Full-size passive CMOS sensors for radiation tolerant hybrid pixel detectors

RD50 Meeting, 21.06.2021

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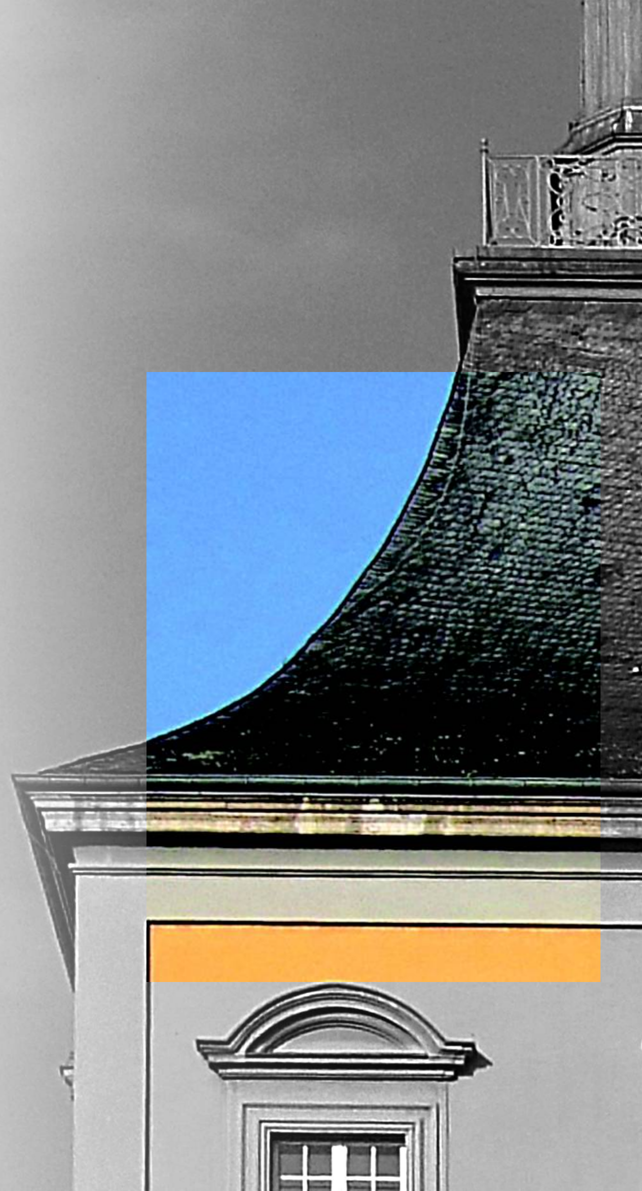

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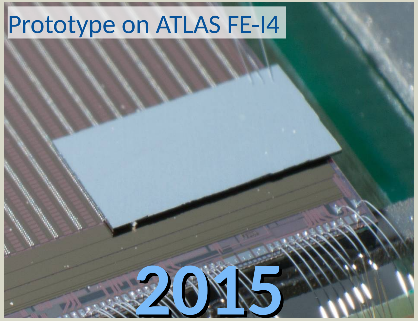
PASSIVE CMOS SENSORS USING LFOUNDRY PROCESS

Large pixel prototype

- 50 x 250 um² pixels, ATLAS IBL planar geometry
- Performance comparable to ATLAS IBL sensors after irradiation > 1 x 10^{15} neq/cm²
- Investigation of AC-coupling schema, pixel biasing schemes (bias dot vs. resistor biasing)

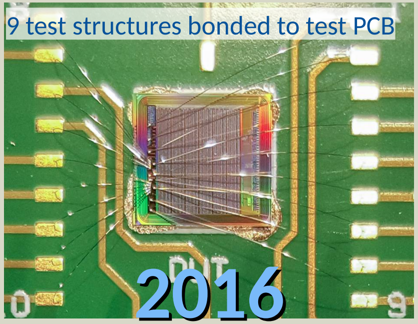
Prototype on ATLAS FE-I4



Test structures

- Many structures produced (> 15)
- Varying designs: guard rings, pixel isolation, implantation geometries
- Investigations of break down with TID (2 master theses)
  → Identified enhanced guard ring structure
- Investigation of sensor capacitances (2 bachelor theses)

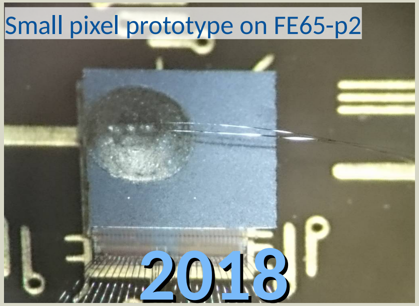
9 test structures bonded to test PCB



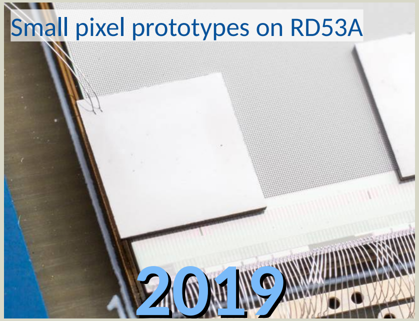
Small pixel prototype

- 50 x 50 um² pixels, ATLAS ITk pixel geometry

Small pixel prototype on FE65-p2

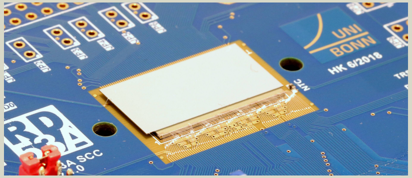


Small pixel prototypes on RD53A

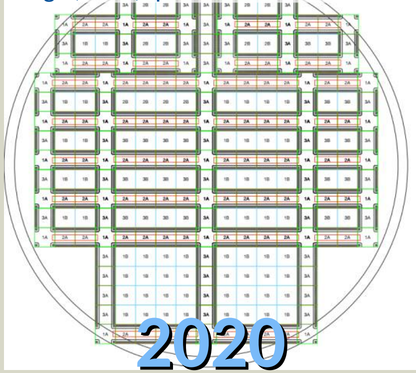


Sensor for ATLAS ITk modules

- 50 x 50 um² and 25 x 100 um² pixels
- Full-size ATLAS ITk pixel modules
- RD53A and RD53B compatible



Single, dual, quad module sensors



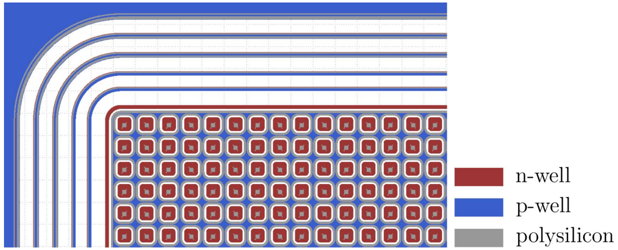
From D.-L. Pohl Trento 2020

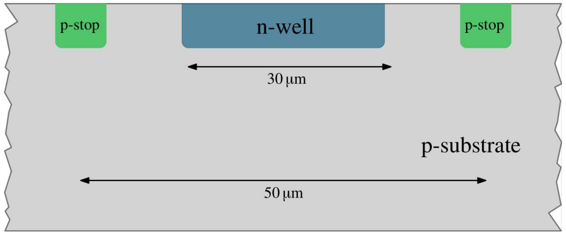
Byproducts of DMAPS efforts

This talk — Dedicated design

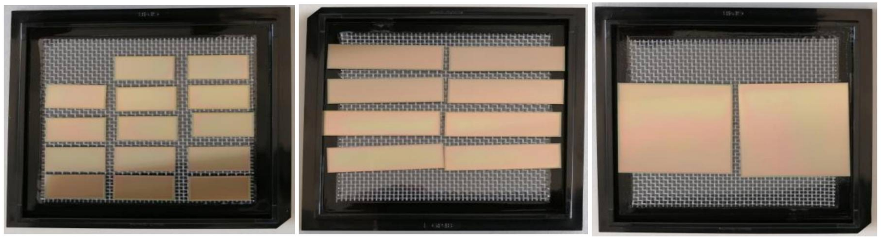
OVERVIEW: FULL-SIZE ITK SUBMISSION

- Passive CMOS pixel sensor in 150 nm LFoundry technology for ATLAS-ITk/CMS
- Float-Zone wafers: 7 - 8 kΩcm resistivity
- 150 um thick, incl. etching, backside implantation and metallization
- Reticle stitching used in order to obtain large sensors
- RD53-sized:
  - RD53A single/double sensors and RD53B quad sensors
- Different pixel designs:
  - 50 x 50 um^2 and 25 x 100 um^2 pixels
  - Poly-silicon as bias resistor (R_{bias} ~4.6 MΩ)
  - DC- or AC-coupled sensors (C_{AC} ~560 fF)



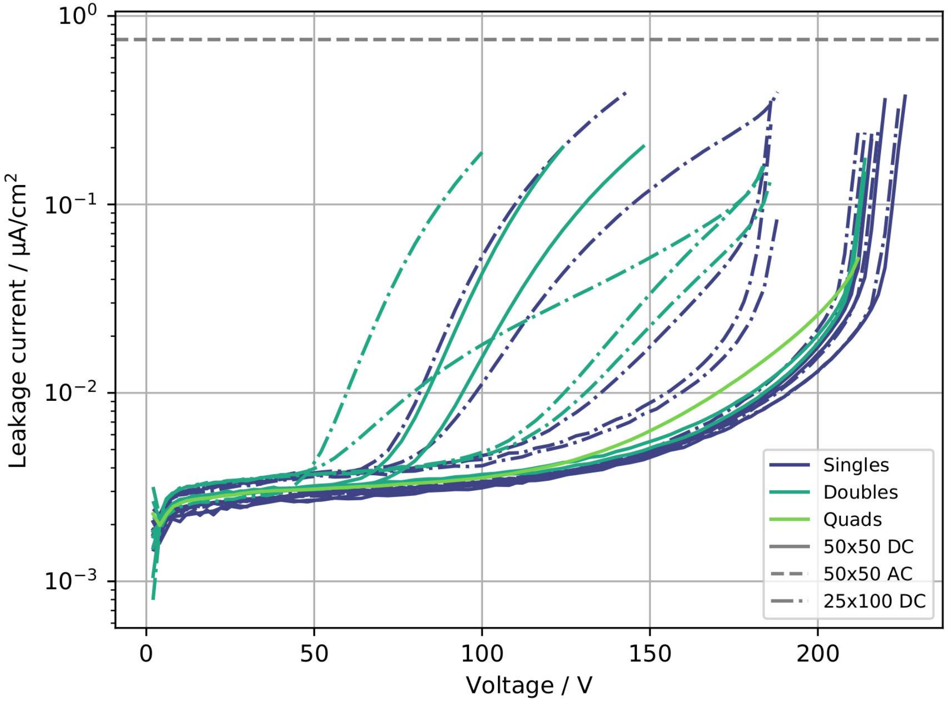


Single Sensors   Double Sensors   Quad Sensors



IV-CURVES

IV-curves of unirradiated sensors from one wafer

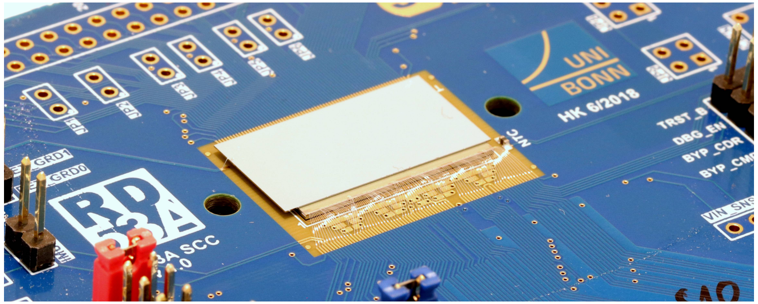


- IV-curve measurement on wafer level using probe station
- Break-down voltage: ~200V
- No systematic differences between various sensor types
- A few sensors show early (random) current increase

  → Backside of sensors is very sensitive

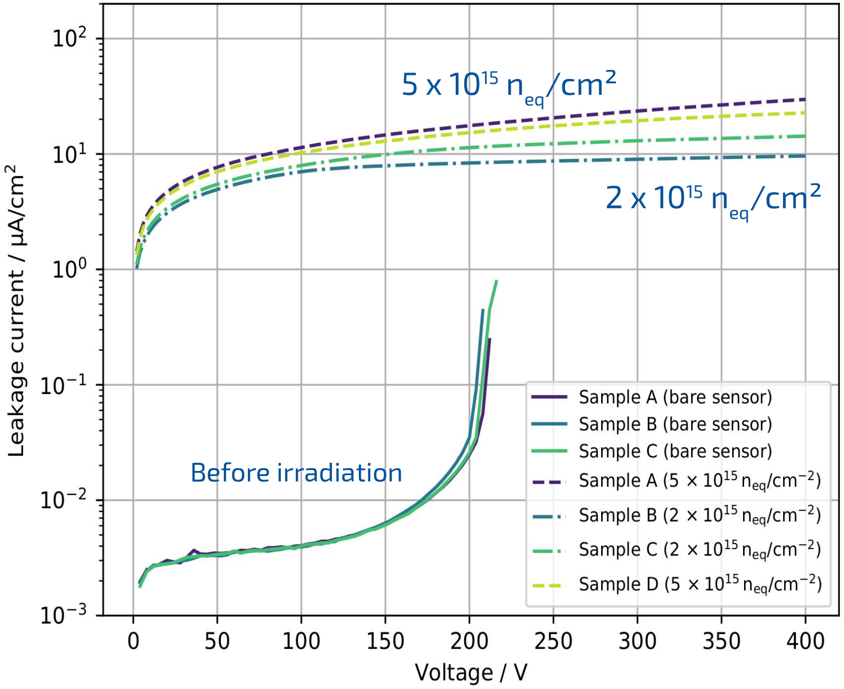
  → Careful handling to avoid scratches at backside

FULL-SIZE ASSEMBLIES



- Assemblies irradiated at Bonn Cyclotron
- Still functional after irradiation
- Noise ~ 25 % higher compared to small prototype
  - Likely due to additional (parasitic) capacitance of bias resistor
  - Capacitance measurement with PixCap65 will be performed soon

IV curves of full-size assemblies



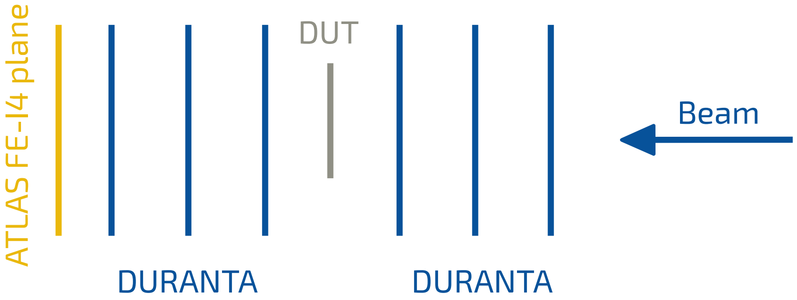
Irradiated samples annealed for 80 min at 60°C

Noise measurements done with **LIN-FE**

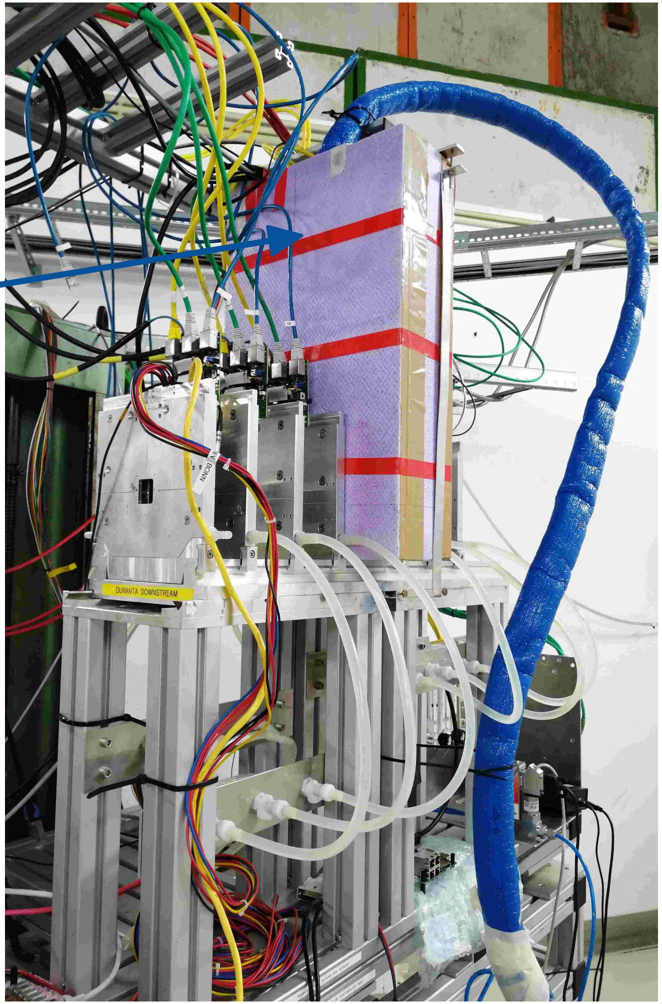
Device	**Noise / e** before irrad.	after irrad.
Sample A, DC	94	101
Sample B, DC	91	100
Sample C, AC	101	102
Sample D, AC	89	100
prototype	**73**	**77**

TESTBEAM SETUP

- Testbeam done at DESY
  - Perpendicular, 5 GeV electron beam
  - Trigger rate: 5 - 7 kHz
- DUT measured in cooling box:
  - Controllable, stable temperature (ΔT ~ 1 °C)
  - Temperature: -15 °C (NTC on R/O chip)
- DUT read out using BDAQ53 R/O system [10.1016/j.nima.2020.164721]



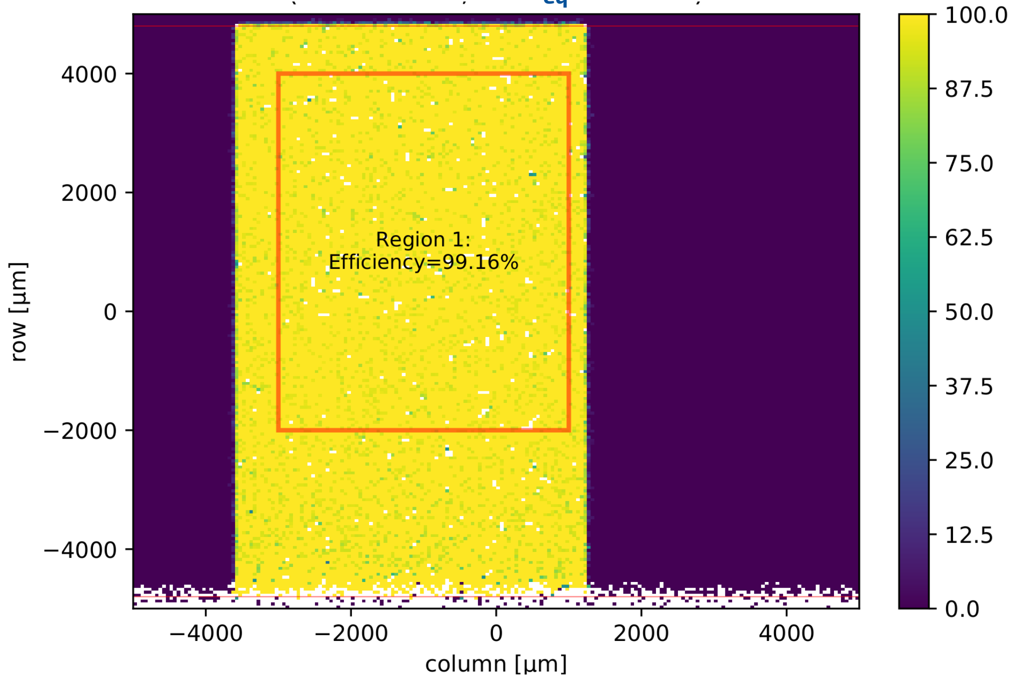
Cooling box with DUT



HIT-DETECTION-EFFICIENCY

- Hit-detection efficiency measured at DESY
  - 5 GeV electrons
- DUT operation conditions:
  - Threshold: ~1300 e, noise occupancy: < 10^{-6}
- After irradiation to $5 \times 10^{15}\ n_{eq}/cm^2$:
  - 99 % efficiency @ 400 V

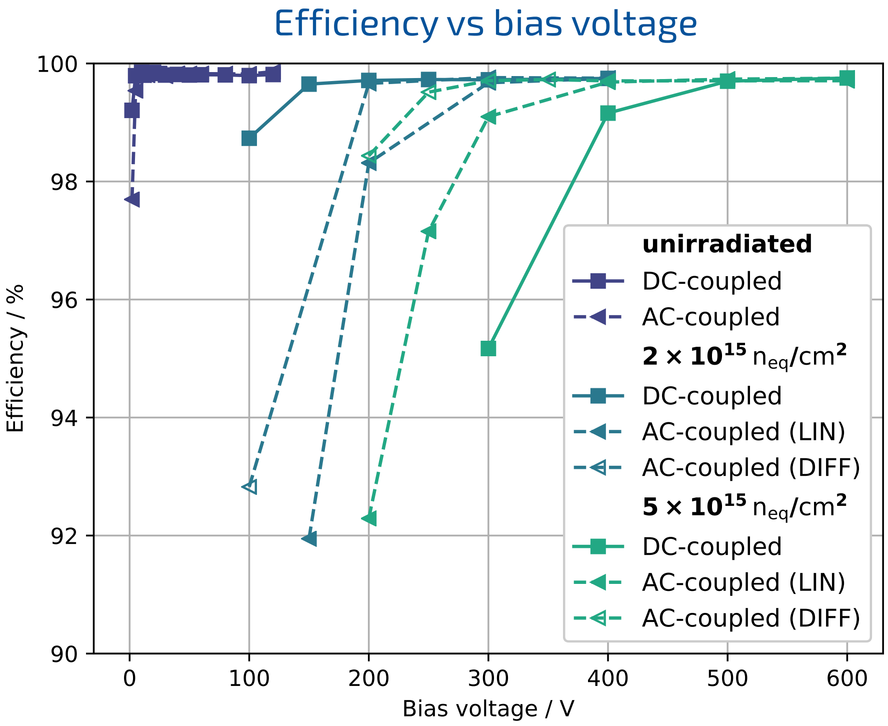
Efficiency map | $5 \times 10^{15}\ n_{eq}/cm^2$ | 400 V | DC-sensor



White pixels diabled during data taking (noisy or stuck)

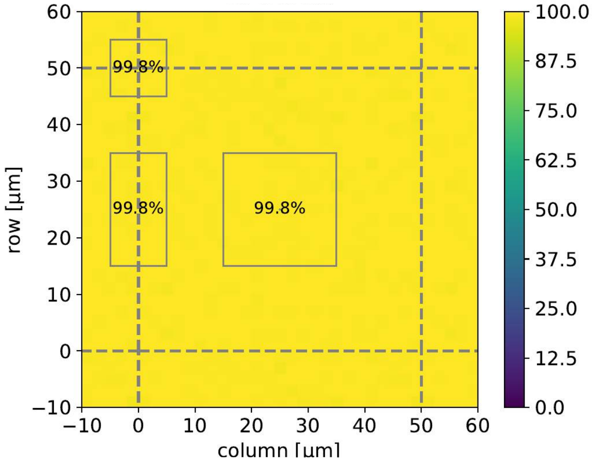
HIT-DETECTION-EFFICIENCY

- Before irradiation:
  - Fully efficient at very low bias voltage (~ 5V)
  - At 80V: 99.8 % efficiency
- After irradiation:
  - > 97 % efficiency reached for all modules
- Differences between LIN-FE and DIFF-FE due to different thresholds
  - LIN: ~ 1300 e
  - DIFF: ~ 900 e

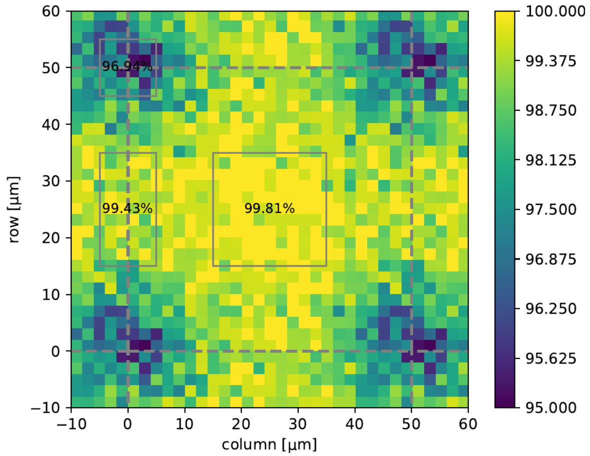


IN-PIXEL EFFICIENCY

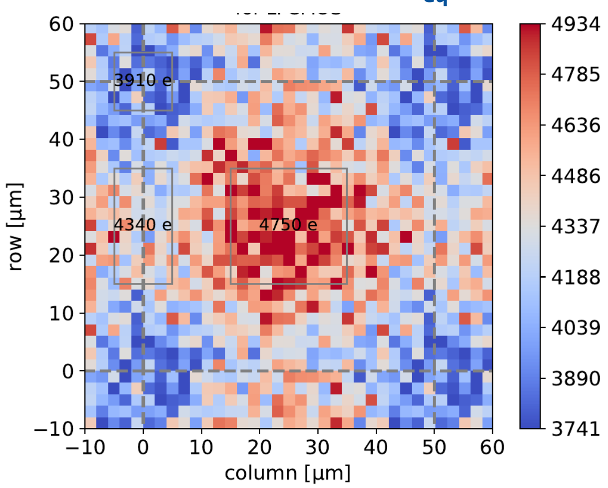
In-pixel efficiency | **non-irrad.** | 80 V



In-pixel efficiency | **5 x 10^{15} n_{eq}/cm²** | 400 V



In-pixel charge | **5 x 10^{15} n_{eq}/cm²** | 400 V

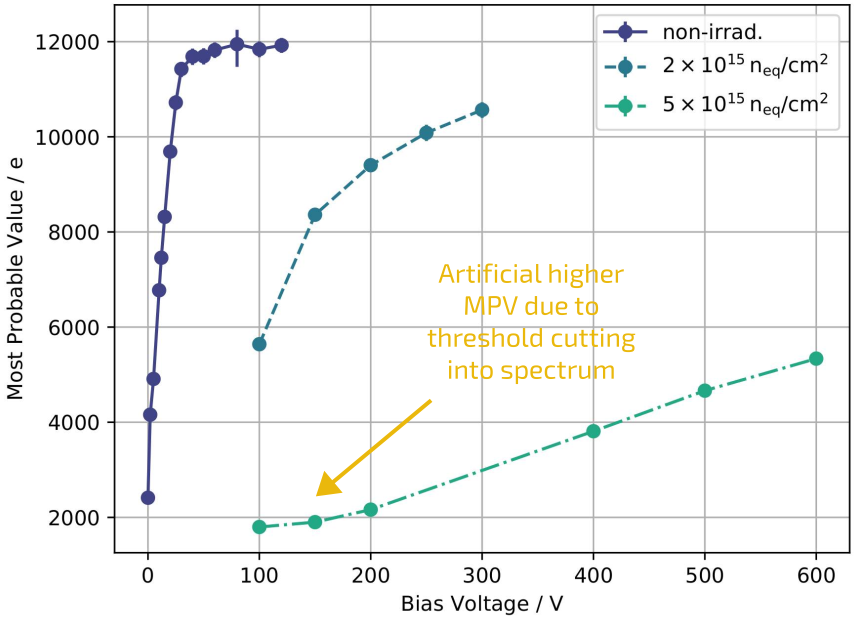


→ efficiency loss happens mainly in pixel corners

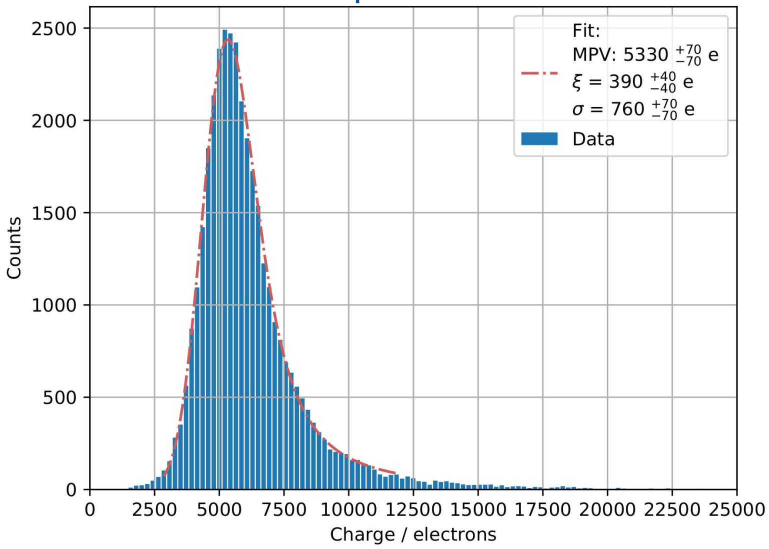
→ can be explained with lower charge in pixel corners due to low electric field and charge sharing

CHARGE MEASUREMENTS

- Charge measured using high precision TDC-method
- After 5 x 10^{15} n_{eq}/cm^2: 5300e charge signal @ 600 V

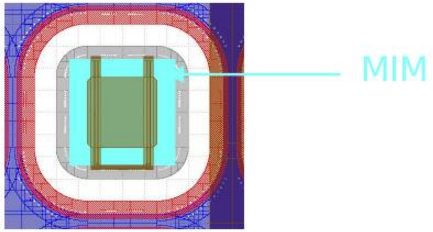


Charge spectrum | 5 x 10^{15} n_{eq}/cm^2 | 600 V | DC-sensor



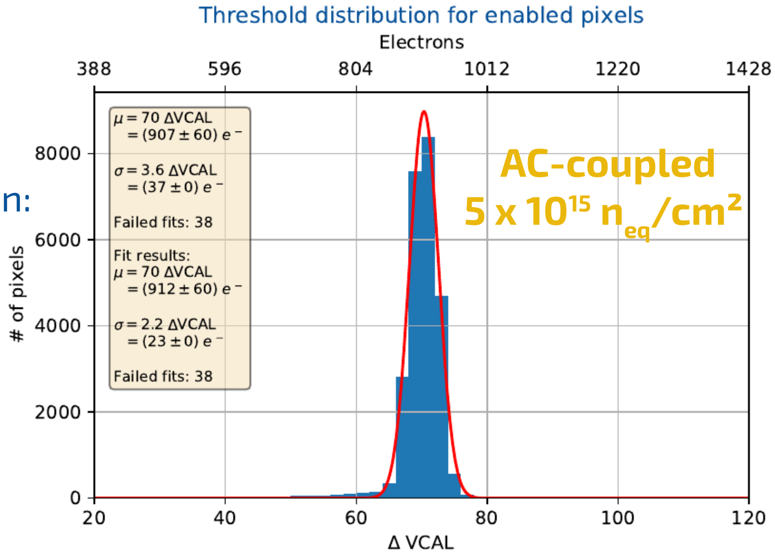
- Before irradiation (using 75 e/h per um):
  - Extracted resistivity: ~8 kΩcm
- Charge collection efficiency after irradiation:
  - 2 x 10^{15} n_{eq}/cm^2: ~ 85 % (10500 e) @ 300V
  - 5 x 10^{15} n_{eq}/cm^2: ~ 45 % (5300 e) @ 600V

AC-COUPLED VS DC-COUPLED



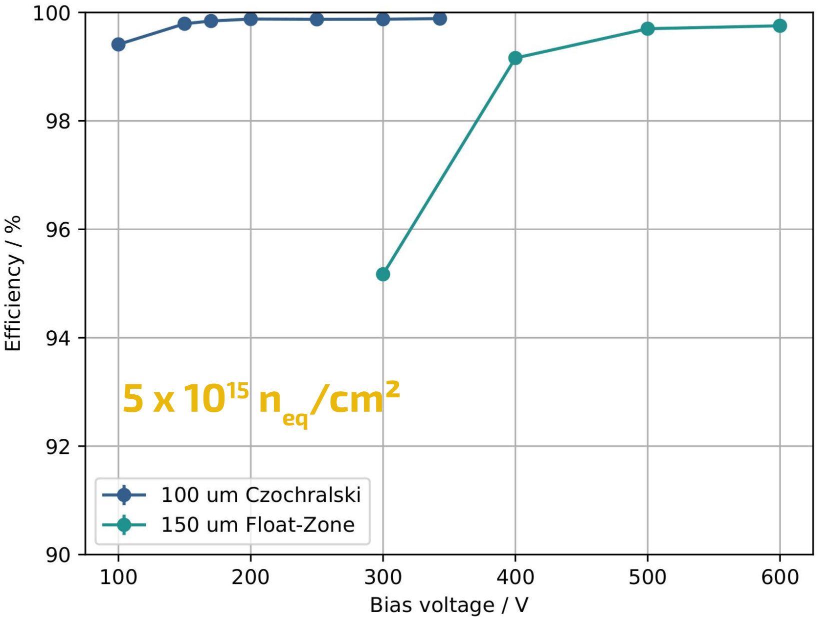
- AC-coupling through MIM-capacitor (~560 fF)
- Advantage that leakage current does not flow into analogue FE pixels:
  - → no leakage current compensation needed
- AC-coupling seems benefitial after irradiation for DIFF-FE
- Charge collection behaviour still under investigation since CCE is unknown (CCE < 1 for AC-coupling → capacitative charge sharing)
  - → Correction factor for measured charge/threshold still unkown: Need to know C_{det}

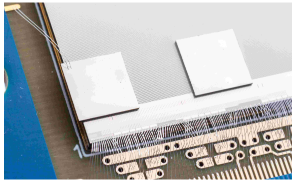
Device	Threshold / e
DC, DIFF-FE, non-irrad.	900
AC, DIFF-FE, 5 x 10^{15} n_{eq}/cm²	**900**
DC, DIFF-FE, 2 x 10^{15} n_{eq}/cm²	1400



COMPARISON TO SMALL PROTOTYPE SENSOR

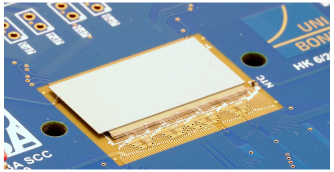
Hit-detection efficiency



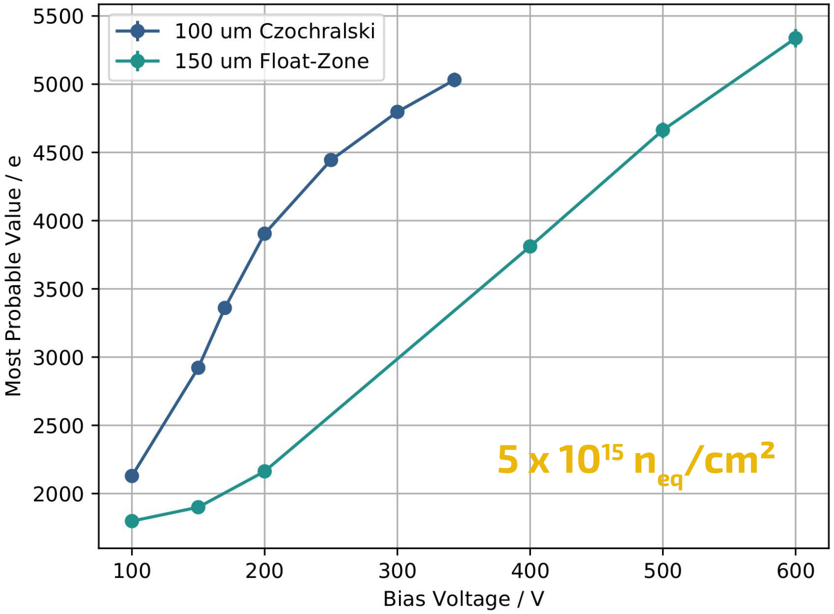


Small prototype
Cz wafer, 100 um
5 – 7 kΩcm

Full-size sensor
FZ wafer, 150 um
7 – 8 kΩcm

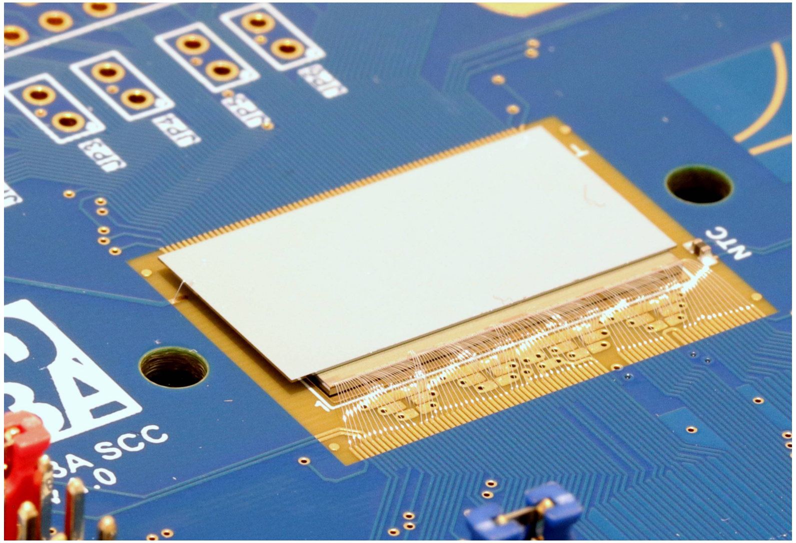


Charge collection



CONCLUSION

- Succesfull fabrication of full-size passive CMOS sensors in 150 nm LFoundry technology
  - Breakdown @ ~200V
  - Backside is very sensitive and some sensors show earlier breakdown from scratches due to improper handling
- Sensors can withstand fluences up to 5 x 10^{15} n_{eq}/cm^2
  - After irradiation sensors can be operated up to voltages of 600V
  - Hit-detection is well above 97 %: @ >400V hit-detection efficiency of > 99 % achieved
  - Collected charge at 600V: ~ 5300 e (5 x 10^{15} n_{eq}/cm^2)
- AC-coupling seems benefitial after irradiation for DIFF-FE:
  - Maintain low threshold

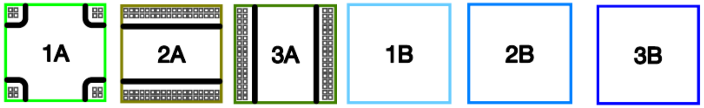


BACKUP

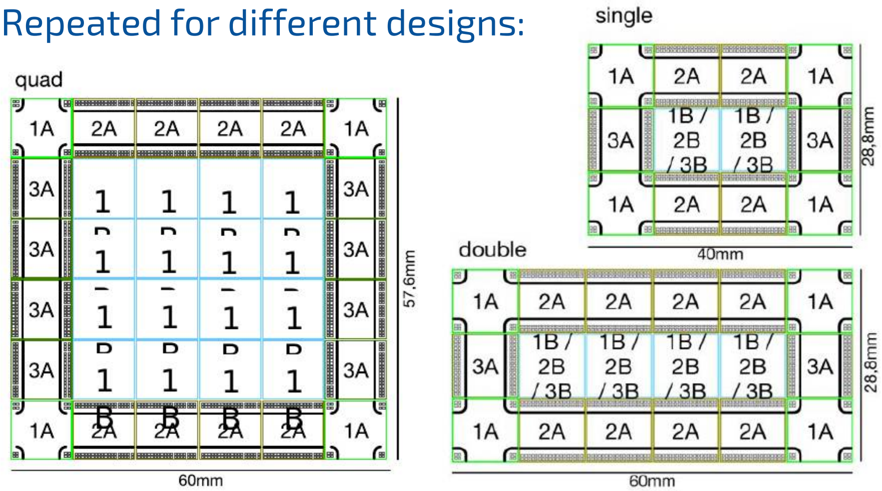
STITCHING AND BIASING

- Sensor size > reticle size → reticle stitching required
- Different reticles:

Edge pixel reticles　　Center pixel reticles

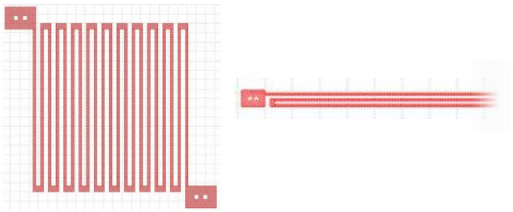


- Repeated for different designs:

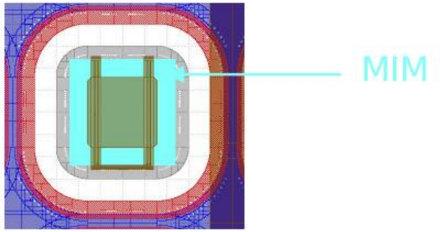


- Resistor biasing for every pixel flavors, likely benefitial to prevent cross-talk
- Bias resistor: ~ 4.6 MΩ

50 x 50 um²　　25 x 100 um²

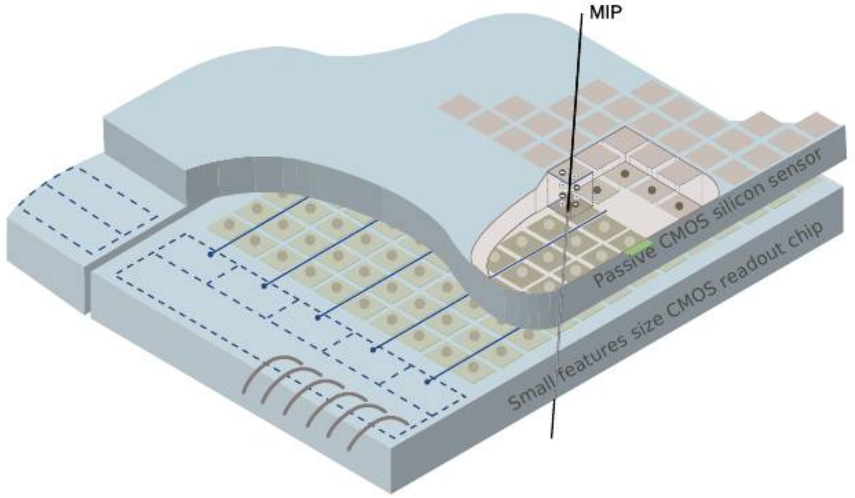


- MIM capacitators for AC-coupling: 560 fF



WHY CMOS PROCESS?

- **Hybrid pixel detectors**: Sensor + R/O chip
- Use commercial high-voltage/high-resistive CMOS processes for planar sensor production:
  - Large wafers (200 mm)
  - High production through-put, low costs
  - Poly-silicon resistors → connection to bias grid
  - MIM-capacitors for AC coupling → no leakage current into R/O pixels
  - Metal layers for redistribution → no enlarged inter-gap pixels
- No active components → **passive CMOS sensors**



[Pohl, David-Leon: 3D-Silicon and Passive CMOS Sensors for Pixel Detectors in High Radiation Environments]

LFoundry 150 nm 1.8V CMOS process
MIM capacitor: 1 fF/um², 2 fF/um²
Poly-silicon resistor: ~ 2.2 kOhm/cm
4 -6 metal option, thick metal
Back-side processing: thinning and implantation
Lithographic stitching

CCE OF AC-COUPLED DEVICES

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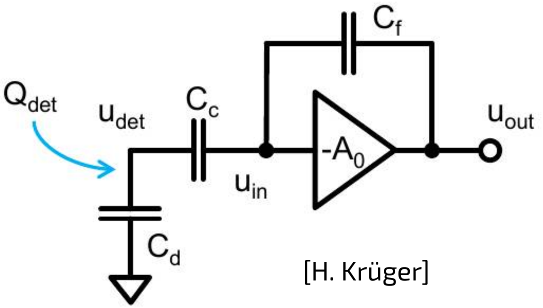
Charge collection from **detector node**



[H. Krüger]

Charge Collection Efficiency

$$\frac{1}{\frac{1}{A_0}\left(\frac{C_d}{C_f}+\frac{C_d}{C_c}\right)+\frac{C_d}{C_c}+\frac{1}{A_0}+1}$$

- Charge transfer function of an AC-coupled device is different for detector charge and injection charge ($1 > CCE_{inj} >= CCE_{det}$)
- Important for calibration is the ratio of the two CCEs

Data indicates that we are somewhere in this region