Radiation hard 3D Pixel sensors for use in ATLAS-ITk at HL-LHC

Characterization of SINTEF 3D sensors

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Presented by Simon K. Huiberts

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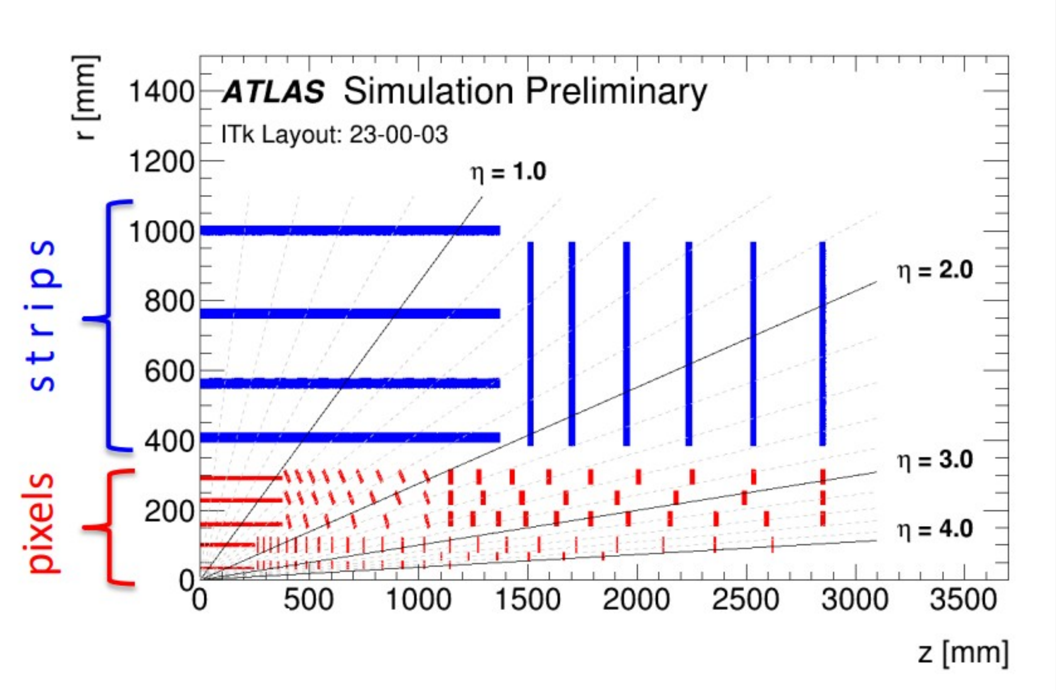
Upgrade of LHC and ATLAS

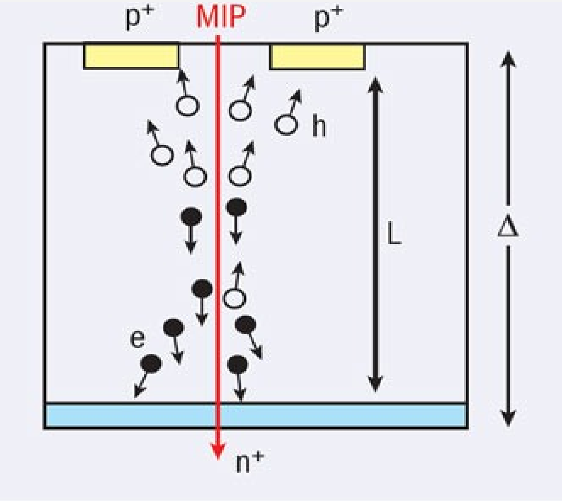
- By 2027 the High-Luminosity LHC should be completed
- An extremely challenging environment for the ATLAS tracking system:
  - Withstand large hadron fluences
  - Handle high data rates
- The Inner Detector (ID) will be replaced by a new all-silicon detector (ITk)
- Tasks of the ITk:
  - Trace particle trajectories
  - Measure momentum
  - Measure vertices of short-lived particles
  - Withstand the increased radiation dose
- To fulfil these criteria the innermost layer is planned to consist of 3D pixel sensors



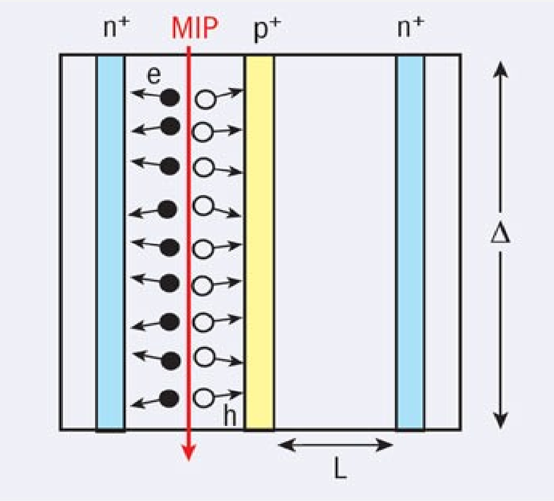
3D pixel sensor technology

- In standard planar sensors (Fig. left), the electrodes are implanted on the top and bottom surfaces of the wafer
- In 3D sensors (Fig. right) holes are etched vertically into the silicon bulk and filled with p-type and n-type electrodes
- Advantages of 3D pixel sensors:
  - Drift distance reduced - > Reduced signal loss due to charge trapping -> High radiation hardness
  - Fast response time
  - Drift distance decoupled from the sensor thickness
  - Low depletion voltage -> High electric fields easily achieved: Low power dissipation

Planar sensor design

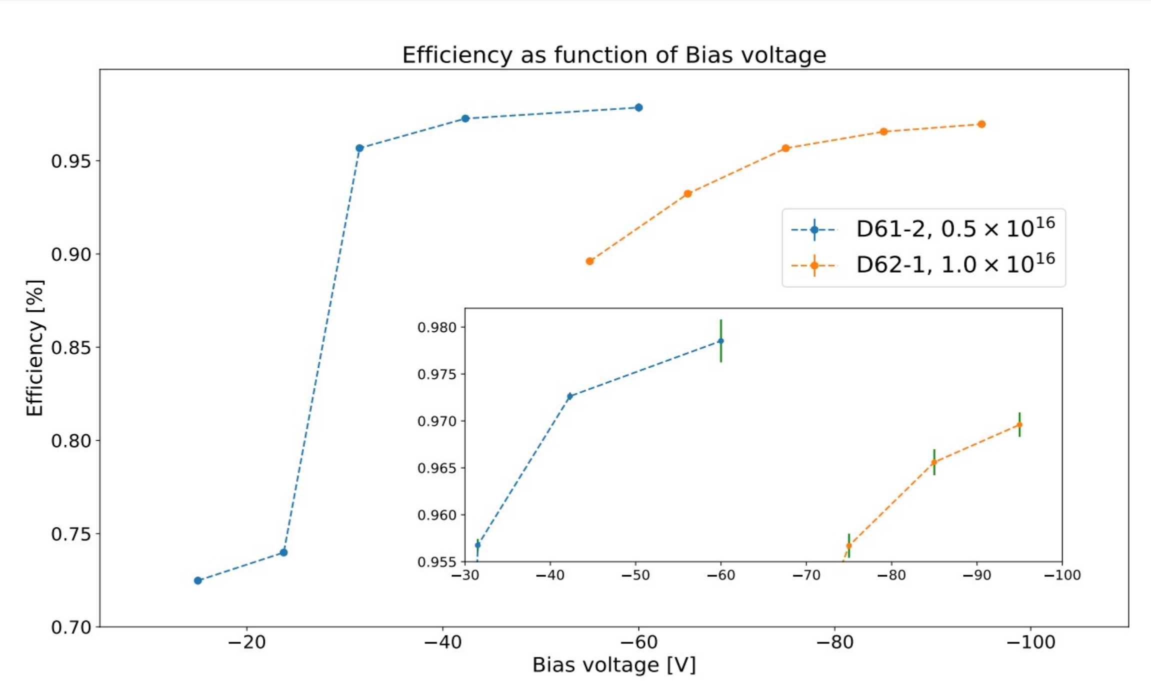


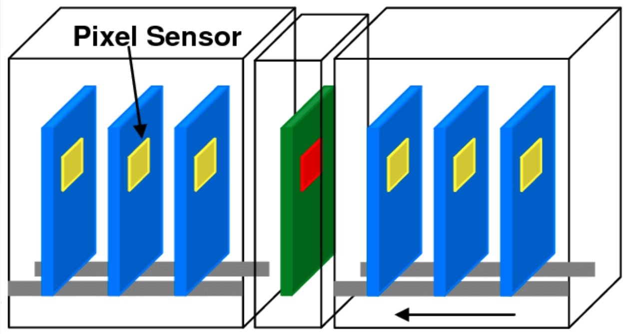
3D sensor design



Efficiency on irradiated SINTEF 3D sensors

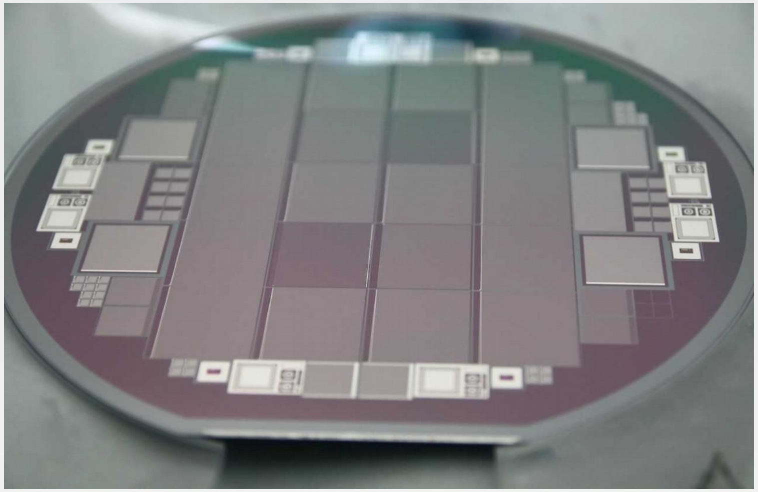
- Test beam at DESY - 4 GeV electron beam
- D61-2 module (blue line)
  - Irritated to Φ = 5 x 10^{15} $n_{eq}cm^{-2}$
  - 100 µm active thickness
  - Efficiency reached above 97% with V_{bias} = 40 V
- D62-1 module (orange line)
  - Irritated to Φ = 1 x 10^{16} $n_{eq}cm^{-2}$
  - 50 µm active thickness
  - Efficiency reached above 96.5% with V_{bias} = 80 V
- Specifications of HL-HLC reached:
  - Maintaining an efficiency of 96% with a fluence at 10^{16} $n_{eq}cm^{-2}$

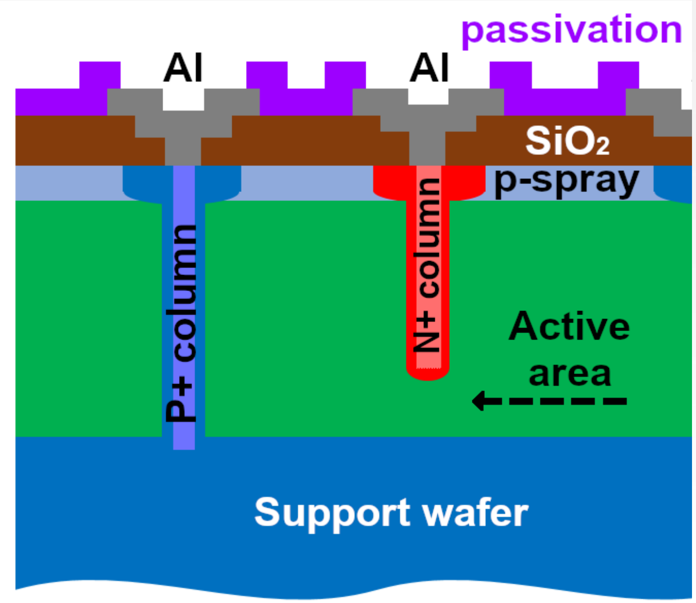




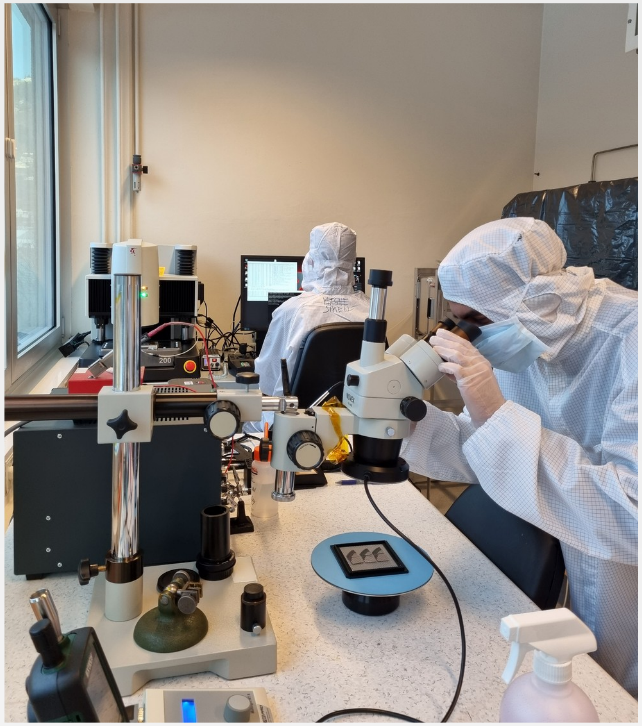
SINTEF 3D pre-production series

- SINTEF will be the tendor for 800 sensors for the ITk
- In 2021, SINTEF completed Run-6 production of 3D sensors - > ATLAS pre-production series
- Fabricated 24 wafers each with 24 sensors
  - 6'' Si-Si p-type wafer with 150 µm active thickness
- 60 main steps in the fabrication process
- SINTEF reported its results in “Trento” workshop in March 2022
- Yield between 63-75% depending on strictness
  - Better than previous runs
- Before flip-chip and mounting, the sensors needs to be tested

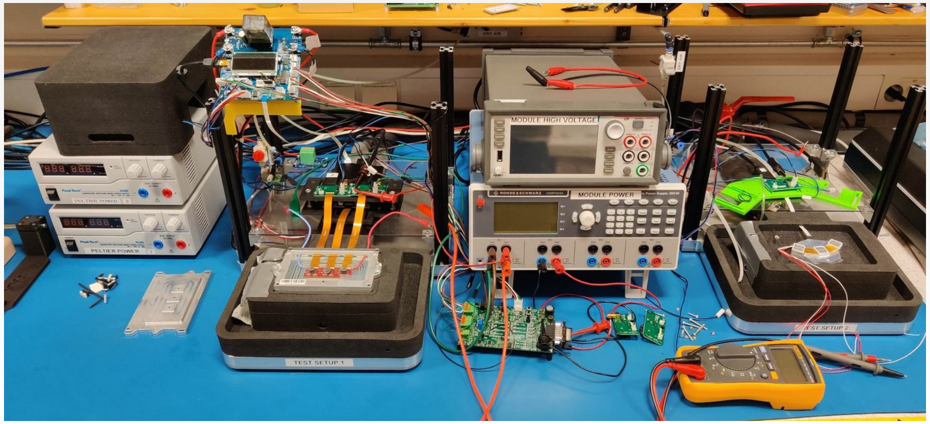




ATLAS ITk group in Bergen

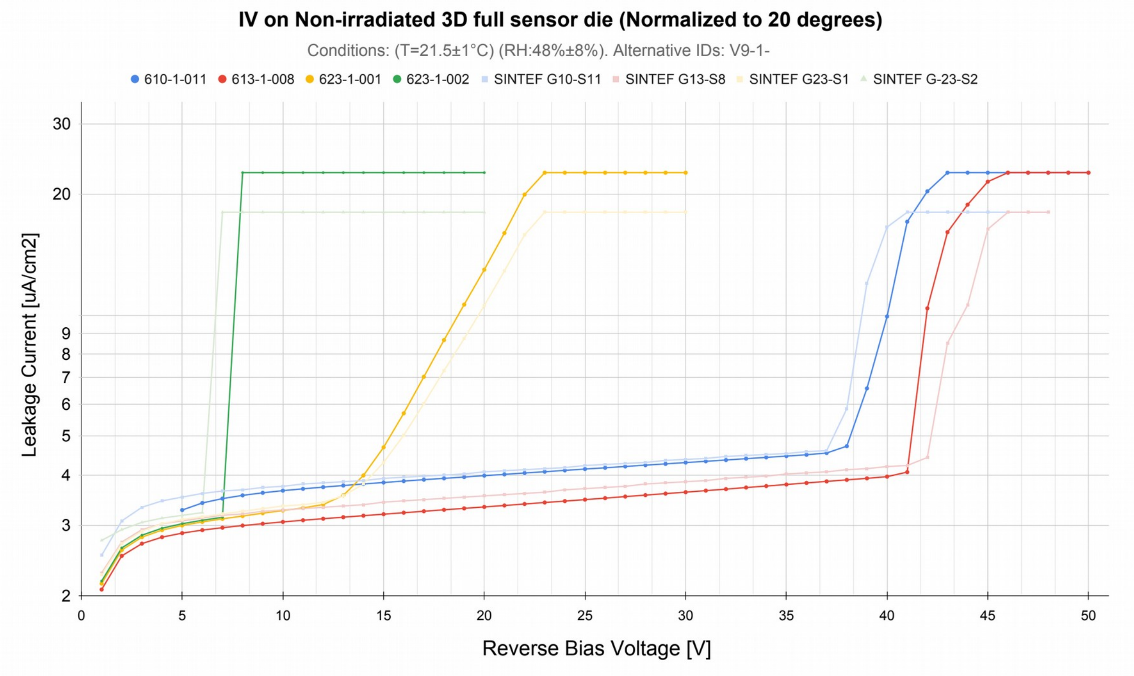


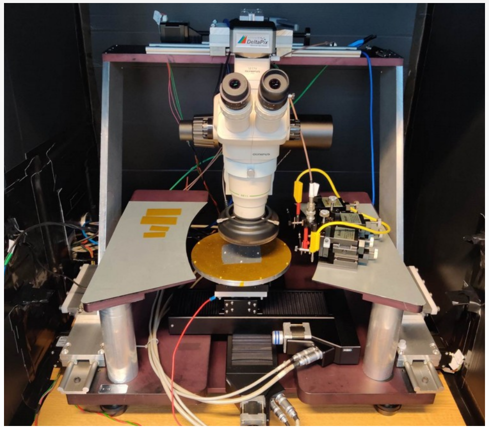
- At UiB developing a facility to test components for implementation in the ITk
- Quality assurance (QA) on pre-production components
- In future perform Quality control (QC) on production components
- Testing procedures:
  - Electrical characterization on bare 3D sensors – Mechanical probe station
  - Metrology on bare 3D and planar modules – SmartScope
- Colleges in Oslo assembly full modules and ship them to Bergen
  - Test fully assembled 3D modules – Complete test setup w/DAQ software
- Next slide show results from electrical testing

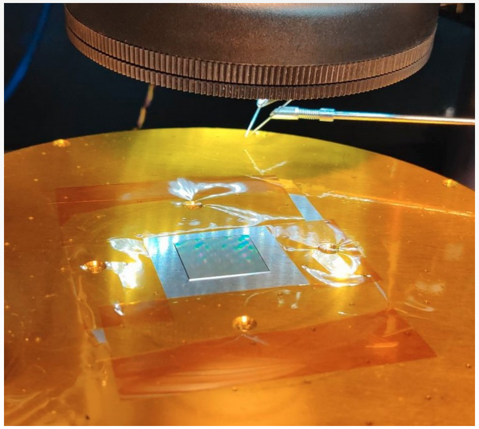


Electrical testing on pre-production SINTEF 3D sensors

- IV (current–voltage curve) on four non-irradiated full sensor samples from SINTEF
- Measured with a mechanical probe station build inside a clean room
- IV showed two sensors with an early breakdown (green and yellow)
- Two sensors with breakdown late breakdown (blue and red)
- Good agreement with results obtained by SINTEF (faded lines)
- Able to successfully test ITk sensor samples with the probe station







Summary

Background

- High-Luminosity LHC leads to a challenging environment for the ATLAS tracking system
- Use radiation hard 3D pixel sensors at the innermost layer
- UiB building a facility to test planar and 3D sensor components for implementation in the Inner Tracker (ITk)

Results

- Test beam results on 3D silicon sensors from run 4 shows high radiation hardness
- Irritated modules had an efficiency above 96% after $\Phi = 5\text{-}\ 10 \times 10^{15}\ n_{eq}/cm^2$

- The 6th run of 3D detectors at SINTEF MiNaLab has been completed
  - This will be the final production design for the 3D sensors at ITk
- At Bergen, just started to test sensors from Run 6
  - Preliminary results from electrical testing shows good agreement with measurements done at SINTEF

Thank you for your attention!

ATLAS EXPERIMENT

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Backup

Figure on slide 2: Technical Design Report for the ATLAS Inner Tracker Strip Detector CERN-LHCC-2017-004. ATLAS-TDR-025, April 2017

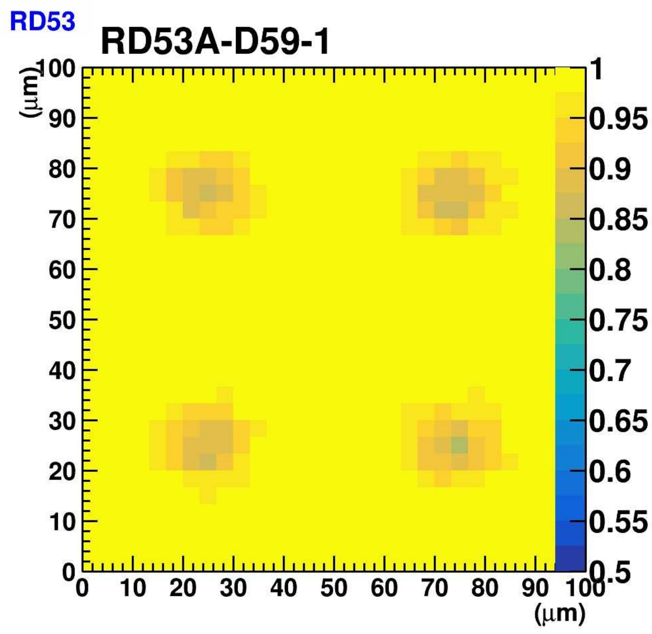
Figure on slide 3: 3D Silicon Sensors: Design, Large area production and Quality Assurance for Pixel Detector Upgrades at the Large Hadron Collider NIMA-S-12 0028

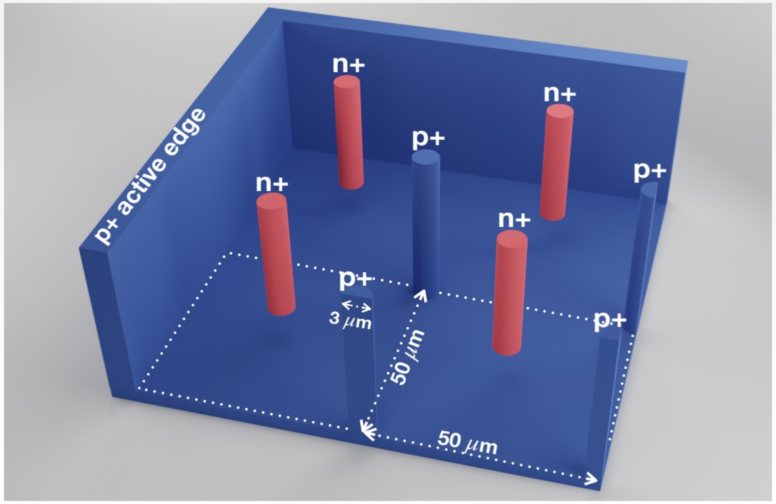
Figure 7: Hu Guo. A ten thousand frames per second readout MAPS for the EUDET beam telescope, (2009).

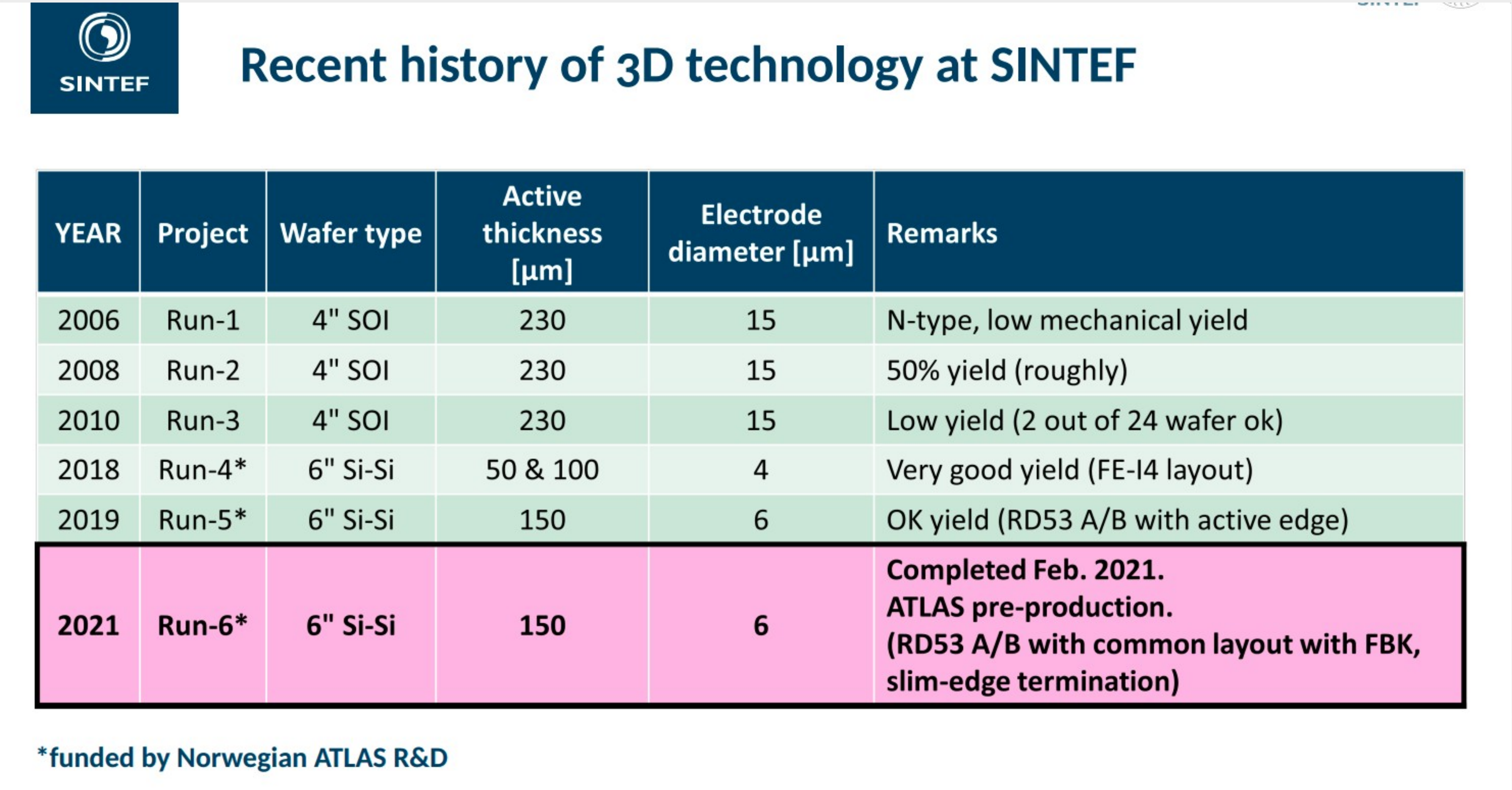
Acknowledgment: The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

Efficiency map on non-irradiated SINTEF 3D sensor

- Efficiency map from test beam at CERN
- Measured in 180 GeV pion test beam:
  - Pointing resolution of 5 µm
- D59-1 module
  - Non-irradiated sensor
  - 100 µm active thickness
  - 50 µm x 50 µm pixel size
- Plot shows an efficiency map averaged over 2x2 pixels
- Overall efficiency was 98.6% at V_{bias} = 10 V
- Inefficient regions visible due to the p+ electrodes
- Consisted with the pointing resolution of the reconstructed track







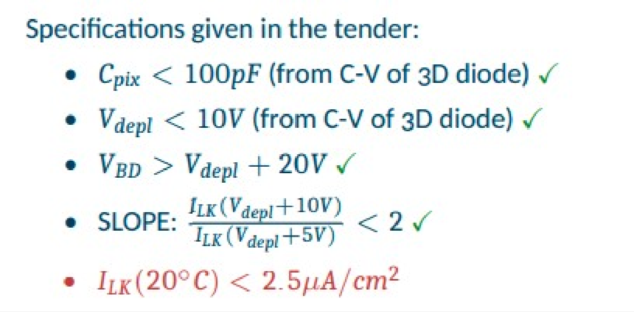
Recent history of 3D technology at SINTEF

YEAR	Project	Wafer type	Active thickness [μm]	Electrode diameter [μm]	Remarks
2006	Run-1	4" SOI	230	15	N-type, low mechanical yield
2008	Run-2	4" SOI	230	15	50% yield (roughly)
2010	Run-3	4" SOI	230	15	Low yield (2 out of 24 wafer ok)
2018	Run-4*	6" Si-Si	50 & 100	4	Very good yield (FE-I4 layout)
2019	Run-5*	6" Si-Si	150	6	OK yield (RD53 A/B with active edge)
2021	**Run-6***	**6" Si-Si**	**150**	**6**	**Completed Feb. 2021.** **ATLAS pre-production.** **(RD53 A/B with common layout with FBK, slim-edge termination)**

***funded by Norwegian ATLAS R&D**

Marco Povoli at ”Trento” Workshop on Advanced Silicon Radiation Detectors

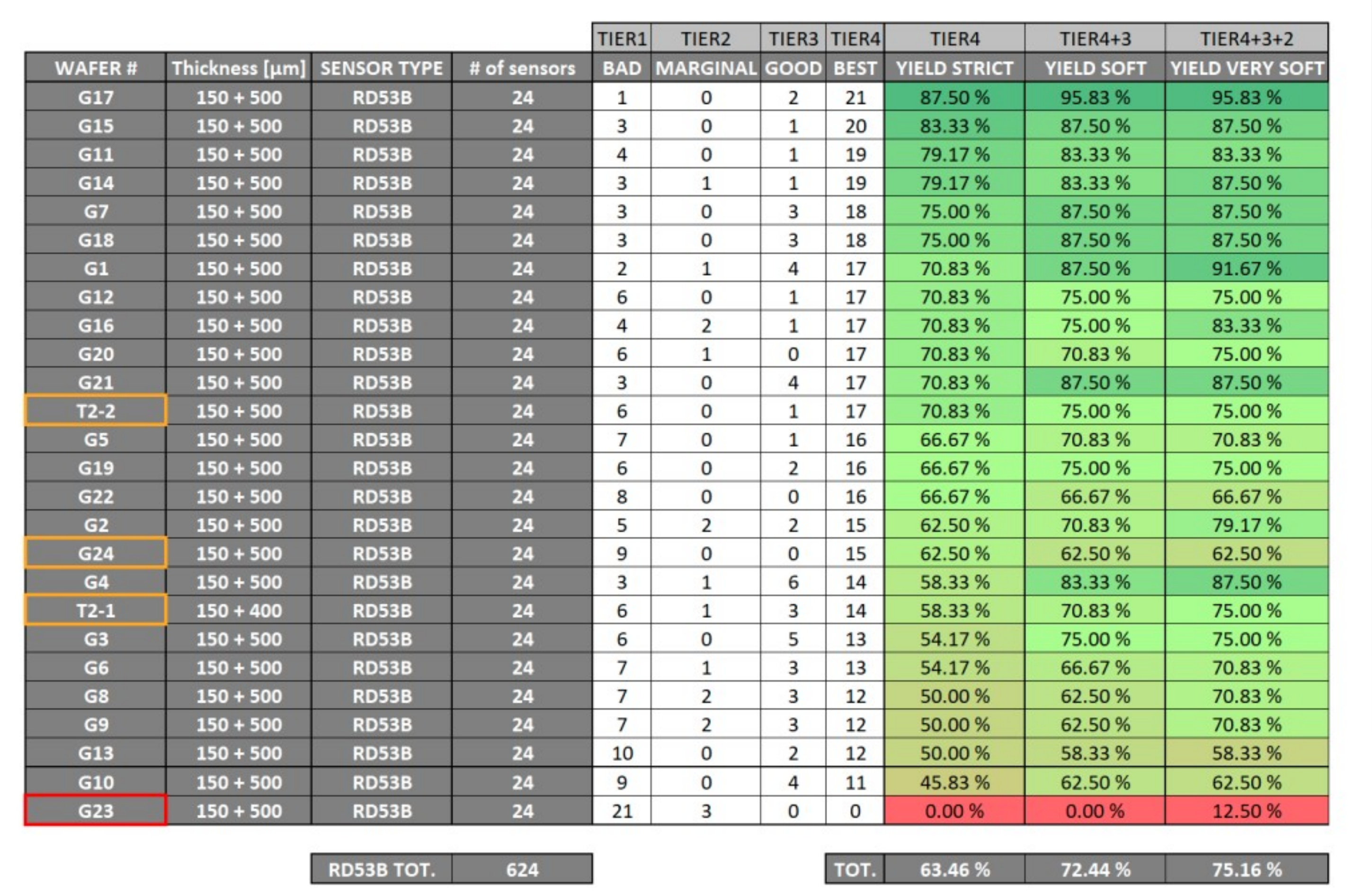
Selection criteria for yield calculation



Specifications given in the tender:

- $C_{pix} < 100pF$ (from C-V of 3D diode) ✓
- $V_{depl} < 10V$ (from C-V of 3D diode) ✓
- $V_{BD} > V_{depl} + 20V$ ✓
- SLOPE: $\frac{I_{LK}(V_{depl}+10V)}{I_{LK}(V_{depl}+5V)} < 2$ ✓
- $I_{LK}(20°C) < 2.5\mu A/cm^2$

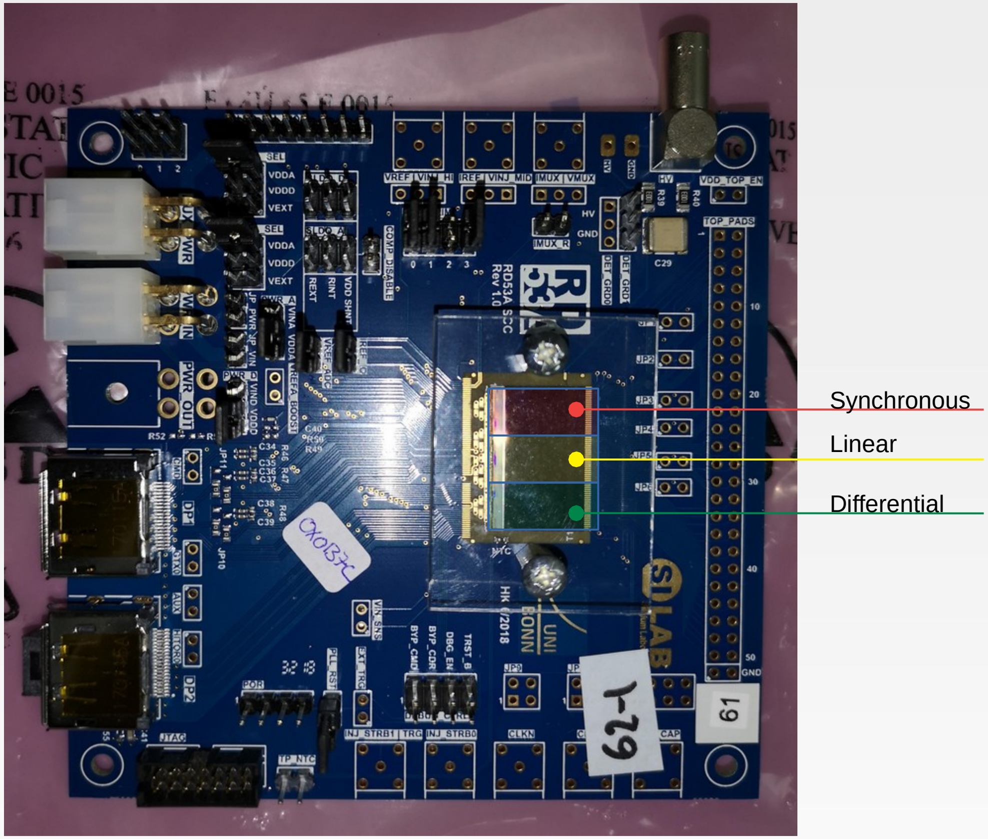
Marco Povoli at ”Trento” Workshop on Advanced Silicon Radiation Detectors



				TIER1	TIER2	TIER3	TIER4	TIER4	TIER4+3	TIER4+3+2
WAFER #	Thickness [µm]	SENSOR TYPE	# of sensors	BAD	MARGINAL	GOOD	BEST	YIELD STRICT	YIELD SOFT	YIELD VERY SOFT
G17	150 + 500	RD53B	24	1	0	2	21	87.50 %	95.83 %	95.83 %
G15	150 + 500	RD53B	24	3	0	1	20	83.33 %	87.50 %	87.50 %
G11	150 + 500	RD53B	24	4	0	1	19	79.17 %	83.33 %	83.33 %
G14	150 + 500	RD53B	24	3	1	1	19	79.17 %	83.33 %	87.50 %
G7	150 + 500	RD53B	24	3	0	3	18	75.00 %	87.50 %	87.50 %
G18	150 + 500	RD53B	24	3	0	3	18	75.00 %	87.50 %	87.50 %
G1	150 + 500	RD53B	24	2	1	4	17	70.83 %	87.50 %	91.67 %
G12	150 + 500	RD53B	24	6	0	1	17	70.83 %	75.00 %	75.00 %
G16	150 + 500	RD53B	24	4	2	1	17	70.83 %	75.00 %	83.33 %
G20	150 + 500	RD53B	24	6	1	0	17	70.83 %	70.83 %	75.00 %
G21	150 + 500	RD53B	24	3	0	4	17	70.83 %	87.50 %	87.50 %
T2-2	150 + 500	RD53B	24	6	0	1	17	70.83 %	75.00 %	75.00 %
G5	150 + 500	RD53B	24	7	0	1	16	66.67 %	70.83 %	70.83 %
G19	150 + 500	RD53B	24	6	0	2	16	66.67 %	75.00 %	75.00 %
G22	150 + 500	RD53B	24	8	0	0	16	66.67 %	66.67 %	66.67 %
G2	150 + 500	RD53B	24	5	2	2	15	62.50 %	70.83 %	79.17 %
G24	150 + 500	RD53B	24	9	0	0	15	62.50 %	62.50 %	62.50 %
G4	150 + 500	RD53B	24	3	1	6	14	58.33 %	83.33 %	87.50 %
T2-1	150 + 400	RD53B	24	6	1	3	14	58.33 %	70.83 %	75.00 %
G3	150 + 500	RD53B	24	6	0	5	13	54.17 %	75.00 %	75.00 %
G6	150 + 500	RD53B	24	7	1	3	13	54.17 %	66.67 %	70.83 %
G8	150 + 500	RD53B	24	7	2	3	12	50.00 %	62.50 %	70.83 %
G9	150 + 500	RD53B	24	7	2	3	12	50.00 %	62.50 %	70.83 %
G13	150 + 500	RD53B	24	10	0	2	12	50.00 %	58.33 %	58.33 %
G10	150 + 500	RD53B	24	9	0	4	11	45.83 %	62.50 %	62.50 %
G23	150 + 500	RD53B	24	21	3	0	0	0.00 %	0.00 %	12.50 %
		RD53B TOT.	624				TOT.	63.46 %	72.44 %	75.16 %

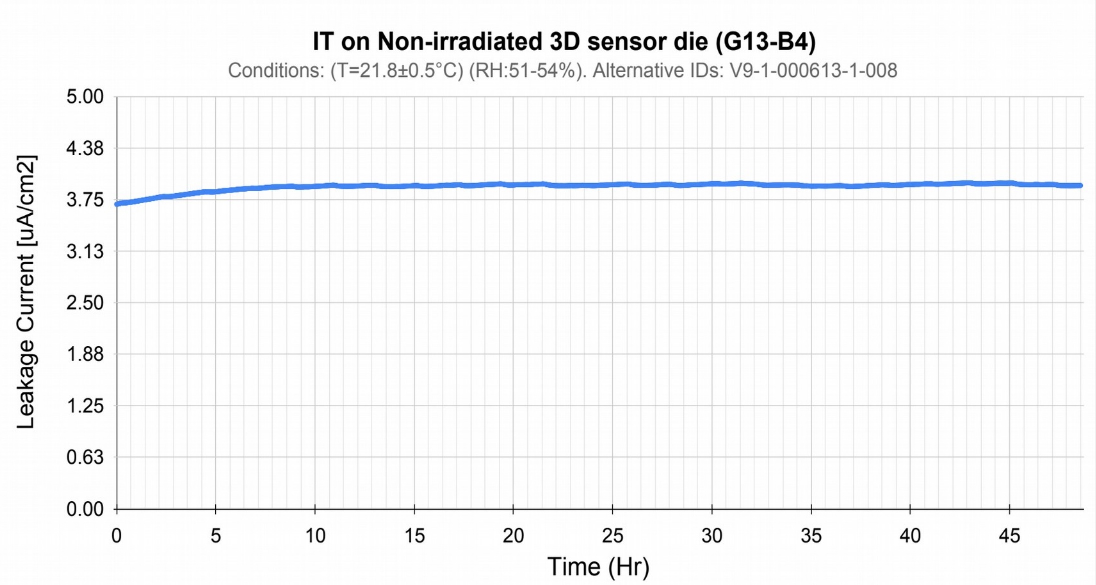
RD53A chip

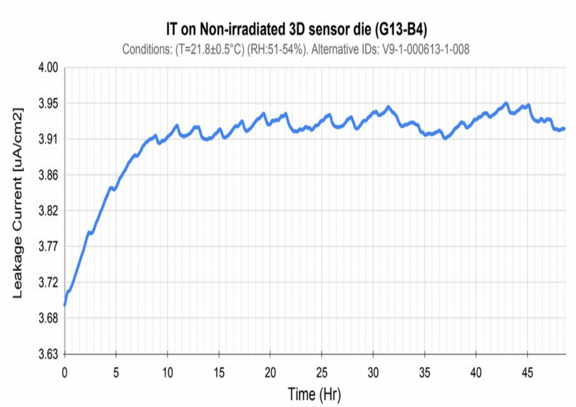
- Designed by the RD53 collaboration:
  - 20 institutions with the support of both ATLAS and CMS experiments
- Prototype ASIC developed for testing purposes
- Front end with three per-amplifier designs:
  - Synchronous
  - Linear
  - Differential
- Results shown are on the Differential Front-end

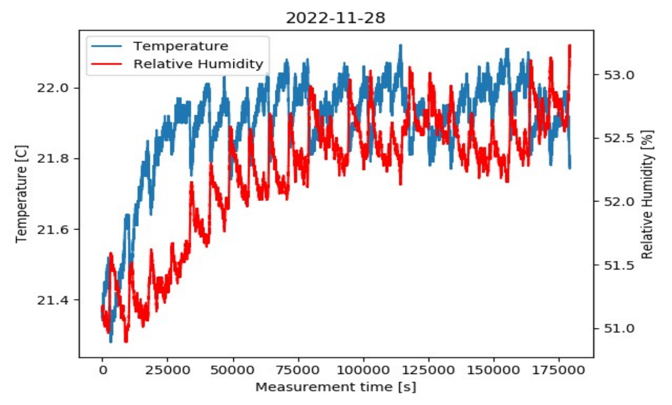


IT on G13-B4 full sensor die

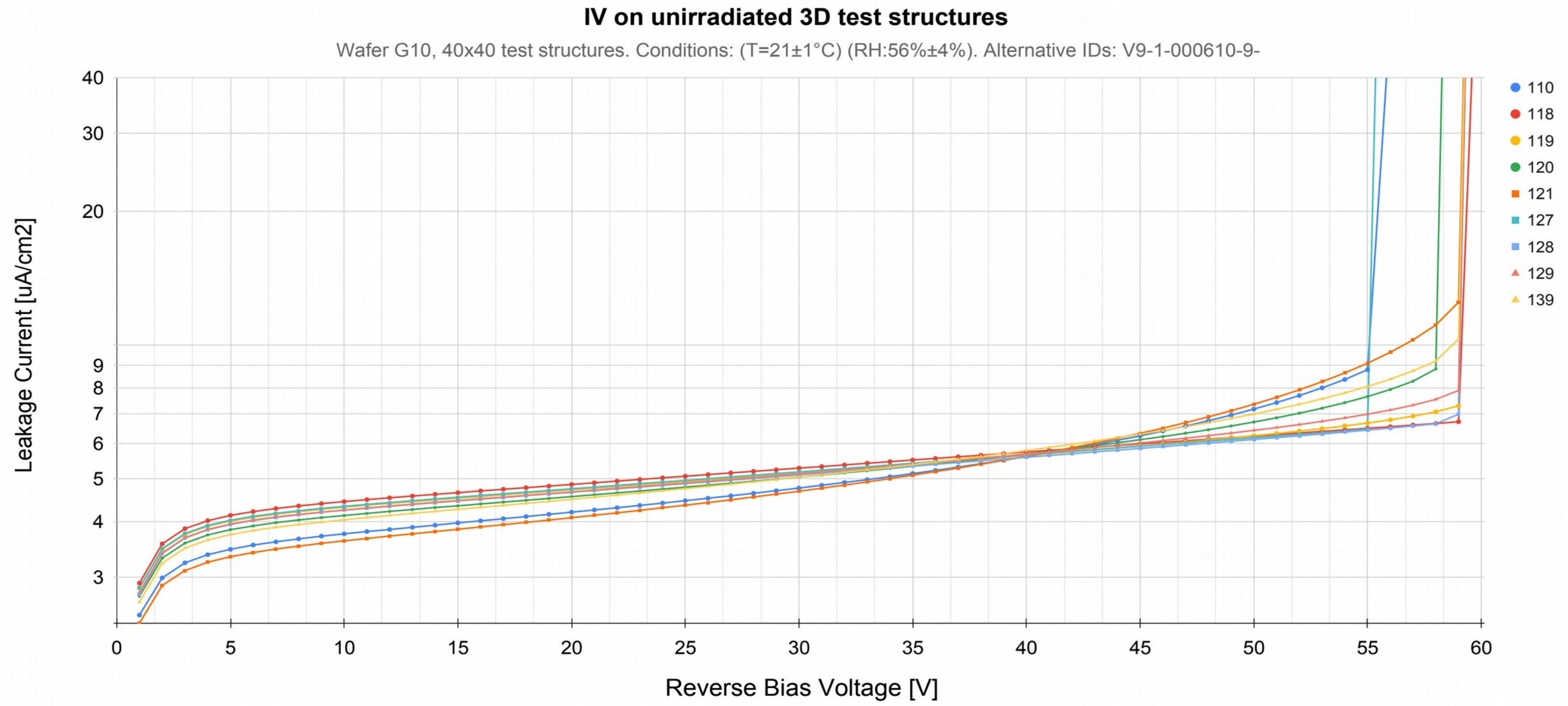
- ID: V9-1-000613-1-008
- 48 hours IT
    - Logging humidity and temperature
- Variations well within specification
    - Specifications 25%
    - Observed fluctuations at 6 %
- Zoomed in on Y-axis
    - IT follows the temperature
    - Rises the first ~ 13 hours
    - Small oscillations







IV on G10-F6 40x40 test structures

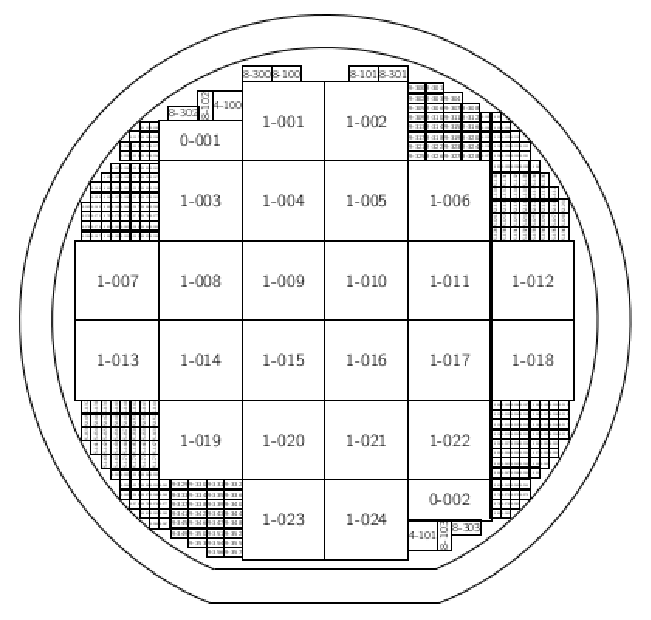


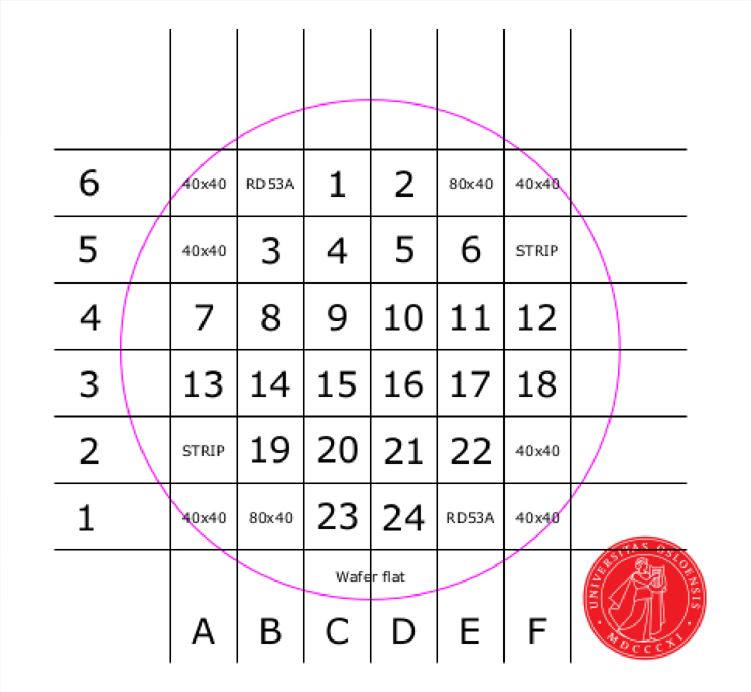
IV on unirradiated 3D test structures

Wafer G10, 40x40 test structures. Conditions: (T=21±1°C) (RH:56%±4%). Alternative IDs: V9-1-000610-9-

- V9-1-00610-9-(110-139): 9 in total
- Leakage current at ~ 4-5 µA/cm^2 at 25 V
- Depletion at 5 V
- Breakdown at 55 – 59 V (well above specification at 25 V)
- Intersect at ~ 40 V
- Data indicates some geographical dependent characteristics of the IV
- Ongoing study

Wafer layout





6	40x40	RD53A	1	2	80x40	40x40
5	40x40	3	4	5	6	STRIP
4	7	8	9	10	11	12
3	13	14	15	16	17	18
2	STRIP	19	20	21	22	40x40
1	40x40	80x40	23	24	RD53A	40x40
	A	B	C	D	E	F

Wafer flat

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