.
  - Measured results are consistent with those provided by vendors.