# Performance of irradiated RD53A pixel modules with passive CMOS sensors

Anna Macchiolo, Arash Jofrehei, Weijie Jin (UZH)

Malte Backhaus, David Bacher, Franz Glessgen, Branislav Ristic (ETHZ)

for the CMS Tracker Collaboration

Design and production with:

Yannick Manuel Dieter, Jochen Christian Dingfelder, Tomasz Hemperek, Fabian Huegging, , David-Leon Pohl, Tianyang Wang, Norbert Wermes, Pascal Wolf

*University of Bonn*

Daniel Muenstermann, *Lancaster University*

*39th RD50 Workshop, 19 November 2021, Valencia*

# Passive CMOS sensor production at LFoundry

- Production of passive CMOS sensors on 150 nm CMOS LF process (6 metal layers)

- Resistivity of p-type FZ bulk material: 3-4 kOhm cm

- 8” wafers thinned down to 150 μm and back-side implanted at LF after front-side processing
  - Aluminum deposition on the backside at IZM
  - Handle wafer transfer to the backside and UBM processing on the front-side

- RD53A compatible sensors implemented
  - 50 μm x 50 μm and 25 μm x 100 μm
  - DC-and AC-coupled (only 50x50) sensors
  - Single chip, double and quad (ATLAS design)

## Wafer layout

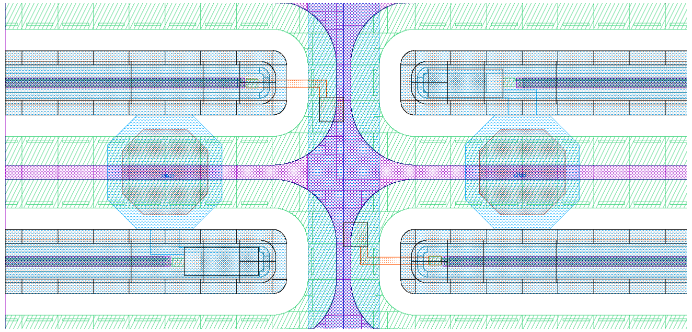
# Passive CMOS sensor production at LFoundry

ETHzürich

Single Sensors Double Sensors Quad Sensors

High resistive poly-silicon layer used as bias resistor

25 μm x 100 μm

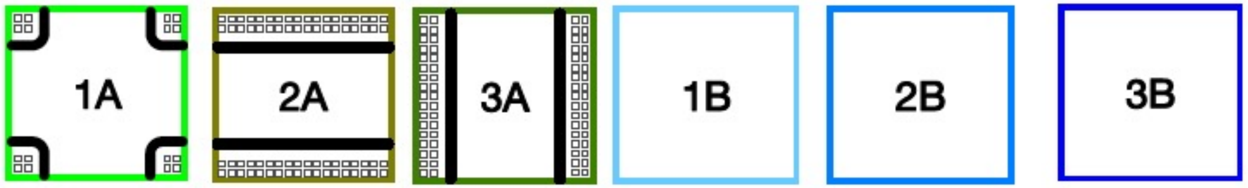


N implant **5 μm × 80 μm**
P stop 4 μm
Poly res. 2 MOhm

Wafer layout

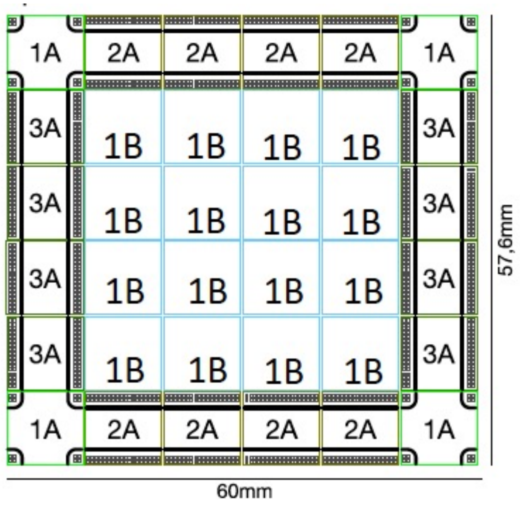
# LFoundry: reticule stitching

- Sensor size > reticle size 26 mm x 32 mm → reticle stitching needed
- Different sub-reticles (~ 1 cm x 1 cm) for edge and active areas:

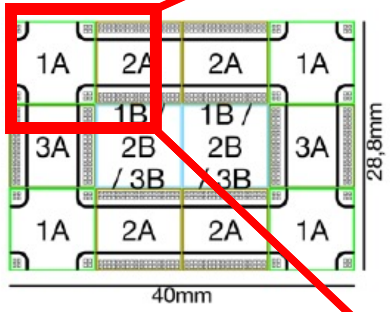


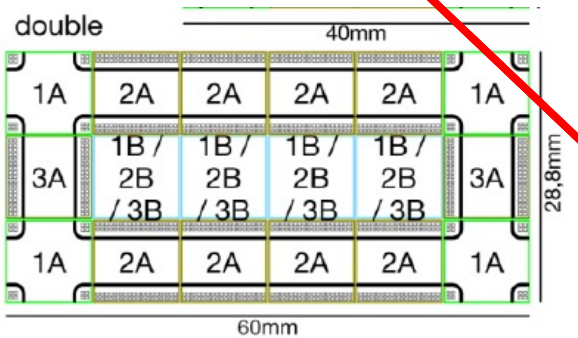

- Repeat them for different designs:

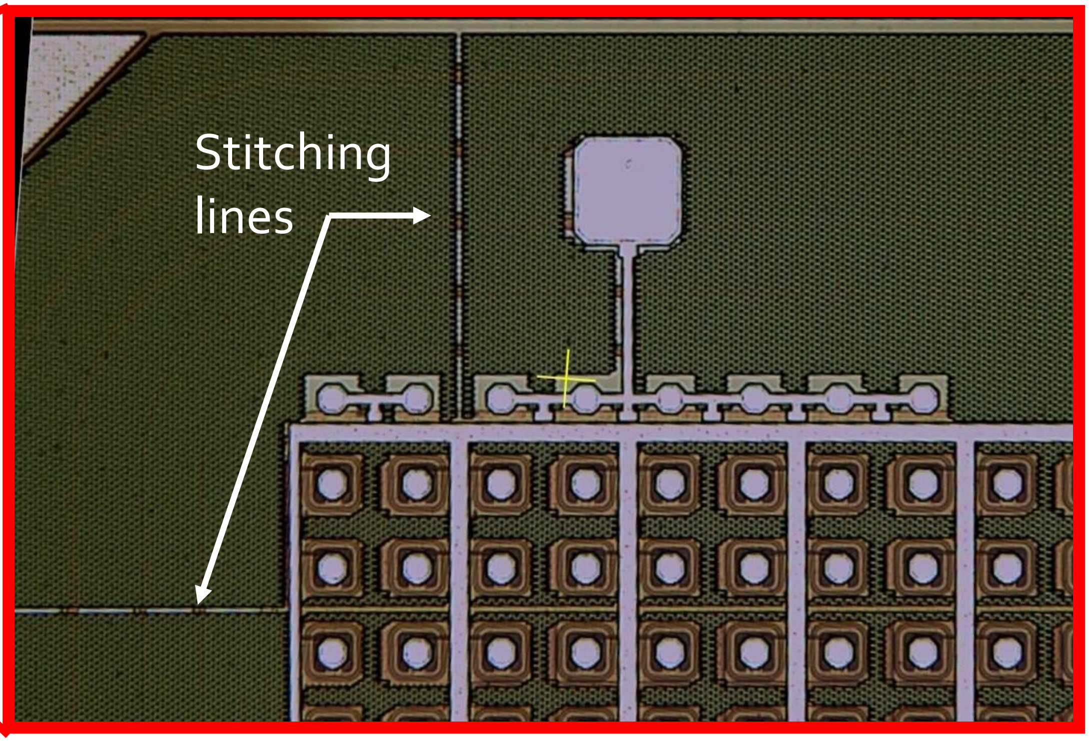
quad




single



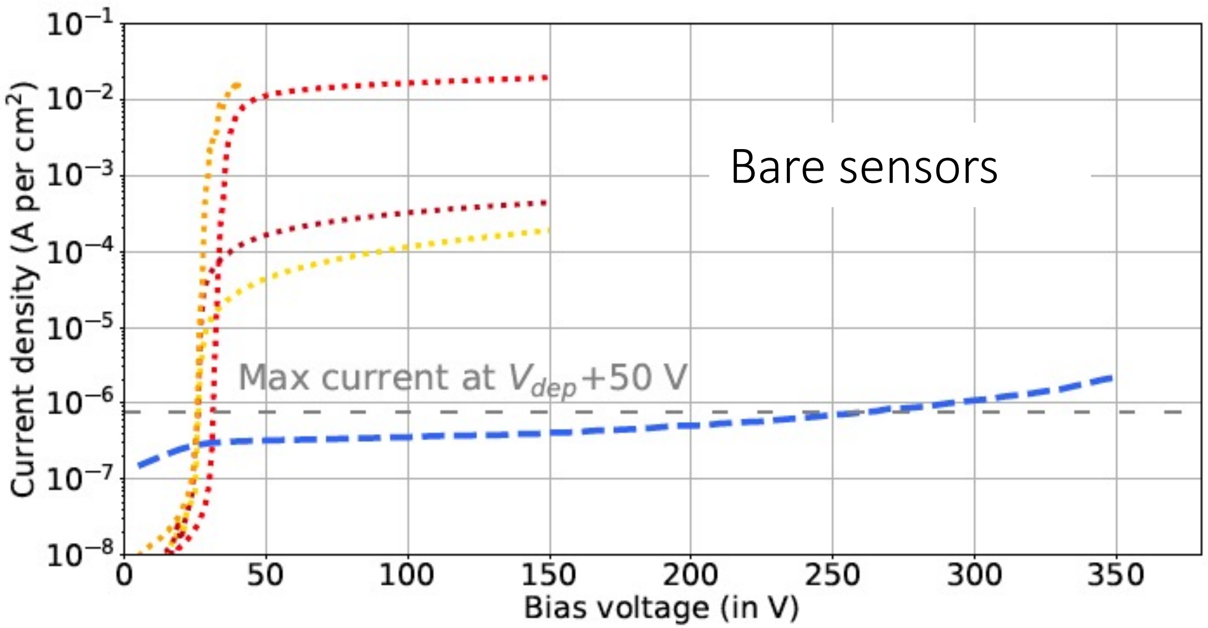



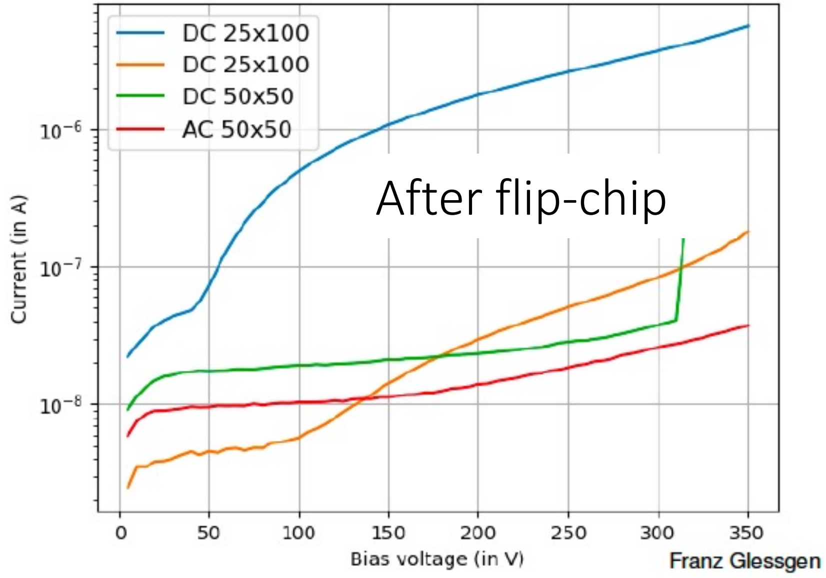



# Leakage current before irradiation

- Very high currents measured on all the sensors at V_bias for which the depletion depth reaches the backside  (V~30V)

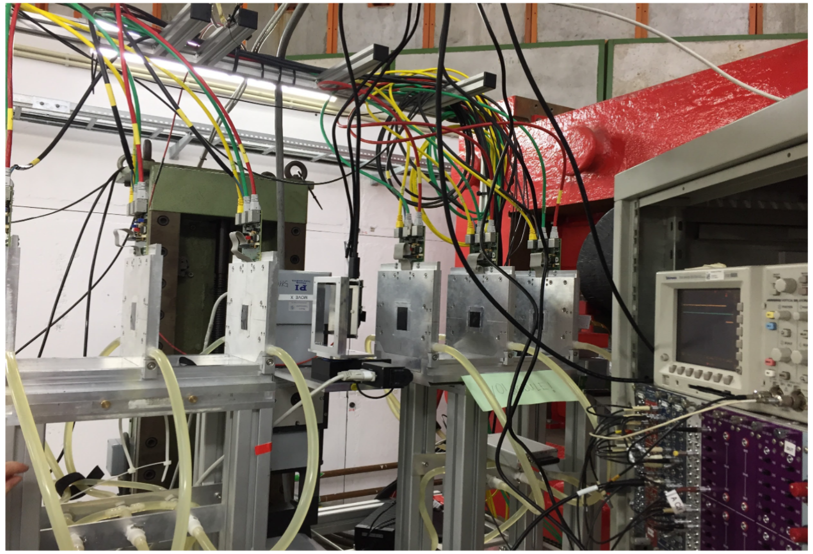
→ Issue solved by optimizing backside processing: backside Boron dose increased x10



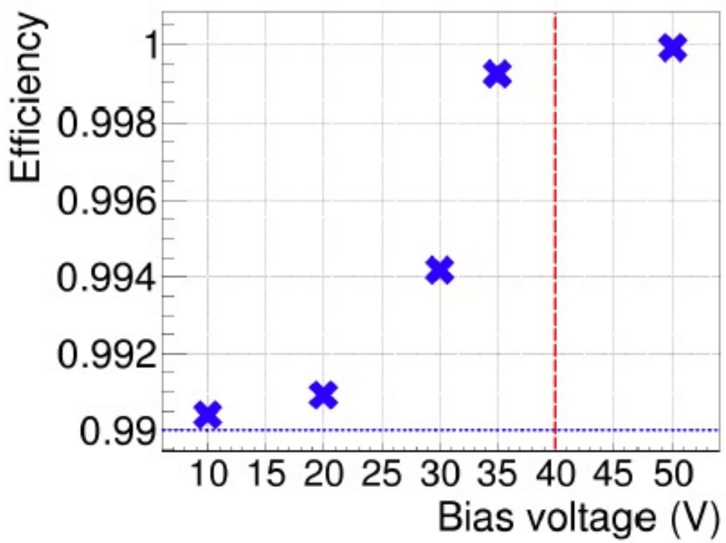
# Test beam @ DESY

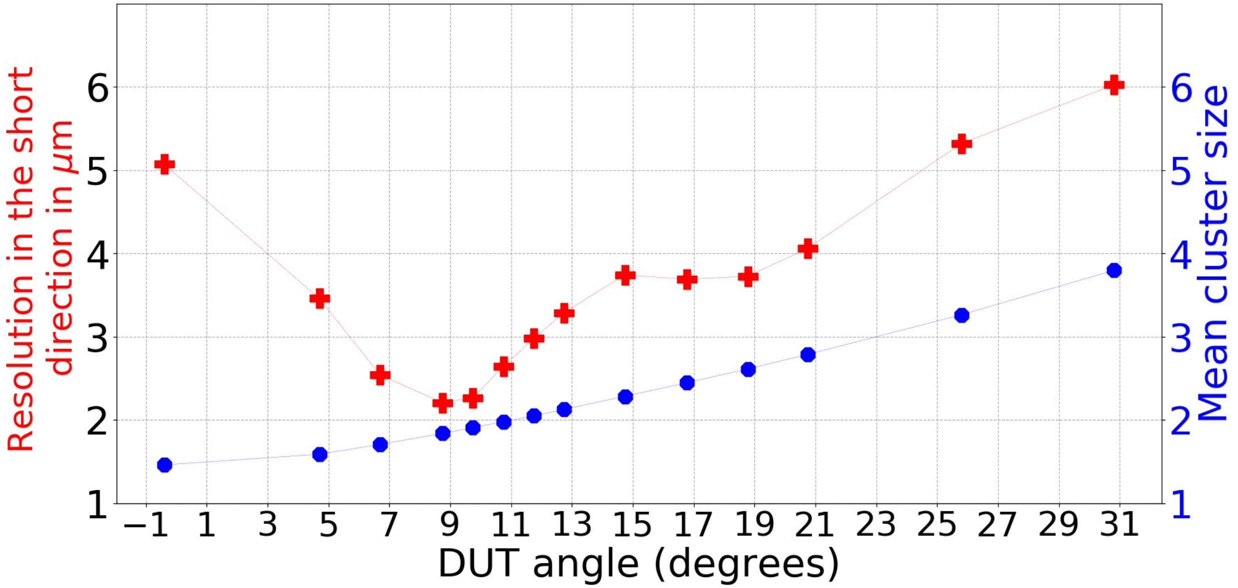
- 5.2 GeV electron beam
- AIDA telescope with 3 upstream and 3 downstream planes.
- Detector Under Test (DUT) to be placed between planes 3 and 4.
- Precise DUT orientation and position control.
- Cooling box @ -35 °C
- Eudaq + BDAQ53 data acquisition



# Results with not irradiated modules

- Unirradiated LF RD53A modules were previously tested both in lab and in beam.
- Position resolution calculated along the $25\mu m$ direction.
- With a sensor thickness of 150 $\mu m$, the cluster width increases from 1 to 2 around the incident angle of $9.5$ degrees.
- While cluster width of 1 gives a binary position and cluster width of 3 or more is prone to under-threshold charges, we expect the most precise position measurements before irradiation to be at incident angles of 9-10 degrees.




*A. Macchiolo, 39th RD50 Workshop, Valencia, 19.11.2021*

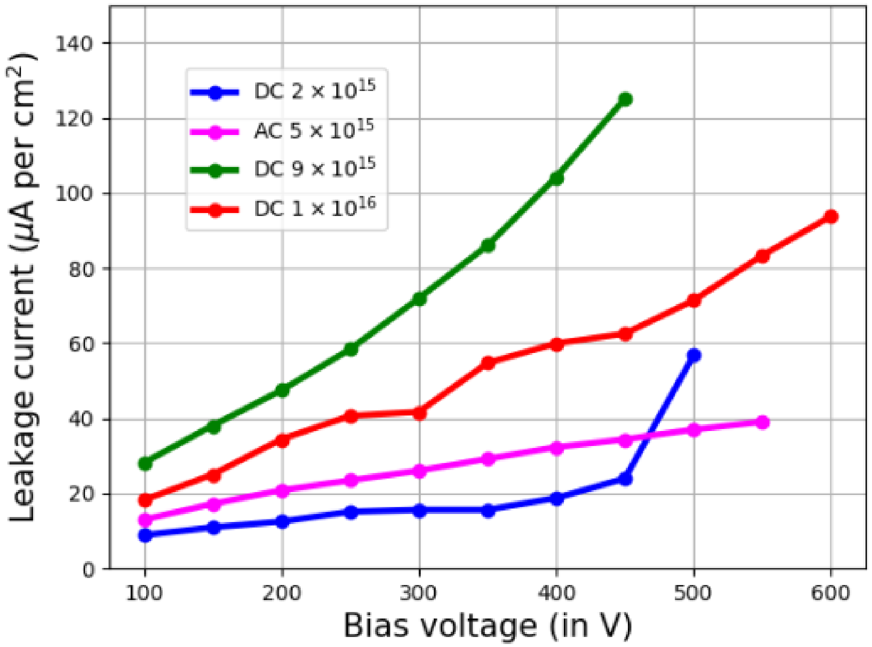
# First irradiation campaign

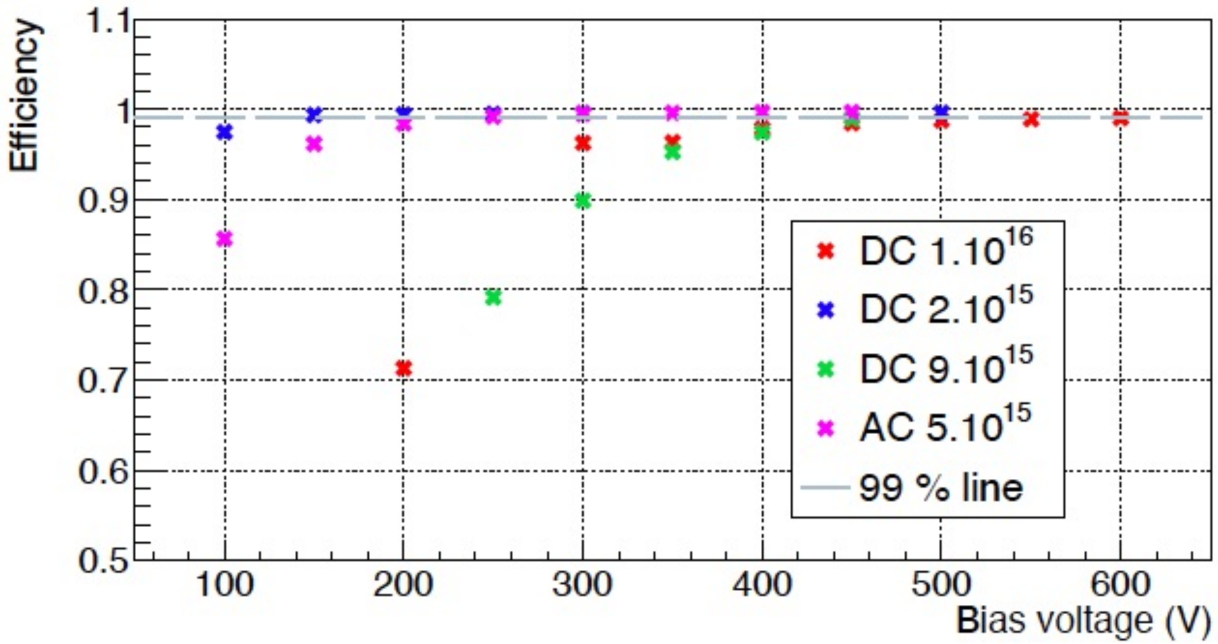
- 4 irradiated and 1 unirradiated single-chip LFoundry modules were studied at DESY in May 2021.
- Irradiation with 23 MeV protons at Karlsruhe
- All modules coated with parylene before irradiation to avoid sparking between sensor and read-out chip

| Module | Pitch ($\mu m^2$) | Type | Fluence ($\frac{N_{eq}}{cm^2}\times 10^{15}$) | Threshold (e) |
|---|---|---|---|---|
| TBA1 | $25 \times 100$ | DC | 10 | 1192 |
| TBA2 | $25 \times 100$ | DC | 2.1 | 1240 |
| TBA3 | $25 \times 100$ | DC | 9.2 | 1219 |
| TBA4 | $50 \times 50$ | AC | 5 | 1208 |

# Efficiency and IV measurements, DESY TB

- Efficiency = $\frac{\#\text{ matched hits } in\ DUT}{\#\ expected\ hits\ from\ telescope}$
- DC $1\times10^{16}$ reached 99% efficiency at 500-600V
- DC $2\times10^{15}$ reached 99% efficiency at 150V
- The 4 irradiated modules were successfully biased to more than 450V as seen in the plots below.

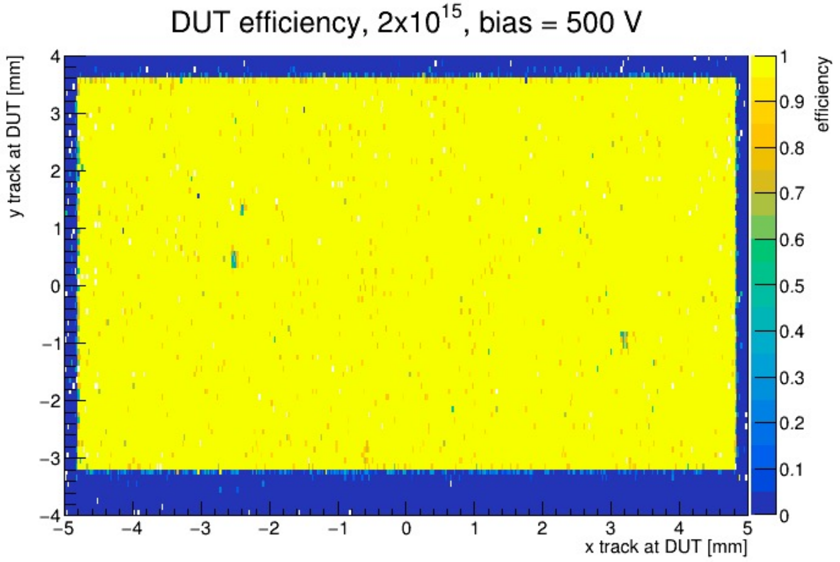


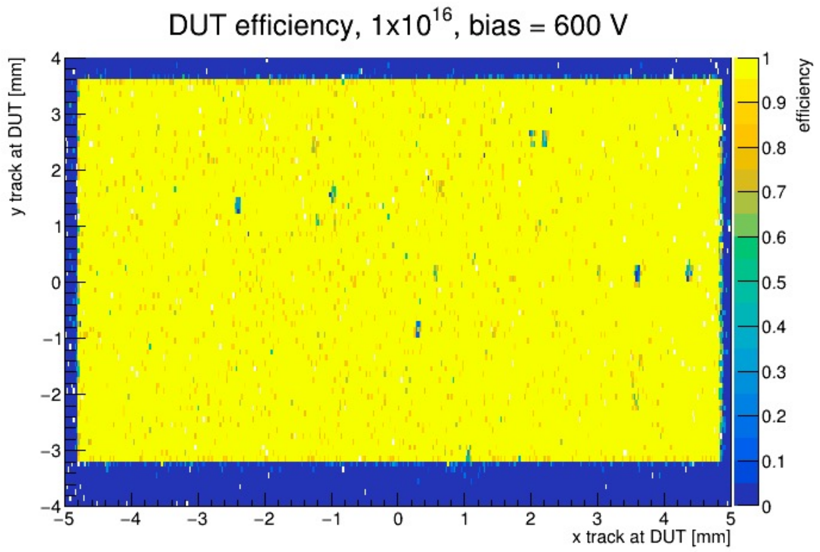



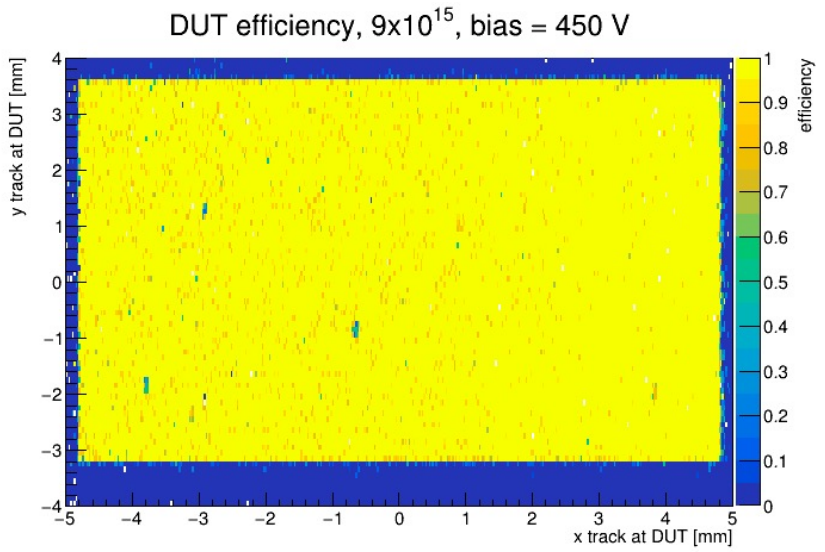
# Efficiency maps

- No systematic damage or gradient of efficiency loss in the fluence range
- No effect of stitching visible, also from a detailed efficiency analysis in the rows adjacent to the stitching line

F. Glessgen, Characterization of passive CMOS sensors with RD53A pixel modules



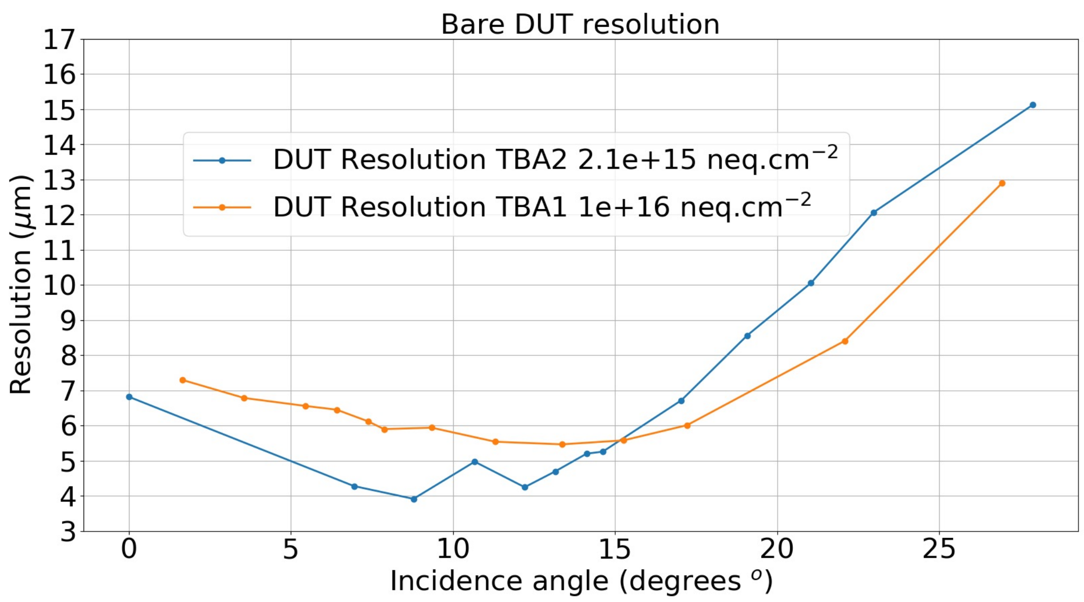



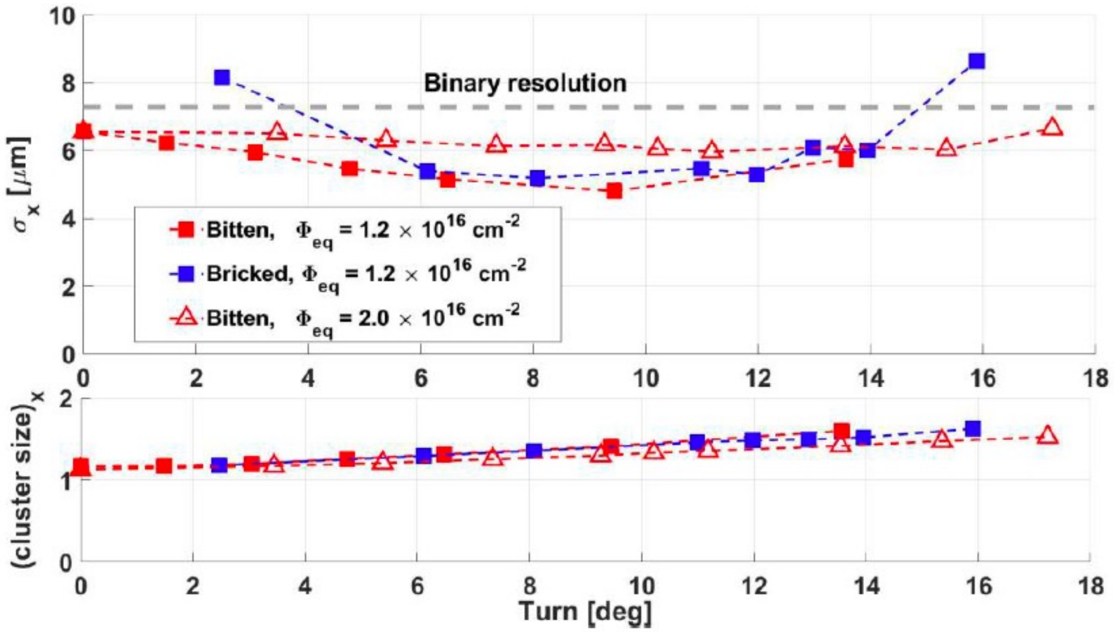



# Position resolution at different incident angles

- The module is rotated around the 100 $\mu m$ side of the pixel cell.
- Cluster size at fluences > 1e16 only slightly above 1
- Achieved similar resolution results after irradiation wrt standard productions.

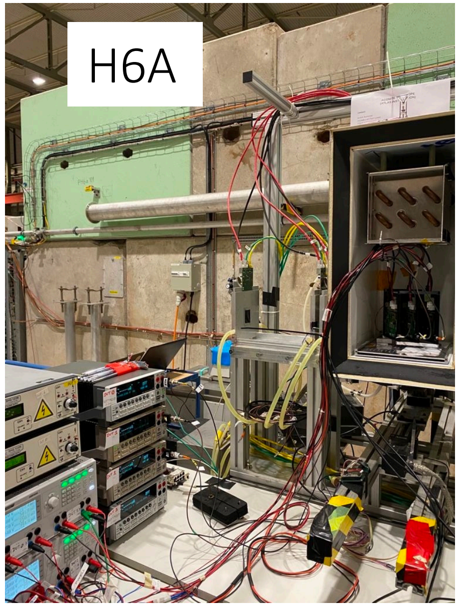
HPK planar sensors, Mohammadtaghi Hajheidari, PSD12

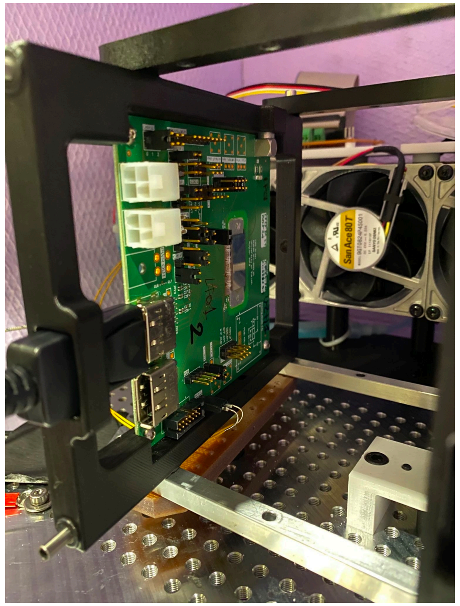


# Test beams @ CERN SPS

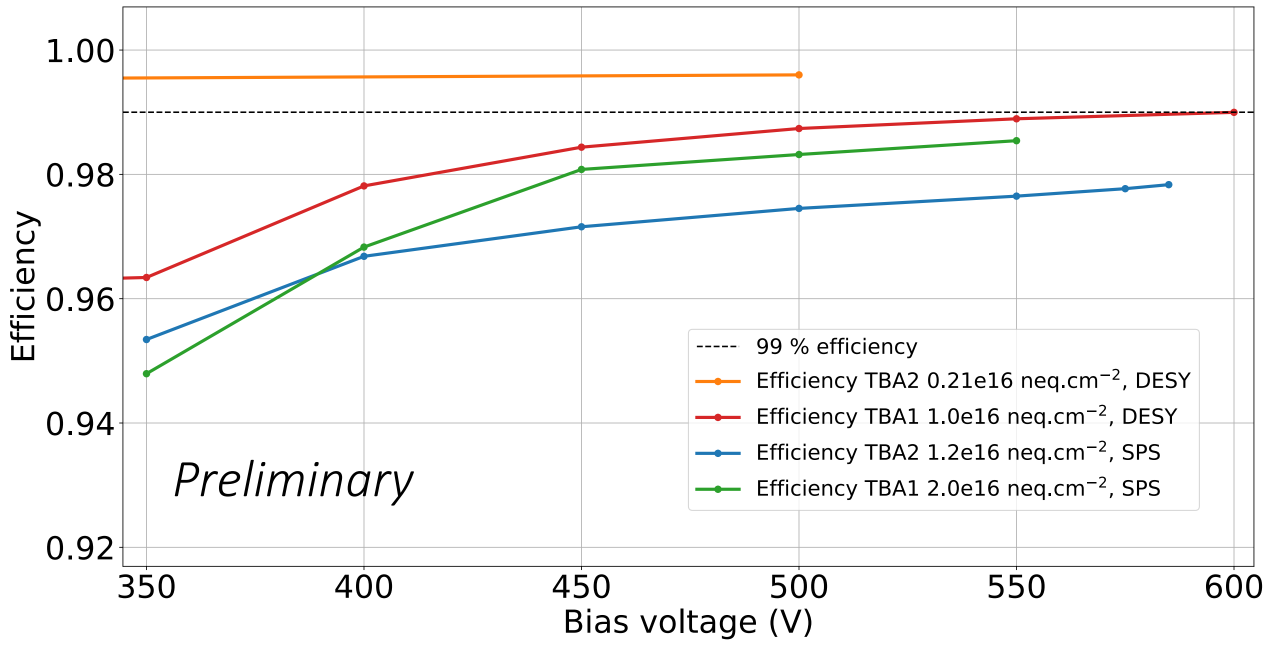
- Two modules re-irradiated to 1.2e16 and 2e16 $n_{eq}$ $cm^{-2}$
- AIDA telescopes at H6A and H6B (Sept. and Nov. CMS IT Pixel TBs)
- New ETH Cooling box @ -35 °C (air T) in H6B
- Eudaq + CMS Ph2_ACF data acquisition



ETH+IFCA teams (a selection in green)

# Second irradiation campaign

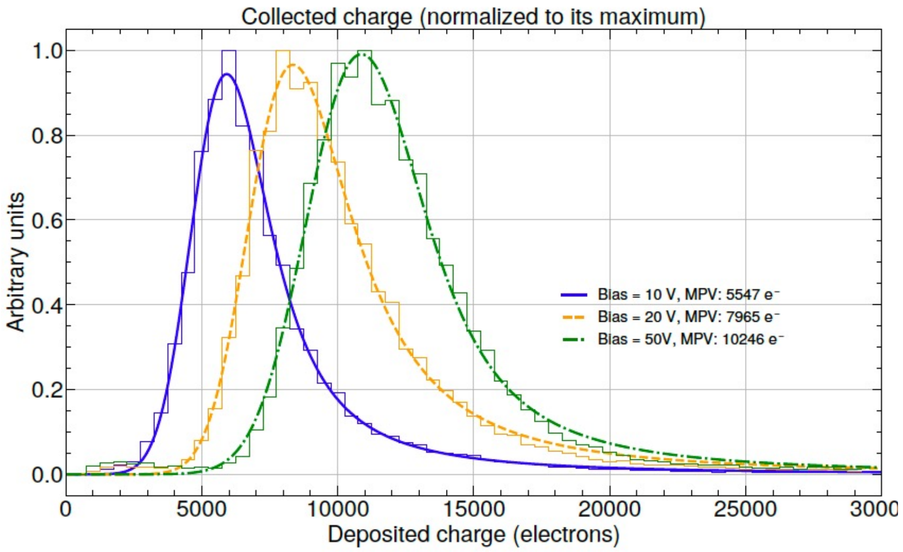


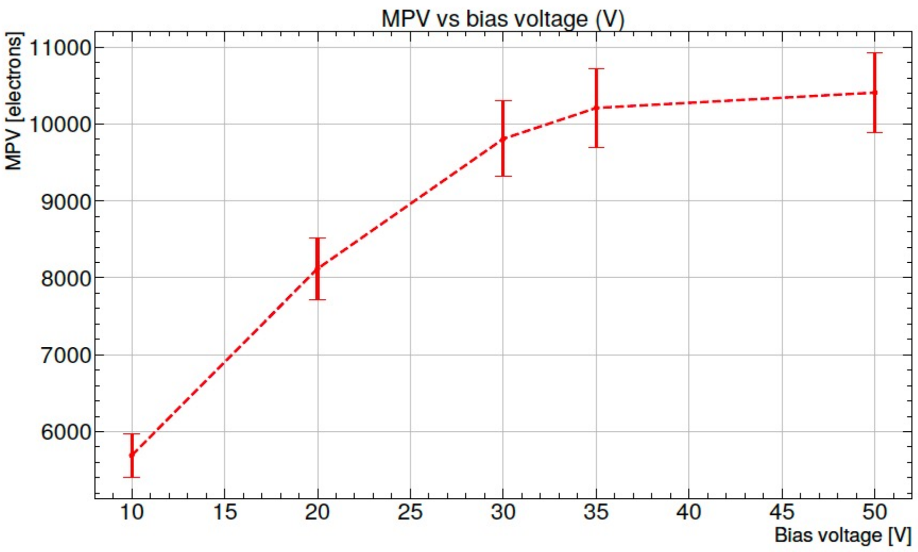

- Module TBA1 re-irradiated up to a total fluence of 2e16
- Module TBA2 re-irradiated up to a total fluence of 1.2e16
- Efficiency ~98% or above in the fluence range 1e16-2e16

# Charge Collection Measurement (I)

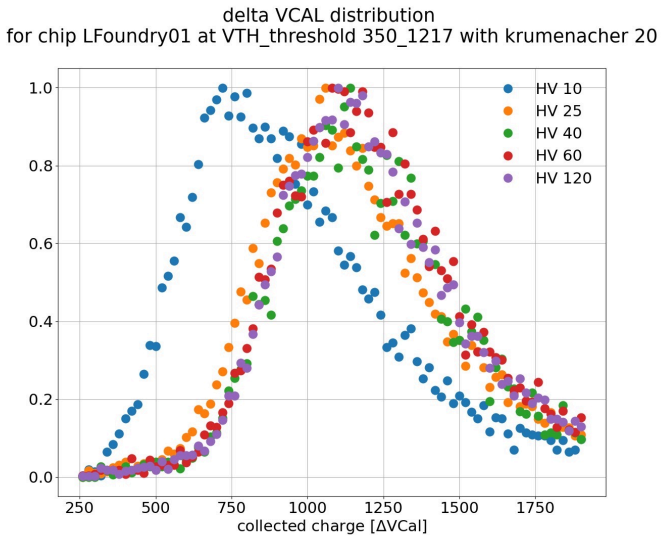
- Charge collection measurements before irradiation performed in TB and with $^{90}Sr$ scans in the lab

*Charge collection results from TB data of a not irradiated module in DESY*



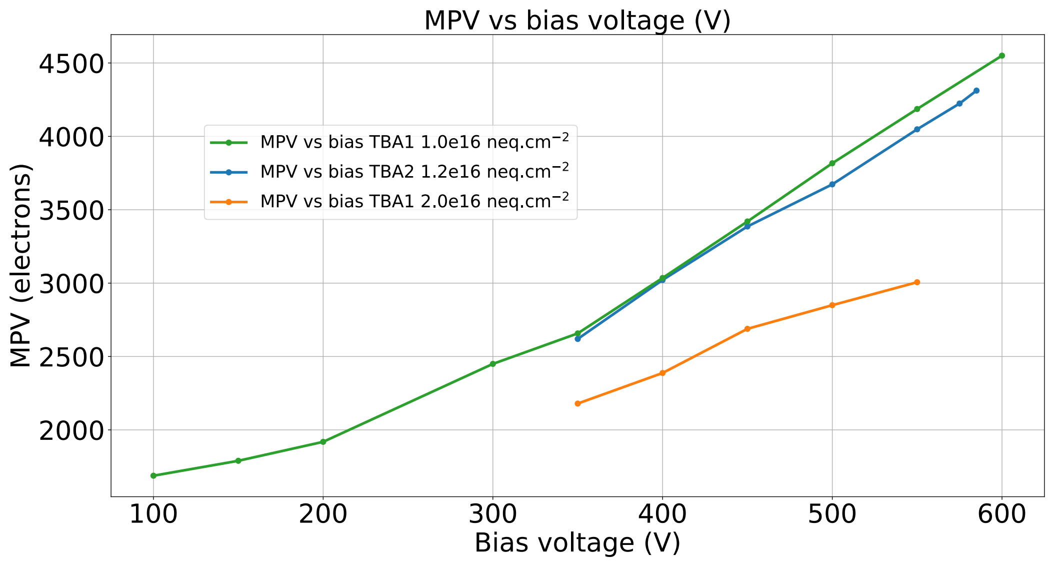

*Charge from 90Sr scan before irradiation*

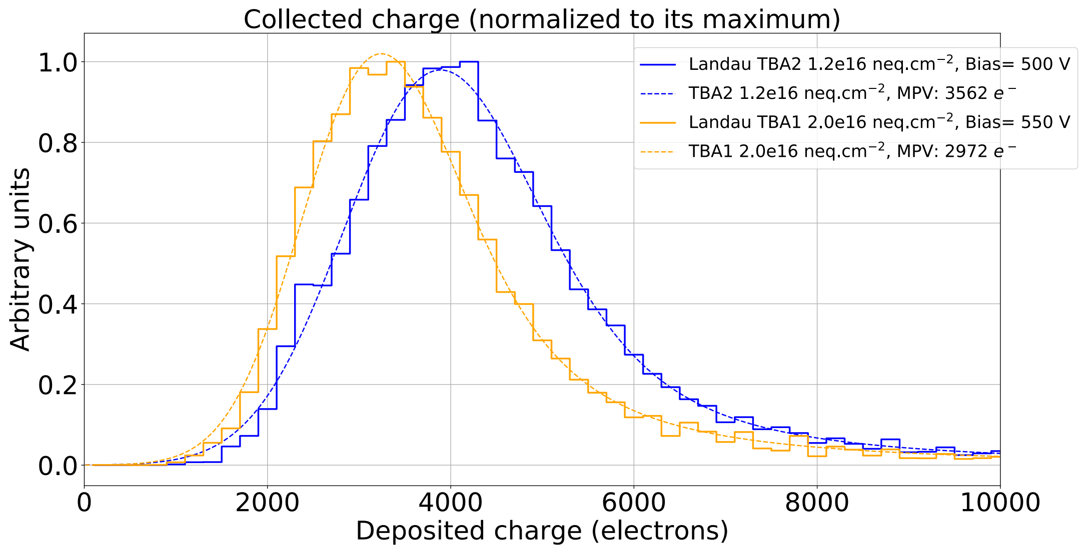


# Charge Collection Measurements (II)

- VCAL to e⁻ slope = 10.5 , offset = 260 e−
- TBA2 at $1.2\times10^{16}$ $neq.cm^{-2}$ collects nearly as much charge as TBA1 at ~ $10^{16}$ $n_{eq}.cm^{-2}$
- Lower charge collection for TBA1 at 2x $10^{16}$ $neq.cm^{-2}$

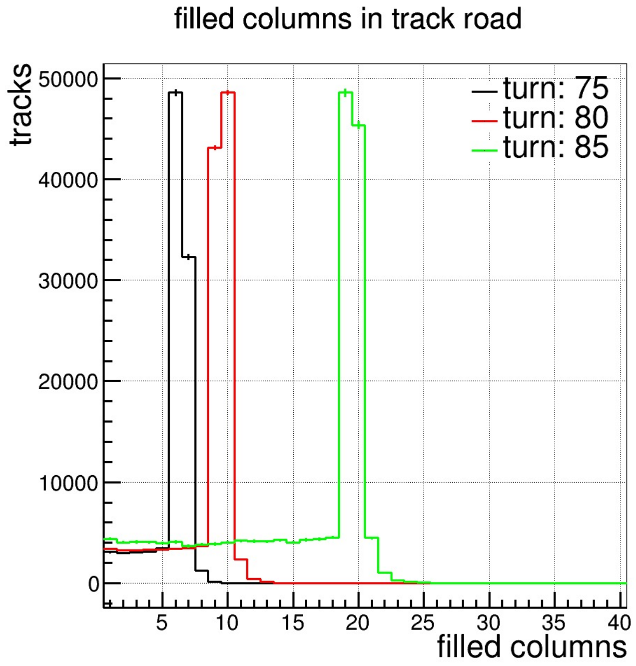
*Charge collection after irradiation at SPS TB*

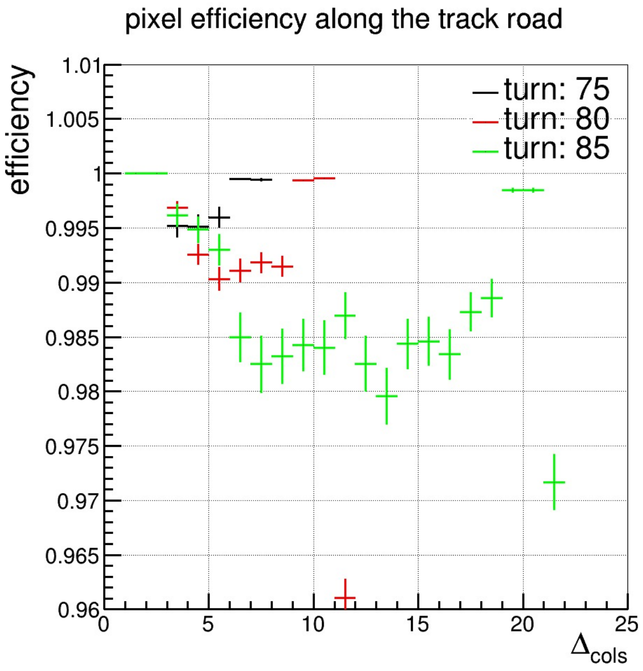


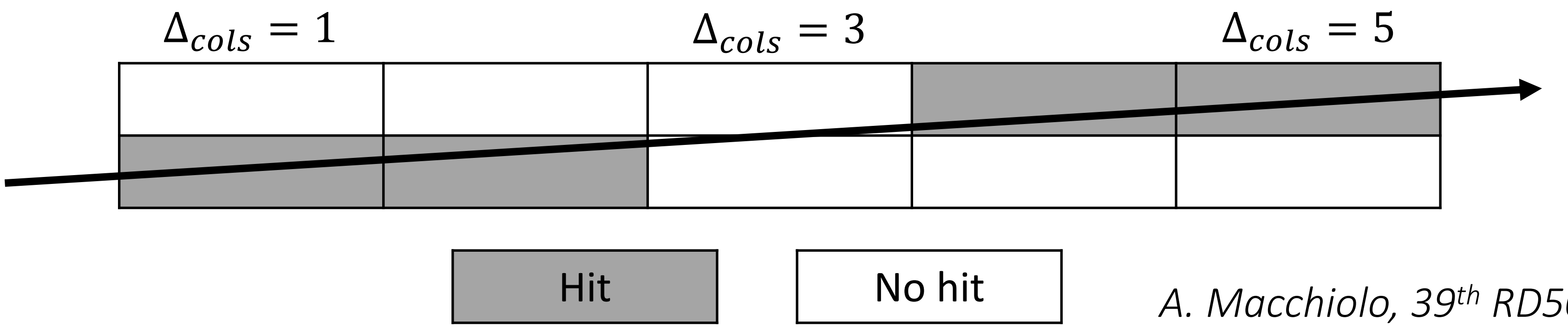



# High $\eta$ analysis

- The incident angle along $\eta$ for the first layer of the CMS inner tracker can get up to 75-85 degrees.
- Challenges like cluster breaking arise in these high angles.
- Test beam analysis strategy with LF 25 $\mu$m x100 $\mu$m single chip modules :
  - Align the DUT and telescope tracks.
  - Define a “road” with a length of $\Delta_{cols}$ in which the track passes through DUT.
  - Look for pixel hits in the DUT around the track road. For the most probable cluster length, determine pixel-to-pixel reconstruction efficiency.
- High efficiency found for all pixel positions in the cluster, to be remeasured after irradiation to validate tracking at high eta

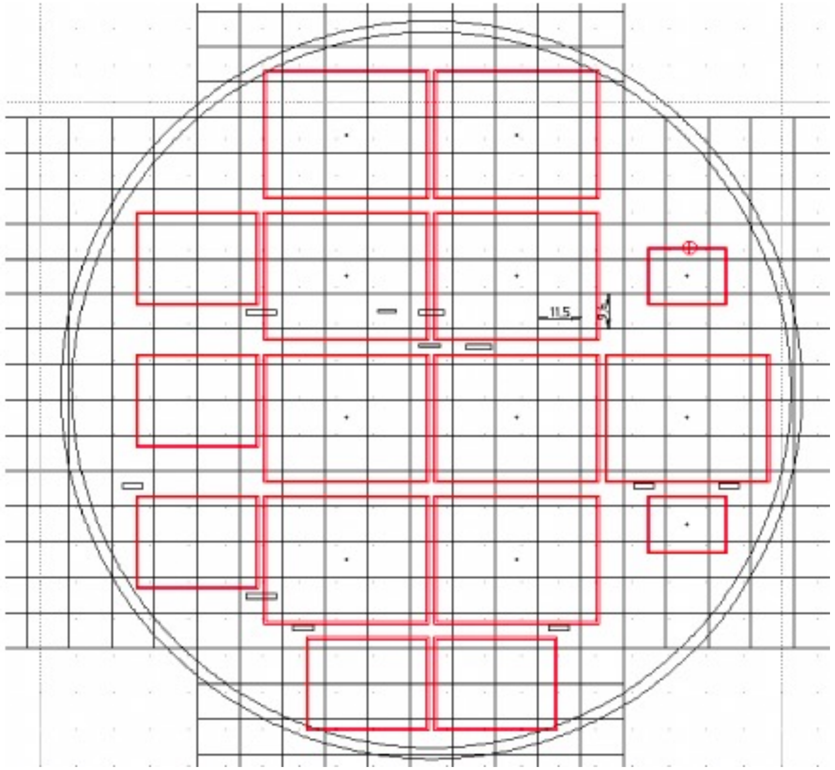


# Future plans

- Characterize more single chip and double chip RD53A modules from 2019 production, before and after irradiation
- New production being designed, GR optimization for 25x100 geometry in progress
  - CMS ROC (CROC) centric
  - Mostly quads, some singles
  - 25x100µm in a **1352 x 434 pixel matrix**
  - Test-structures between CROC quads:
    - New GR structures
    - 25x25 um$^2$ pixel matrices



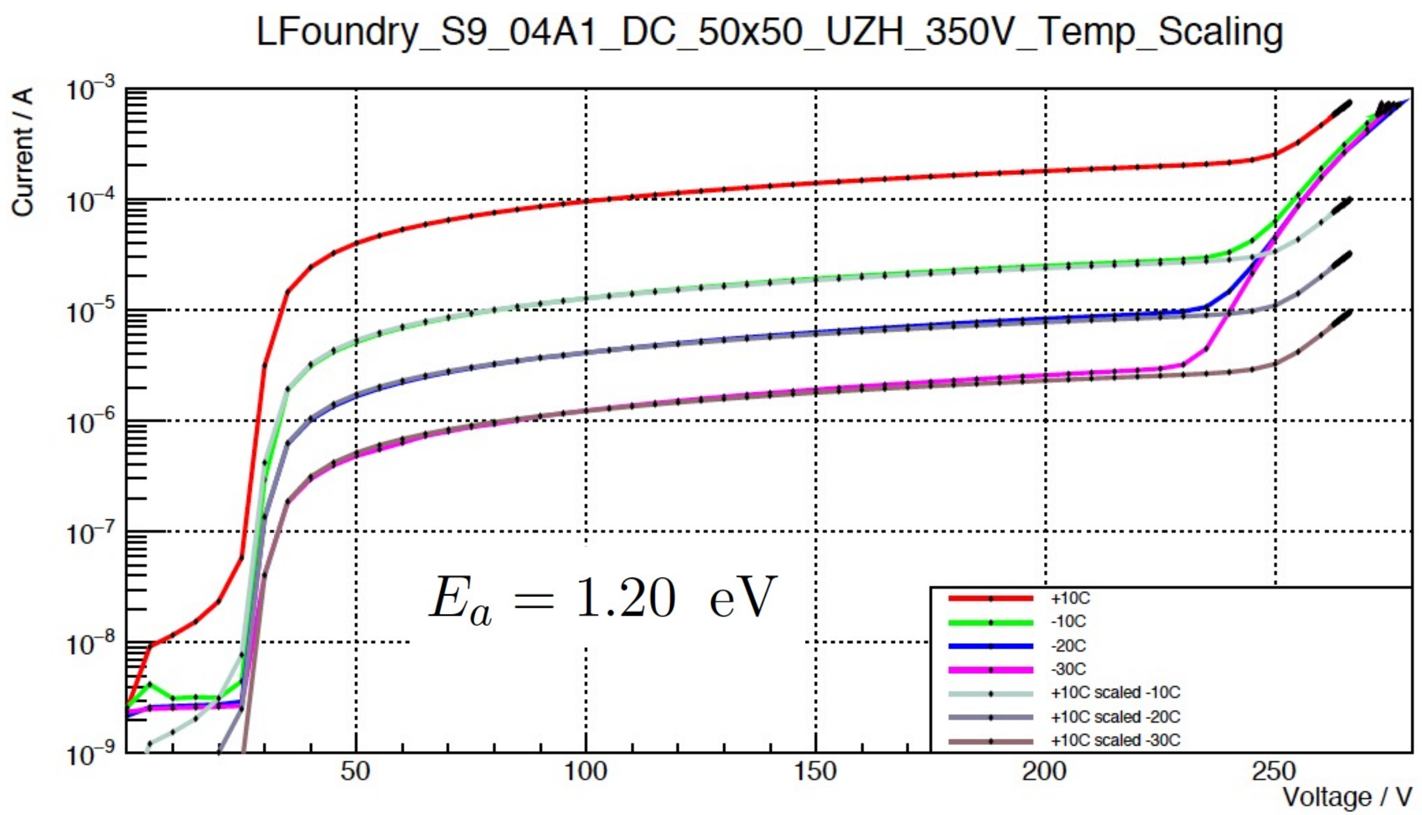
# Summary

- Small on-pixel structures in passive sensors are possible using the CMOS technology
- 2-D stitching technology does not cause degradation of the performance
- Irradiated RD53A modules with passive CMOS sensors were investigated before and after irradiation up to a fluence of 2e16 $n_{eq}$ $cm^{-2}$
- Lab and test beam measurements show comparable performance compared to standard productions.
- The use of 8” wafers could potentially reduce the production cost.

# Additional material

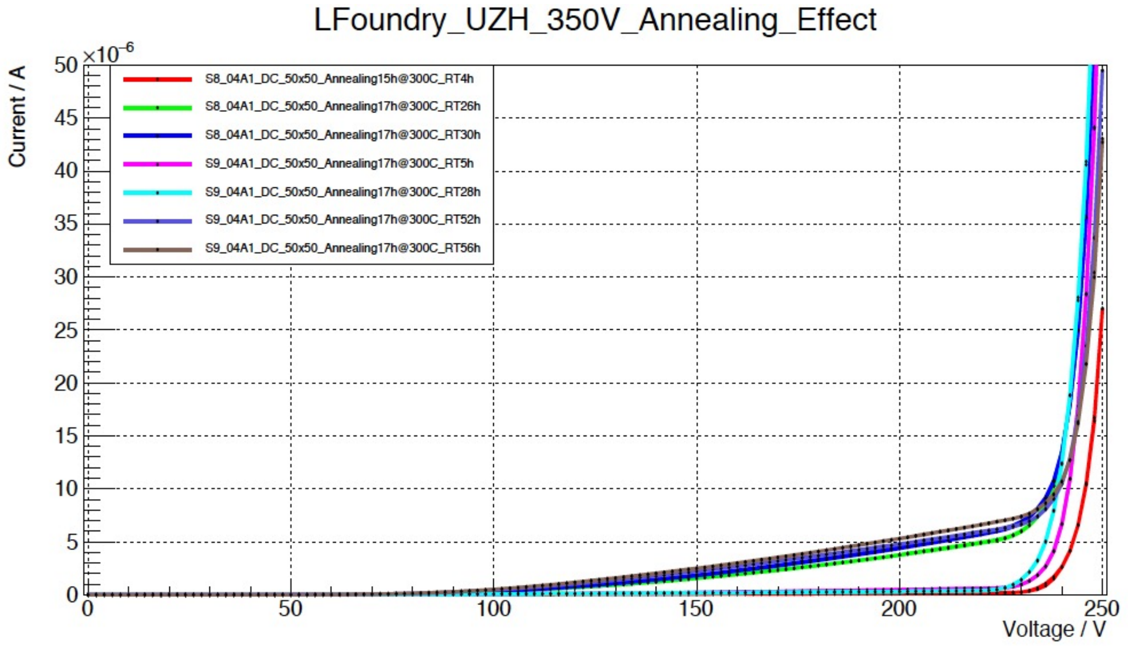
# Scaling with temperature

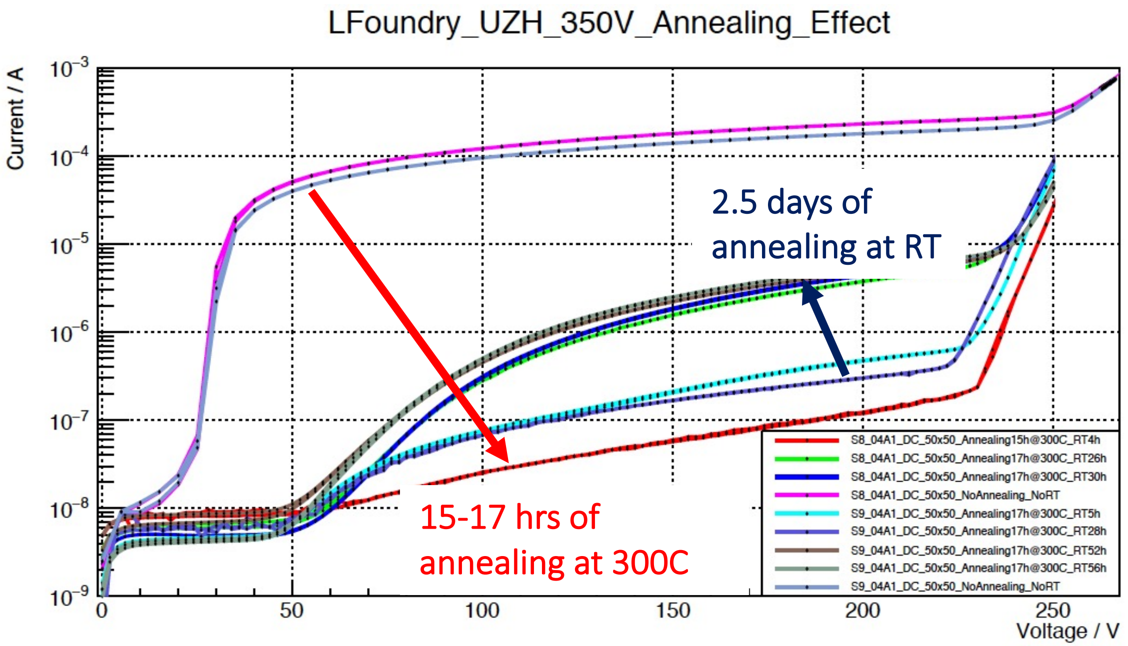
- IV taken at +10,-10,-20,-30C
- IV curve at 10C scaled to lower T using the formula for bulk generated current: $I = a\,T^2 e^{-\frac{E_a}{2K_B T}}$
- Good agreement found with data taken directly at those T
- $V_{bias}$ at which the current jumps increases at lower T and in the ramp down



# Performance after annealing

- Additional annealing over several days was tested with different times in an oven at T= 300 C

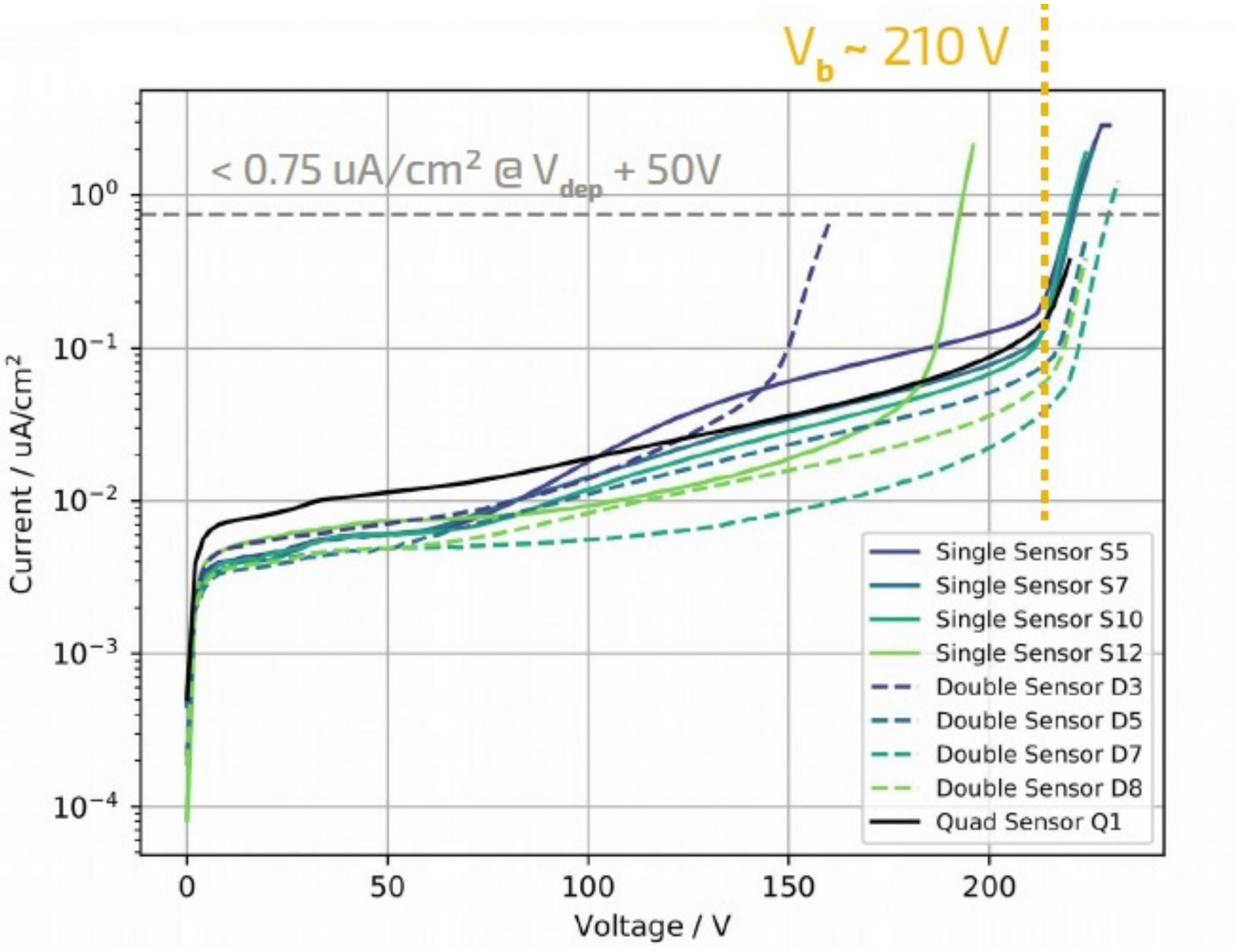


# Wafer without back-side metallization and process at LFoundry/IZM

- Wafer with no back-side metallization shows low current levels

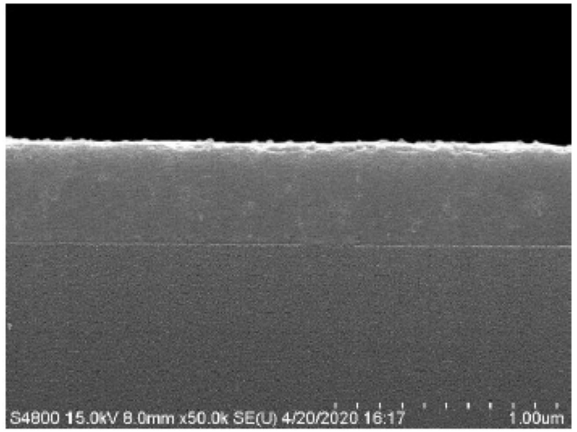
- Problems at Alu-siicon interface for other wafers?
  - Increase of the backside Boron implant dose

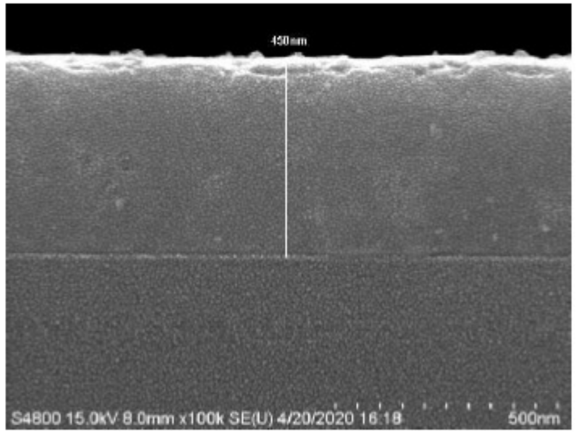



*A. Macchiolo, IT sensor Meeting, 6 October 2020*

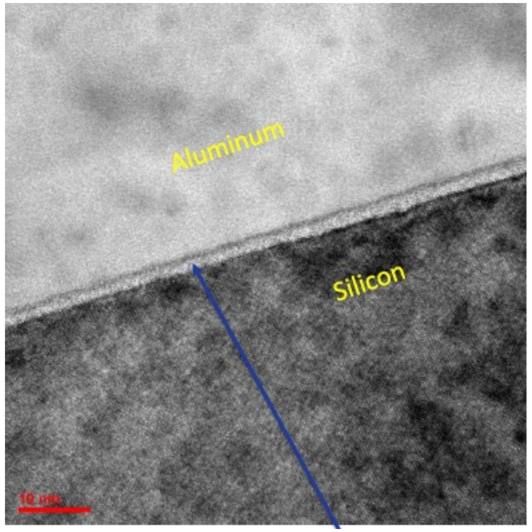
# Backside analysis

- About 450 nm metal layer on the silicon back surface
- No evidence of heavy silicon damage/cracking due to Alu spiking into silicon



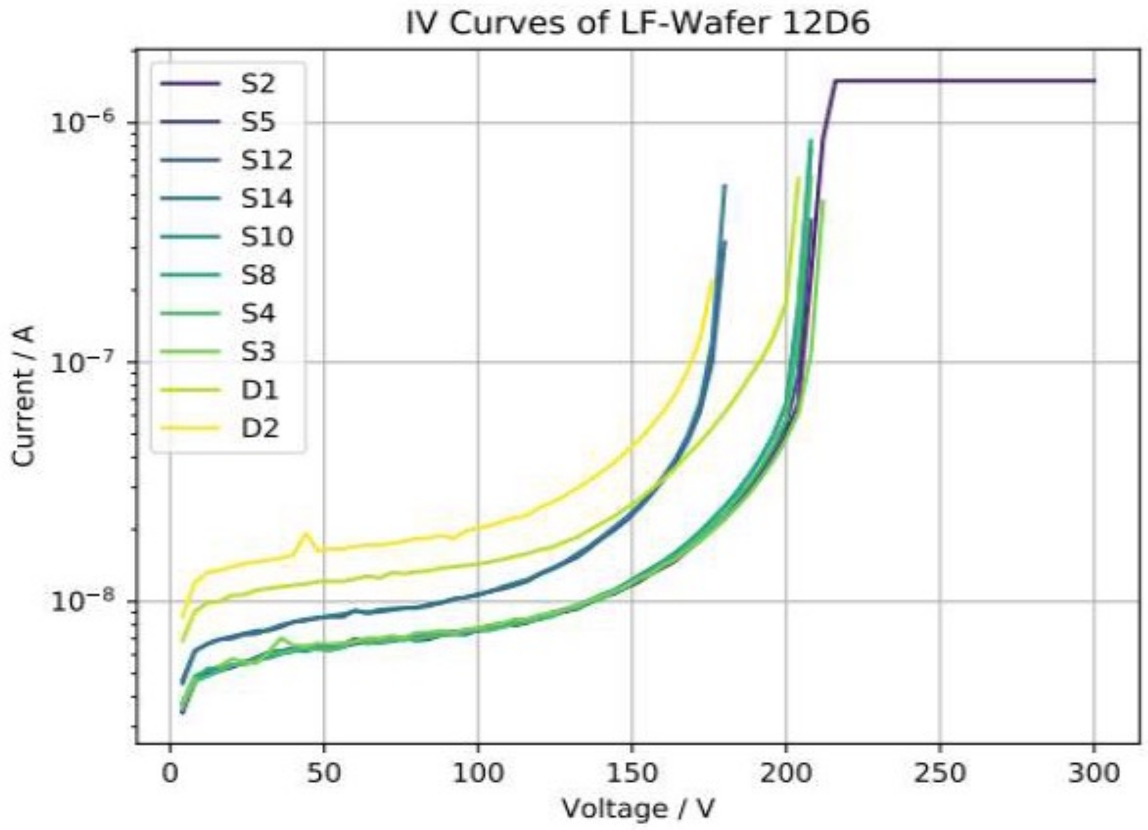




- TEM analysis: Interface layer between Silicon and Aluminum observed, likely due to silicon precipitates during the metal (AlSi) deposition process



# Wafers with higher Boron implant dose on the backside

- Two wafers received an higher Boron implant dose on the backside at LFoundry:
  - Wafer 1: 10x old dose
  - Measured directly at IZM after Alu deposition and removal of the handle wafer on the front side
  - Low leakage current level < 1 uA up to breakdown voltage

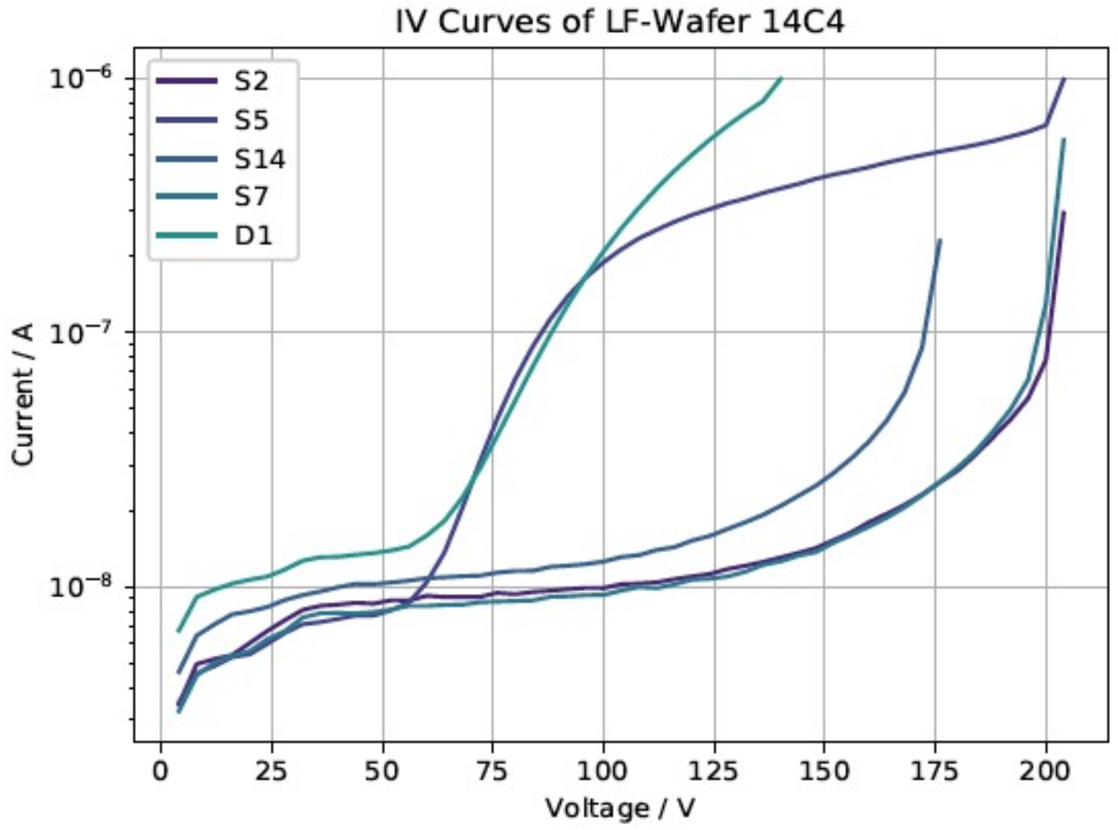



*A. Macchiolo, IT sensor Meeting, 6 October 2020*

# Wafers with higher Boron implant dose on the backside

- Two wafers received an higher Boron implant dose on the backside at LFoundry:
  - Wafer 2: 20x old dose

Demonstration of the feasibility of stitching implants and metal lines across neighboring reticule cells




*A. Macchiolo, IT sensor Meeting, 6 October 2020*