TCAD Process and device simulation of OVERMOS, a CMOS 180nm MAPS detector

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on behalf of OVERMOS project collaboration

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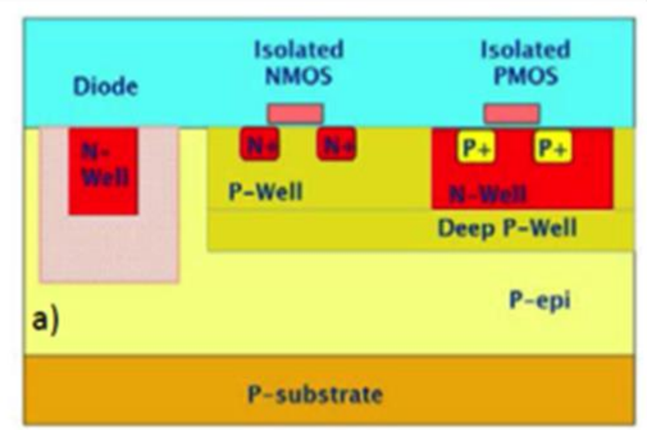
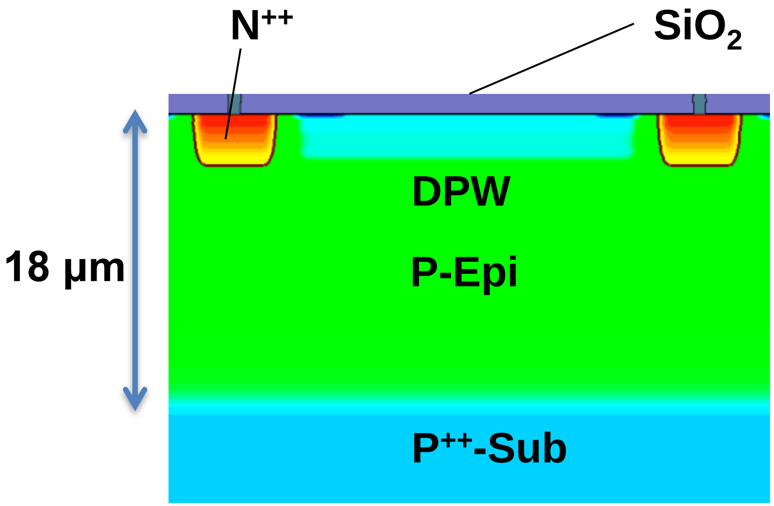
Overview

- OVERMOS description
- Charge collection of OVERMOS using calibrated laser
- TCAD simulation: comparisons of TCAD simulations with irradiated and non-irradiated OVERMOS devices
- Conclusions – next steps

OVERMOS description

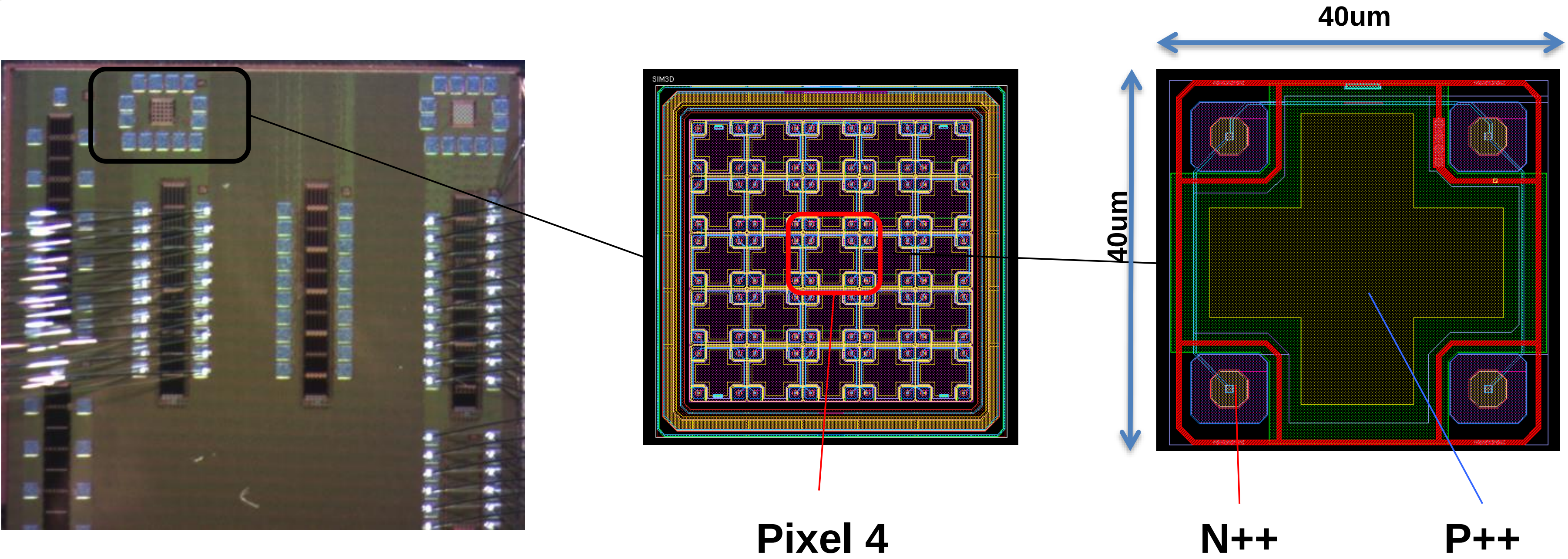




OVERMOS is a CMOS MAPS project demonstrator fabricated using:

- TJ 180 nm Hi-res 18 um thick epitaxial layer 1kOhm –cm
- Small (3.5x3.5 um2) n-collecting nodes
- Multi diode arrangements within pixel
- CMOS DPW ~ originally proposed for DECAL of ILC

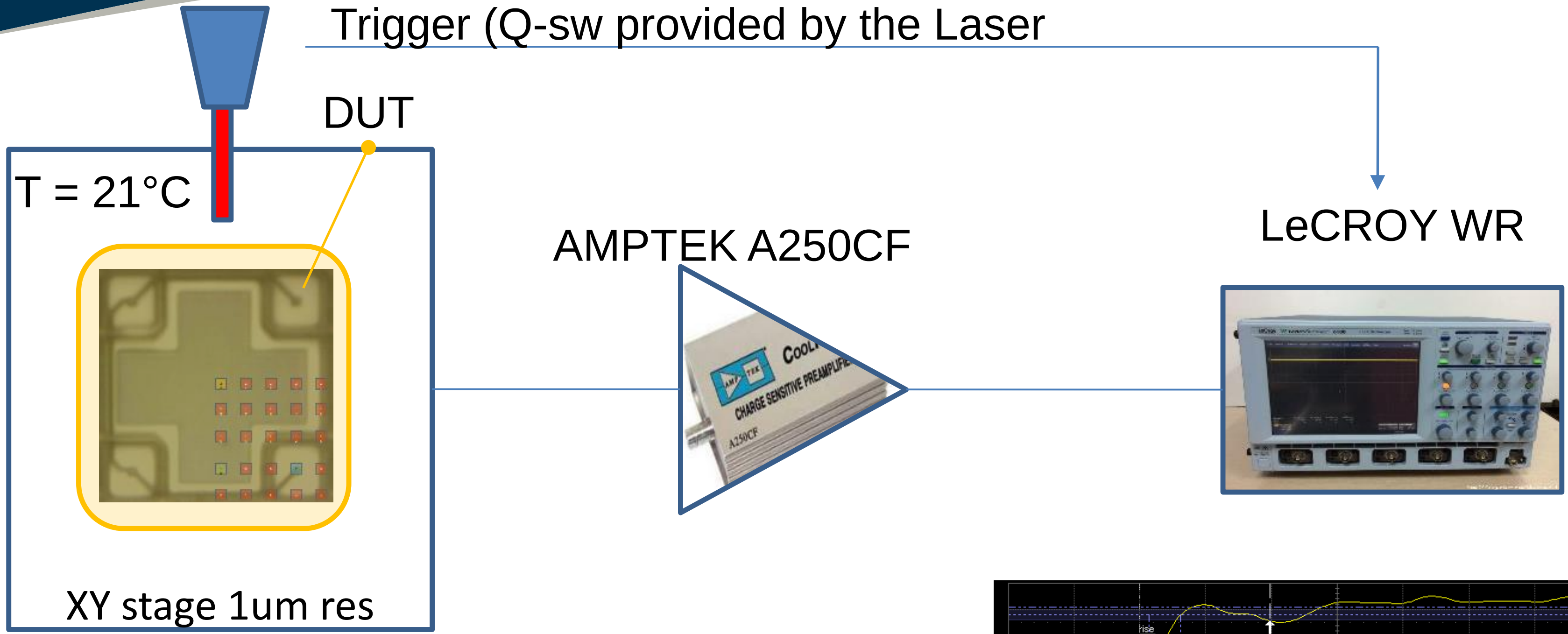
OVERMOS description



- Synopsys TCAD modelling of fabrication process and electrical performances have been carried out to investigate and compare test results with simulations

- OVERMOS devices have been n-irradiated to Φ [1e13,5e13,1e14,5e14,1e15]

OVERMOS Laser Test



Trigger (Q-sw provided by the Laser

DUT

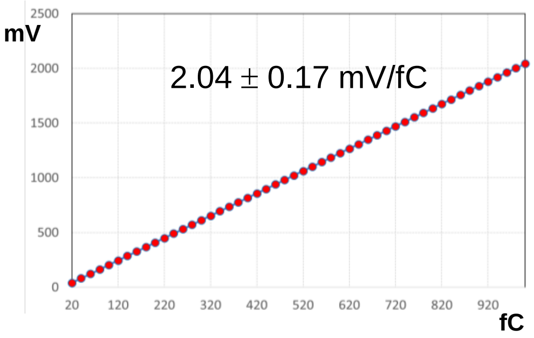
T = 21°C

XY stage 1um res

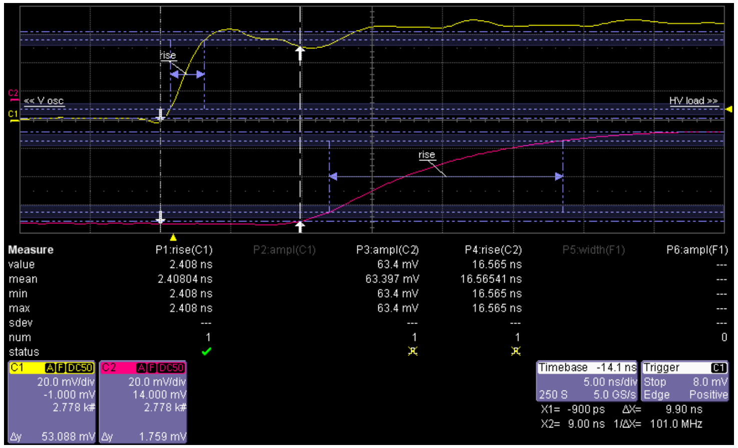
AMPTEK A250CF

LeCROY WR

Nd:YAG Trilite Laser



2.04 ± 0.17 mV/fC



Measure	P1:rise(C1)	P2:ampl(C1)	P3:ampl(C2)	P4:rise(C2)	P5:width(F1)	P6:ampl(F1)
value	2.408 ns		63.4 mV	16.565 ns		---
mean	2.40804 ns		63.397 mV	16.56541 ns		---
min	2.408 ns		63.4 mV	16.565 ns		---
max	2.408 ns		63.4 mV	16.565 ns		---
sdev	---		---	---		---
num	1		1	1		0
status	✓		✗	✗		

C1 A F DC50
20.0 mV/div
-1.000 mV
2.778 k#
Δy 53.088 mV

C2 A F DC50
20.0 mV/div
14.000 mV
2.778 k#
Δy 1.759 mV

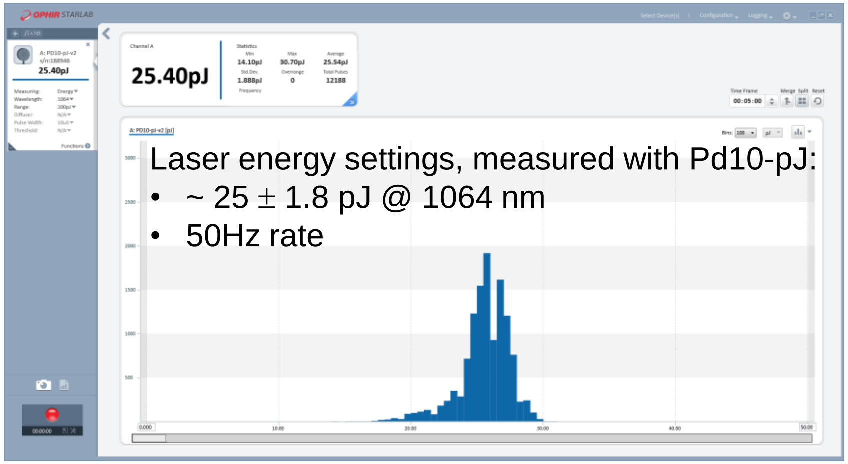
Timebase -14.1 ns
5.00 ns/div
250 S 5.0 GS/s

Trigger C1
Stop 8.0 mV
Edge Positive

X1= -900 ps ΔX= 9.90 ns
X2= 9.00 ns 1/ΔX= 101.0 MHz

OVERMOS Laser Test

Beam size measurement using destructive test



A: PD10-pJ-v2
s/n:188946
25.40pJ

Measuring: Energy
Wavelength: 1064
Range: 200pJ
Diffuser: N/A
Pulse Width: 10uS
Threshold: N/A

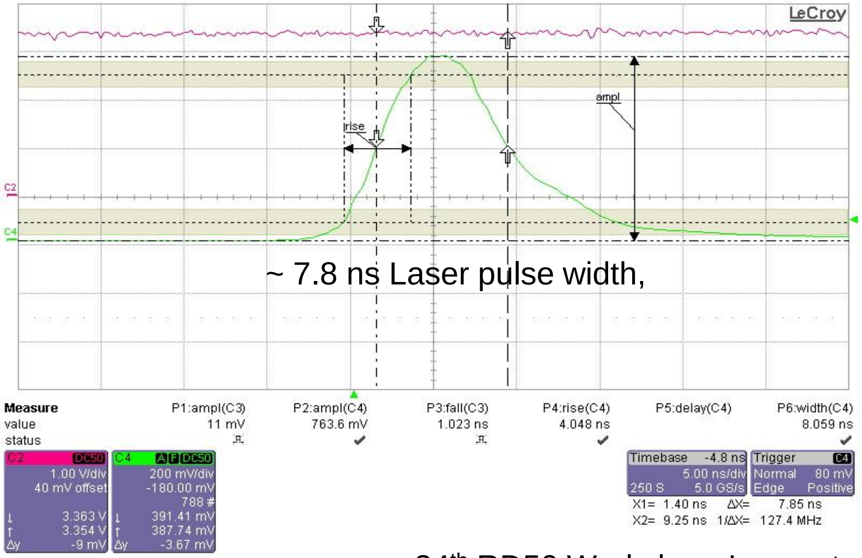
Channel A
25.40pJ

Statistics		
Min	Max	Average
14.10pJ	30.70pJ	25.54pJ
Std.Dev.	Overrange	Total Pulses
1.888pJ	0	12188
Frequency		

A: PD10-pJ-v2 [pJ]

Laser energy settings, measured with Pd10-pJ:

- ~ 25 ± 1.8 pJ @ 1064 nm
- 50Hz rate



~ 7.8 ns Laser pulse width,

Measure	P1:ampl(C3)	P2:ampl(C4)	P3:fall(C3)	P4:rise(C4)	P5:delay(C4)	P6:width(C4)
value	11 mV	763.6 mV	1.023 ns	4.048 ns		8.059 ns
status		✓		✓		✓

C2 DC50
1.00 V/div
40 mV offset
↓ 3.363 V
↑ 3.354 V
Δy -9 mV

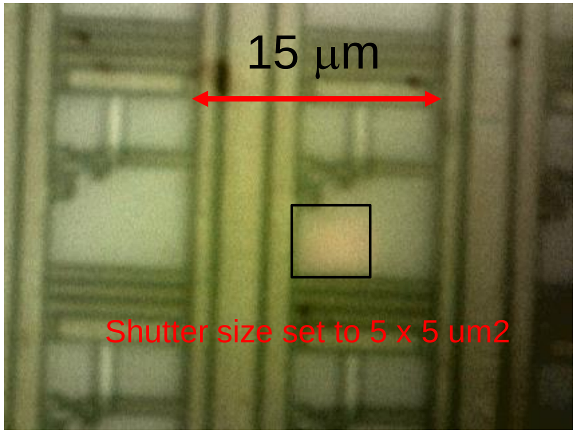
C4 A F DC50
200 mV/div
-180.00 mV
788 #
↓ 391.41 mV
↑ 387.74 mV
Δy -3.67 mV

Timebase -4.8 ns
5.00 ns/div
250 S 5.0 GS/s

Trigger C4
Normal 80 mV
Edge Positive

X1= 1.40 ns ΔX= 7.85 ns
X2= 9.25 ns 1/ΔX= 127.4 MHz

Pre hit

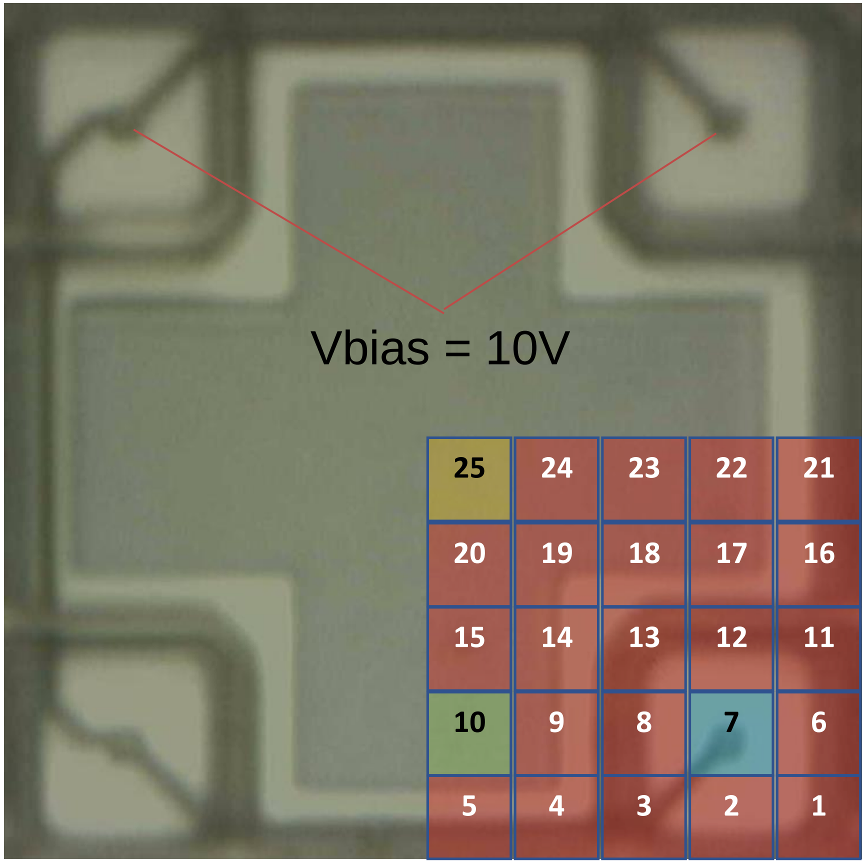


Shutter size set to 5 x 5 um2

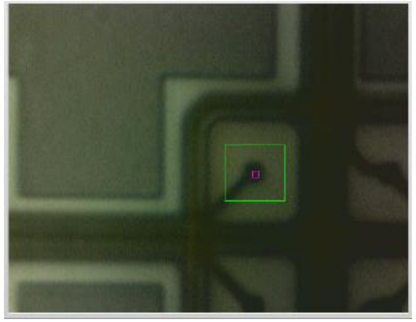
Post hit

OVERMOS Laser Test

OVERMOS

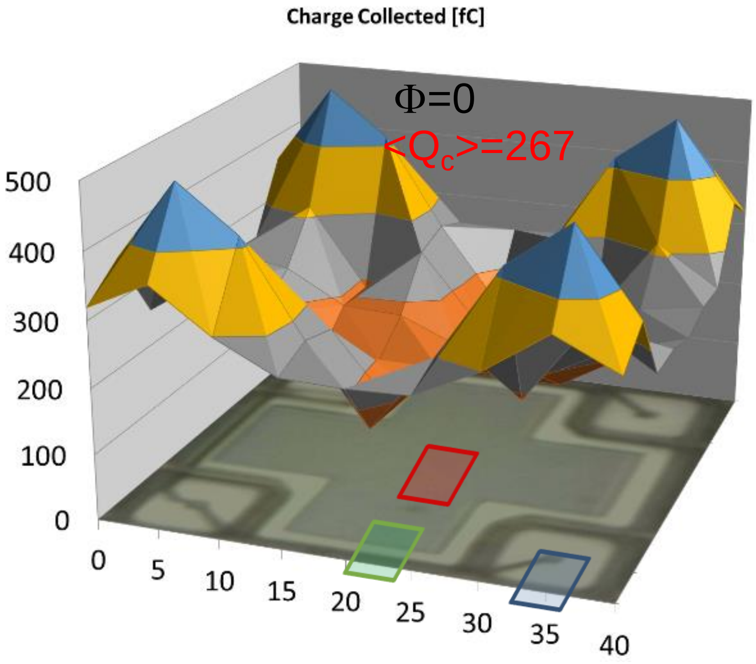


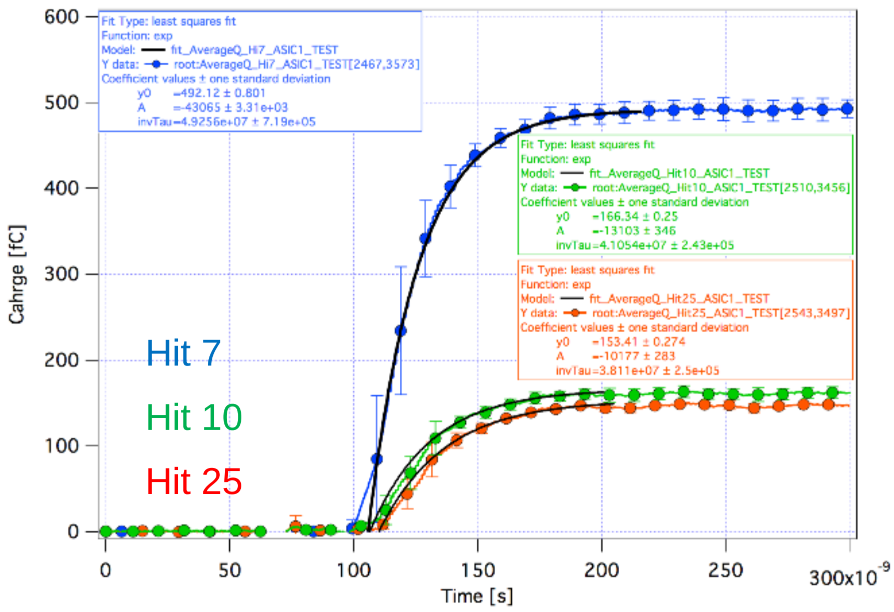
Cu shielded OVERMOS



OVERMOS Laser scan 5 x 5 um2 beam size
25 points, repeated over entire pixel area to give map of collected charge
The kinematics of charge collection of three points (7,10,25) is compared with TCAD simulations for non-irradiated and irradiated devices

OVERMOS Laser Test





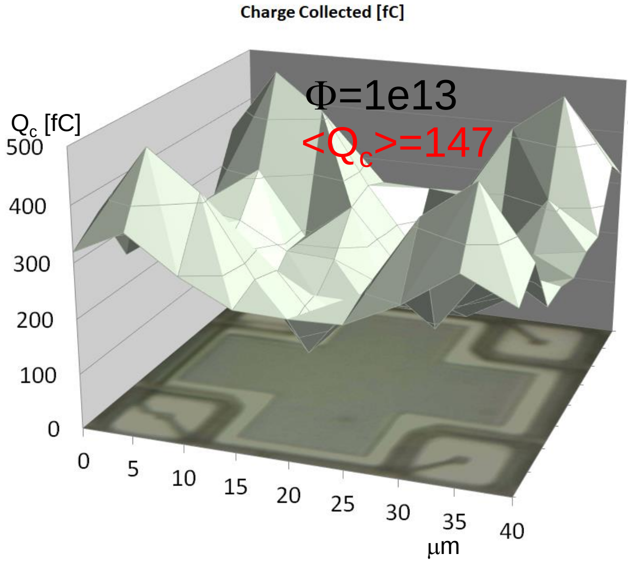
<Q> = 492.1 [fC] Collection time: 44.6±0.36 ns

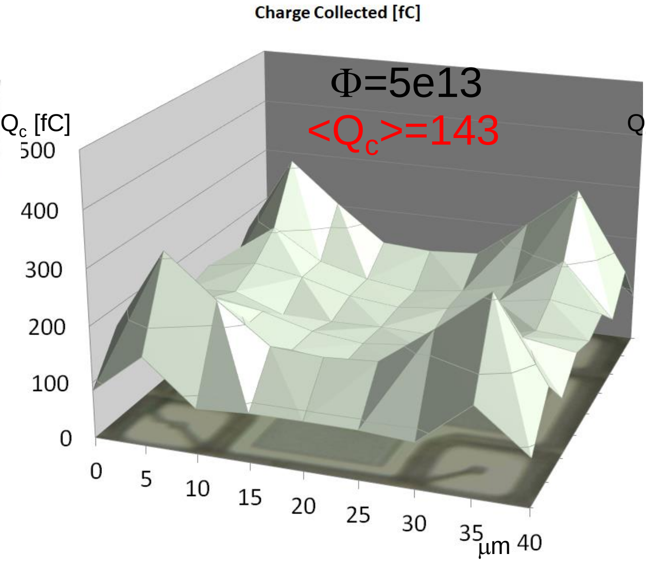
<Q>= 166.34 [fC] Collection time: 53.5±0.31 ns

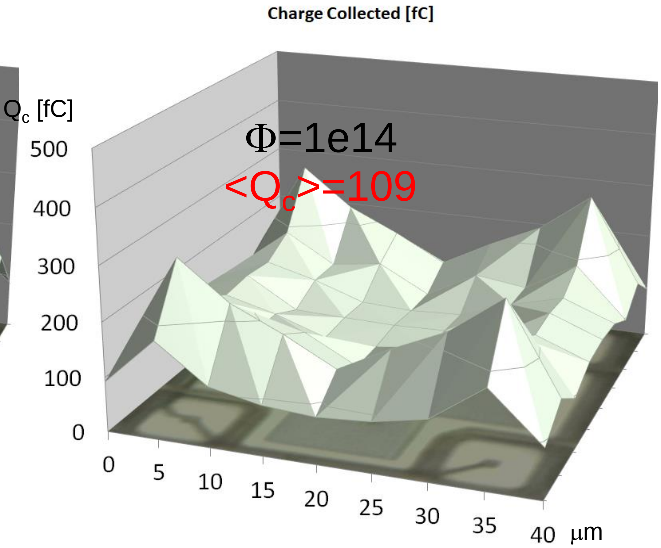
<Q>= 153.4 [fC] Collection time: 57.6±0.52 ns

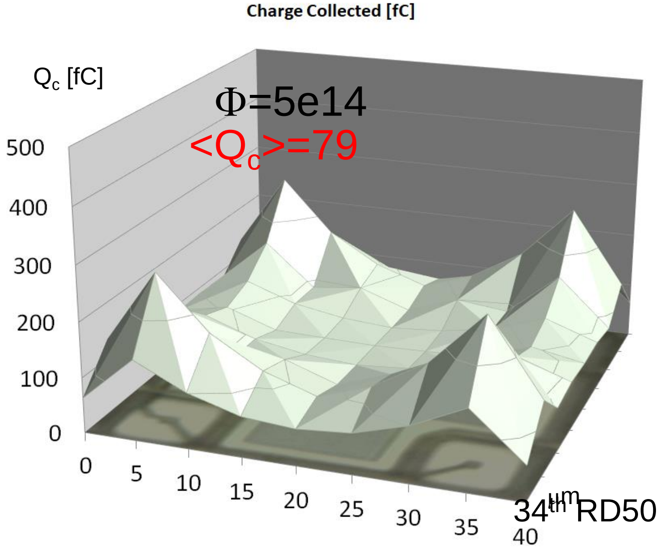
OVERMOS Laser scan 5 x 5 um2 beam size
10 non – irradiated pixels Laser Test results

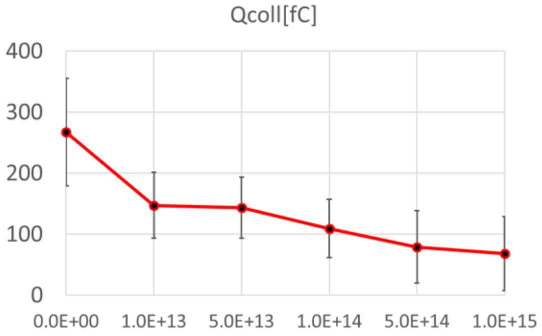
OVERMOS Laser Test

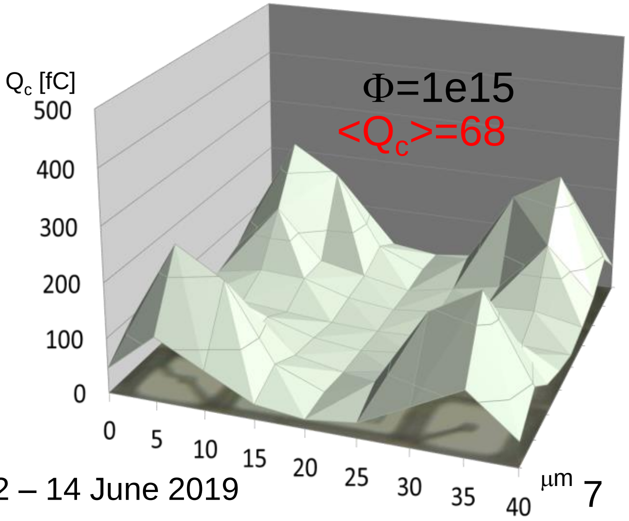






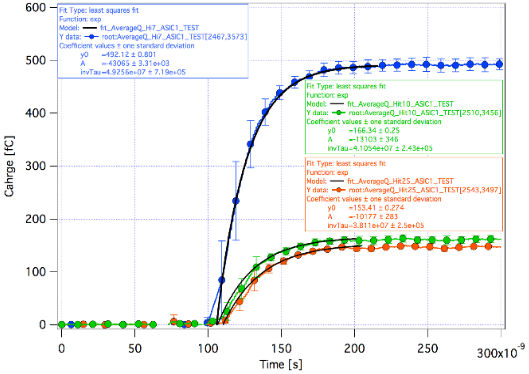




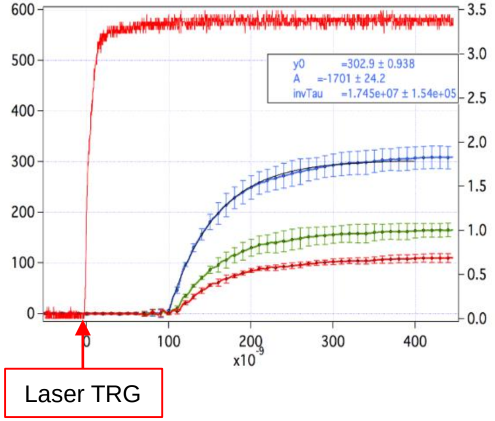


OVERMOS Laser Test

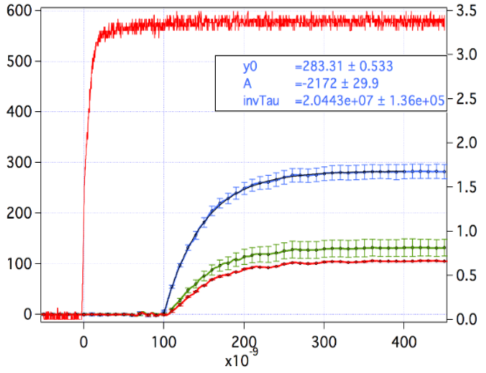
$\Phi=0$



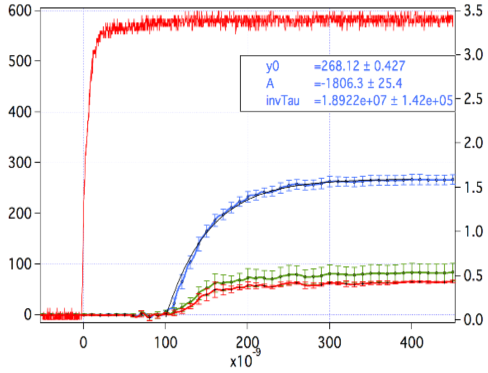
$\Phi=1e13$



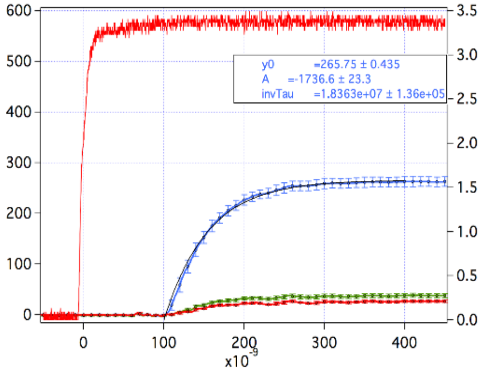
$\Phi=5e13$



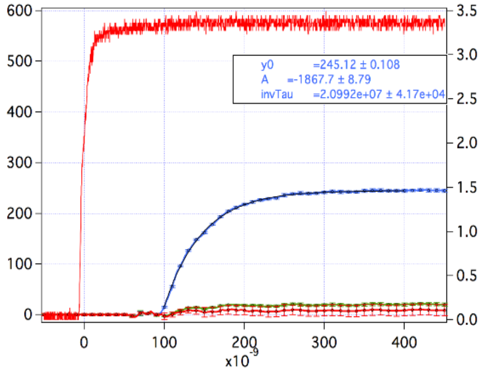
$\Phi=1e14$

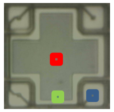


$\Phi=5e14$



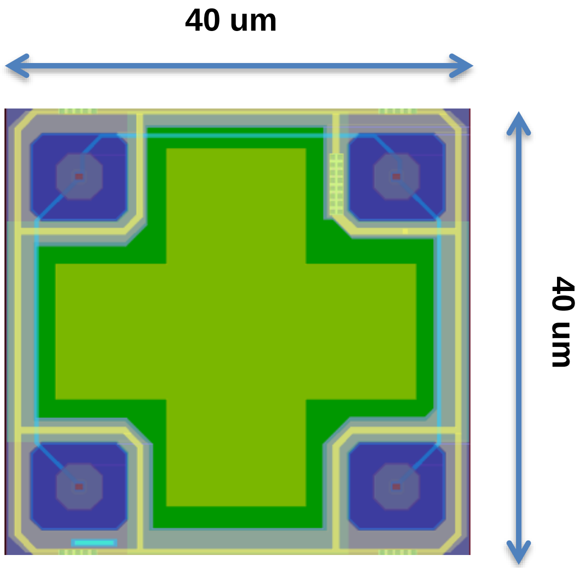
$\Phi=1e15$



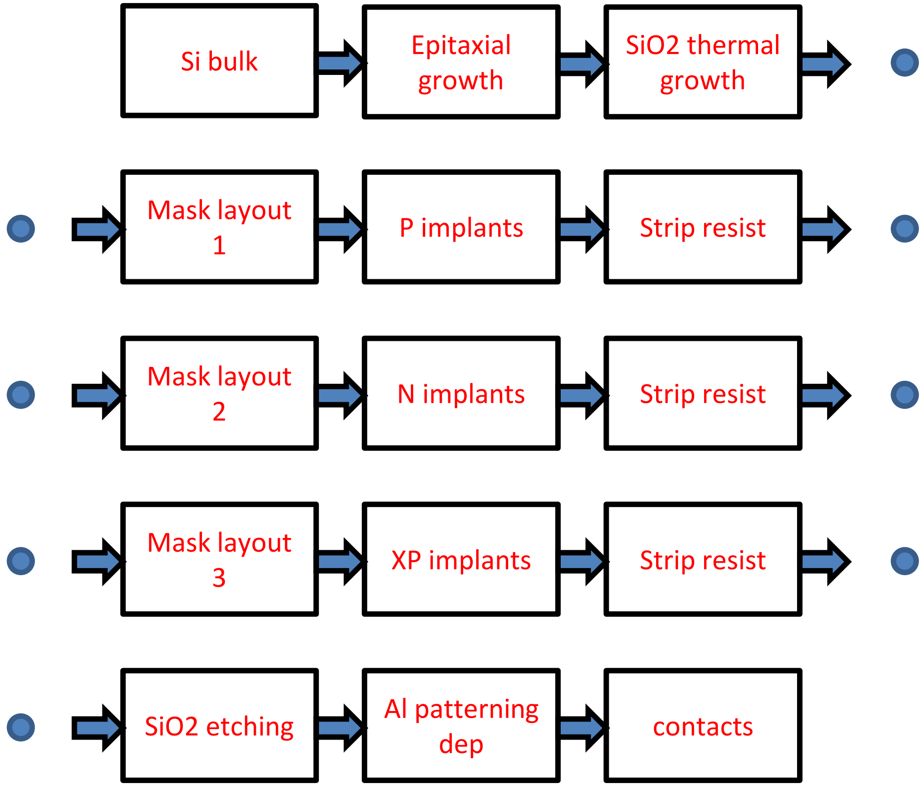


Kinematics of charge collection – fC
Laser beam exits the cavity around 100 ns after the trigger

TCAD simulation



Pixel .gds


Si bulk → Epitaxial growth → SiO2 thermal growth →

→ Mask layout 1 → P implants → Strip resist →

→ Mask layout 2 → N implants → Strip resist →

→ Mask layout 3 → XP implants → Strip resist →

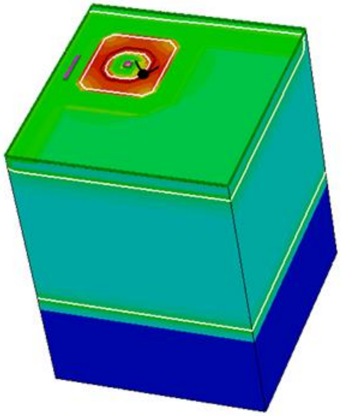
→ SiO2 etching → Al patterning dep → contacts

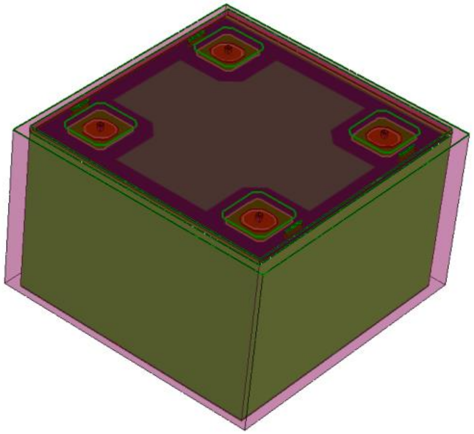
- A simplified TJ CMOS fabrication process of OVERMOS has been implemented in SPROCESS
- Around 15 simulated steps, which include epitaxial growth on Si bulk, SiO2 thermal growth, N/P implant, etching, thermal annealing, metal deposition, contacts placement

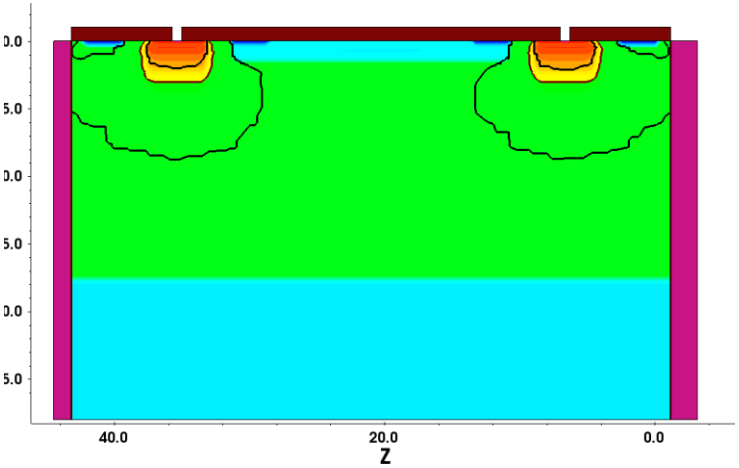
TCAD simulation

🟥 SiO2

🟪 PolySi

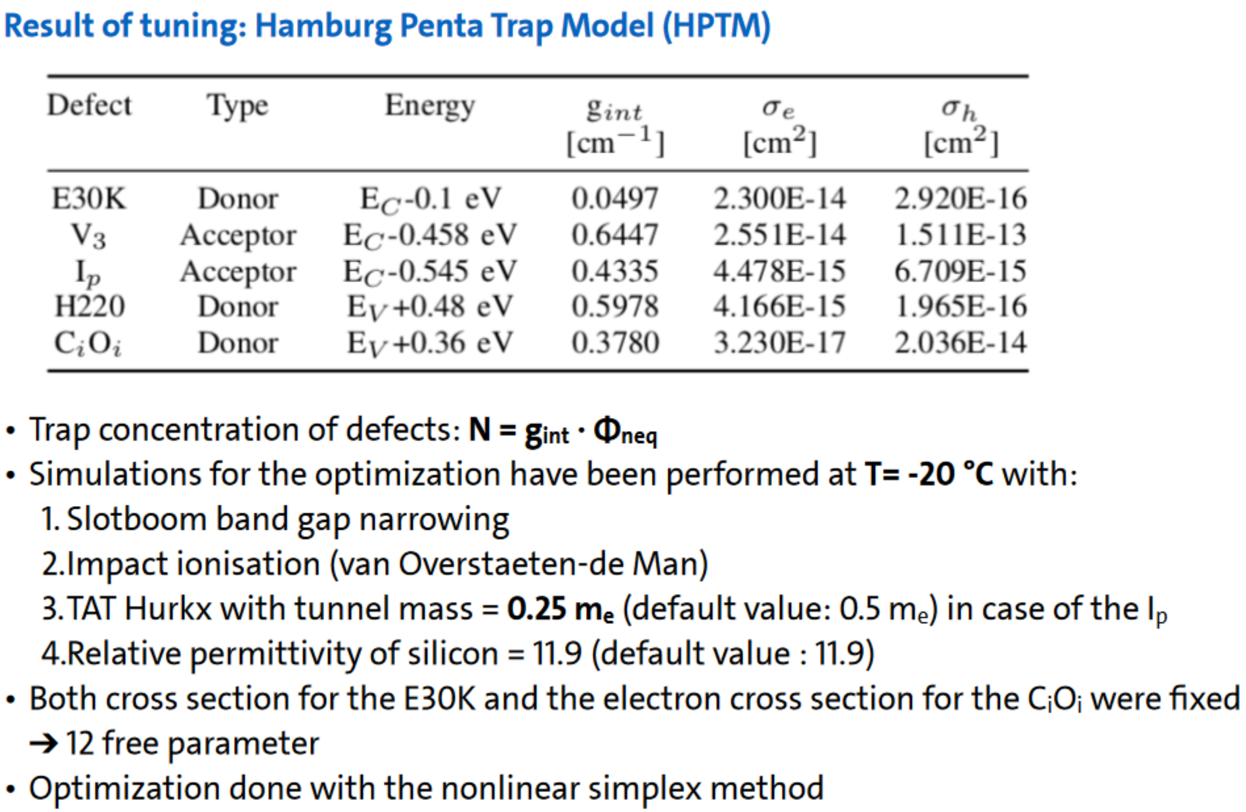






- For DC studies only ¼ pixel is simulated
- For CC studies using Laser light, an extra PolySi box surrounds the pixel, with high SRV to simulate non-reflecting boundaries (added as an SDE directive within SPROCESS)
- Thermally grown 8.1 nm SiO2 for interface traps effects; around 0.2 nm minimum mesh size
- Thick deposited SiO2 for better Delaunay meshing/optical attenuation/reflection (will implement STI next)
- <u>Emulation</u> of CoSi2 silicide for optical attenuation in non-NS regions (will implement silicide growth next)

TCAD simulation
HPTM



Result of tuning: Hamburg Penta Trap Model (HPTM)

Defect	Type	Energy	g_{int} [cm^{-1}]	σ_e [cm^2]	σ_h [cm^2]
E30K	Donor	E_C-0.1 eV	0.0497	2.300E-14	2.920E-16
V_3	Acceptor	E_C-0.458 eV	0.6447	2.551E-14	1.511E-13
I_p	Acceptor	E_C-0.545 eV	0.4335	4.478E-15	6.709E-15
H220	Donor	E_V+0.48 eV	0.5978	4.166E-15	1.965E-16
C_iO_i	Donor	E_V+0.36 eV	0.3780	3.230E-17	2.036E-14

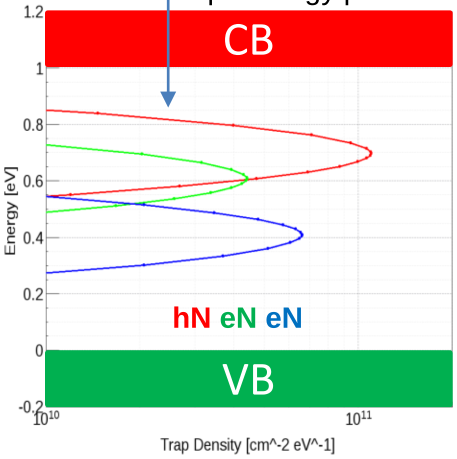
- Trap concentration of defects: **$N = g_{int} \cdot \Phi_{neq}$**
- Simulations for the optimization have been performed at **T= -20 °C** with:
  1. Slotboom band gap narrowing
  2. Impact ionisation (van Overstaeten-de Man)
  3. TAT Hurkx with tunnel mass = **0.25 m_e** (default value: 0.5 m_e) in case of the I_p
  4. Relative permittivity of silicon = 11.9 (default value : 11.9)
- Both cross section for the E30K and the electron cross section for the C_iO_i were fixed
  ➔ 12 free parameter
- Optimization done with the nonlinear simplex method

- A factor 1.66 has been applied to g_{int} to account for n irradiation

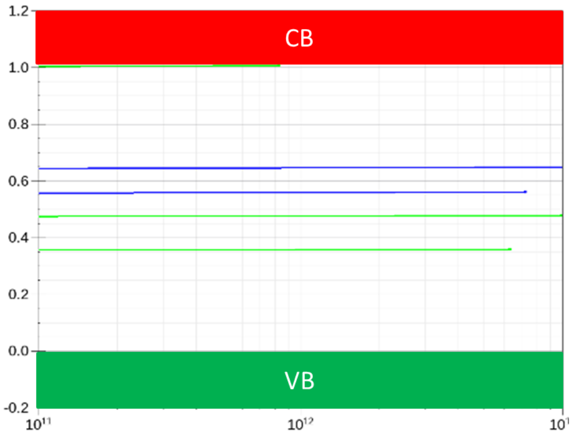
TCAD simulation

DLN=30

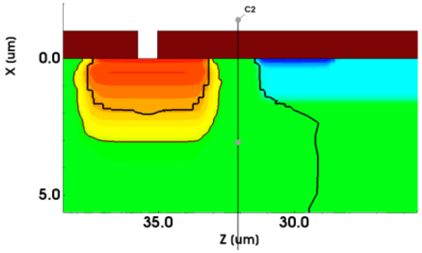
Interface traps energy plot

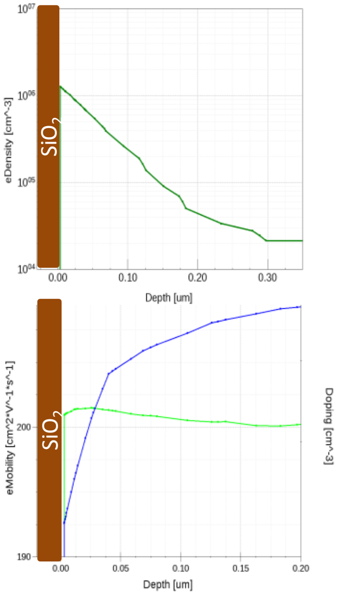


Bulk traps energy plot



1.2e11 Oxch
[0.007,10,10]





Interface Defect	Level	Concentration	σ
Acceptor	E_C-0.4 eV	40% of acceptor N_{IT} ($N_{IT}=0.85\cdot N_{OX}$)	0.07 eV
Acceptor	E_C-0.6 eV	60% of acceptor N_{IT} ($N_{IT}=0.85\cdot N_{OX}$)	0.07 eV
Donor	E_V+0.7 eV	100% of donor N_{IT} ($N_{IT}=0.85\cdot N_{OX}$)	0.07 eV

Fixed oxide-charge (**Oxch**) density and interface traps (**Oxint**) included

Interface traps distributed among 3 energy levels, Gaussian , σ = 70meV

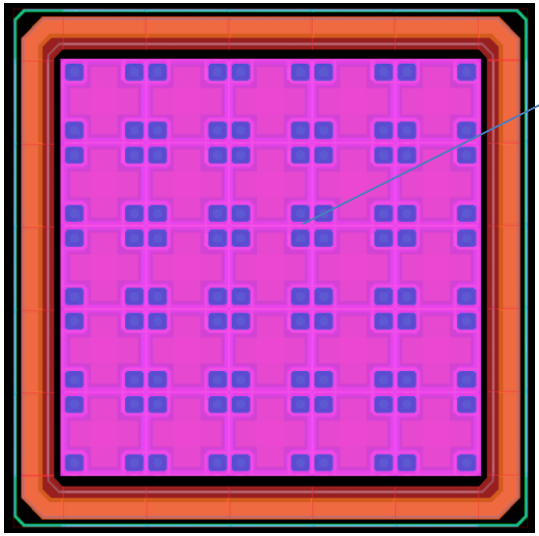
Ratio Oxint/Oxch ~ 0.9

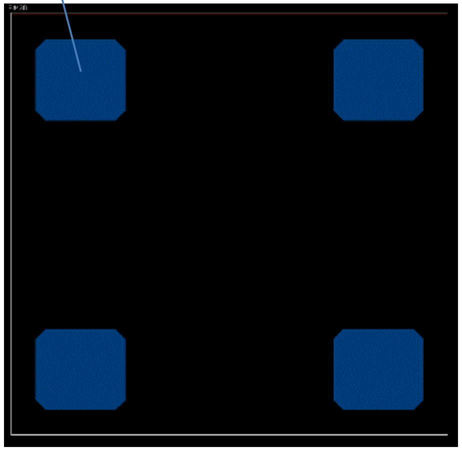
Simulations 1.2e11 Oxch

Xsection 1E-15 cm^-2

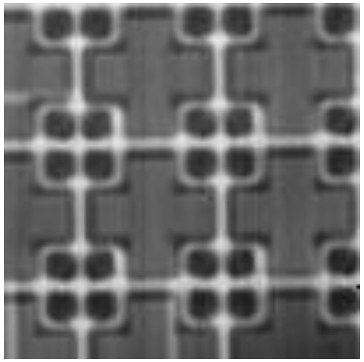
* ***Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC***, *DOI:* 10.1109/TNS.2017.2709815

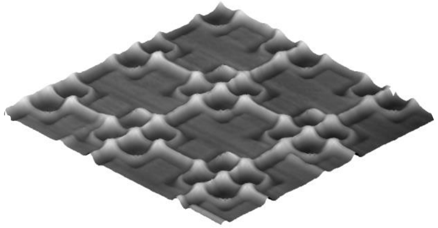
TCAD simulation





Non − silicide

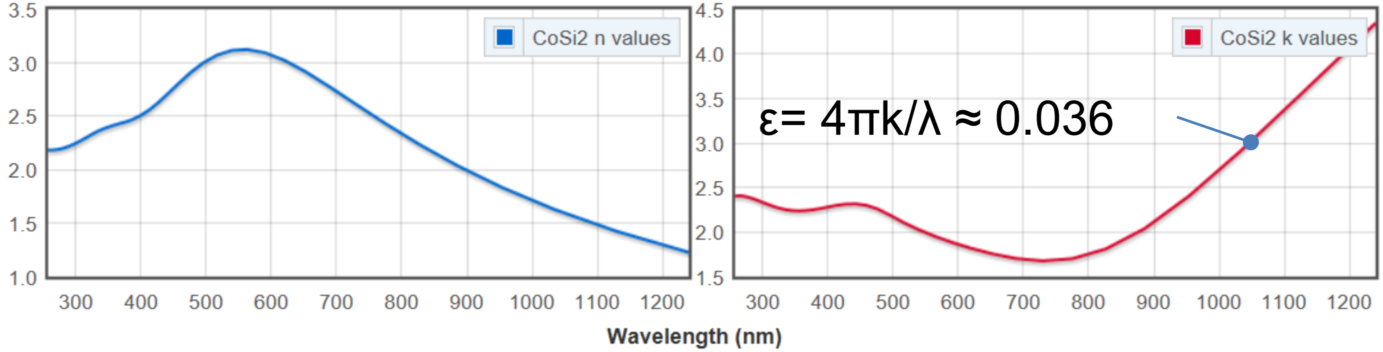




TJ 180nm SL uses $CoSi_2$ for lower delay lines
$CoSi_2$ attenuates light, reducing generated charge
Scanning using confocal microscope revealed ‘height differences’ with respect to non−NS regions

TCAD simulation

ε of CoSi2



$\varepsilon = 4\pi k/\lambda \approx 0.036$

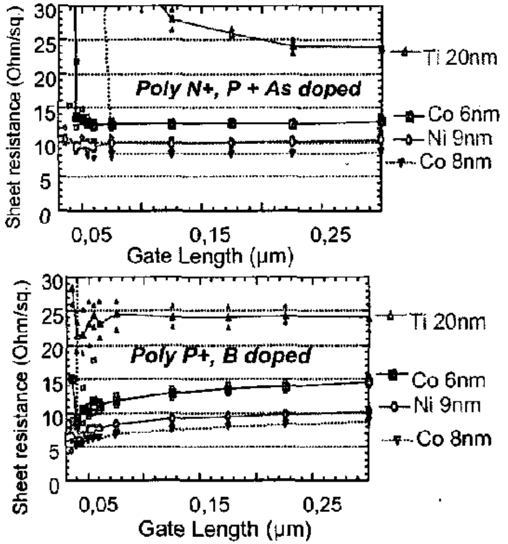


Figure 7: Poly N+ doped (top) and P+ doped (bottom)

$CoSi_2$: Actual attenuation at 1064 nm depends on real CoSi2 thickness
~ inferred from TJ STEM
<u>Assumed to be 40 nm</u>

$$\exp(-0.036*40) \approx 0.23$$

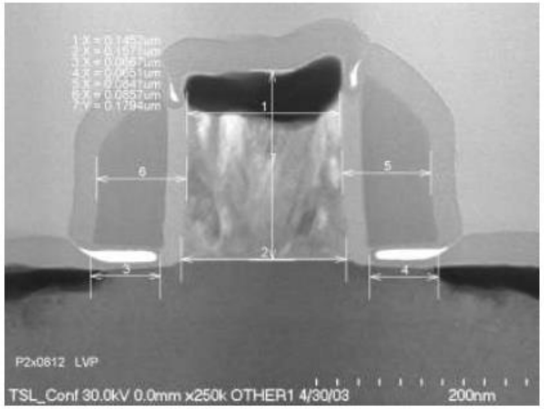
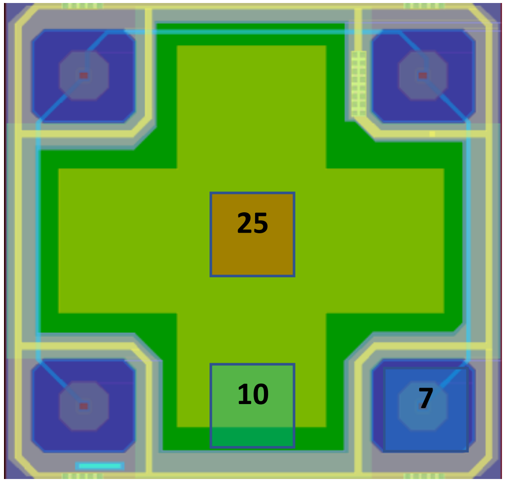


Figure 5.2-3 – STEM, LVP – L/W draw = 0.18/10 um

TCAD simulation

SiO2: For normal incidence $$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2$$

And transmitted: 1- R @ λ = 1064 nm, n_2=1.4469   R = 3.3%, T =96.6%, k = 0
Small attenuation through SiO2, around 96.6 % of Light transmitted



Attenuation through SiO2 only in NS regions (7) and through SiO2-CoSi2 in others (10,25)

TCAD simulation

Physics models: SDEVICE parameters for Optical generation

- OpticalGeneration (QuantumYield (StepFunction (EffectiveBandgap))
- ComplexRefractiveIndex (CarrierDep(Imag) WavelengthDep(Imag)) * extinction coeff. only
- OpticalSolver (OptBeam (LayerStackExtraction (WindowName = "LaserW“ Position = (0, Y_hit, Z_hit) Mode = ElementWise * Laser window of 5 x 5 um2, centre position retrieved from .gds, default NumberOfCellsPerLayer

- Wavelength= 1.064 * Incident light wavelength [um]
- Intensity= @<20000.0*exp(-0.036*@Silicide_Thick@)*0.966>@
- PolarizationAngle= 0 Theta= 90 Phi = 0

➢ Manually estimated expected charge from $\mathrm{n} = (1-R)(1-e^{-\alpha zmax})\frac{P}{h\nu z_{max}}$ ~416fC

For z_{max}=20 [µm], R = 0.966 (SiO_2 attenuation only , i.e. hit 7)

TCAD simulation

Physics models: SDEVICE parameters for mobility and recombination

- Temperature = 21°C
- Fermi
- SRH (DopingDep,TempDep, ElectricField (Lifetime = Hurkx)
- Mobility(PhuMob Enormal (Lombardi PosInterfaceCharge)
- HighFieldSaturation(EParallel)
- RefDens_eEparallel_ElectricField_HFS= 1e17
- UniBo for impact ionization (incl. Auger, Eparallel)
- Same RefDens for interpolation of Fava to F
- Excluded flat elements by increasing TOX (or using FlatElementExclusion)

Math models

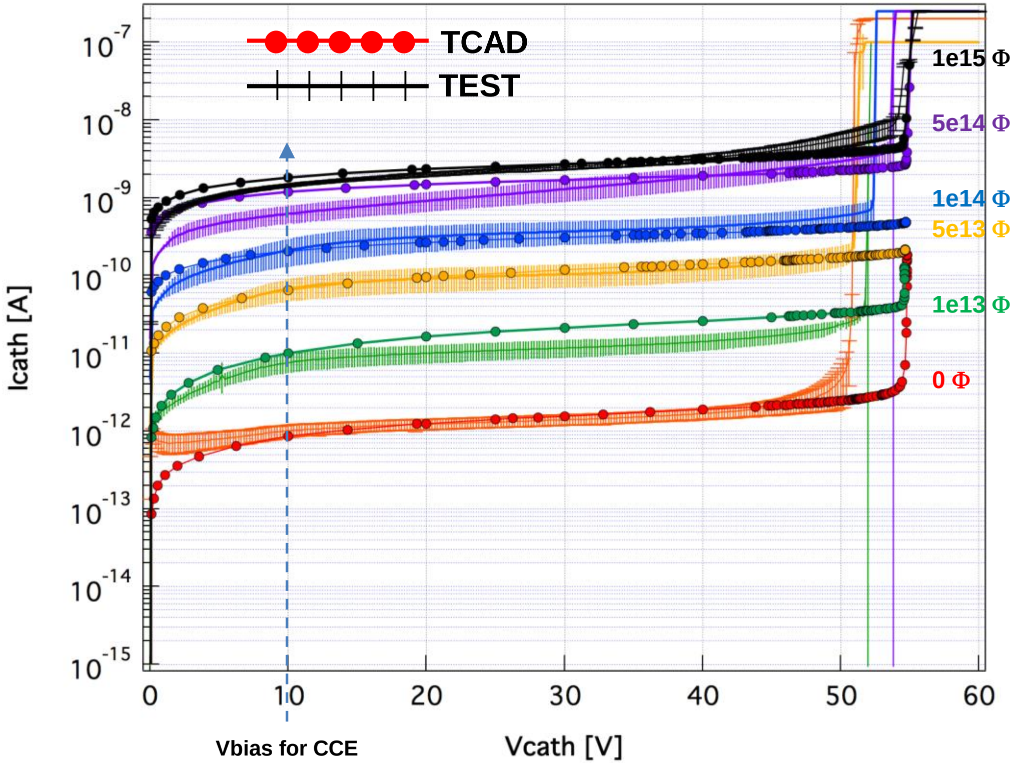
- ILS[iterative (gmres(120), tolrel= 1.0e-8, tolunprec=1e-4, tolabs=0, maxit=200)]
- ParallelToInterfaceInBoundaryLayer(FullLayer -ExternalBoundary)
- Geometricdistances **at interfaces*
- e/hMobilityAveraging=ElementEdge * *for interface mobility degradation*)
- TrapsDLN=30
- Traps(Damping=100)
- At high fluences (1e15) Explicit traps filling at the beginning of transient simulation, then ‘unfreezing’ before charge injection (longer initial transients)

TCAD simulation IV

DC IV plots up to BV

<IV>[10] measured OVERMOS + σ

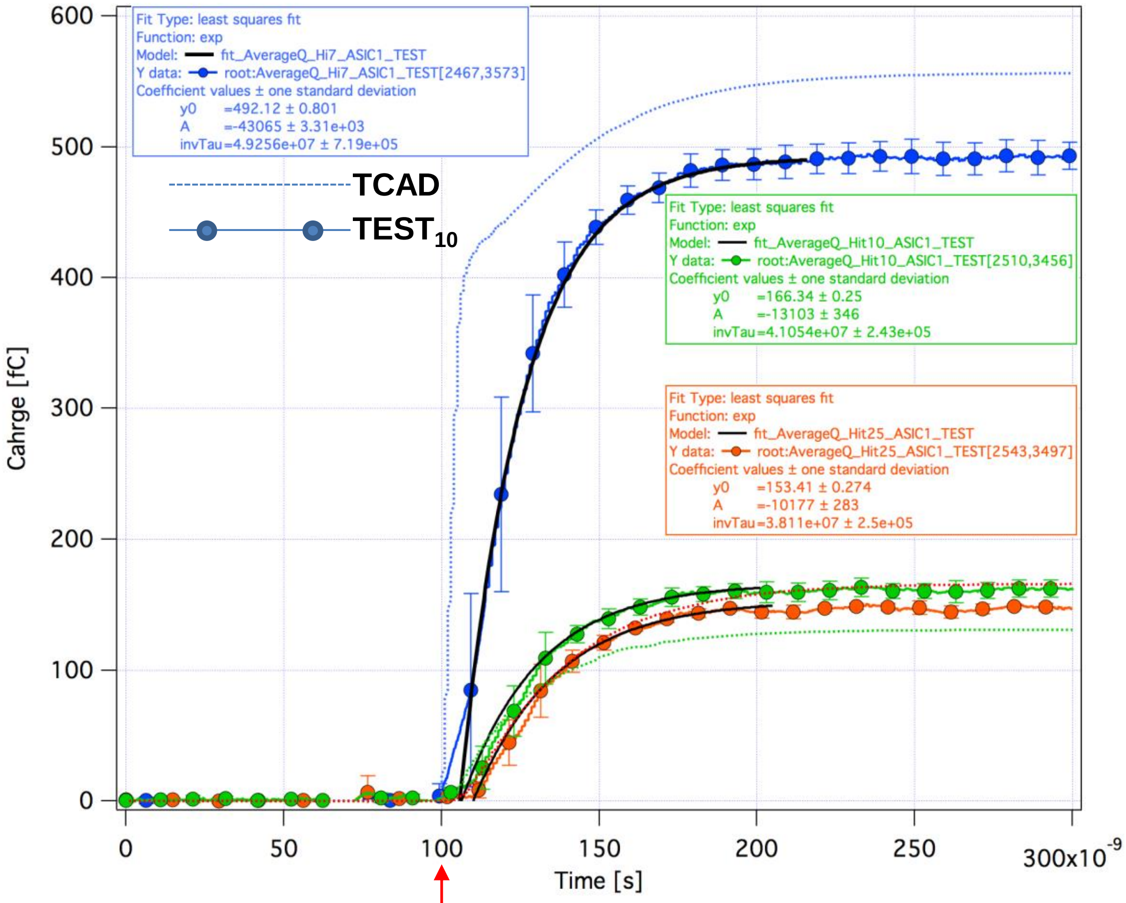
IV TCAD Oxch 1.2e11, OxINT 1.1e11



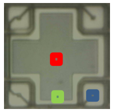
Φ	I_{leak_μ}[A] @10V	I_{leak_TCAD}[A] @10V	Δ%	$^{a}BV_{\mu}$[V]	BV_{TCAD}[V]
0	1.0e-12	0.85e-12	15	50.8	54.79
1e13	7.5e-12	1e-11	-33.3	52	54.6
5e13	6.72e-11	7.47e-11	-11.1	51.2	54.7
1e14	2.1e-10	2.06e-10	1.9	52.4	54.7
5e14	6.21e-10	1.18e-9	-90	53.6	54.8
1e15	1.43e-9	1.83e-9	-28	54.4	54.8

^{a}BV defined as V: $(\Delta I/\Delta V)_{max}$

TCAD simulation CC



Laser Hit

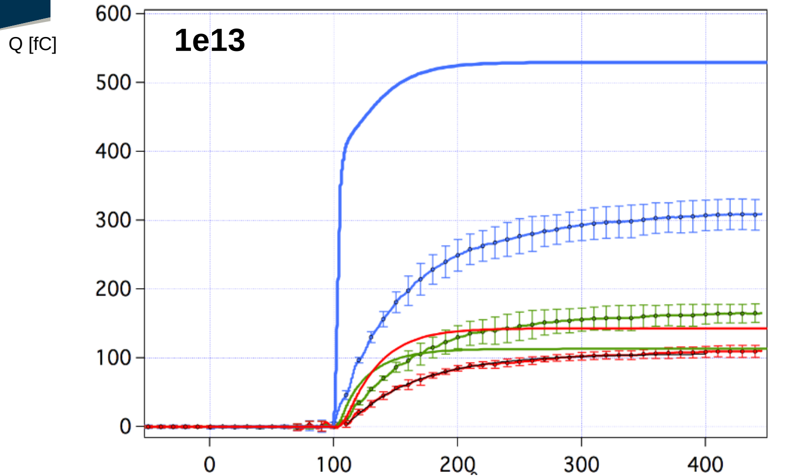


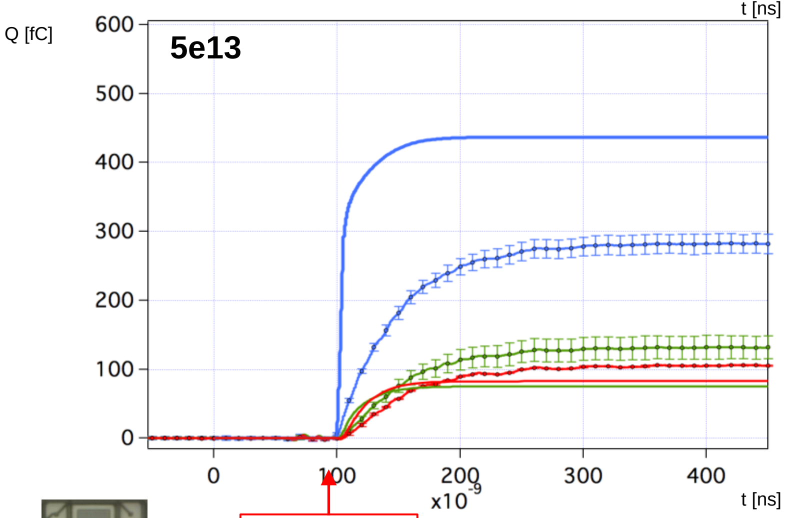
Q_{coll}	Test	TCAD	Δ%
<Qh7>	492	556	**-13**
<Qh10>	166	131	**21**
<Qh25>	153	166	**-8.4**

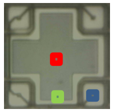
$T_{coll10-90}$	Test	TCAD	Δ%
$<t_{coll}h7>$	44.6	45.2	**1.3**[a]
$<t_{coll}10>$	53.5	59.9	**12**[b]
$<t_{coll}25>$	57.6	68	**18**[c]

[a] hit7 with CA delay subs: 9.1%
[b] hit10 with CA delay subs: 17.7%
[c] hit25 with CA delay subs: 23.3%

TCAD simulation





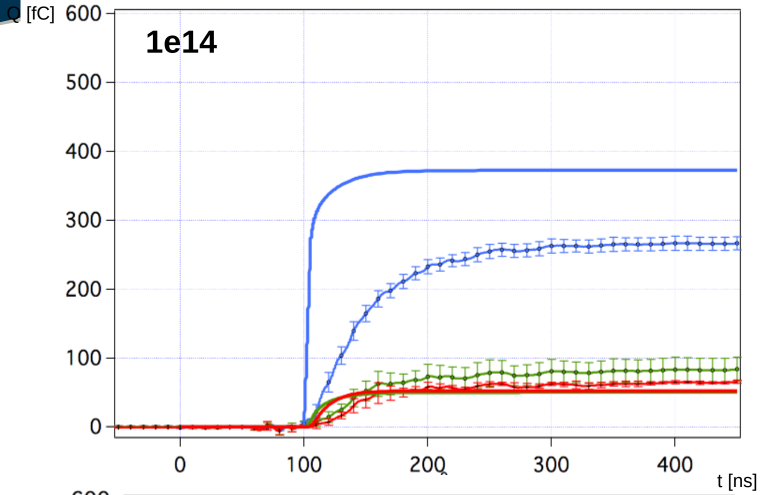


Laser Hit

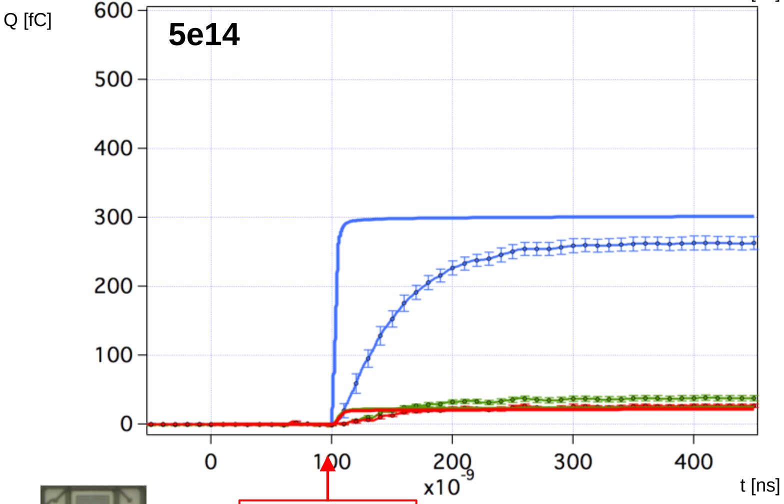
Q_{coll}	Test	TCAD	Δ%
<Qh7>	309	529	**-71**
<Qh10>	165	113	**31**
<Qh25>	110	143	**-30**

Q_{coll}	Test	TCAD	Δ%
<Qh7>	282	437	**-54**
<Qh10>	132	75	**43**
<Qh25>	106	82	**22**

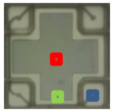
TCAD simulation



Q_{coll}	Test	TCAD	Δ%
<Qh7>	265	373	**-40**
<Qh10>	82	51	**37**
<Qh25>	65	53	**18**

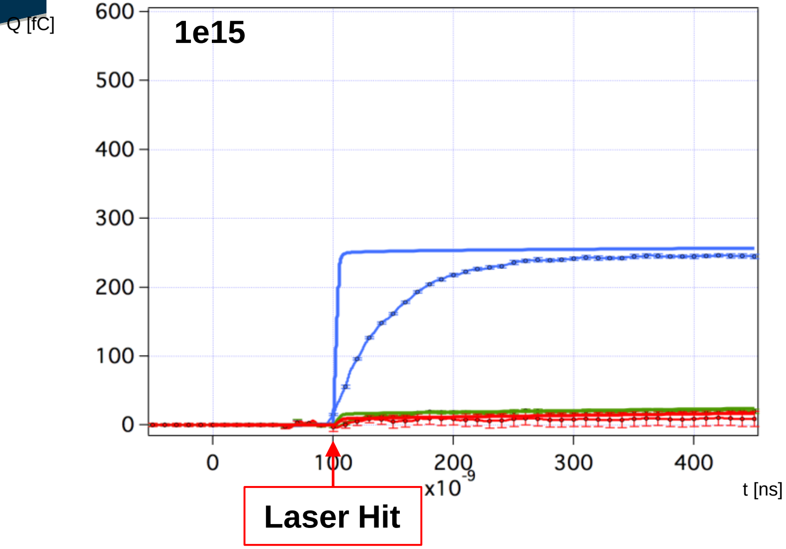


Q_{coll}	Test	TCAD	Δ%
<Qh7>	263	301	**-14**
<Qh10>	38	24	**-36**
<Qh25>	27	23	**-14**

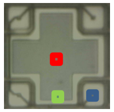


Laser Hit

TCAD simulation



Q_{coll}	Test	TCAD	Δ%
<Qh7>	246	257	**-4**
<Qh10>	21	24	**-14**
<Qh25>	10	17	**70**



RD50 funding request

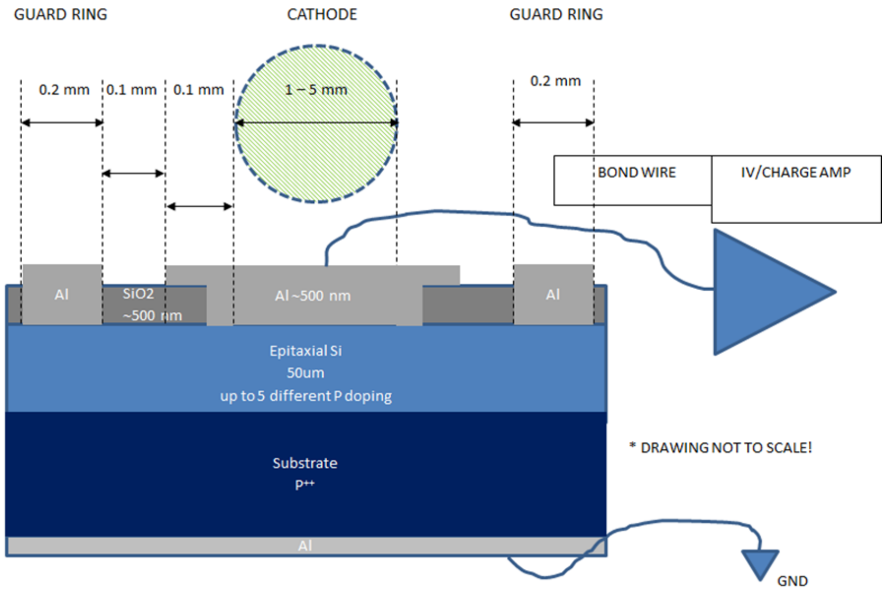
1. RAL PPD, UK
2. IHEP, China
3. JSI, Slovenia
4. University of Birmingham, UK

We propose to fabricate a number of Schottky and n+p diodes on p-type epitaxial (50um thick) silicon wafers, of doping concentration as they are normally used in CMOS MAPS devices, to investigate radiation bulk damage in CMOS sensors

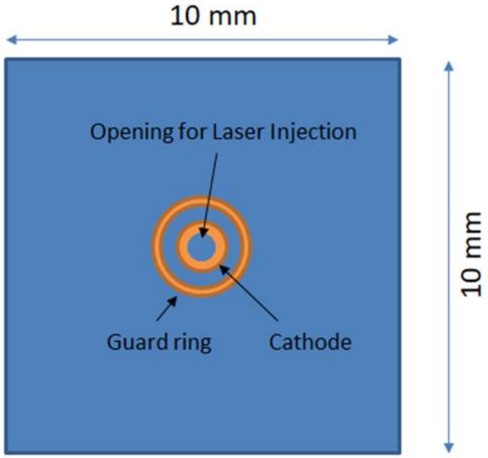
The purpose is to gain a deep understanding of radiation damage in such structures with a view to develop reliable damage models that can be implemented in TCAD device simulators (Synopsys or Silvaco).

We will purchase 6 inch wafers, 25 x 5 doping levels (1e13, 1e14, 1e15, 1e16 and 1e17 cm^{-3}), total **125 wafers**.
The remaining wafers, upon agreement, could be distributed among other groups and/or RD50 institutes interested in participating in this project, whether at device design and/or at device test level

Conclusion

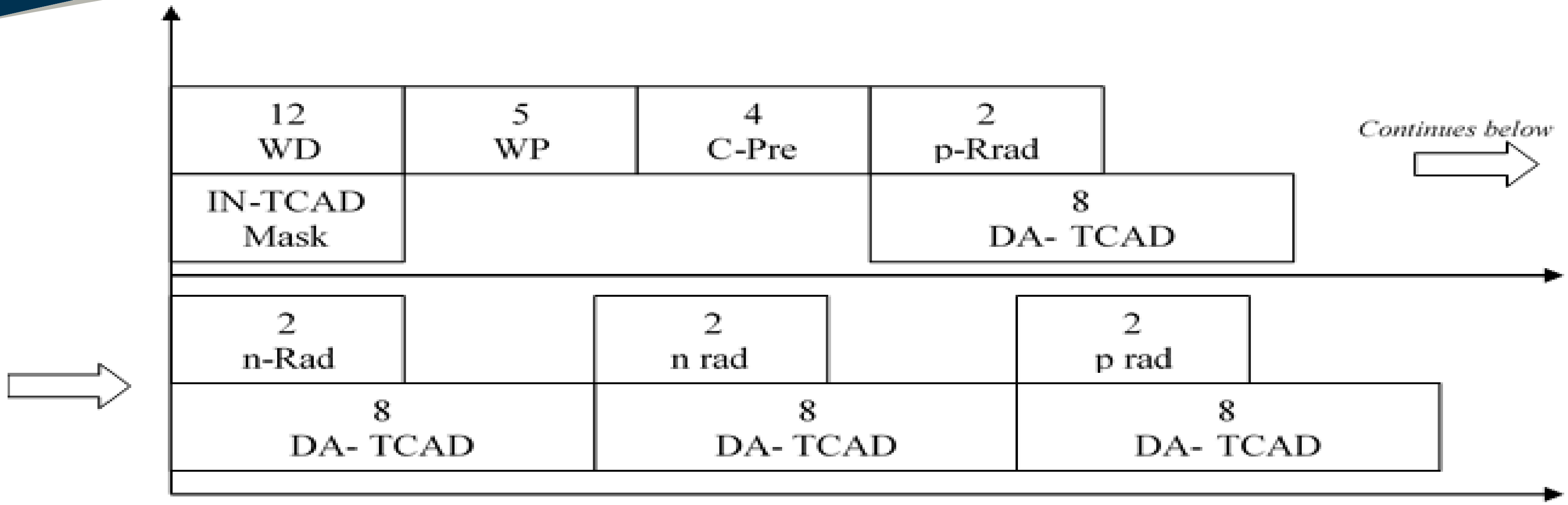


* DRAWING NOT TO SCALE!



Wafers purchase through IHEP
Schottky devices fabrication and modelling will take place at RAL, UK
N+P junctions fabrication at Carleton University, Canada
Neutron irradiation and tests at JSI
Proton irradiation at Birmingham

Conclusion



WD: delivery of Silicon wafers
IN-TCAD: initial TCAD simulation
WP: processing of an initial 10 wafers
C-Preelectrical and CCE characterization and comparison with TCAD;
p-Rad/ n-Rad: DUTs p/n irradiation (passive and online)
DA-TCAD: data analysis

The total duration of the project is estimated at ~53 weeks.

If interested please get in touch!

Conclusion

- Measured IV characteristics of non-irradiated and irradiated OVERMOS up to Breakdown

- Measured CC characteristics of non-irradiated and irradiated OVERMOS using laser injection

- TCAD 3D simulations using a simplified device obtained using SPROCESS. The SPROCESS scripts allow simulation of devices fabricated using TJ 180nm SL (diodes, MOSFETs)

- TCAD simulations of non-irradiated OVERMOS seem to reproduce well experimental results, both in DC and in CC, with maximum discrepancy of the order of ~20%

- Implementation of HPTM in TCAD, up to n-fluences of 1e15 cm-2. Bigger discrepancies observed for TCAD simulations of irradiated OVERMOS w.r.t. experimental results, both in DC and in CC (< factor of 2)

THANK YOU

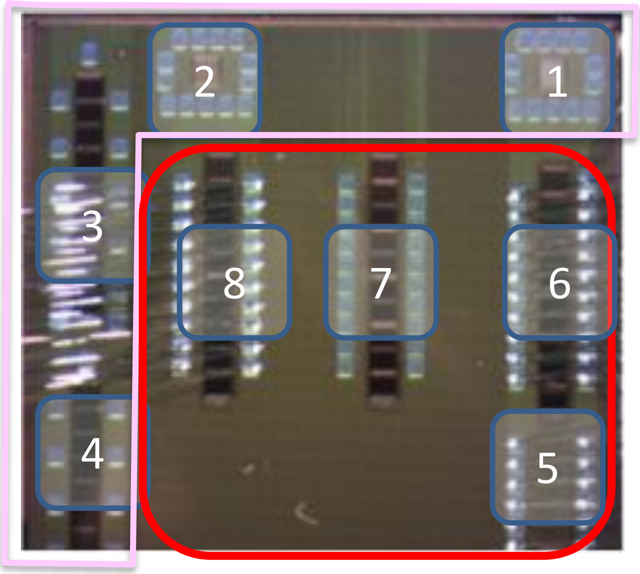
BACKUP

2: Basic Passive: 5x5 of 40 x 40 um

3: Basic Passive Large: 5x5 of 40 x 400 um merged

4: Basic Passive Large: 5x5 of 40 x 400 um

PASSIVE



1: Symmetric Passive: 5x5 of 40 x 40 um

8: Basic Active Large 5x5 of 40 x 400 um

7: Basic Active Large Merged 5x5 of 40 x 400 um

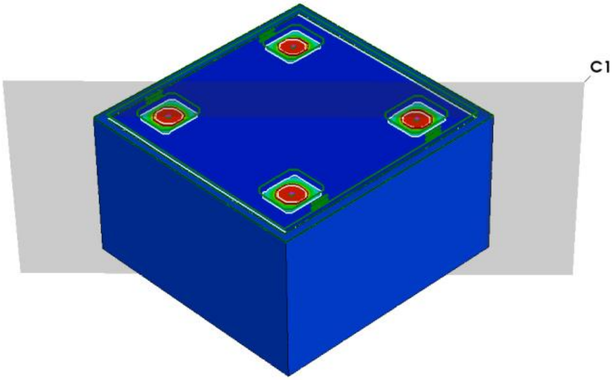
6: Basic Active AC Large 5x5 of 40 x 400 um independent diode biasing AC coupled

5: Basic Active: 5x5 of 40 x 40 um

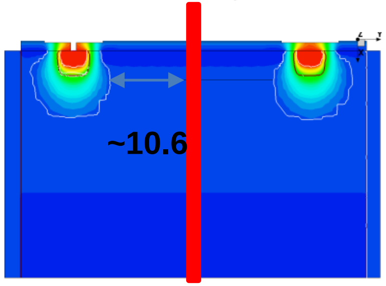
ACTIVE

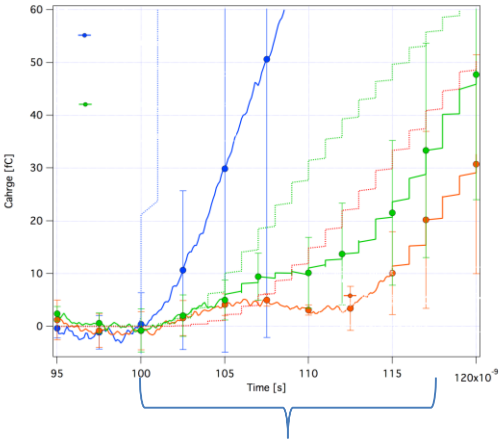
- The PASSIVE pixels feature different arrangements of the collecting nodes, still of the same size (4 x 4 um2)
- The ACTIVE pixels, i.e. with in-pixel electronics, all allow analogue readout of the pixels

BACKUP



Hit 25

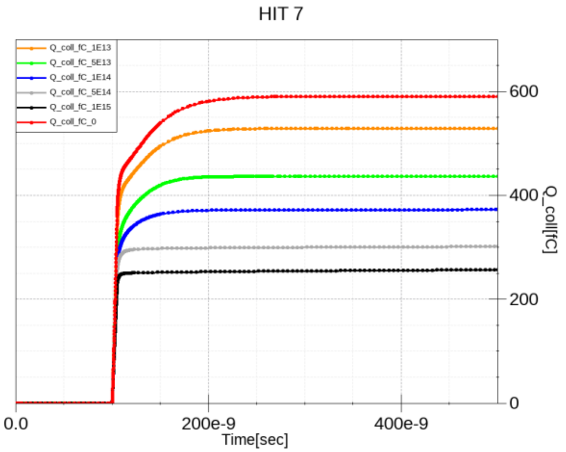




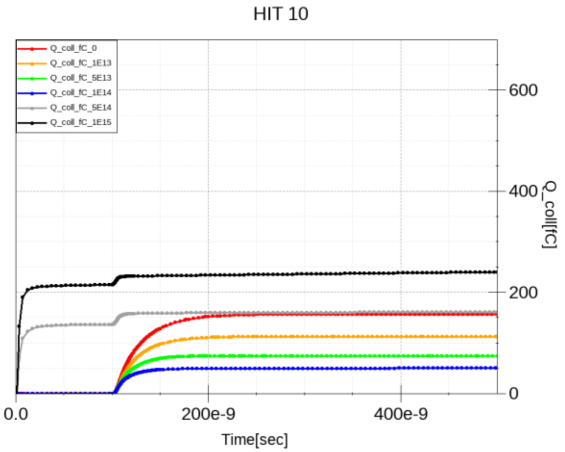
$\Delta t_{1\%}$~16.8 ns

- The maximum delay in signal output is from hit 7
- Assuming diffusion until the edge of DR, ~$z^2/(2D)$=16 ns for hit 25

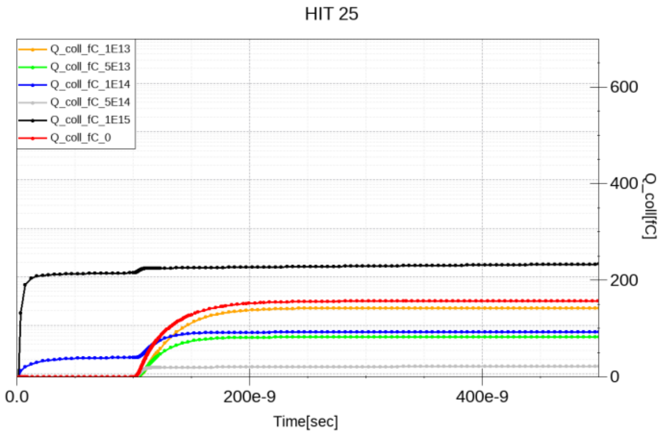
BACKUP



HIT 7

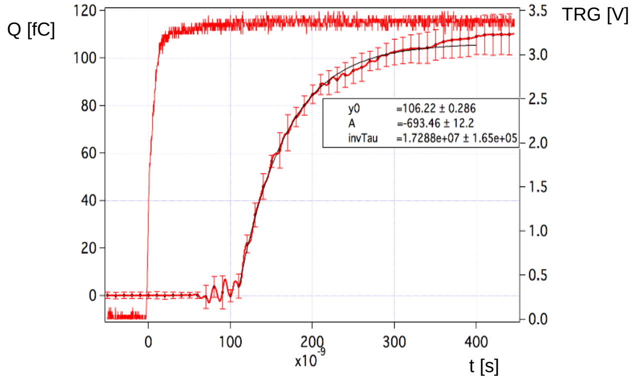


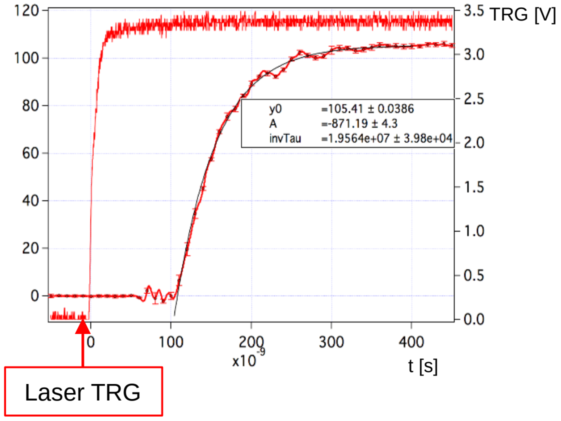
HIT 10



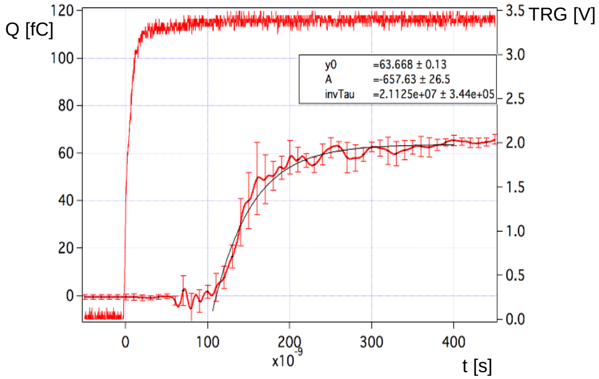
HIT 25

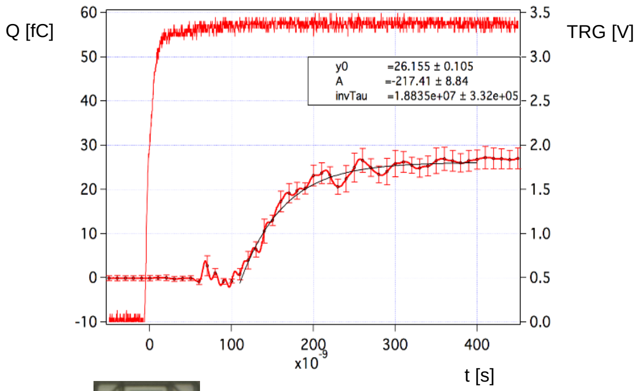
OVERMOS Laser Test

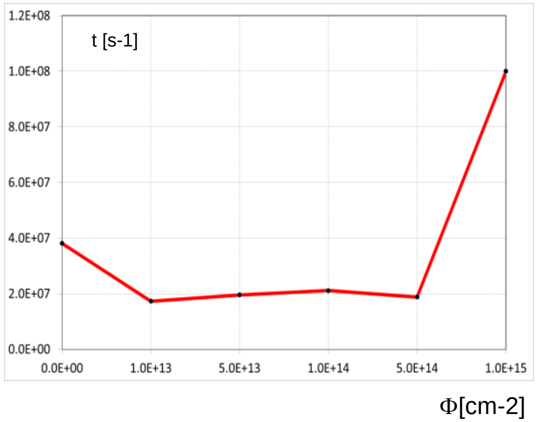

Φ=1e13

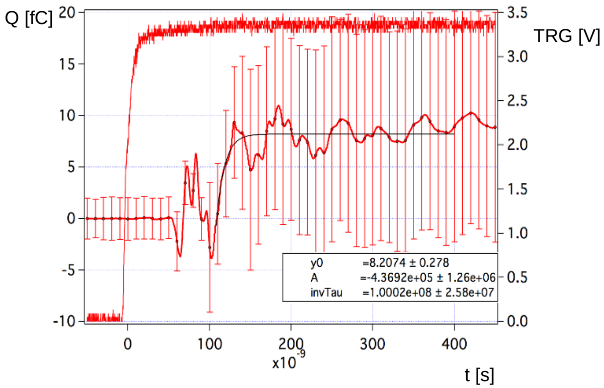

Φ=5e13

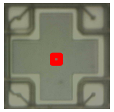
Laser TRG


Φ=1e14


Φ=5e14




Φ=1e15

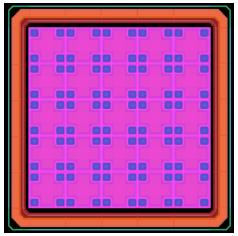


Kinematics of charge collection – charge collection time of point 25

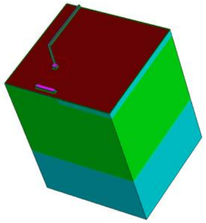
TCAD simulation

Simulations time

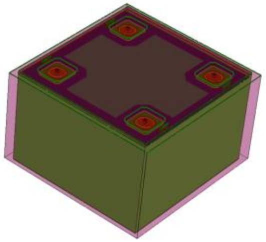
Layout editing

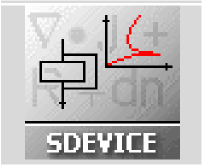


Process simulation
~5500 secs

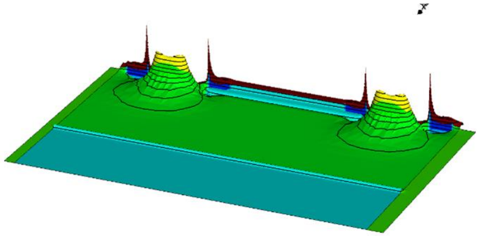


Process simulation – SDEVICE
~4000 secs





DC/CC simulation
>200k secs



Running on WS Intel Xeon Gold 5122 4 Core Processor, 3.6GHz, 16GB 2.4GHz RAM, 240GB SSD 6Gb/s