Passive CMOS Strip: Results update

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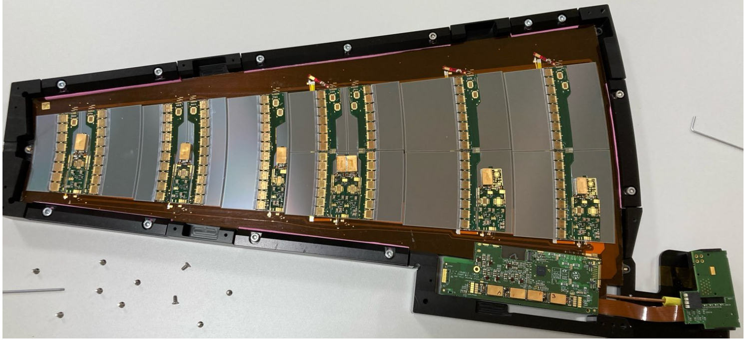
20/06/2024 Dortmund - Verbund CMOS meeting

Motivation

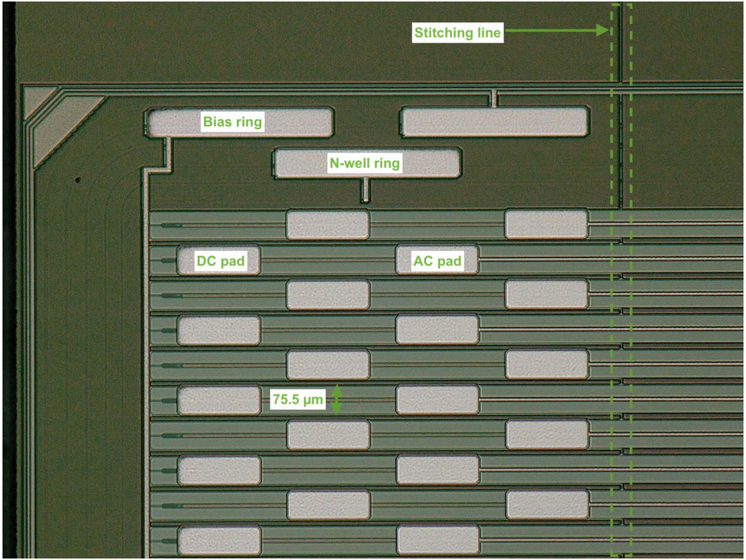
- All ATLAS and CMS upgrade strip detectors are fabricated in Hamamatsu Photonics HPK
- Seems like large area strips only are fabricated in microelectronics foundries
- Here we want to show that also CMOS foundries can fabricate strip detectors and do not have any impact in the performance



Passive CMOS Strip

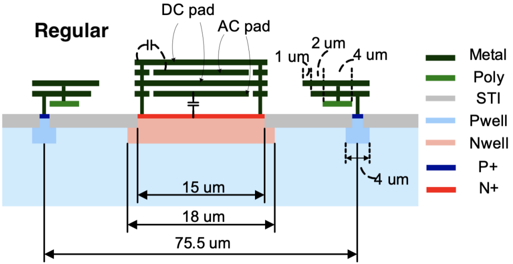
- Fabrication in LFoundry with a 150 nm production
- NO electronics included → therefore Passive
- FZ 150 µm thick wafer
- We fabricated 2.1 cm and 4.1 cm long strips:
  1. 1 cm^2 reticle used (2 set of masks used)
  2. The strips had to be stitched 3 or 5 times
- We want to demonstrate that stitching does not affect the performance of the strips

Passive CMOS strip detector



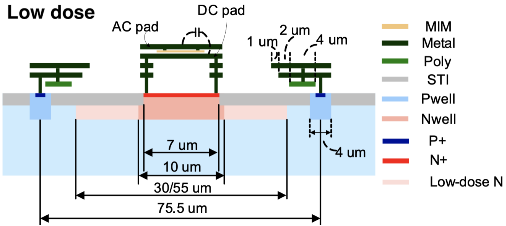
Two designs of strips: Regular design and Low Dose design

Regular design



- Similar to the ATLAS strip design

Low dose design

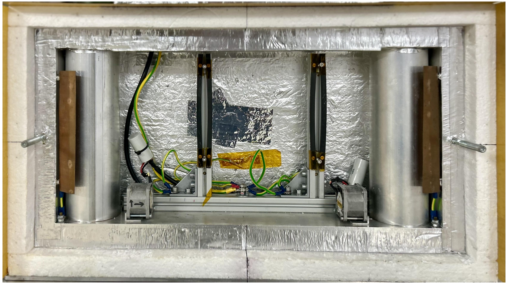


- Using low dose implant and a MIM capacitor

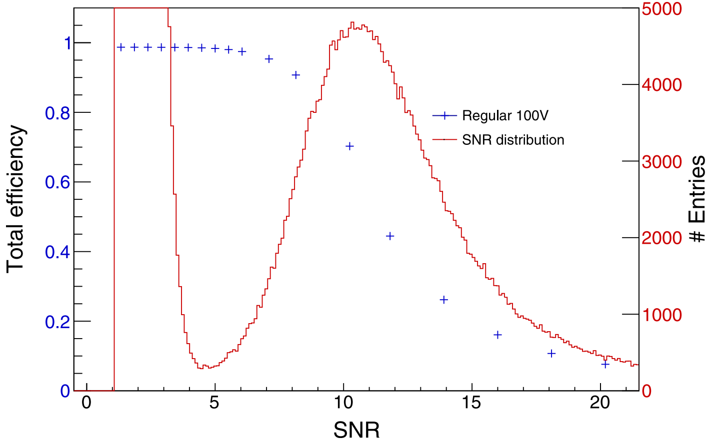
Testbeam results

Test Beam results

- Measurements at DESY, with ADENIUM Telescope (6 planes of Alpide sensors)
- Several TB campaigns
- Electron beam 4.2 GeV (might vary in each campaign)
- Readout with ALiBaVa system
- Cooling to $-45\,°C$ (two possibilities: with dry ice and chiller + peltiers setup)
- CMS reference plane



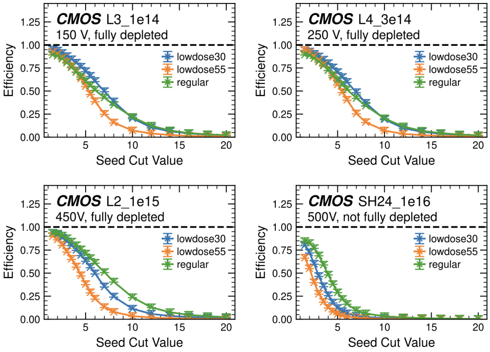
Signal to noise ratio



[N. Davis et al., NIMA 1064 (2024) 169407]

TB analysis, seed cuts

Efficiency Vs. Seed Cut

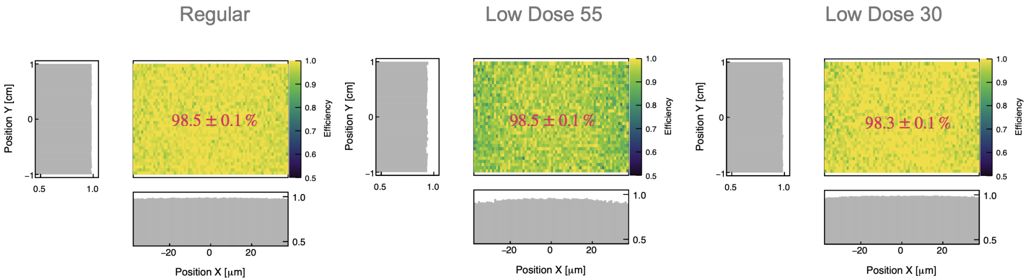


[F. Lex, DPG 2024]

- Seed cuts are crucial to take only the signal and exclude the noise
- High irradiated sensors have rather bad seed cut

Testbeam results, unirradiated sensors @100 V

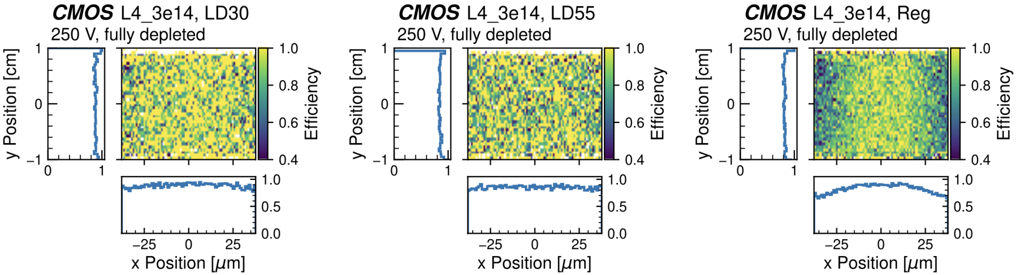
In-hit hit efficiency



[N. Davis, DPG 2024]

- Good efficiency in the sensor
- No impact of the stitching

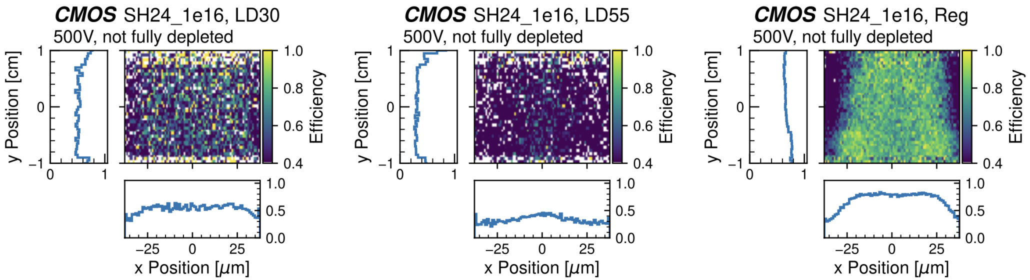
Testbeam in-strip hit efficiency, neutron irradiated



[F. Lex, DPG 2024]

- Neutron irradiated $3 \times 10^{14}\ n_{eq}/cm^2$
- In strip efficiency starts to decrease in the interstrip region for the regular

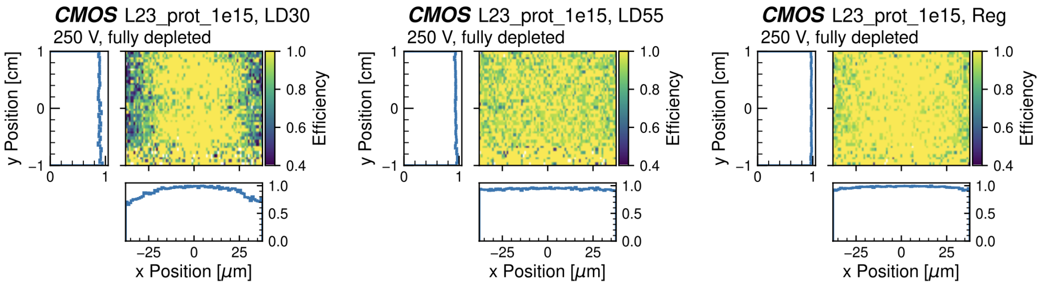
Testbeam in-strip hit efficiency, neutron irradiated



[F. Lex, DPG 2024]

- Neutron irradiated $1 \times 10^{16}\,\mathrm{n_{eq}/cm^2}$
- Sensors not fully depleted, therefore the low efficiency
- In strip efficiency decreases in the interstrip region for the regular

Testbeam in-strip hit efficiency, proton (CERN) irradiated

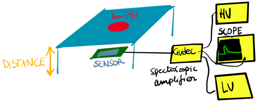


[F. Lex, DPG 2024]

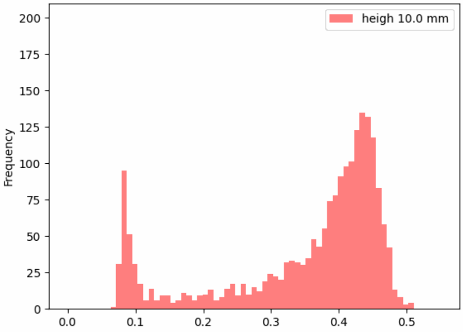
- Proton irradiated $1 \times 10^{15}\ n_{eq}/cm^2$
- Good efficiency after proton irradiation
- starts to loose efficiency between strips

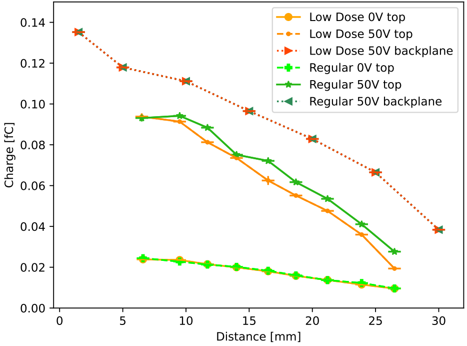
Other lab results

Alpha measurements: Measurements taken with alpha + amplifier



Signal amplitude vs distance of alpha source





[M. Baselga et al., Vertex23]

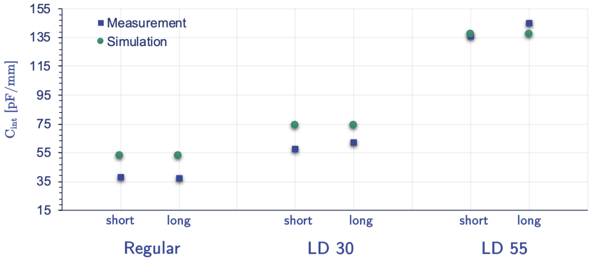
TCAD simulations (Synopsys Sentaurus)

TCAD simulations

- Simulation of the interstrip capacitance also fits rather well with the measurements
- Simulation not from real values of the doping concentrations but approximation that fits rather well capacitance and current values

Interstrip Capacitance C_{int} @ 500 kHz

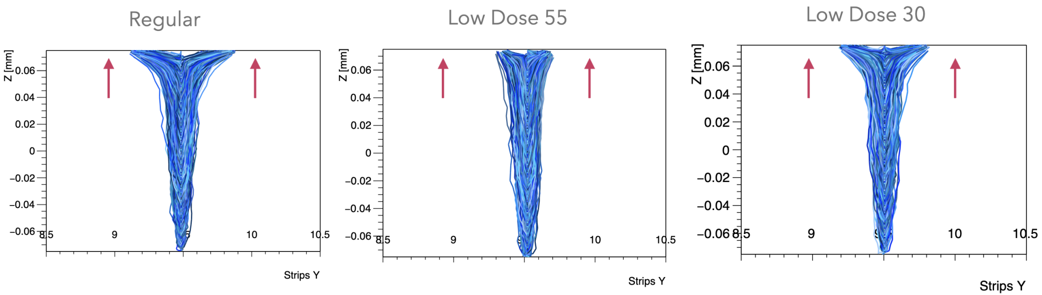
Capacitance values are means of measured/simulated values between 50 V and 80 V



[I. Zatocilova, DPG 2024 and NIMA 1061 (2024) 169132]

Allpix2 simulation

- Regular & Low Dose 30: strong drift towards collection electrode



Allpix2 2024 workshop

Radiation Damage Models in TCAD

Surface effects
oxide charge build- up
interface trap states formation

Bulk effects
deep level traps
recombination centres creation

LHCb/CERN Bulk Model

Perugia Bulk+Surface Model

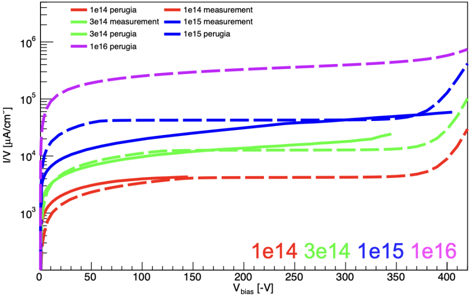
Introducing traps in silicon region

Modifying recombination models

⬅ Bulk trap levels distribution in the Perugia model

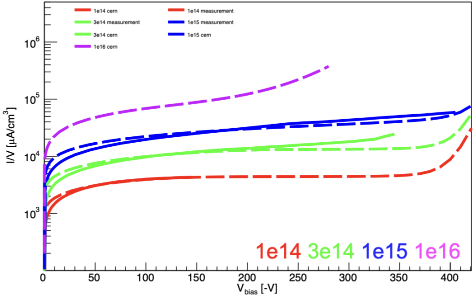
Leakage Current after Irradiation

Perugia Bulk+Surface Model



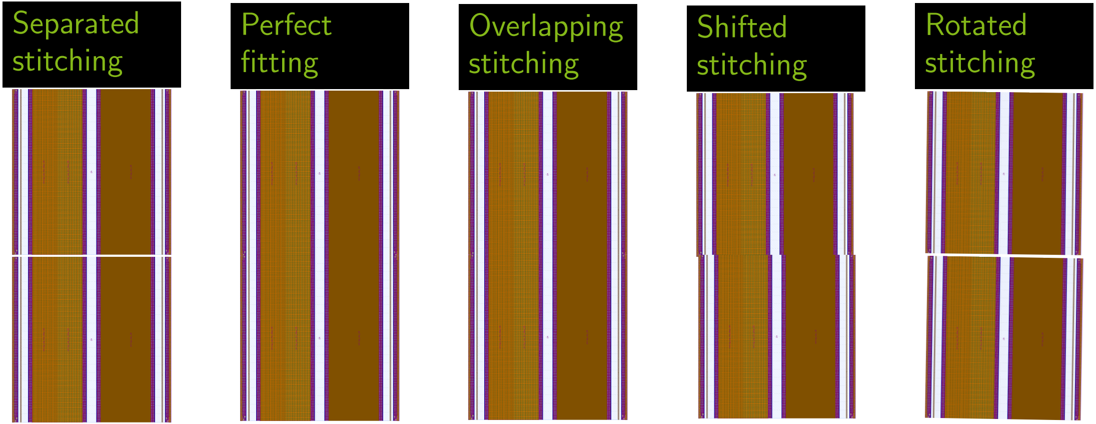
Normalization factor 0.25

CERN Bulk+Perguia Surface Model



Normalization factor 4

Different stitching mismatch possibilities (Images for context, NOT TO SCALE)



Only separated stitching considered

Simulations

1 µm stitching

- NOT REALISTIC
- Simulations for proving the concept, and simulating an extreme although not possible situation
- And, of course, for the fun 💃

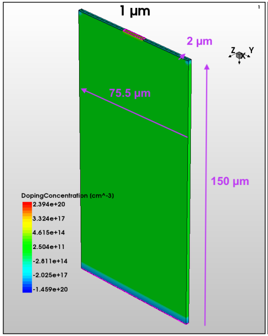
150 nm stitching

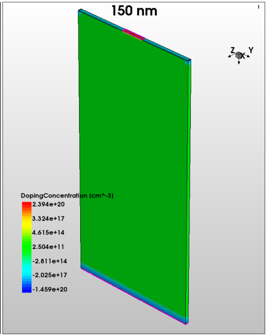
- Worst case scenario
- probably that is not what happens (I would expect something <5 nm)
- We don't know the alignment precision of the stepper motor from LFoundry, therefore 150 nm stitching is a value we know about the resolution

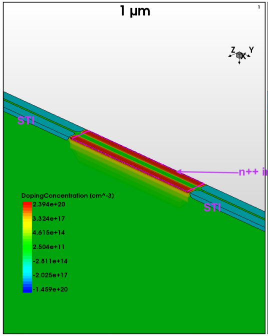
2 µm long regular design simulated

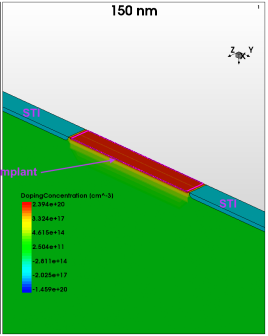
**** To be presented to iWoRiD24 ****

Stitching TCAD simulation doping profile - 2 µm long strip



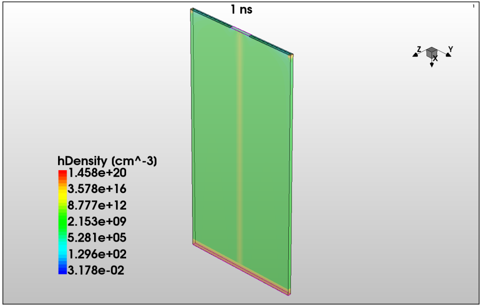




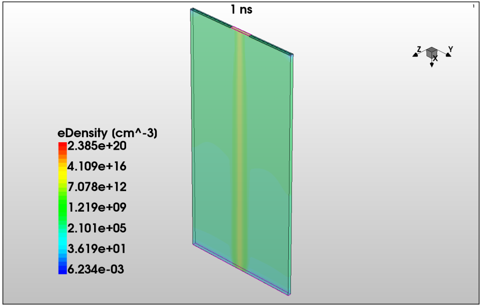


Transient - Particle going through middle of the stitching (1 μm) V=100 V

Holes density

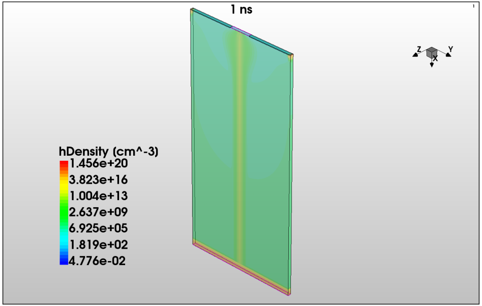


Electrons density

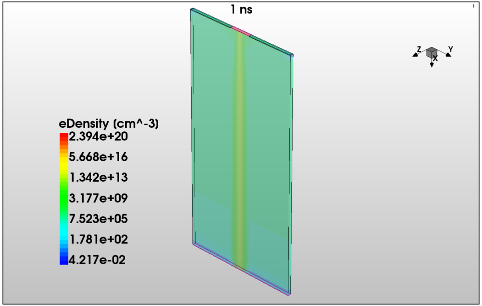


Transient - Particle going through middle of the stitching gap 150 nm) V=100 V

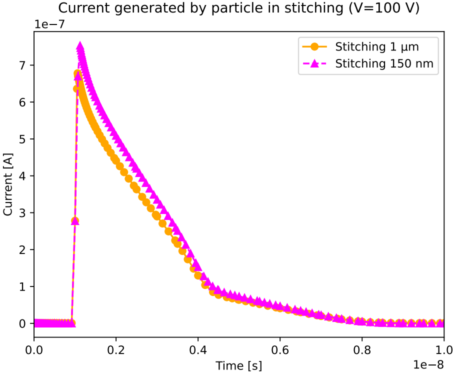
Holes density

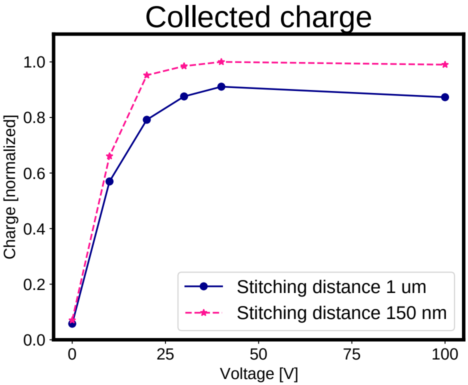


Electrons density



Stitching TCAD simulation - Charge comparison V=100 V





Conclusions

Stitched strips do not show any impact in the performance, neither measurements or simulations

- Low efficiency after irradiation between strips not fully understood yet
- Low dose designs do not show the performance as intended, but regular design is the most adequate
- Next submission only regular design

Contributions from last year

- iWoRiD23
- PSD
  - Proceedings: NIMA 1061 (2024) 169132
- RD50
- Hiroshima (HSTD13)
  - Proceedings: NIMA 1064 (2024) 169407
- VERTEX23
  - Proceedings: PoS(VERTEX2023)067
- TREDI24
- DPG2024
- DPG2024
- DPG2024
- TBBT24
- Allpix2 2024 workshop

Old publications

- NIMA 1033 (2022) 166671
- NIMA 1039 (2022) 167031

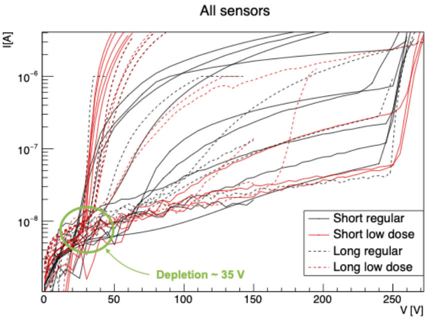
Backup

last year results

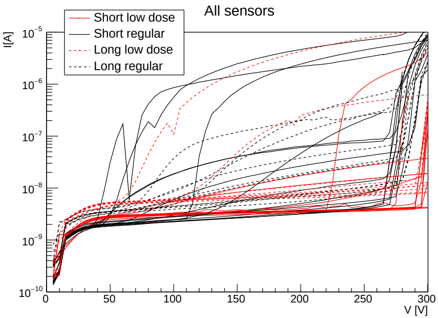
Electrical characterization: IV

- Two different back processing:
  1. First had very often an early break down voltage when reaching the depletion the backplane
  2. Second had an improvement with the break down voltage

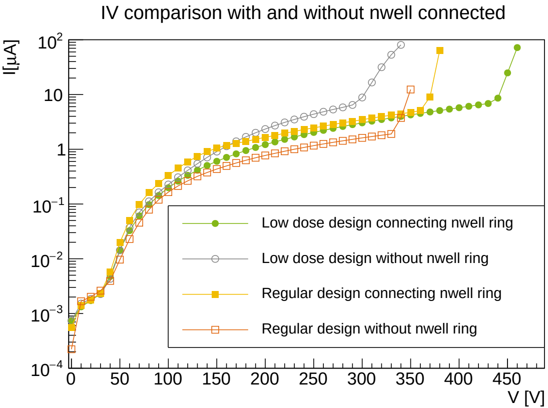
First back processing

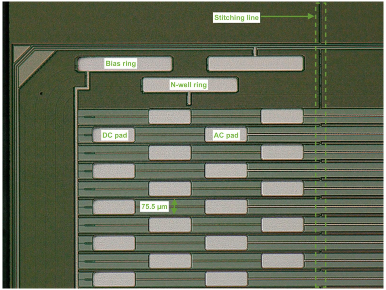


Second back processing



technische universität dortmund

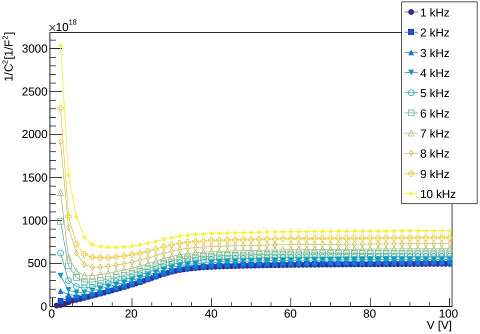




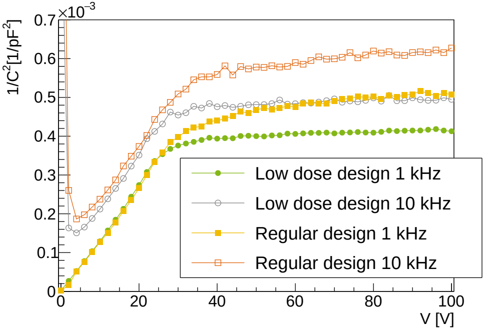
- IV curve shows an improvement when biasing the bias and the nwell ring together
- Probably the break down is happening to the edge of the detector

Electrical characterization: CV

CV with the bias pad



CV with the bias pad and nwell ring

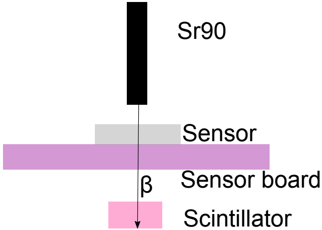


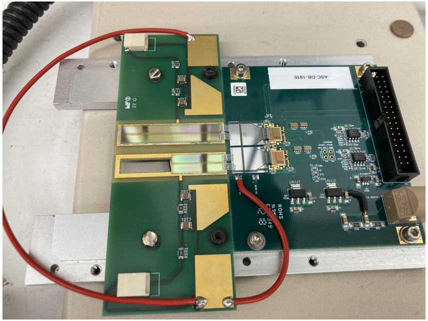
- Decrease of capacitance when increasing the frequency
- The effect decreases biasing the nwell ring → some edge effect

Lab Setup: Alibava board

- Readout is done with ALiBaVa system, it contains a mother board and a daughter board populated with two Beetle readout chip (from LHCb)
- It allows an analogue readout of the signal of 258 channels (two Beetle chips)

Sketch of the β source setup

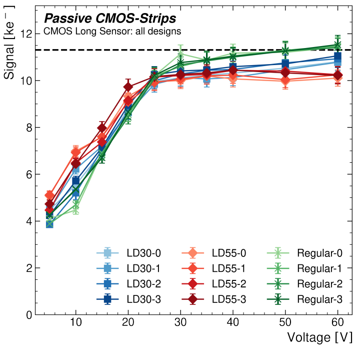


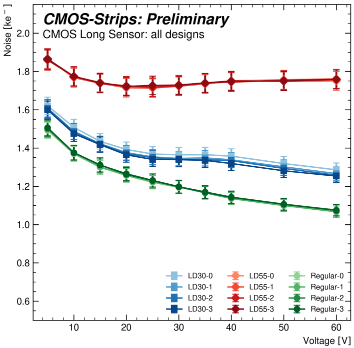


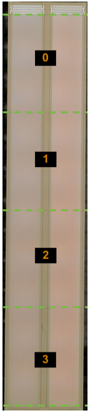
→ Daughter board (with two beetle chips) bonded to the passive CMOS strips

Charge in the ALiBaVa setup: Long detector with Sr^{90} source

- Sr^{90} source located on top of 4 different positions (shown in right image)





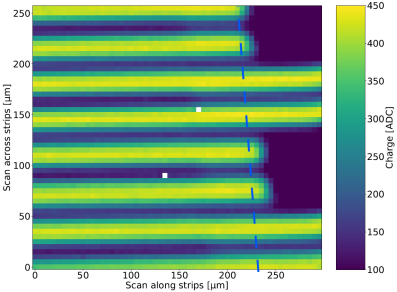


[NIMA 1033 (2022) 166671]

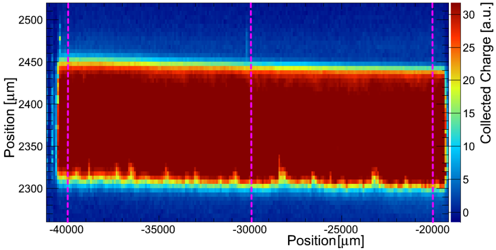
- The three different flavours have similar signal (expected $\sim$ 11500 electrons)
- Low Dose 55 µm has higher noise $\rightarrow$ it has higher inter strip capacitance

Transient Current Technique measurements

TCT and edge TCT with IR laser



Collected charge of the regular design of a long sensor as a function of the laser position at 50 V, illuminating from top [NIMA 1033 (2022) 166671]

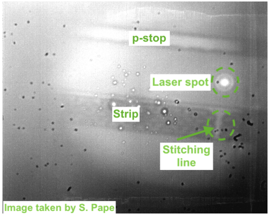


Edge TCT charge from a short LD30 sensor at 100 V (fully depleted). Stitching does not change the collected charge [N. Sorgenfrei, 40th RD50, CERN]

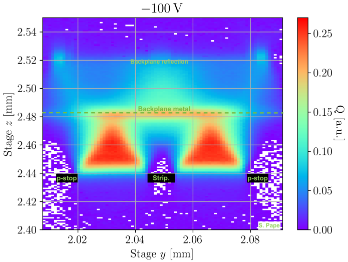
Two Photon Absorption Transient Current Technique measurements

- TPA-TCT measurements were performed at CERN SSD
- The charge in stitching and outside stitching does not show any difference

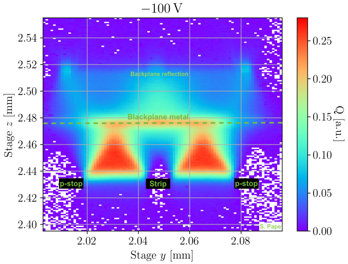
IR image



TPA-TCT in the stitch area



TPA-TCT outside the stitch



- Measurements from Sebastian Pape, Michael Moll, Marcos Fernandez Garcia, and Esteban Curras. More details about this technique in this talk

Irradiated samples

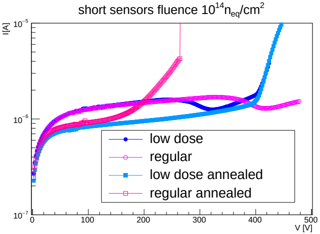
We wanted to test the sensors under irradiation, we shipped samples to:

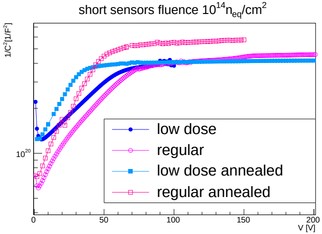
- 23 MeV protons @ KIT
- Neutrons at Ljubljana
- 24 GeV protons @ IRRAD (CERN)

Irradiated: IVs and CVs

Irraidated with protons at KIT

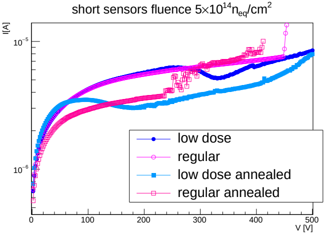
- 23 MeV protons at fluence $1 \times 10^{14}\, n_{eq}/cm^2$

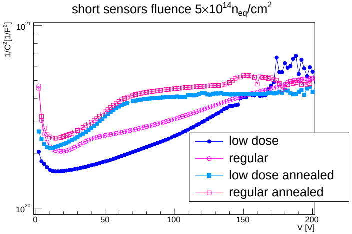




CV at 1 kHz

- 23 MeV protons at fluence $5 \times 10^{14}\, n_{eq}/cm^2$

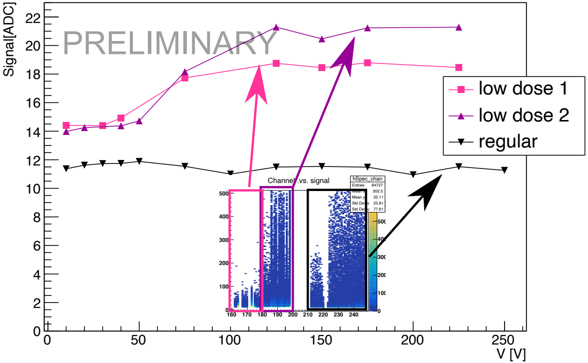




CV at 1 kHz

Irradiated: ALiBaVa setup with Sr^{90}

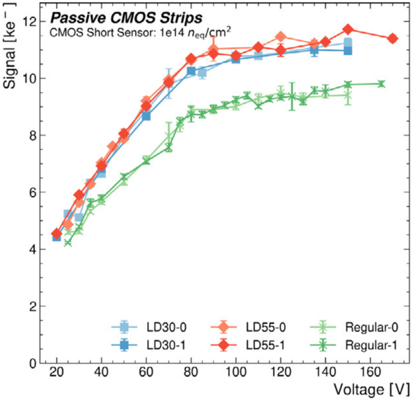
Irraidated with protons at KIT $5 \times 10^{14}\, n_{eq}/cm^2$ (23 MeV and annealed)



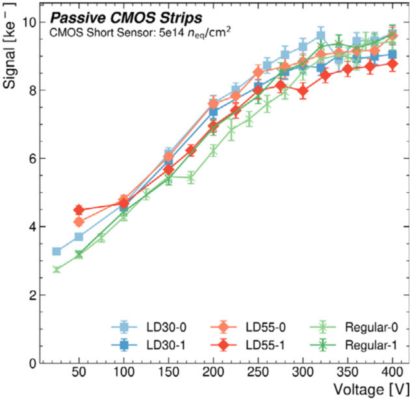
[12th PSD 2021 Birmingham]

- Data not calibrated
- Regular design seems to stop working after irradiation

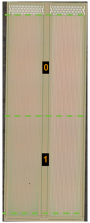
Signal of a short detector with Sr^{90} source irradiated



Neutrons fluence $1 \times 10^{14}\ n_{eq}/cm^2$



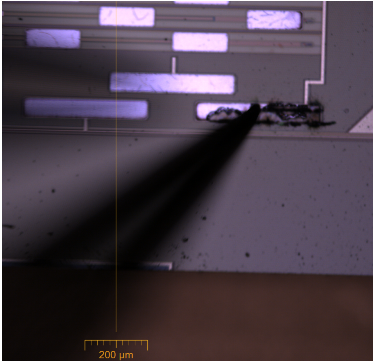
Neutrons fluence $5 \times 10^{14}\ n_{eq}/cm^2$

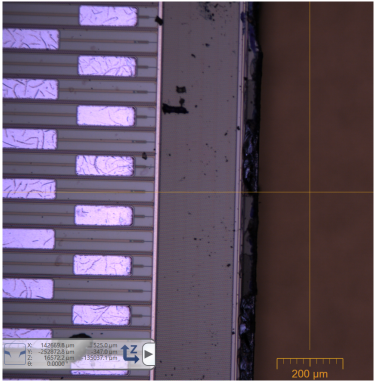


[NIMA 1039 (2022) 167031]

Electrical stress to some sensors

- Sensors irradiated at CERN we tried to reach the break down voltage (not reached at 800 V)
- Some burned damage was inflicted in the sensors (slide 6 shows a non burned edge detector)





Conclusions and future work

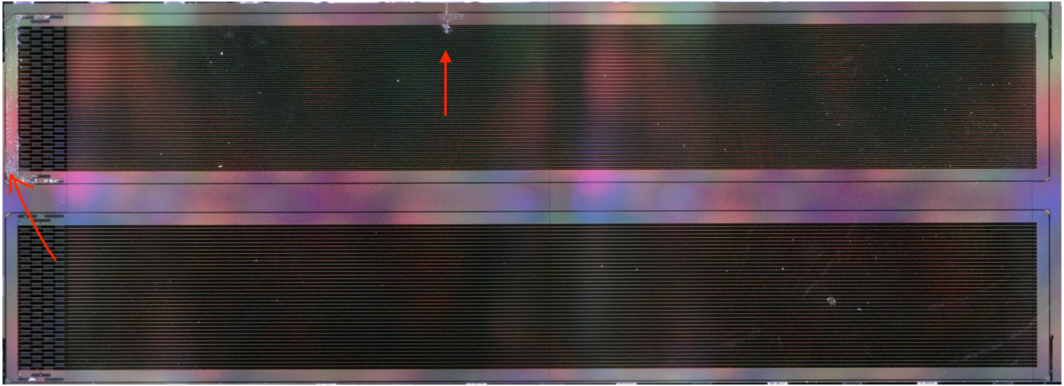
Conclusions

- So far, stitching does not have any impact in the performance of the strip detectors before and after irradiation
- Currently wrapping up the irradiated measurements, finishing the testbeam analysis and studying if there is a problem with the burning detectors

Future work

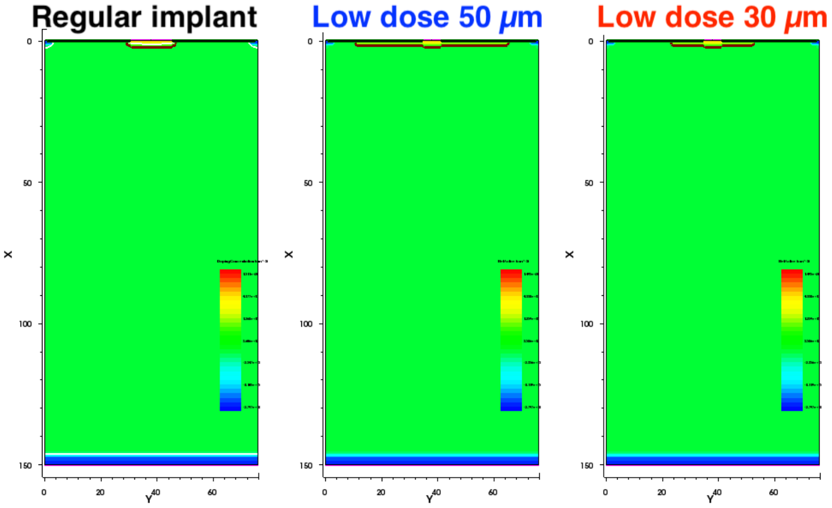
- Planning a new production with the electronics implemented in the strips is ongoing $\rightarrow$ that would allow to avoid all the bondings of the strips to the chips
- Production of a full wafer size strip detector with a CMOS foundry

Irradiated with 23 MeV protons



- some burned guard rings after some electrical stress

TCAD simulations: Simulated device



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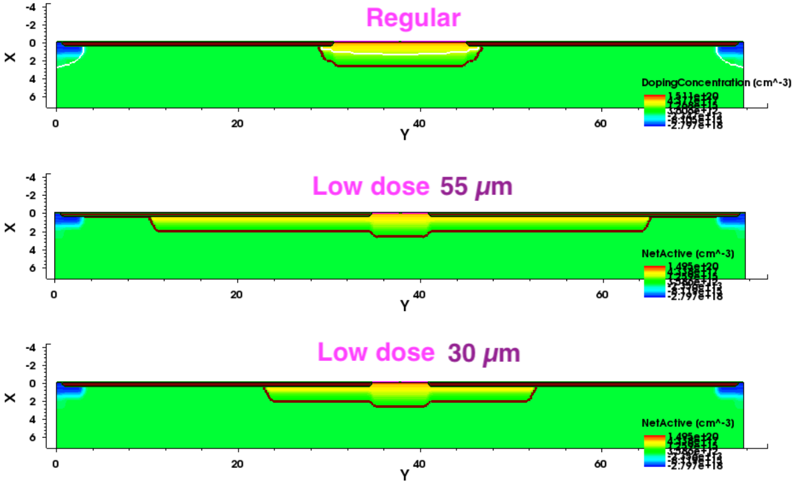
TCAD simulations: Simulated device zoom



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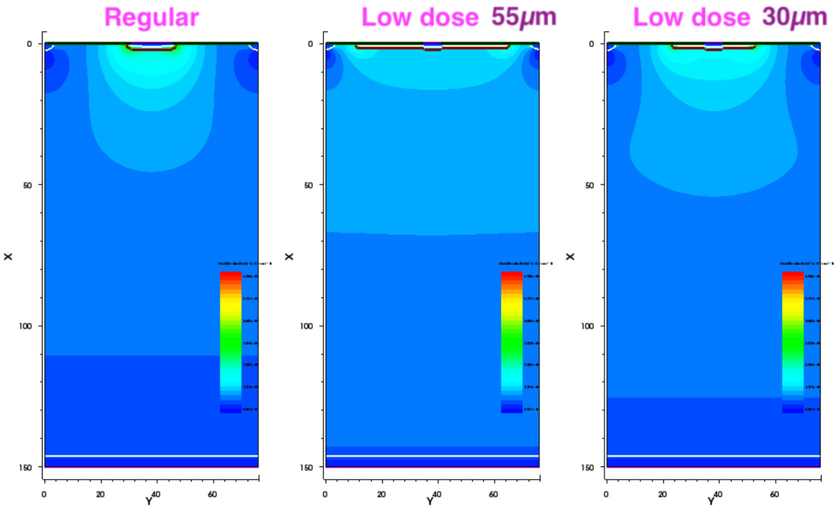
TCAD simulations: Simulated Electric field at 100 V



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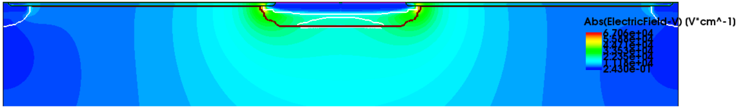
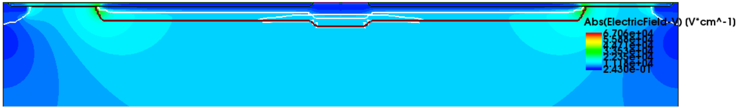
TCAD simulations: Electric field zoom

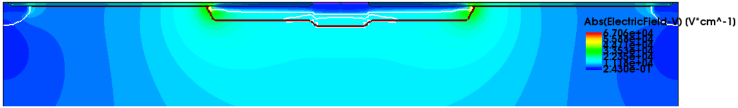
Regular implant



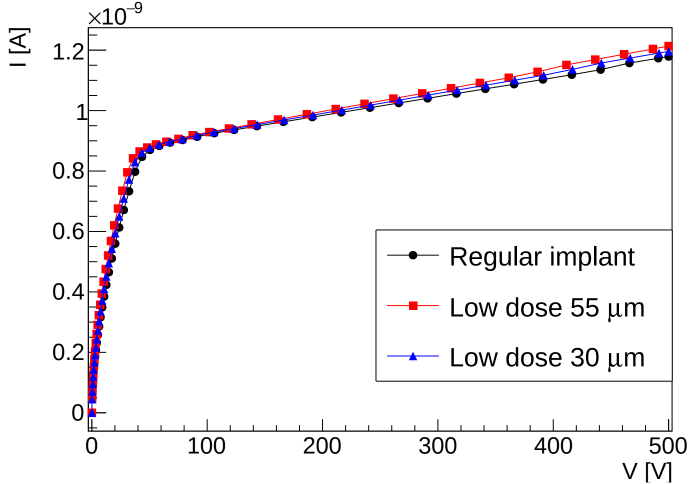
Low dose 55 μm



Low dose 30 μm



TCAD simulation: Current voltage curve



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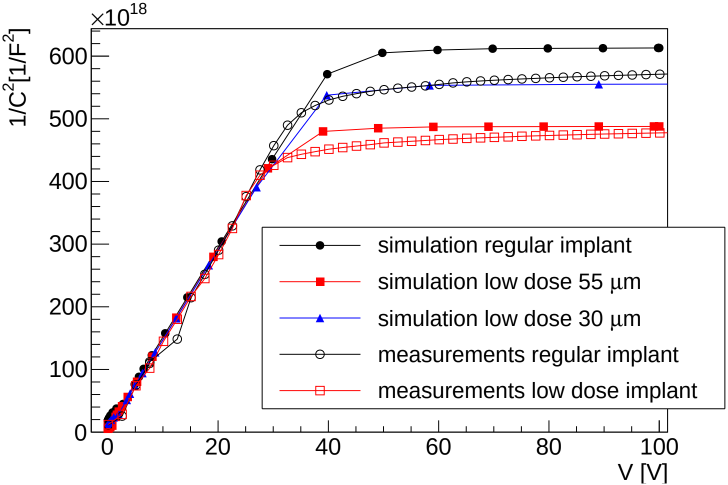
TCAD simulation compared with data: capacitance voltage curves



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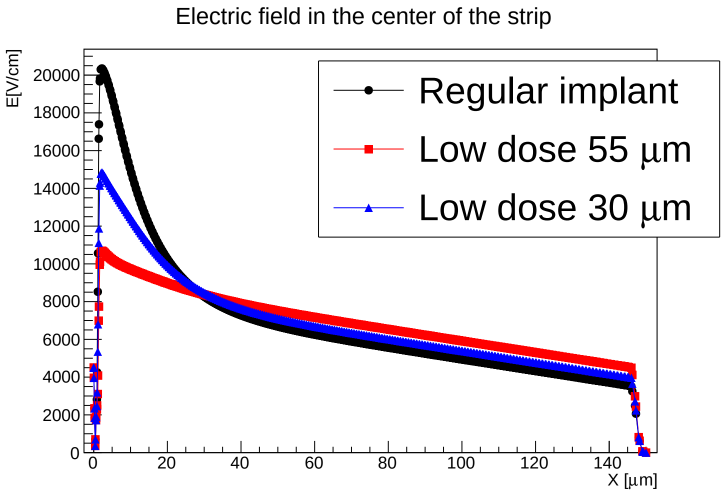
TCAD simulation: Electric field 100 V at the center of the strip



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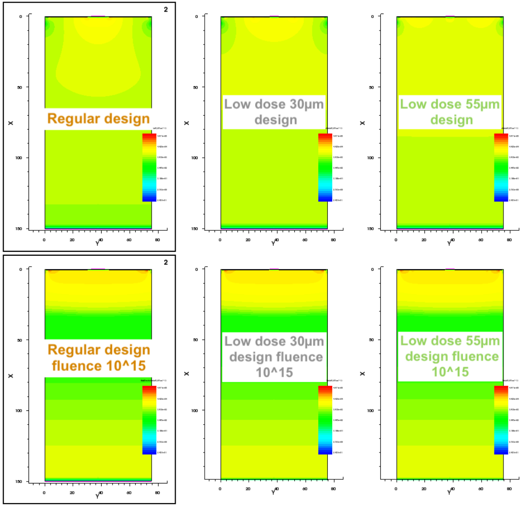
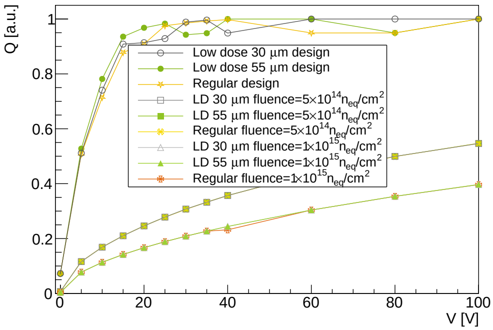
TCAD simulation: Irradiated electric field

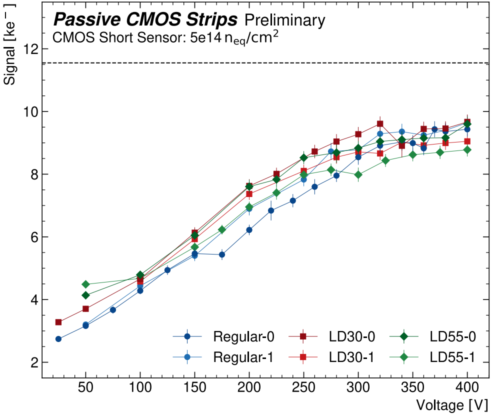


MIP particle going through center of the strip

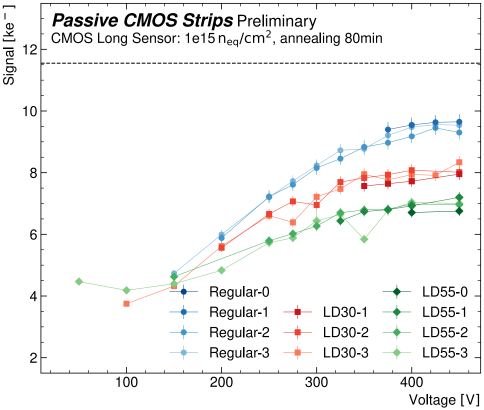


Irradiated: Charge in the ALiBaVa setup with Sr^{90}

Signal of a short detector with Sr^{90} source irradiated



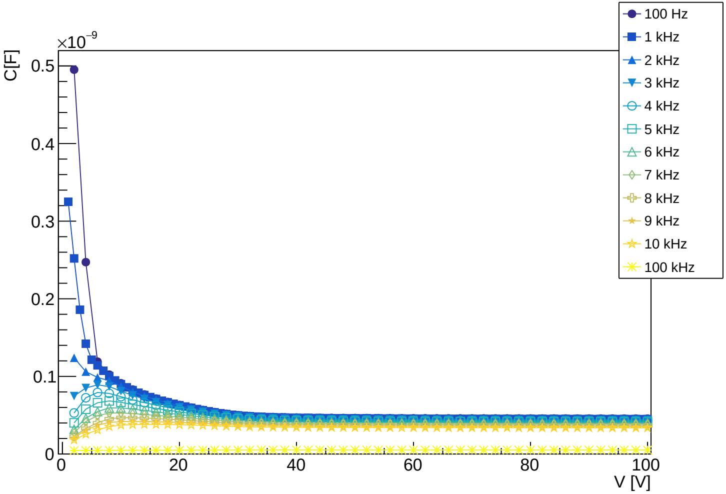
Neutrons $5 \times 10^{14}\ n_{eq}/cm^2$



Neutrons $1 \times 10^{15}\ n_{eq}/cm^2$

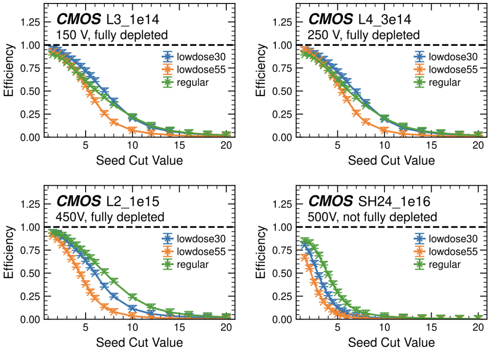
[N. Sorgenfrei, 40th RD50, CERN]

CV



C[F]
×10^-9
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
V [V]
100 Hz
1 kHz
2 kHz
3 kHz
4 kHz
5 kHz
6 kHz
7 kHz
8 kHz
9 kHz
10 kHz
100 kHz

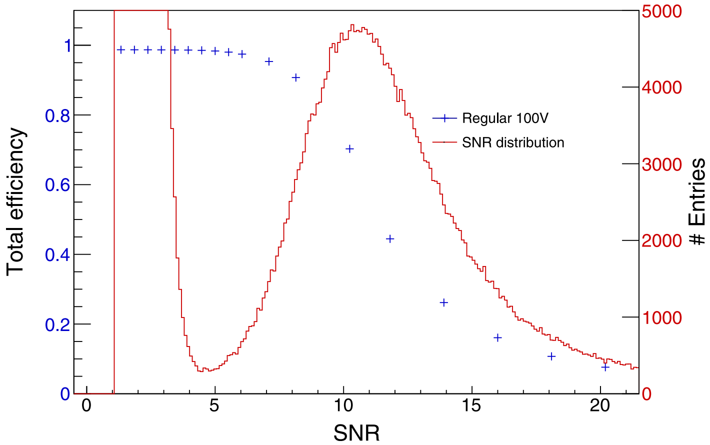
Efficiency Vs. Seed Cut



- Seed cuts are crucial to take only the signal and exclude the noise
- High irradiated sensors have rather bad seed cut

[F. Lex, DPG 2024]

Signal to noise ratio

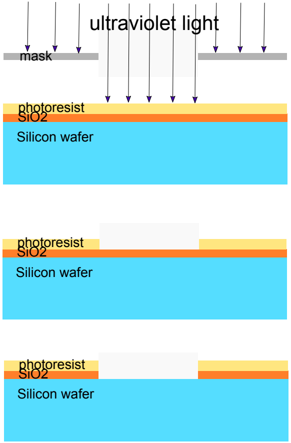


[N. Davis et al., NIMA 1064 (2024) 169407]

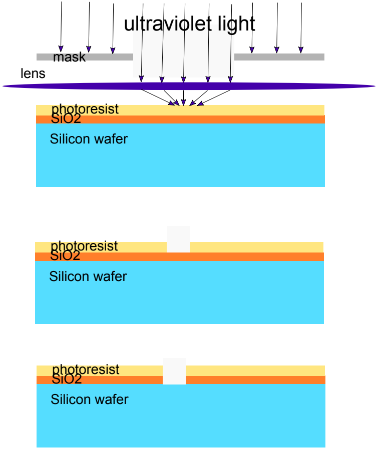
TCAD simulations

What changes regarding microelectronic foundries?

Microelectronics photolitography



CMOS photolitography



Semiconductor device fabrication

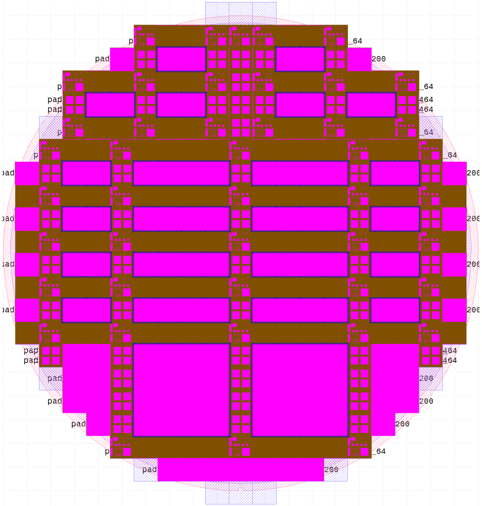
MOSFET scaling (process nodes)

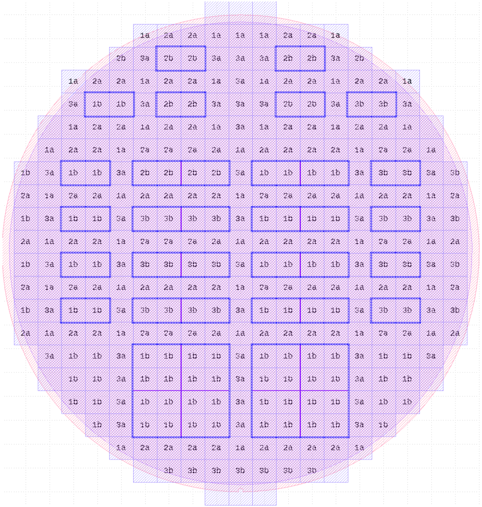
- 10 μm – 1971
- 6 μm – 1974
- 3 μm – 1977
- 1.5 μm – 1981
- 1 μm – 1984
- 800 nm – 1987
- 600 nm – 1990
- 350 nm – 1993
- 250 nm – 1996
- 180 nm – 1999
- 130 nm – 2001
- 90 nm – 2003
- 65 nm – 2005
- 45 nm – 2007
- 32 nm – 2009
- 22 nm – 2012
- 14 nm – 2014
- 10 nm – 2016
- 7 nm – 2018
- 5 nm – 2020

Future

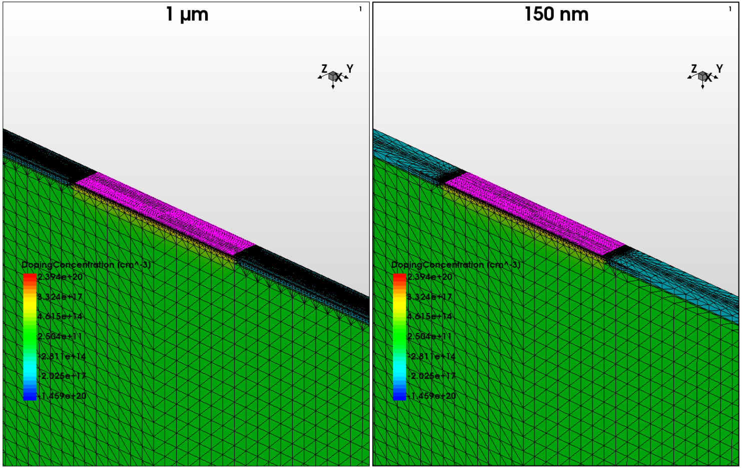
- 3 nm ~ 2022
- 2 nm ~ 2023

Mask layout

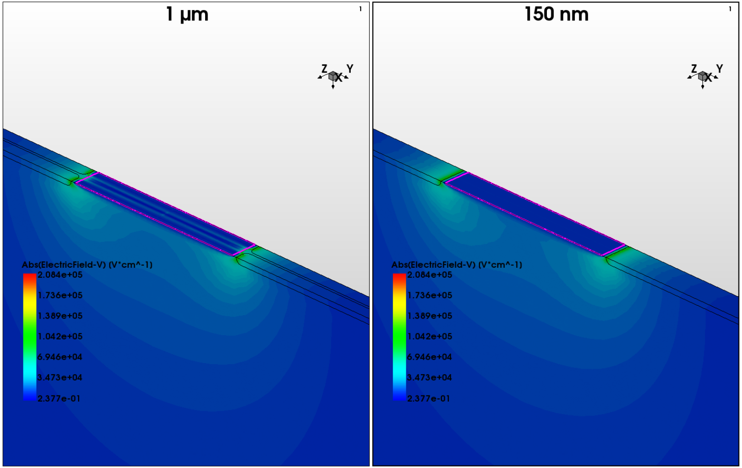

pad
200
464
64


1a 2a 2a 1a 1a 1a 2a 2a 1a
2b 3a 2b 2b 3a 3a 3a 2b 2b 3a 2b
1a 2a 2a 1a 2a 2a 1a 3a 1a 2a 2a 1a 2a 2a 1a
3a 1b 1b 3a 2b 2b 3a 3a 3a 2b 2b 3a 3b 3b 3a
1a 2a 2a 1a 2a 2a 1a 3a 1a 2a 2a 1a 2a 2a 1a
1a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 1a
1b 3a 1b 1b 3a 2b 2b 2b 2b 3a 1b 1b 1b 1b 3a 3b 3b 3a 3b
2a 1a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 1a 2a
1b 3a 1b 1b 3a 3b 3b 3b 3b 3a 1b 1b 1b 1b 3a 3b 3b 3a 3b
2a 1a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 1a 2a
1b 3a 1b 1b 3a 3b 3b 3b 3b 3a 1b 1b 1b 1b 3a 3b 3b 3a 3b
2a 1a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 1a 2a
1b 3a 1b 1b 3a 3b 3b 3b 3b 3a 1b 1b 1b 1b 3a 3b 3b 3a 3b
2a 1a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 2a 2a 1a 2a 2a 1a 2a
3a 1b 1b 3a 1b 1b 1b 1b 3a 1b 1b 1b 1b 3a 1b 1b 3a
1b 1b 3a 1b 1b 1b 1b 3a 1b 1b 1b 1b 3a 1b 1b
1b 1b 3a 1b 1b 1b 1b 3a 1b 1b 1b 1b 3a 1b 1b
1b 3a 1b 1b 1b 1b 3a 1b 1b 1b 1b 3a 1b
1a 2a 2a 2a 2a 1a 2a 2a 2a 2a 1a
3b 3b 3b 3b 3b 3b 3b

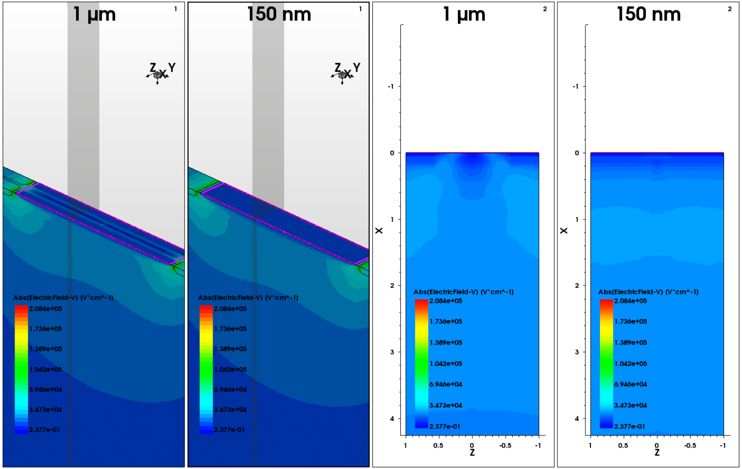
Stitching TCAD simulation doping profile - zoom with mesh



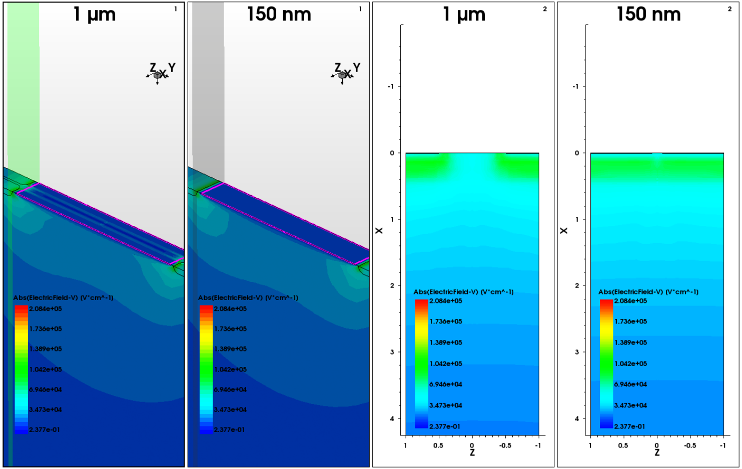
Stitching TCAD simulation - E field 100 V



Stitching TCAD simulation - E field 100 V



Stitching TCAD simulation - E field 100 V



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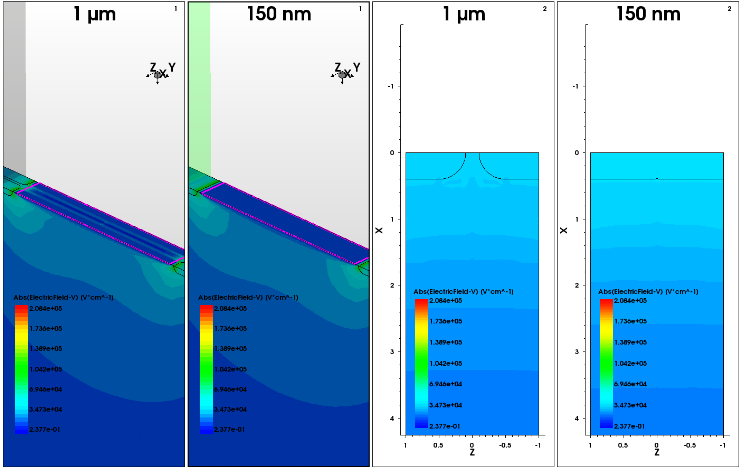
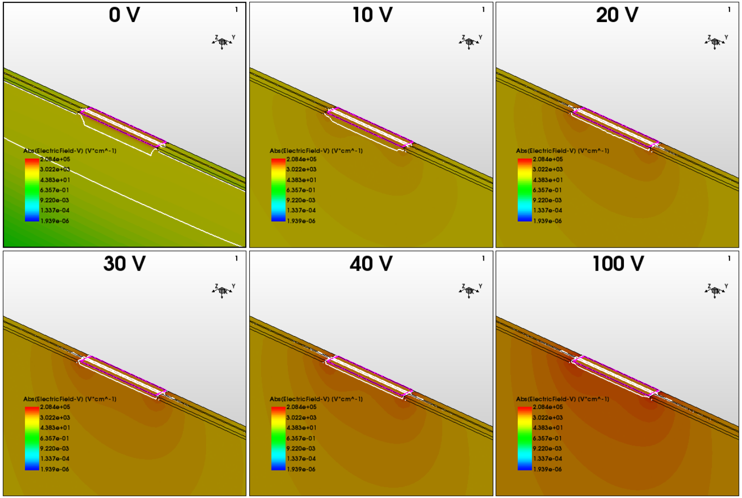
Stitching TCAD simulation - E field 100 V



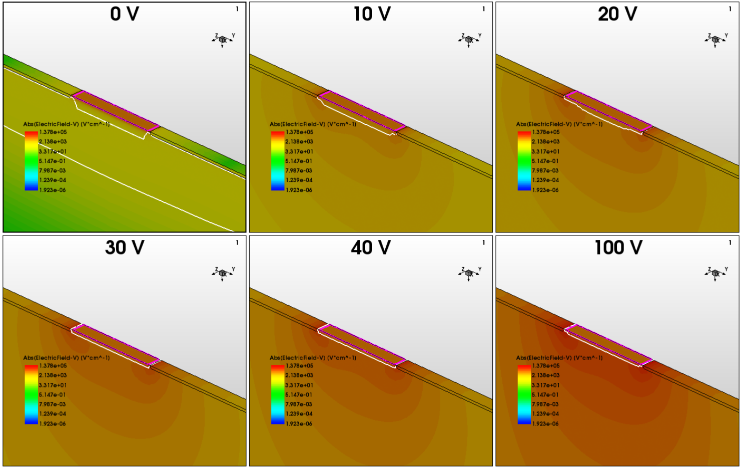
Stitching distance 1 μm

Stitching 1 µm: E field

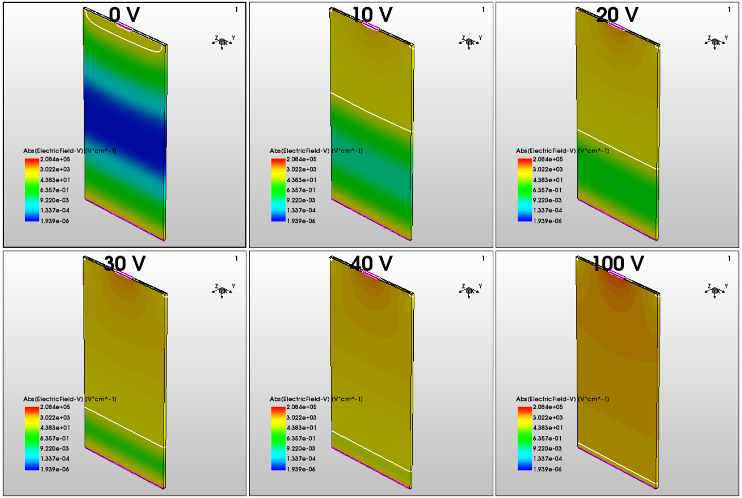


Stitching 150 nm

Stitching 150 nm: E field



Stitching 1 µm: E field



Stitching 150 nm: E field