ANALYSIS OF THE QUALITY ASSURANCE RESULTS FROM THE INITIAL PART OF PRODUCTION OF THE ATLAS18 ITK STRIP SENSORS

13th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD13), Vancouver, Canada

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ATLAS ITk

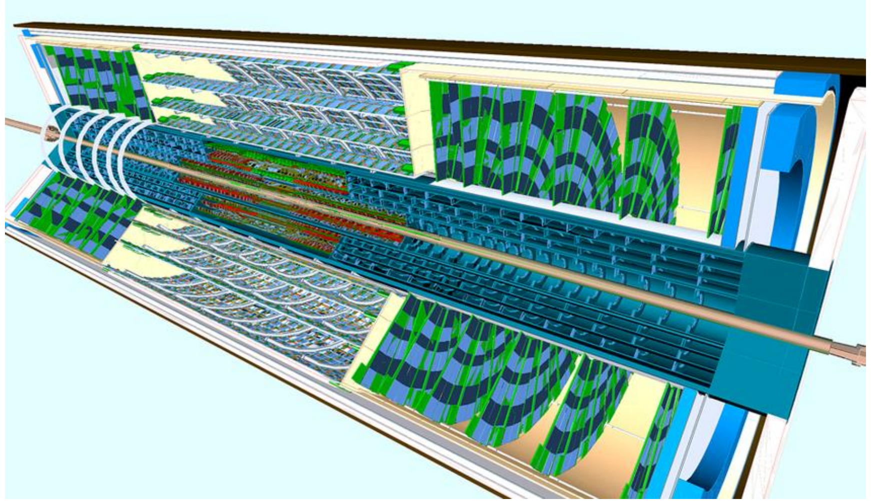
Introduction

For an introduction to the ATLAS upgrade ITk Strip Detector see the talk on Monday from George Iakovidis,
The ATLAS ITk Strip Detector System for the Phase-II LHC Upgrade

Relevant information related to this can be found in these posters of this conference:

- P.S. Miyagawa et al, *Analysis of the results from Quality Control tests performed on ATLAS18 Strip Sensors during on-going production*
- Y. Unno et al, *Analysis of MOS capacitor with p layer with TCAD simulation*
- A. Fournier et al, *Hot spot visual evaluation of breakdown locations in ATLAS18 ITk strip sensors and test structures*

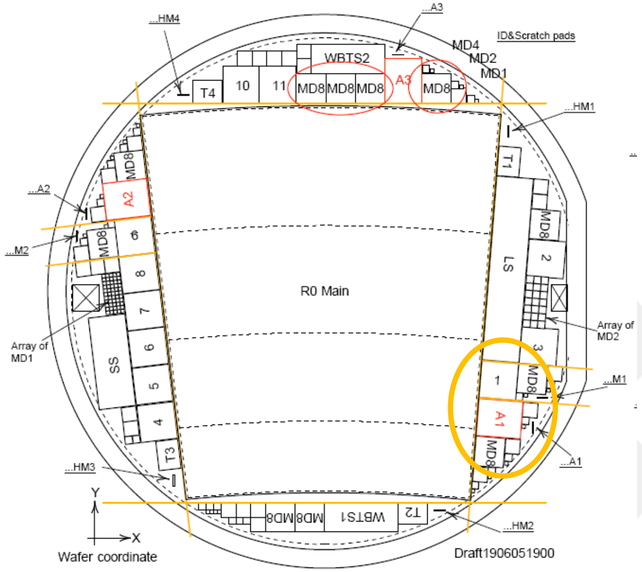
ATLAS Inner Tracker (ITk) Strip Sensors



- The ATLAS Inner Detector at CERN is undergoing an upgrade, resulting in the all-silicon Inner Tracker (ITk) detector [1, 2] to fulfill major physics objectives and to meet the stringent requirements of the experiment.

- The **Strips sensors** for the ATLAS ITk are manufactured on 6-inch, p-type, FZ silicon wafers [3].
  - Most of the wafer area: MAIN sensor
  - Peripheral "half-moons" (test devices)

- **Strip detector** divided in three regions.
  - Barrel (x1): sensors parallel to the beam axis
  - EndCap (x2): sensors perpendicular to the beam axis



[1] See G. Iakovidis' talk in this conference
[2] See S. Passaggio, The ATLAS ITk Pixel Detector: status and roadmap.
[3] Y. Unno et al, "Specifications and pre-production of n^+-in-p large-format strip sensors fabricated in 6-inch silicon wafers, ATLAS18, for the Inner Tracker of the ATLAS Detector for High-Luminosity Large Hadron Collider", 2023 JINST 18

Quality Assurance (QA)

QA purposes

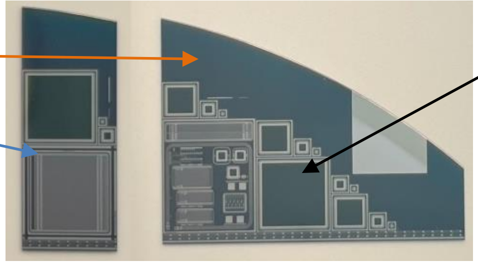
- **Quality Assurance (QA)** aims to ensure that quality requirements are met throughout the entire fabrication process for the ATLAS ITk development.
- QA goes hand in hand with Quality Control (QC) [4], the part responsible for identifying defects and providing acceptance testing checks for the finished main sensors to be installed in the experiment.
- QA is founded on monitoring the technology stability and keeping track of variations during the manufacturing process, plus making sure that the radiation hardness holds to the required levels as validated during prototyping phase.
- Samples irradiated with neutrons (Ljubljana, 5.1e14 n_{eq}/cm^2 and 1.6e15 n_{eq}/cm^2), protons (Birmingham/CYRIC, 5.1e14 n_{eq}/cm^2, 66 Mrad) and gamma (Prague, 66 Mrad).
- QA is used to predict and prevent deviations in key parameters.

[4] Poster presentation: Paul M: Analysis of the results from Quality Control tests performed on ATLAS18 Strip Sensors during on-going production

Quality Assurance (QA)

QA pieces and tests

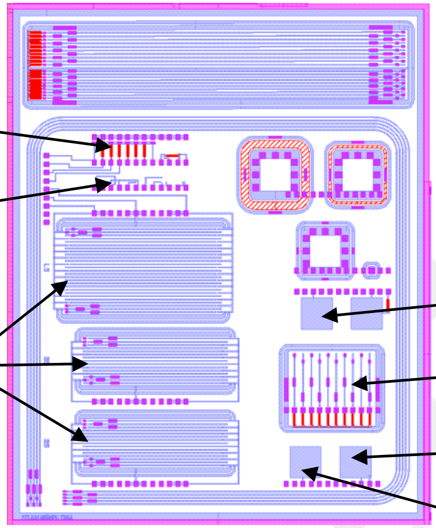
- There are two QA test pieces diced from each wafer.
  - Testchip&MD8
  - Mini&MD8



- Test devices:
  - 1×1 cm^2 miniature strip detectors (“**Mini**”)
  - Large area (8×8 mm^2) diodes (“**MD8**”)
  - ATLAS **test chip**, with several test structures
- Several QA pieces sampled per batch for irradiations and tests.
- All parameter must be within defined thresholds.
  - “Hard” thresholds: given by the sensors specs (e.g., CCE, VBD, VFD)
  - “Soft” thresholds: defined by the collaboration according to the production statistics to control the process variability (e.g., VFB, t_ox, VPT).

Testchip&MD8 structures

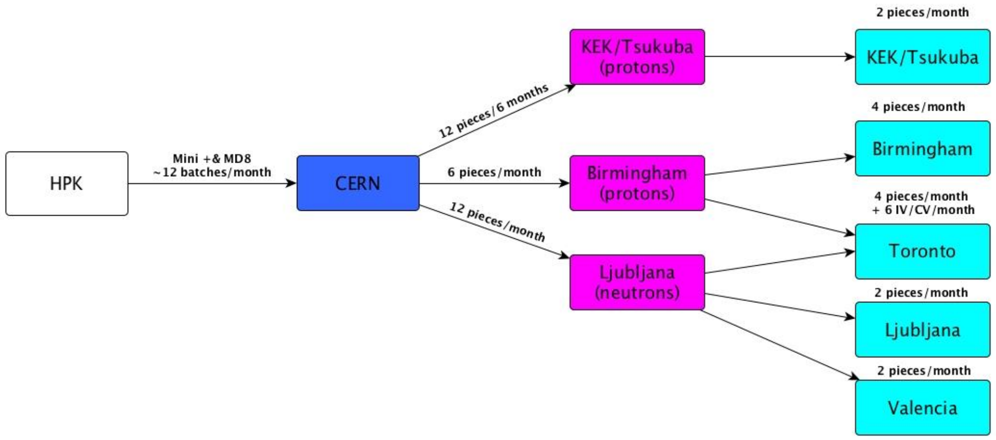
a) Monitor Diode (MD8)
b) Bias resistors
c) Interdigitated structures
d) Field-oxide capacitor
e) MOS with p-stop implant
f) Coupling capacitor
g) PTP structure
h) Cross-bridge resistors (CBR)



Test chip

QA Production Status

- The QA production process will extend for about 4 years, and involves 20,800 sensors. It has recently surpassed the halfway point of fabrication.
- The main work of production QA consists of measuring a sample of QA pieces pre- and post-irrad from all batches and to validate the production batches.
- During the first 2 years of production, 306 batches have been approved and 6 have been rejected and will be replaced later. In total, 1421 pieces have been distributed for tests.
- A delivery of sensors and QA pieces is received and distributed for irradiation and test every month for approval.
- By contract, the collaboration has a four-month window to accept or reject the batches based on whether the measured parameters fall within valid thresholds. Therefore, approval decisions are made every month.

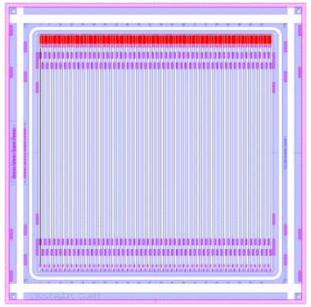


Analysis of the parameters

QA Analysis

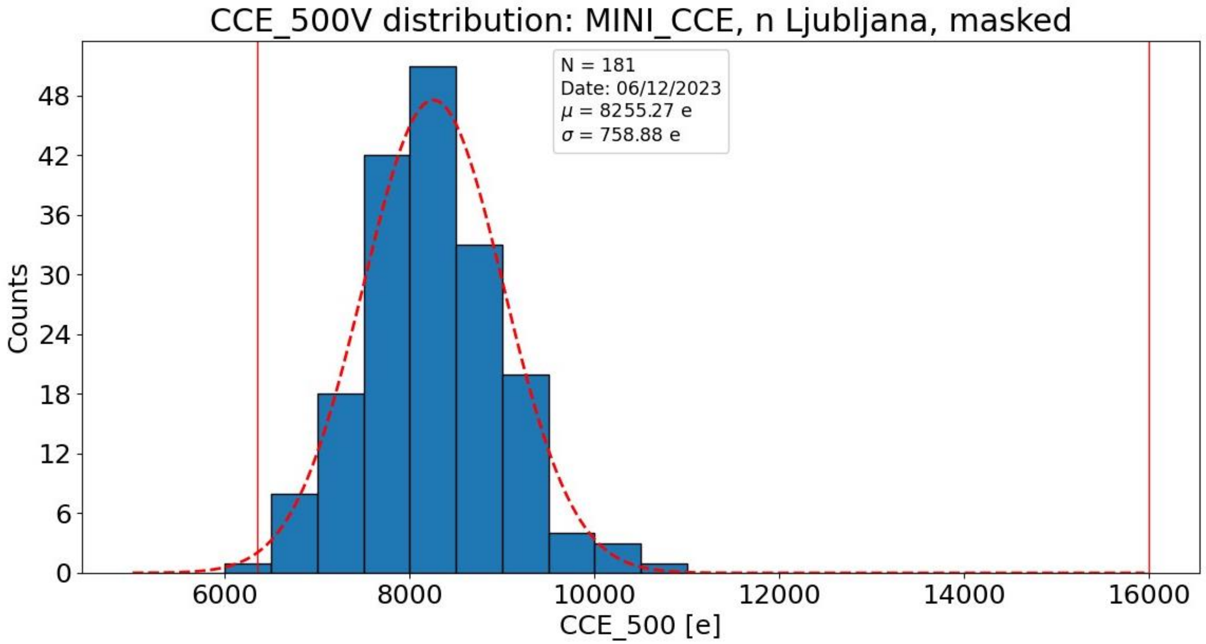
- All the data from the tests is uploaded by the test sites to the **ITk Production Database**, shared among all members of the collaboration.
- At this stage, we are conducting analysis of all the available data up to this point.
- Python scripts have been developed to collect data for each measured parameter, analyze them, obtain the statistics, and show the results primarily through distribution and time-evolution plots.
- The parameters presented below will be the most relevant or some having interesting features.

Charge Collection Efficiency (CCE) of Mini Sensors

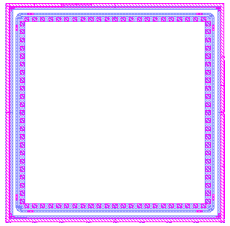


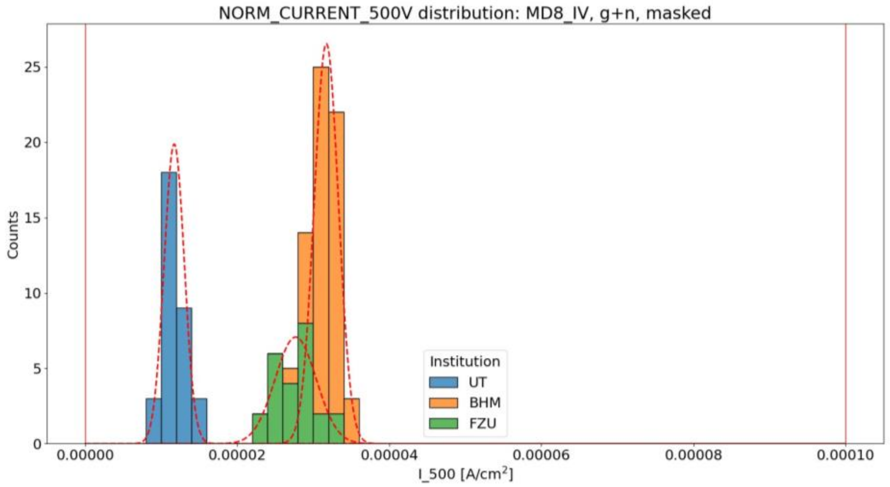
Evaluated parameter: Collected charge at 500 V

- Measured with the ALiBaVa System.
- Pure neutron irradiation is more damaging than real-experiment scenarios.
- The selection of a minimum threshold for this parameter was derived based on Signal-to-Noise (S/N) considerations and the radiation simulations (6350 e^-).
- The low bin crosses the minimum threshold due to the bin width, but all the values are higher than the threshold.



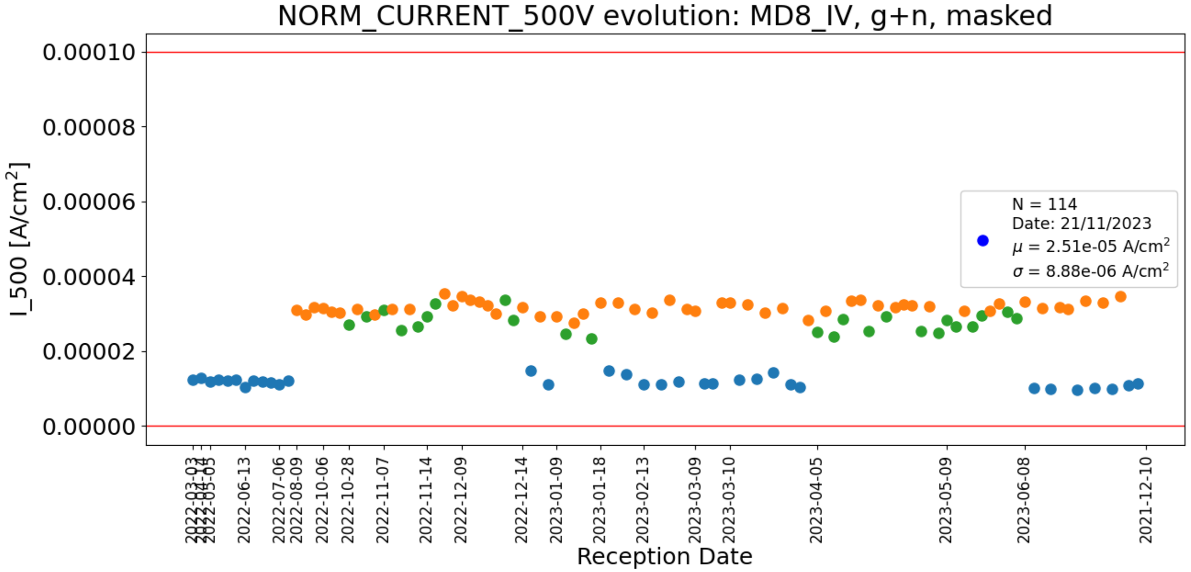
Leakage current of MD8 diodes





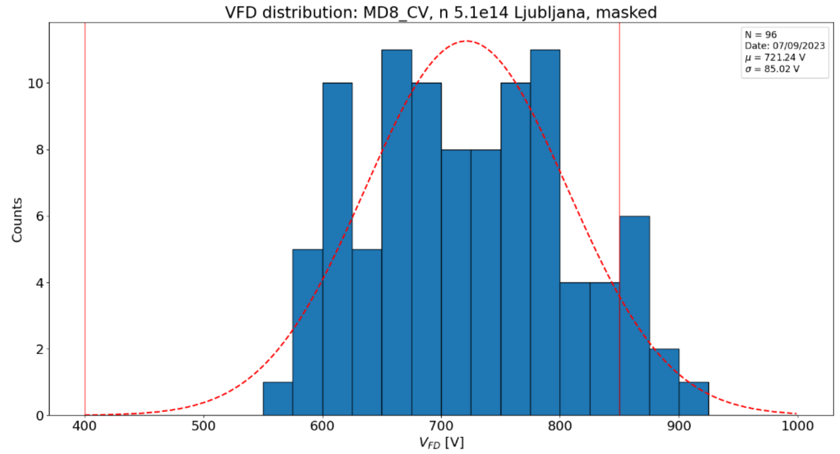
Evaluated parameter: Current at 500 V

- In the distribution plot, three distinct distributions can be identified for gamma+neutrons (γ+n) irradiation (66 Mrad + 1.6e15 n_{eq}/cm^2), each corresponding to the current measured at different test sites.



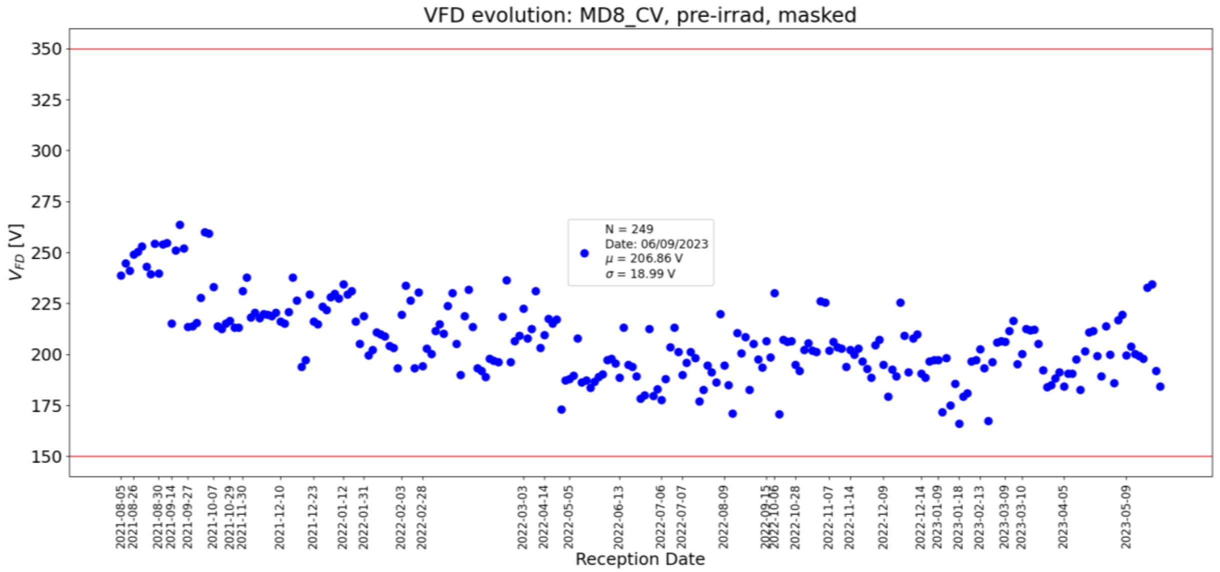
- The time-evolution plot shows the behavior of the tested parameter throughout production.
- The values remain stable throughout the production for a given test site.
- Small differences between test sites due to different test temperatures and possible larger annealing in further test site.

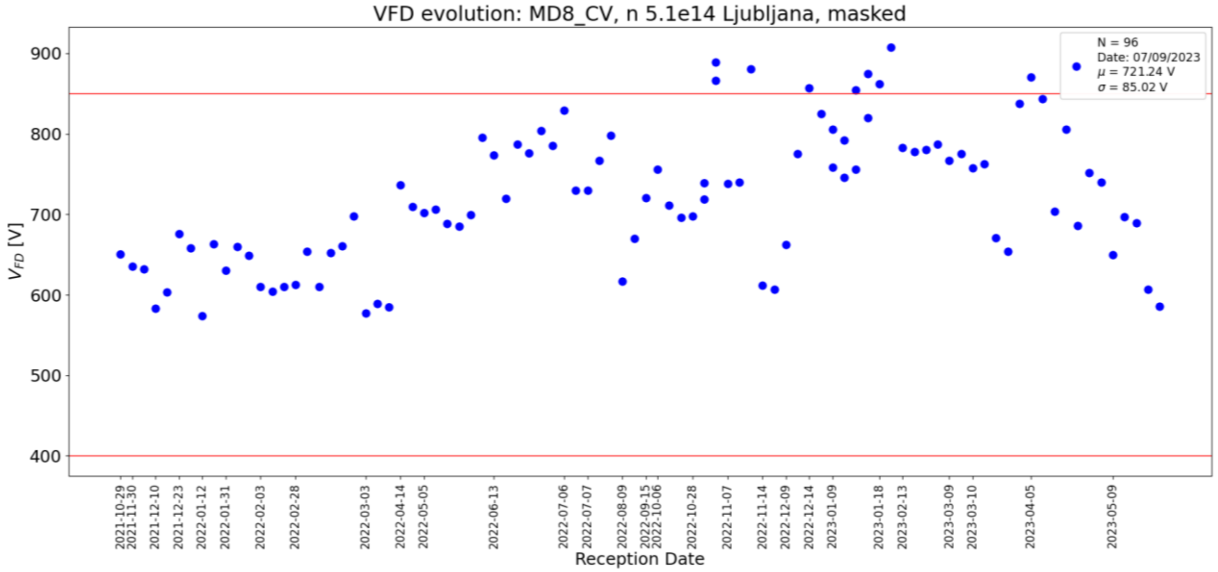
CV of MD8 diodes



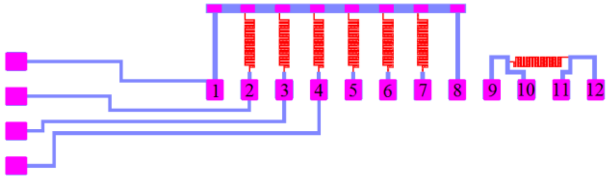
Evaluated parameter: Full depletion voltage (VFD)

- The pre-irradiated VFD exhibits a decreasing trend over time, which appears to stabilize lately.
- The neutron-irradiated VFD registers some values out of thresholds.
- The collected charge at 500 V is above threshold for those batches.
- The batches have been accepted. Under investigation.





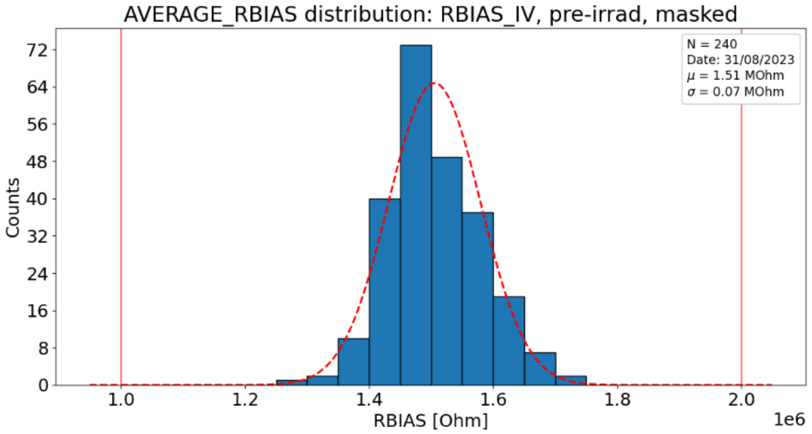
Resistance of Bias Resistors

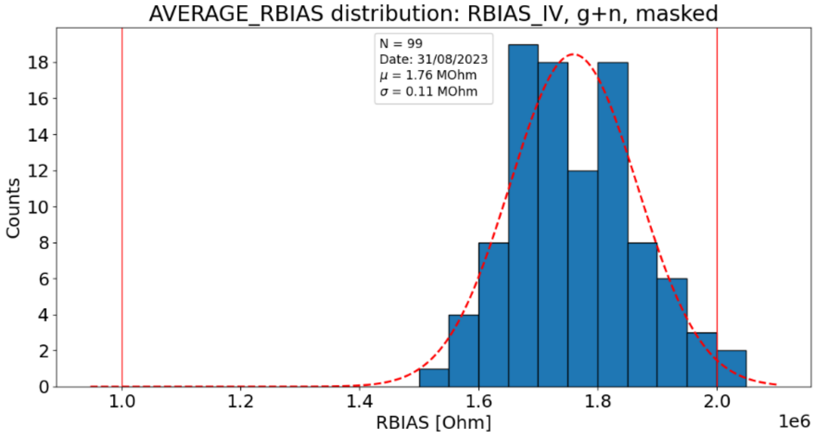


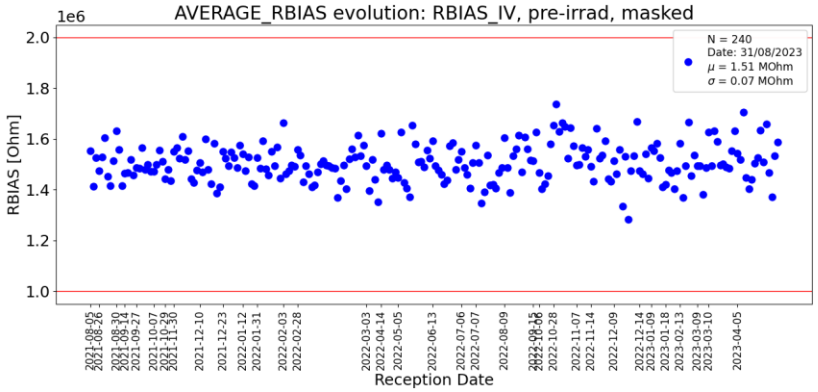
Evaluated parameter:

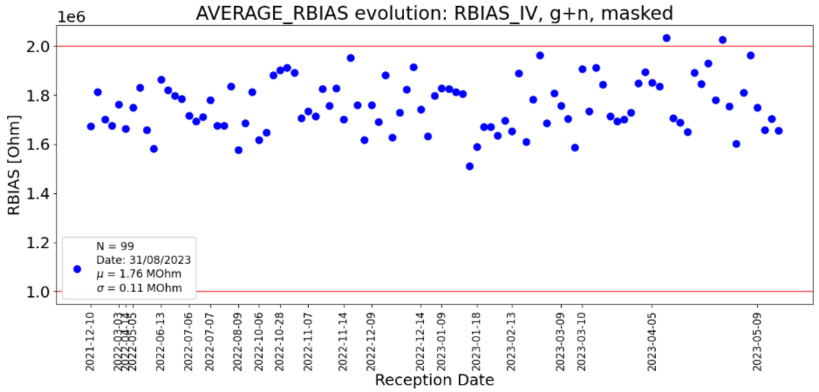
R_{bias}

- The R_{bias} values for both pre- and γ+n-irradiated conditions exhibit a well-defined Gaussian distribution.
- Slight increase in the resistance attributed to radiation effects (1.51 MΩ → 1.76 MΩ).
- Measurements are temperature corrected (DOI: https://doi.org/10.1016/j.nima.2023.168119).

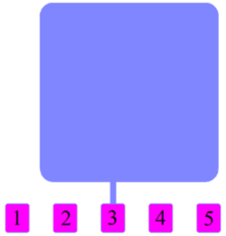


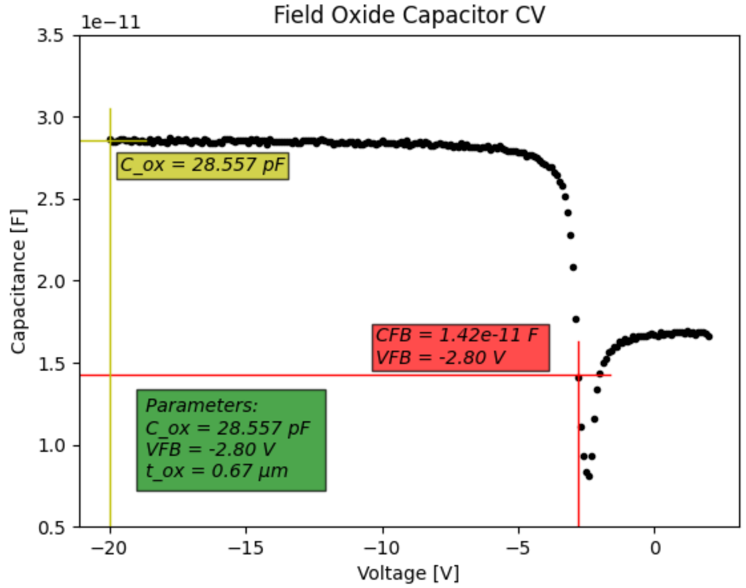






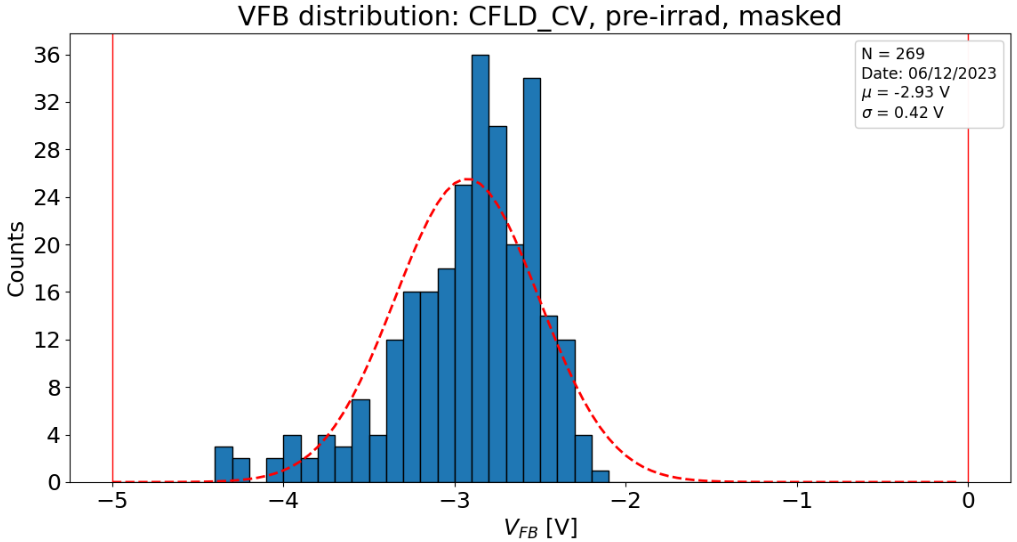
CV of Field Oxide MOS Capacitor

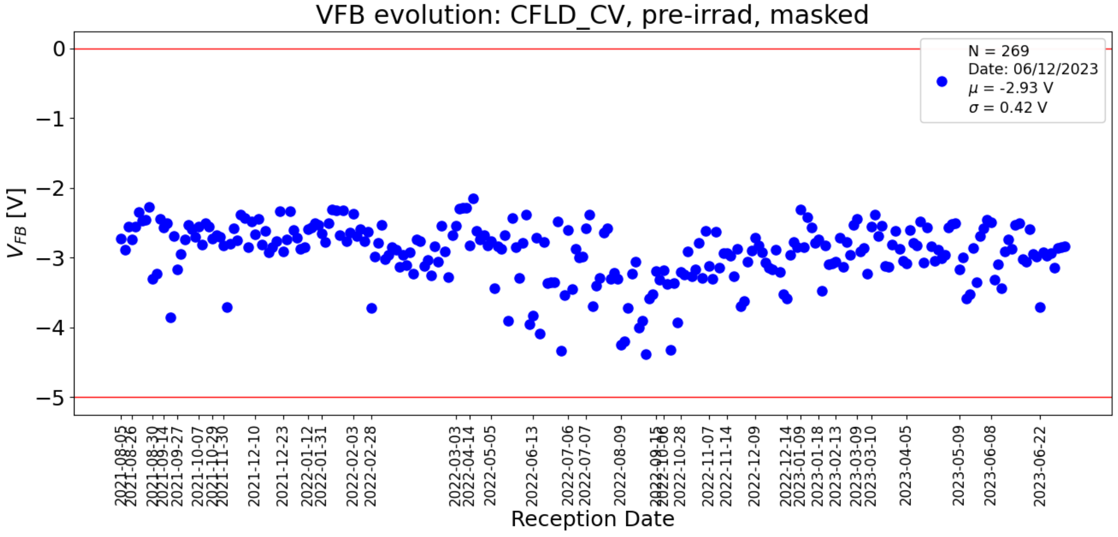




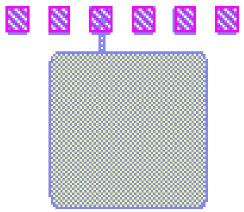
Evaluated parameter: Flat-band Voltage (VFB)

- High dispersion in VFB values.
- In general, a bit low values. Interface traps or trapped charge in the oxide.
- The VFB distribution shows a slight tail to low values in a few batches.



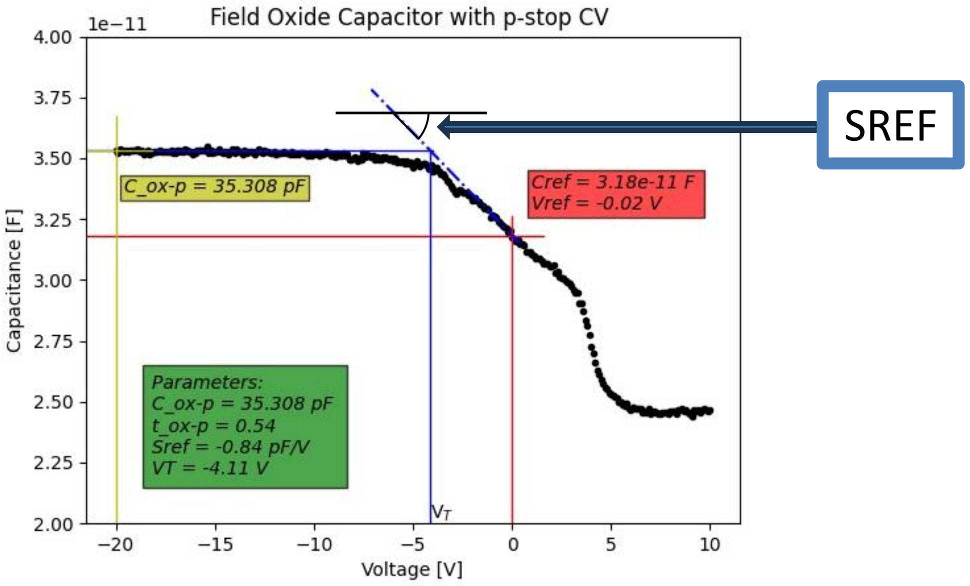


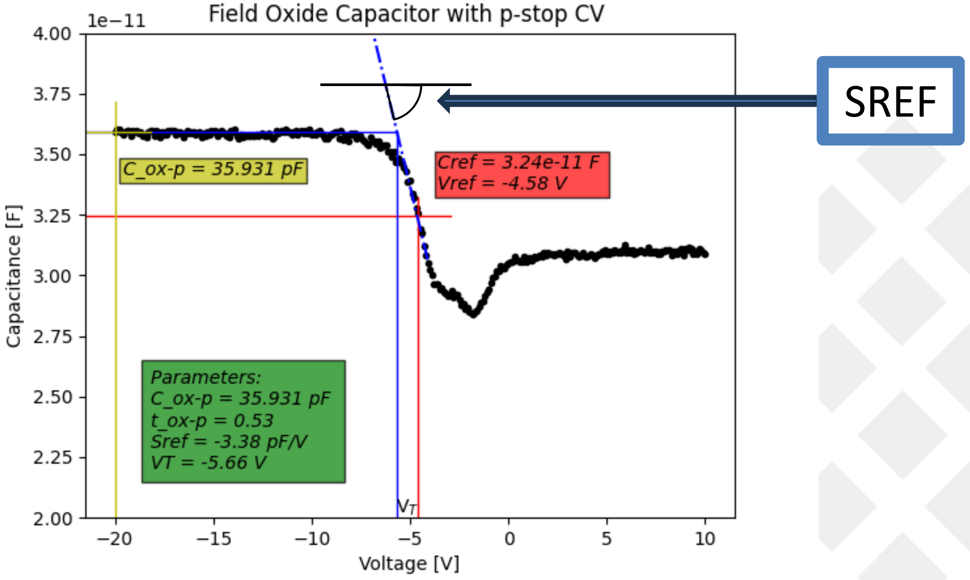
CV of MOS capacitor with p-stop implant



Evaluated parameter:
Slope of the depletion process (SREF)

- MOS capacitor with a p-stop implant in the silicon underneath the silicon oxide.
- The p-stop implant affects the depletion rate of the silicon immediately underneath the oxide.
- The slope of the CV curve from accumulation to depletion is indicative of the p-stop doping level.
- A fast depletion rate indicates a lower p-stop doping profile (for the physics behind, see [5]).
- SREF (the initial slope of the CV curve at the beginning of depletion) is the parameter to watch.



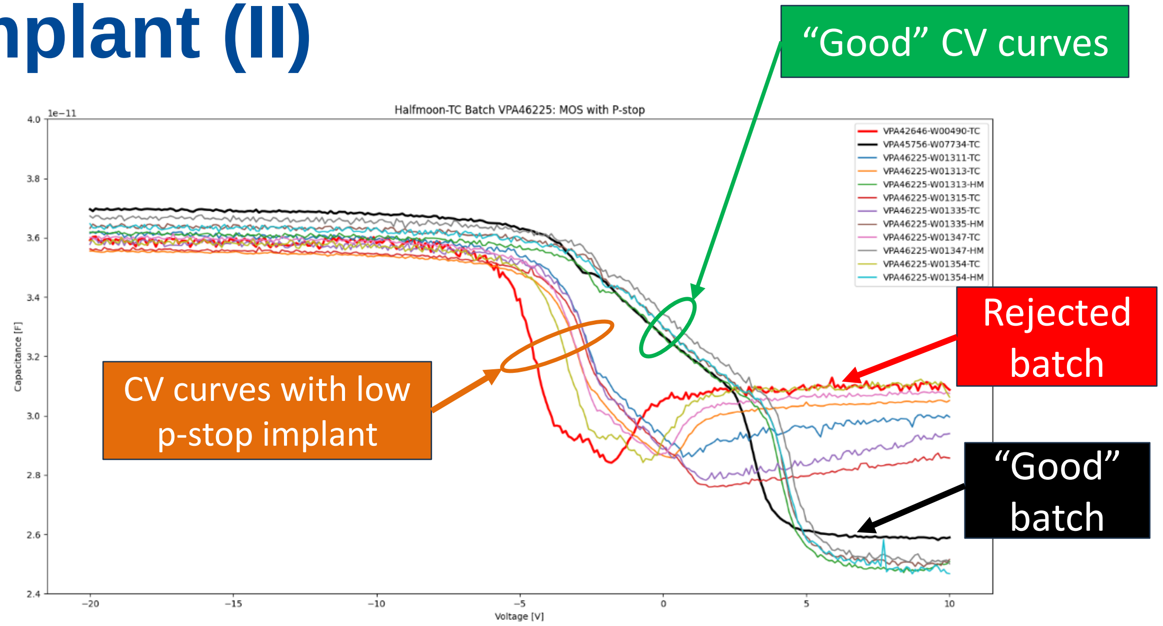


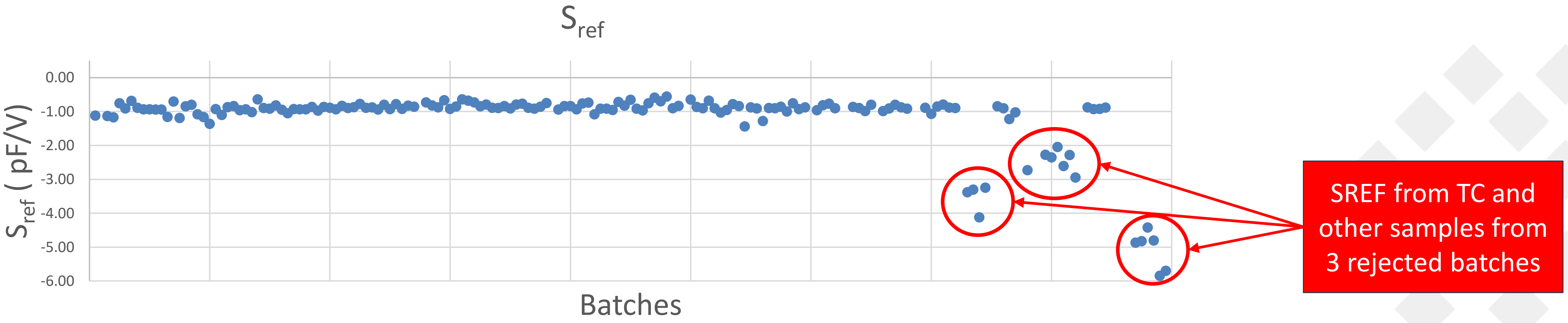
[5] Poster presentation in this conference: Y. Unno et al, *Analysis of MOS capacitor with p layer with TCAD simulation*.

CV of MOS capacitor with p-stop implant (II)

Rejected batches

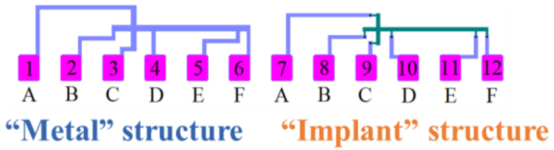
- A few batches have been rejected due to a low p-stop doping.
- The plot below, where SREF is represented for different batches, clearly shows the batches where the implant is low. Several data points measured for the suspect batches, unlike a typical one.
- Features corroborated by PTP performance on half-moons and MAIN sensors [6].





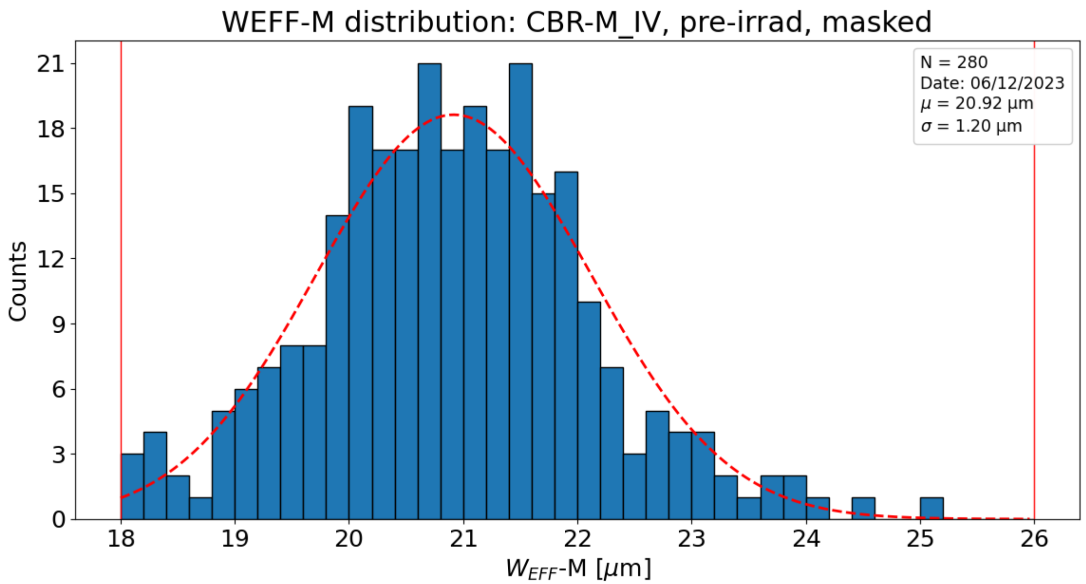
[6] P.S. Miyagawa et al, Analysis of the results from Quality Control tests performed on ATLAS18 Strip Sensors during on-going production

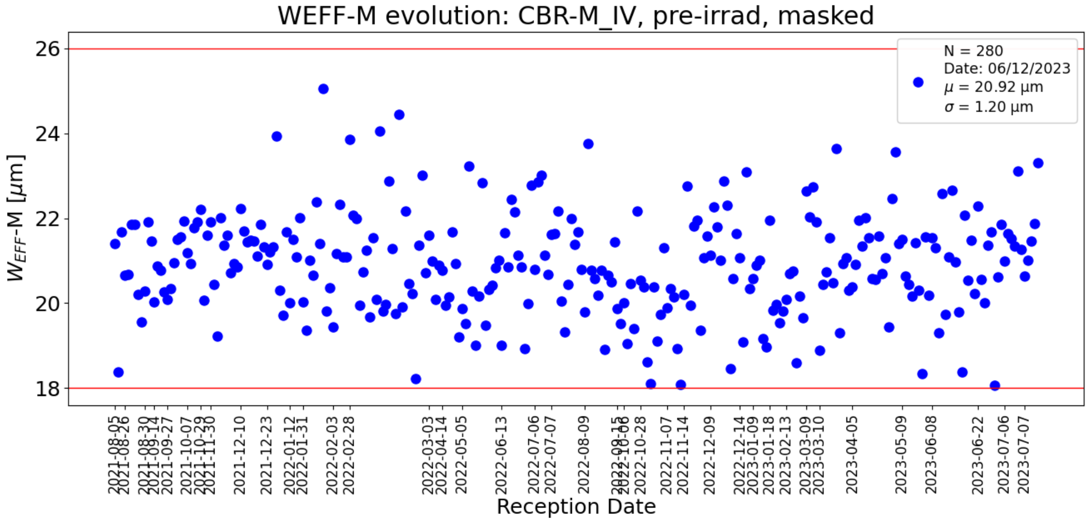
Cross-Bridge Resistors (CBR)



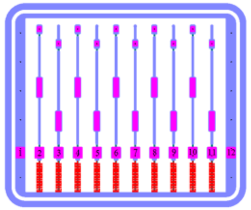
Evaluated parameter:
Effective linewidth of the metal strip (WEFF-M)

- Only measured on non-irradiated samples.
- High dispersion due to hard-to-measure low resistance values (~0.02 Ohm/□).
- The mean (21 µm) of the effective linewidth of the metal (WEFF-M) is slightly below the nominal value (22 µm).
- This discrepancy could suggest a potential over-etching of the metal.
- Not a critical effect, but to be watched.





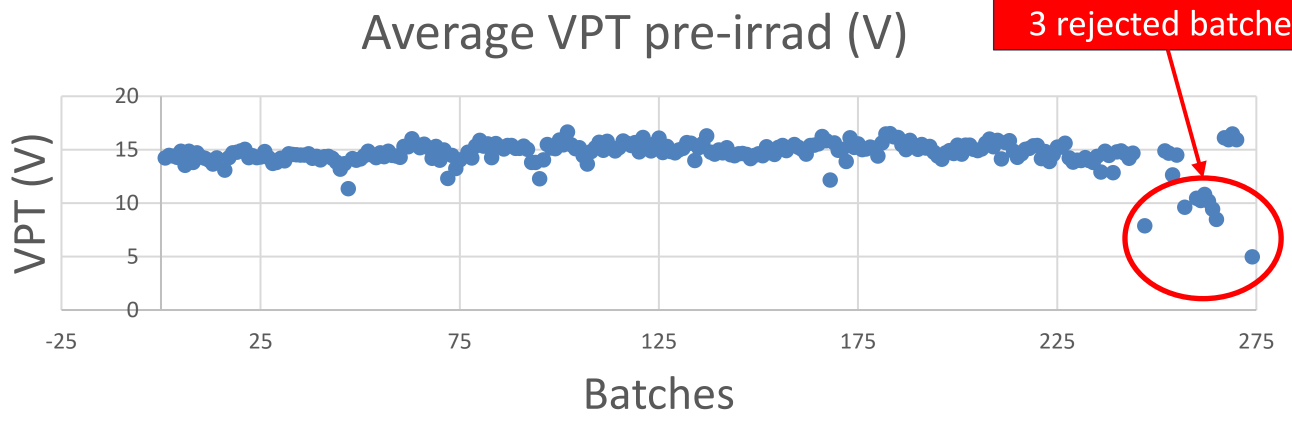
Punch-through Protection (PTP)

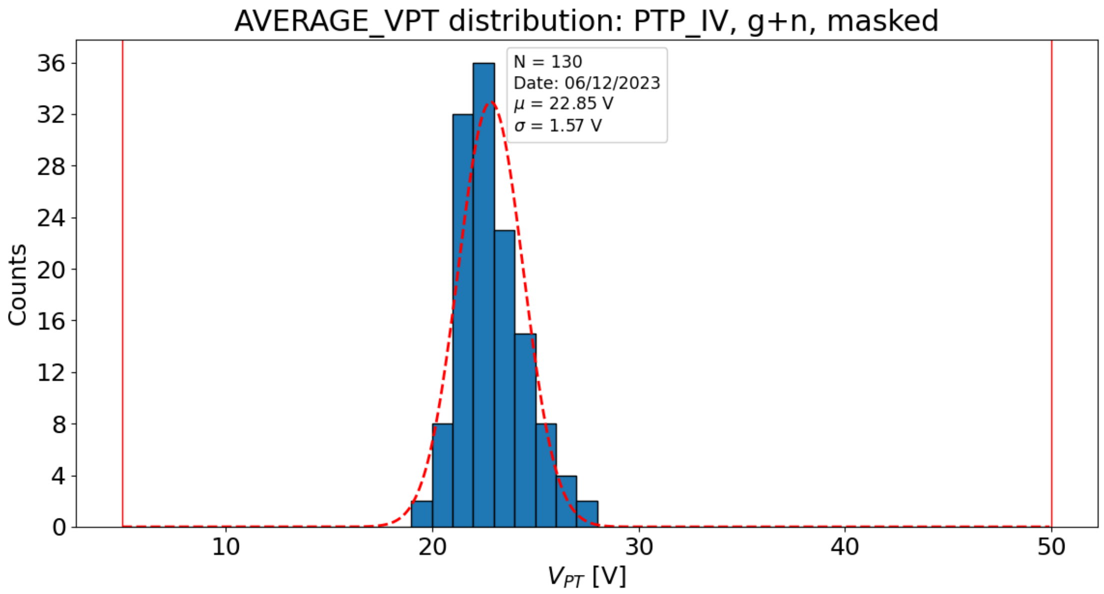


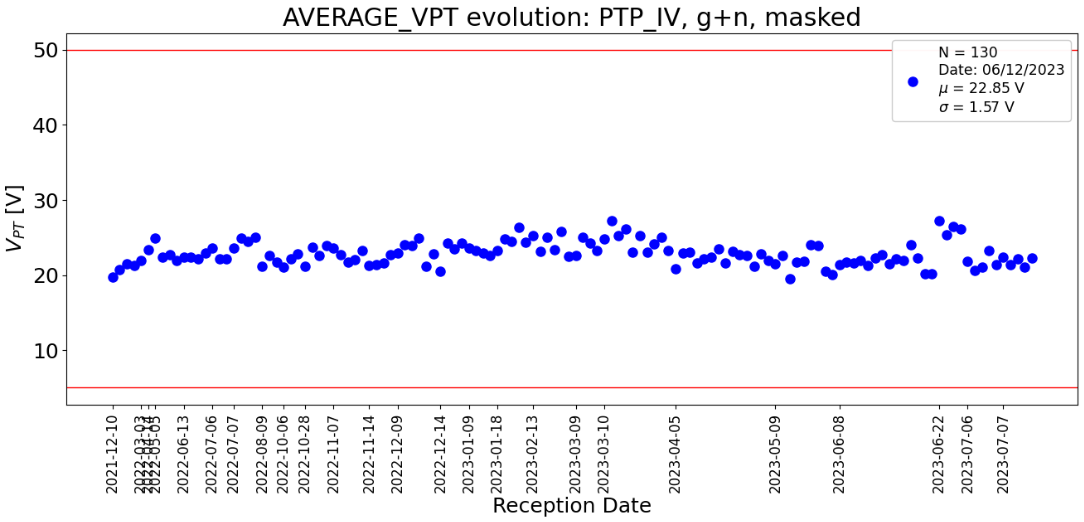
Evaluated parameter:
Punch-through voltage (VPT)

- The VPT in irradiated samples remains at values which ensure the functionality of the punch-through protection structure after irradiation in the real experiment.
- Pre-irradiated VPT is lower in samples with low p-stop implantation.

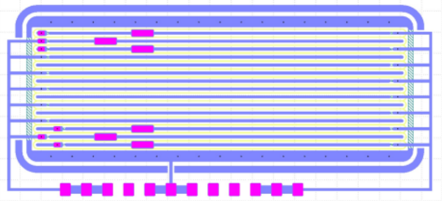
VPT from TC and other samples from 3 rejected batches





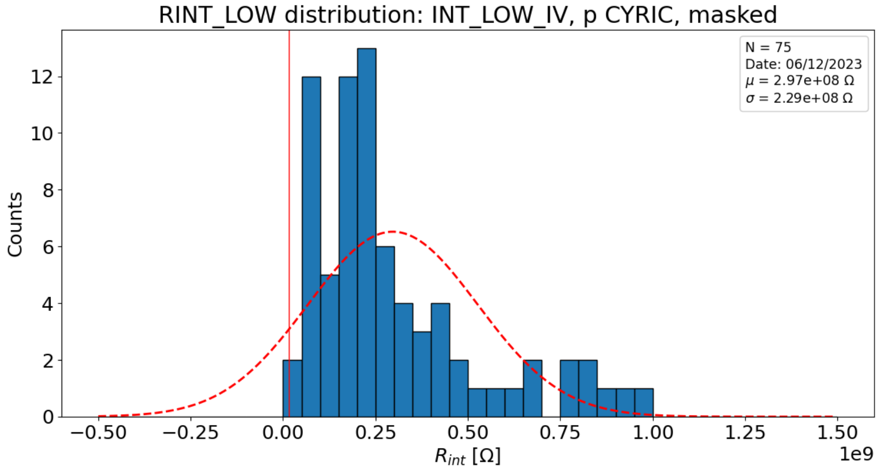


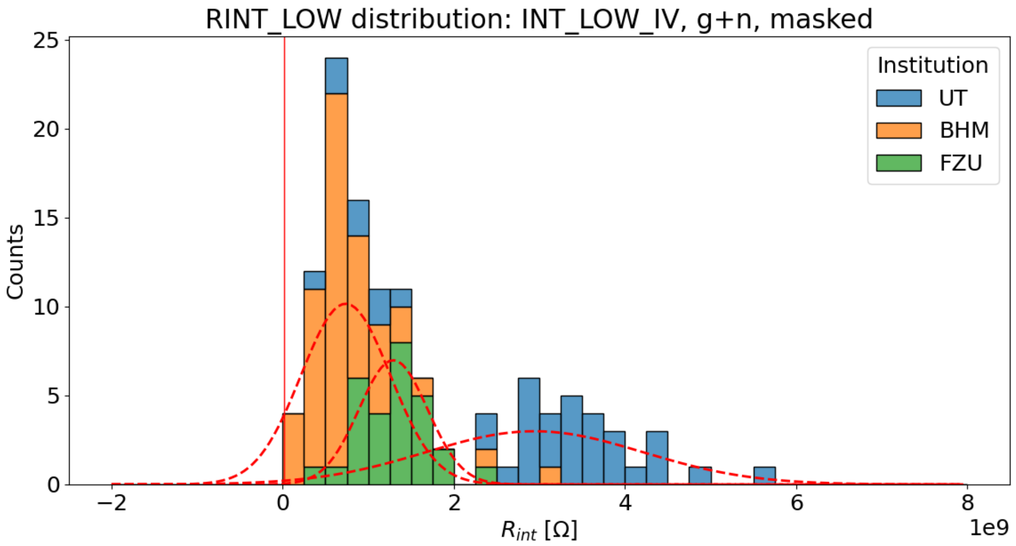
Interdigitated structures

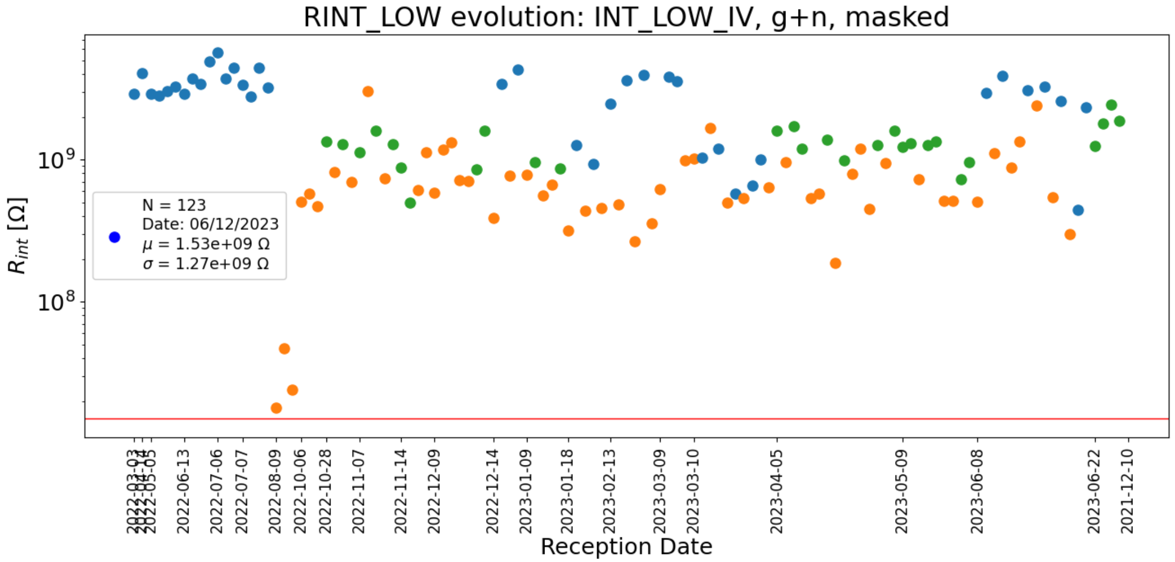


Evaluated parameter:
Inter-strip resistance (R_{int})

- The inter-strip resistance is measured in the testchip with a specific structure designed for this purpose [7].
- R_{int} exhibits three clear distributions depending on the test site in γ+n-irradiated samples. Possibly due to larger annealing in further test site and different test temperatures.







[7] M. Ullán et al., Quality assurance methodology for the ATLAS Inner Tracker strip sensor production, Nucl. Instrum. Meth. A 981 (2020) 164521.

Conclusions

Conclusions

- Scripts that can access the ITk database have been developed. These scripts allow for a detailed analysis of the results of production QA tests and the identification of trends.
  - The distribution and the evolution plots have shown to be useful for monitoring the technological stability.
  - This analysis has also allowed us to evaluate the full QA process and the specifics of the different test sites.
- After 2 years of QA evaluation we have obtained enough statistics to state that production progresses satisfactorily.
  - 306 batches have been approved and 3 (1%) have been rejected due to low p-stop doping.
  - In some batches, some parameters have slightly exceeded the defined “soft” thresholds. This probably belongs to the normal statistic deviation. We are watching those parameters closely.
  - The encountered features are well understood and stable.
- The 3 rejected batches confirm the need for QA testing.
- The QA test and irradiation sites are fully operational and the production QA is progressing smoothly.

Future work

- Analyze correlations between parameters.
- Re-define and further adjust thresholds for each parameter.
- Review measurement setups and operational conditions if necessary.

Thanks for your attention

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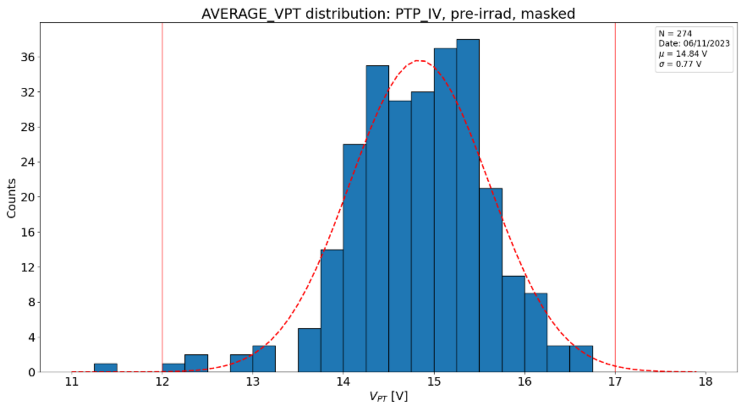
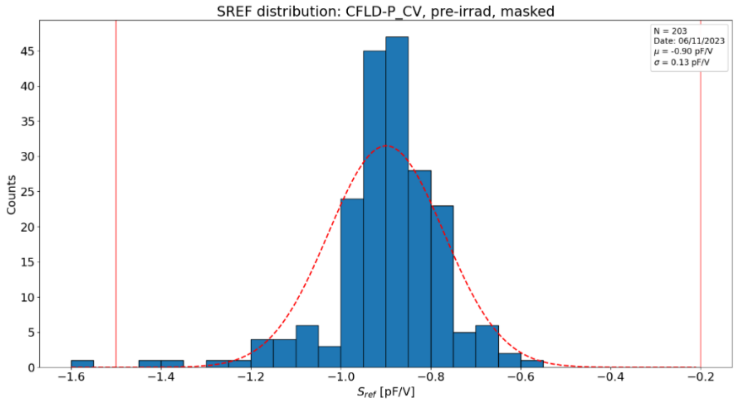
Backup

MOS with p-stop implant





Evaluated parameter: SREF

- A correlation may be observed between the slope at the depletion region for this structure (SREF) and the Punch-through Voltage (VPT) associated with the PTP structure. Therefore, SREF serves as a reliable indicator of the quality of the p-stop implantation in the sensor.