TCAD and recent defect studies

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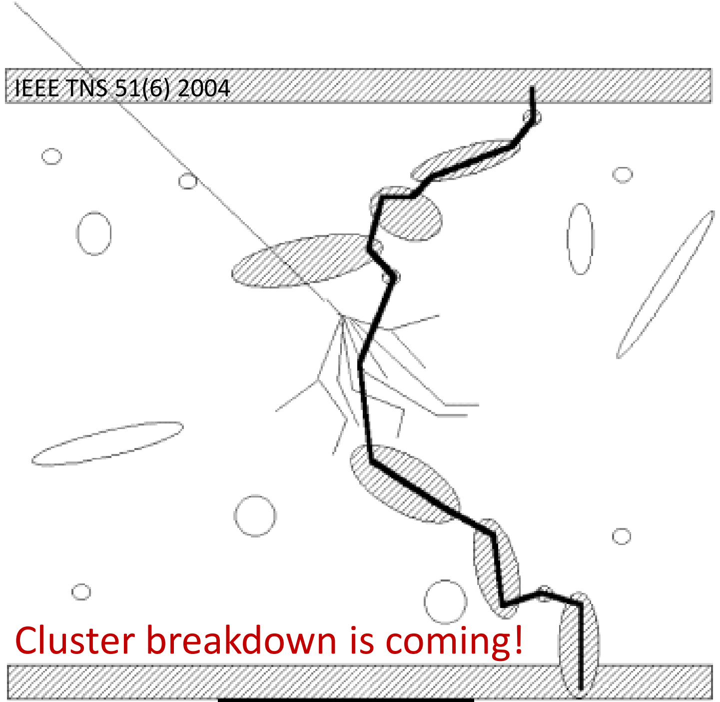
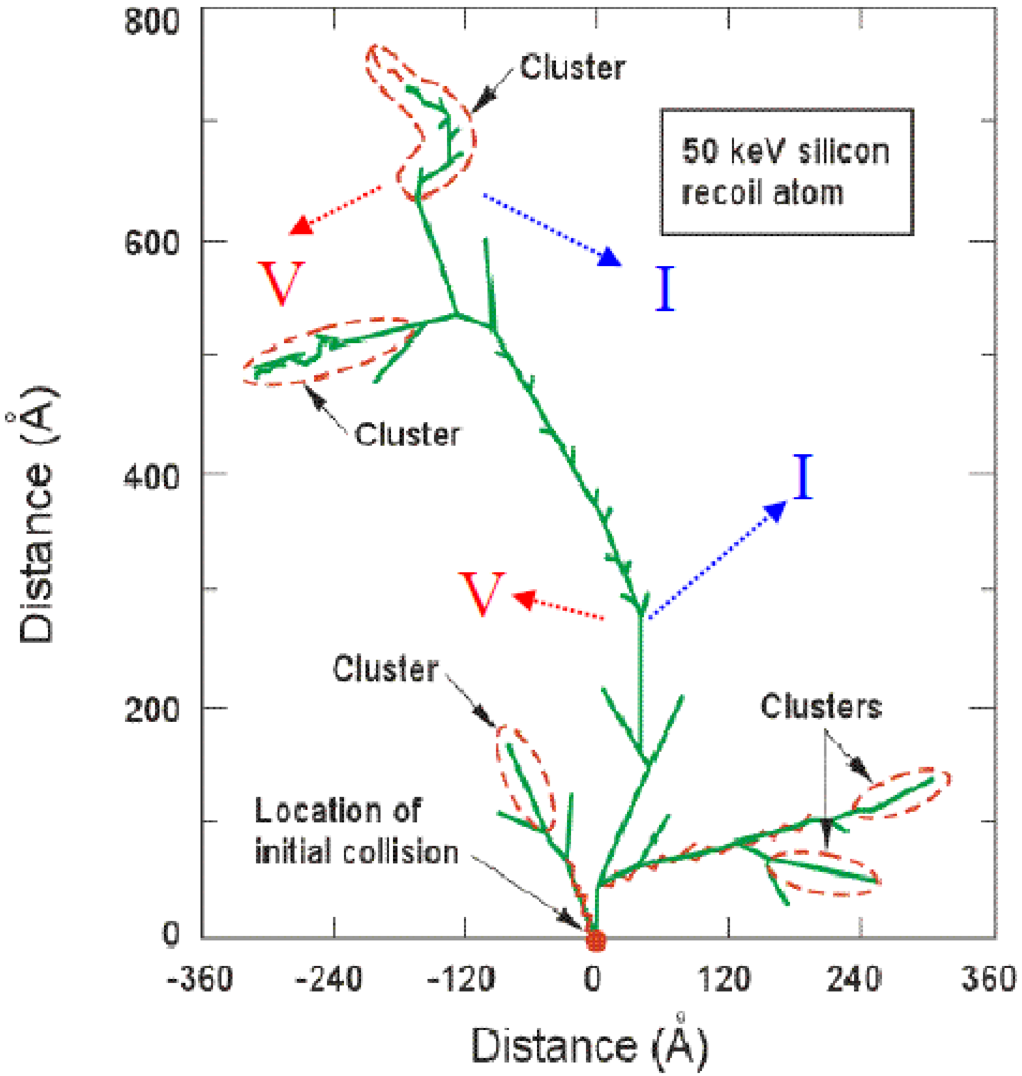
Introduction

1. Radiation damage of detectors: consequences
2. Simulation of radiation damaged detectors
3. Examples



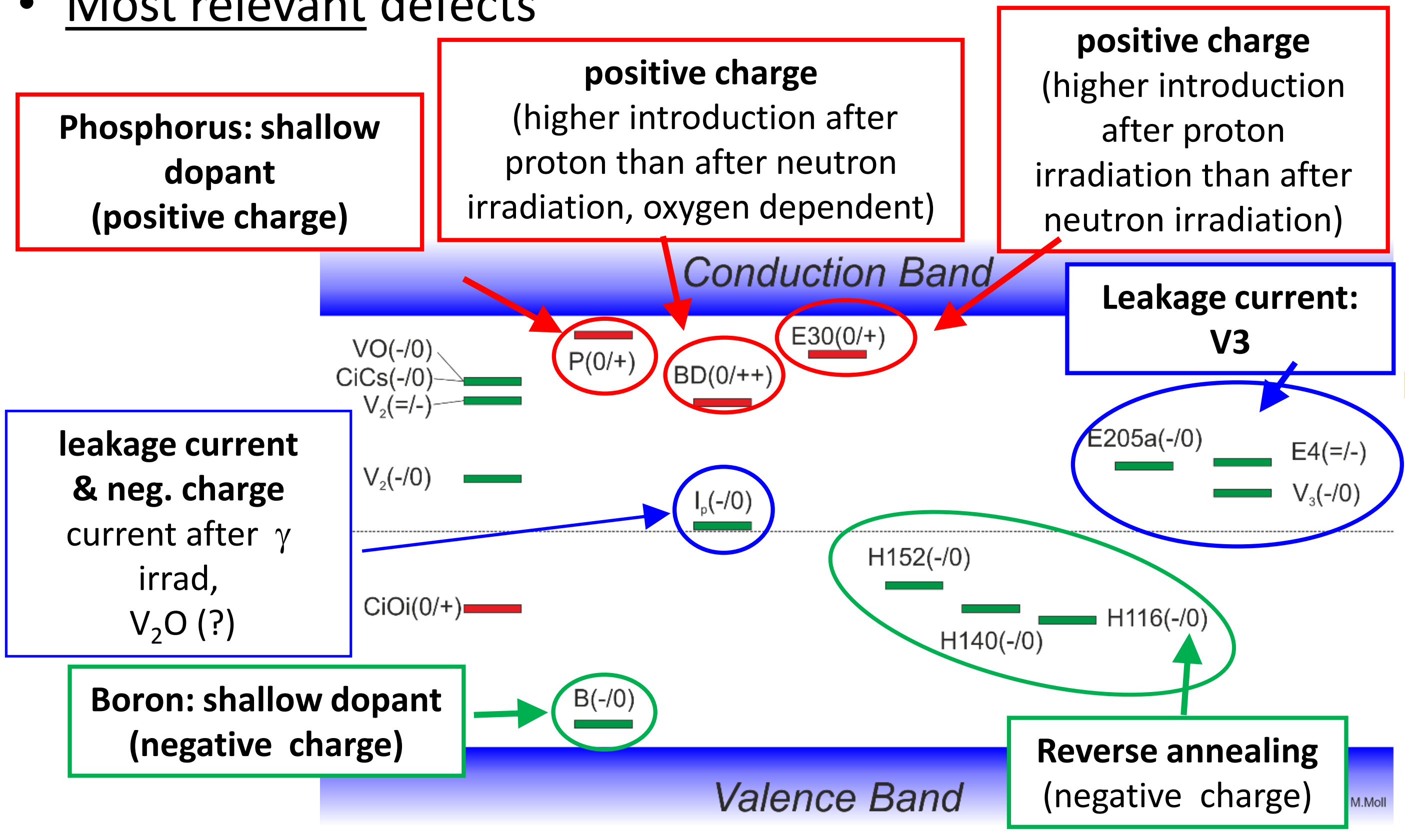
Cluster breakdown is coming!

van Lint 1980



Radiation Damage: Microscopic View

- Most relevant defects


Phosphorus: shallow dopant (positive charge)

positive charge (higher introduction after proton than after neutron irradiation, oxygen dependent)

positive charge (higher introduction after proton than after neutron irradiation)

Leakage current: V3

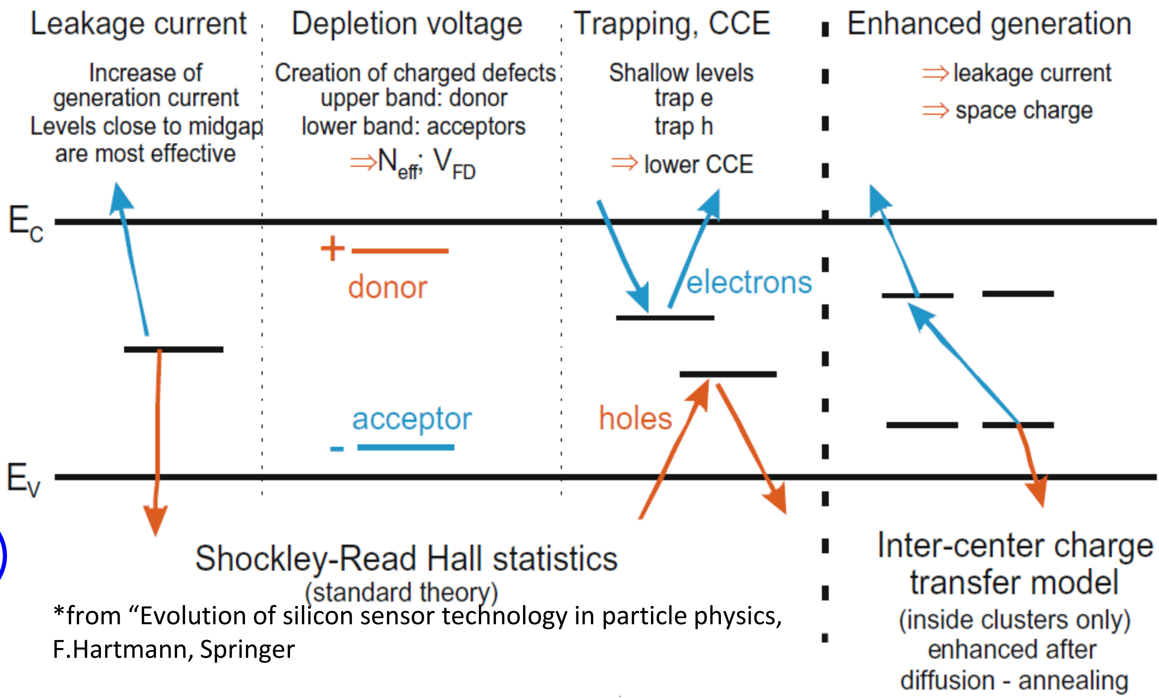
leakage current & neg. charge current after γ irrad, V_2O (?)

Boron: shallow dopant (negative charge)

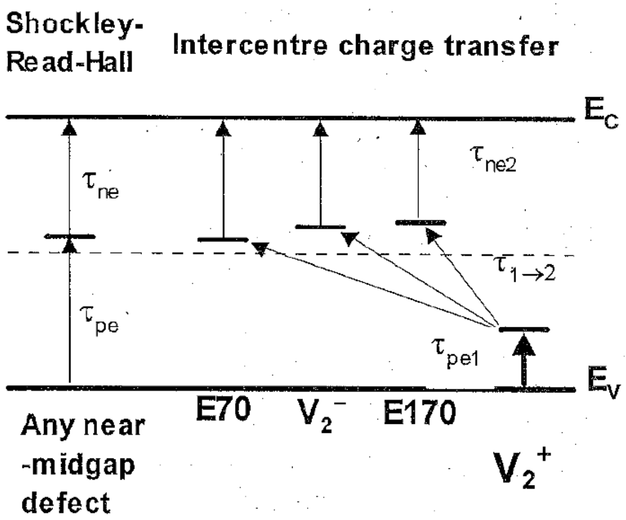
Reverse annealing (negative charge)

- **Trapping:** Indications that E205a and H152K are important (further work needed)
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and particle energy and (for some) on material!

*from M.Moll Sevilla Master Class, Nov. 2018



*from "Evolution of silicon sensor technology in particle physics, F.Hartmann, Springer



Inter-center charge Transfer: For a review, IEEE TNS, 43(6) 1996 S.J.Watts et al., Experimental Results, E. Fretwurst et al. 2(5),2000 Journal of Optoelectronics and Advanced Materials

Radiation Damage Macroscopic View : Degradation of Device Performance

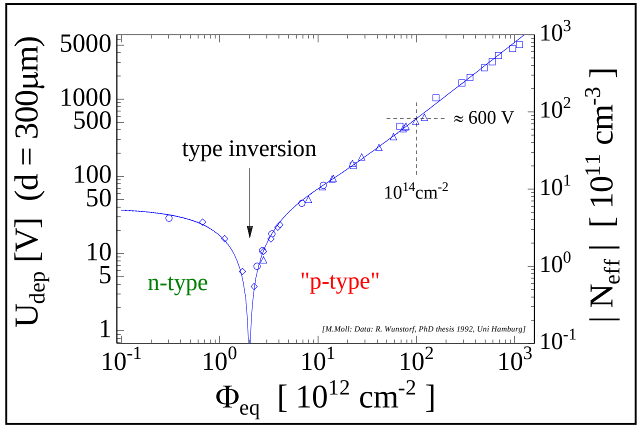
Bulk Damage (Non Ionizing Energy Loss)

- Point and cluster defects in the silicon lattice
  - Increase of leakage current
  - Change of the space charge in the depletion region, increase of full depletion voltage
  - Trapping of drifting charge
- I-V, C-V and CCE on pad diodes, DC strips, DC pixels

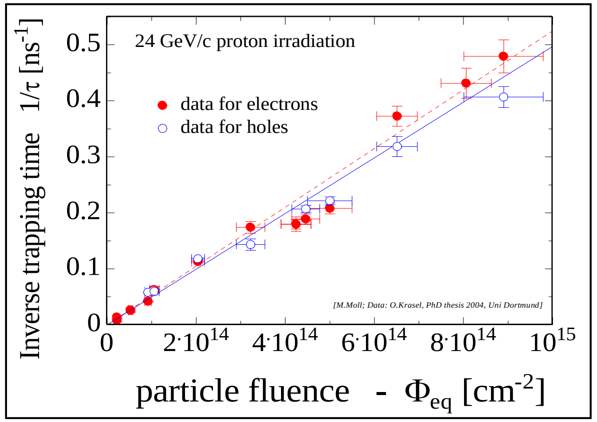
Surface Damage (Energy loss by Ionization)

- Build up of oxide charges, border and interface traps
  - Increase of Surface current
  - Change of the electric field near the Si-SiO_2 interface
  - Trapping near to the Si-SiO2 interface
- C-V/I-V on MOS capacitors, MOSFET and gate controlled diodes, AC coupled detectors, MAPS/HVCMOS detectors

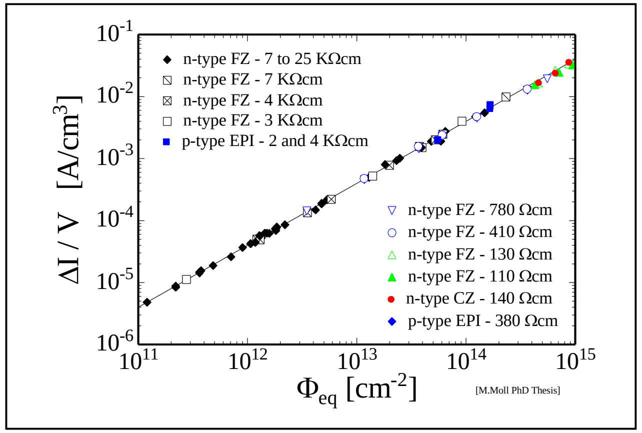
Macroscopic Bulk Effects



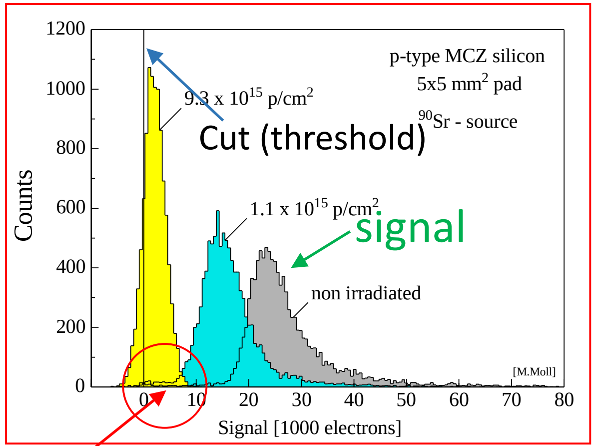
Depletion Voltage (N_{eff})



Charge Trapping



Leakage Current



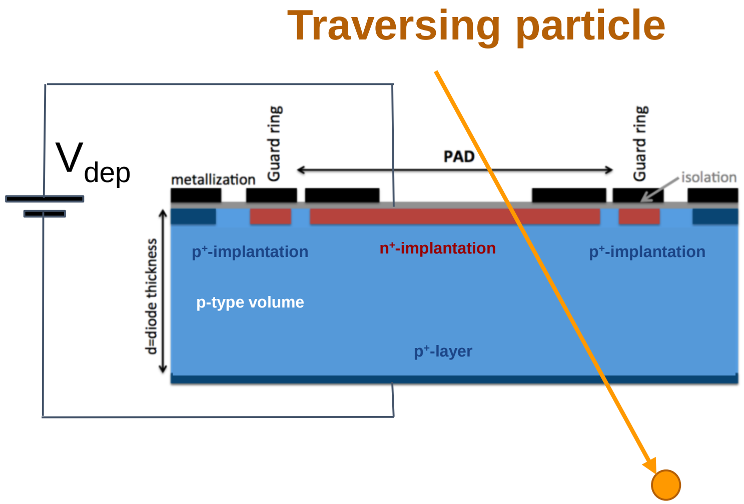
noise

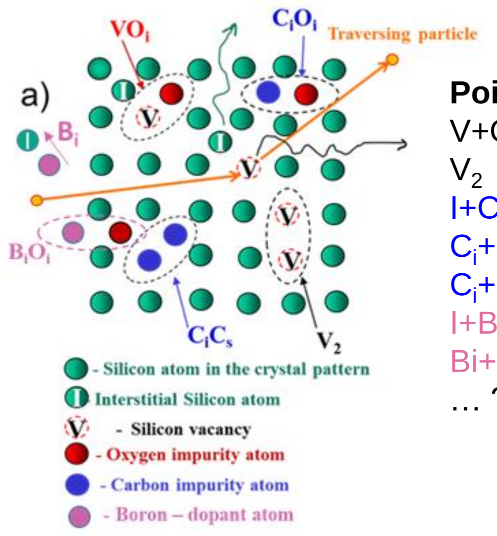
Signal to Noise Ratio

*from M.Moll Sevilla Master Class, Nov. 2018 and J.Schwandt 32th RD50 Workshop

Acceptor Removal and LGAD

- Radiation induced de-activation of *B* as a shallow dopant leading to the change of V_{dep} and N_{eff} on the macroscopic level
- Originated from B_iO_i complex formation

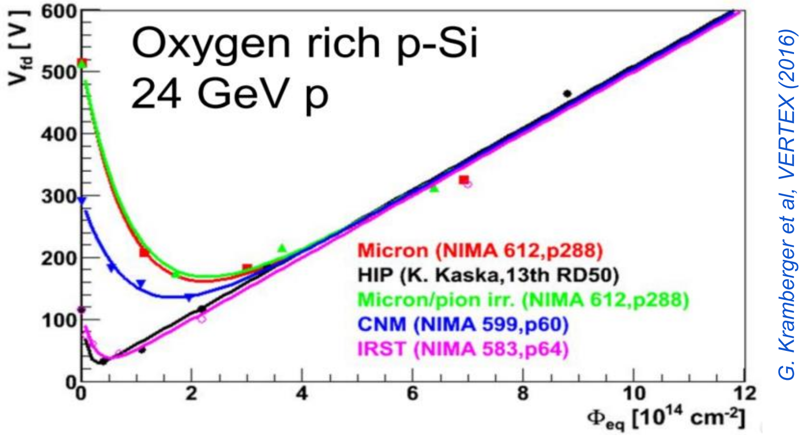




Point defects:
V+O → VO
V_2
$I+C_s \rightarrow C_i$
$C_i+C_s \rightarrow C_iC_s$
$C_i+O_i \rightarrow C_iO_i$
I+Bs → Bi
Bi+Oi → BiOi
… ? …

Competing reactions involving *B*, *C*, Si_i and O_i

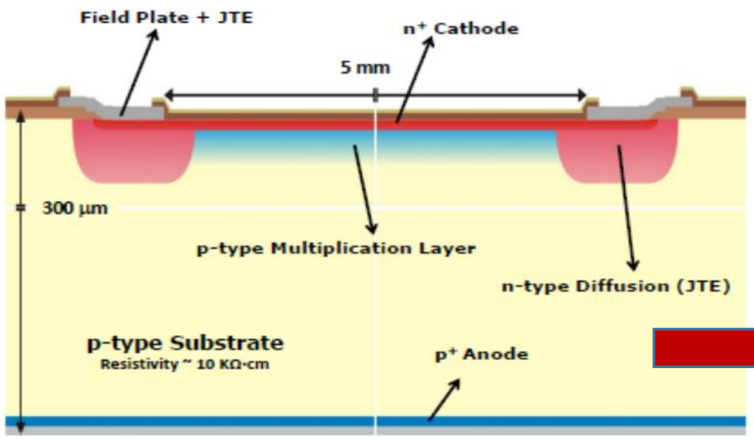
Macroscopic observation:

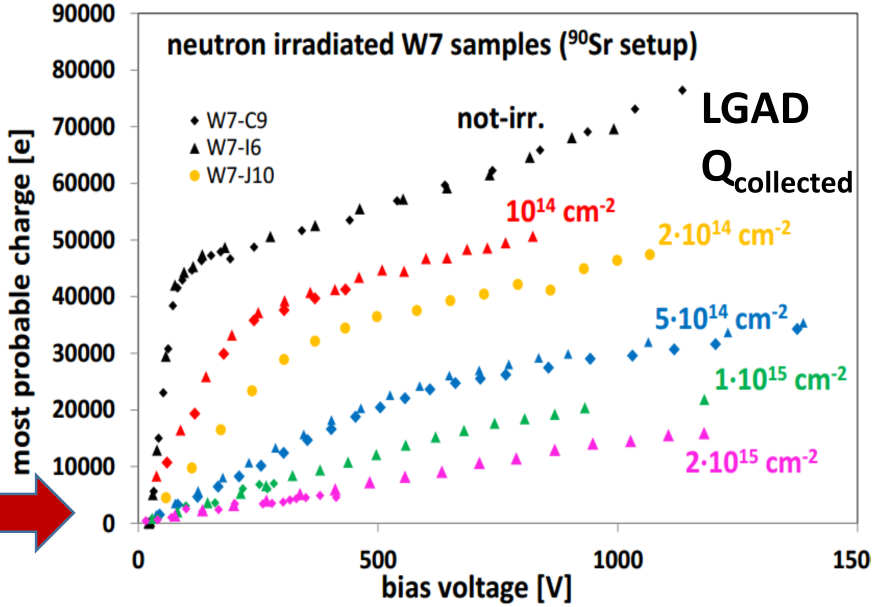


G. Kramberger et al, VERTEX (2016)

Shift of V_{dep} obtained from C-V measurements

Critical in Low Gain Avalanche Detectors: Acceptor removal implies a reduction in the dopant concentration in the multiplication layer. LGAD gain decreases due to the acceptor removal effect.





*From Gurimskaya Yana et al. RADECS 2019

TCAD simulation of Radiation Damage

Physics models: Works by modelling electrostatic potential (Poisson's equation) and carrier continuity (drift-diffusion, dd, mainly). It solves the non-linear partial differential equations in a device by the finite element method (mesh plus semiconductor equations and boundary conditions in discrete form , solves the system by the Bank-Rose Algorithm).

Poisson

$$\varepsilon_s \nabla . E = -\varepsilon_s \nabla^2 \psi = q(p - n + N_D - N_A) - \rho_{traps}$$

Electron continuity

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla . \underline{J}_n + (G - B)$$

where (dd)

$$\underline{J}_p = q\mu_n \underline{E} - qD_p \nabla p$$

Hole continuity

$$\frac{\partial p}{\partial t} = \frac{-1}{q} \nabla . \underline{J}_p + (G - B)$$

where (dd)

$$\underline{J}_n = q\mu_n \underline{E} + qD_n \nabla n$$

See Fichtner, Rose, Bank, "Semiconductor Device Simulation", IEEE Trans. Electron Devices 30 (9), pp1018, 1983

Different versions of physics models available

- Different models of mobility, bandgap…
- Generation and recombination rates may include avalanche effects, charge generation by high-energy particles…

Radiation Damage (Shockley-Read-Hall, SRH approach) will change the R_{net} recombination rate and ρ_{traps} charge density due to traps. Good for simulate point defects, bad for simulation of cluster defects (but Philips mobility model is available and cluster consequences on I_{leak} can be simulated tweaking on deep traps models).

Global approximate Newton methods, R.E.Bank, D.J.Rose, Numerische Mathematik, 1981, 37(2), pp. 279-295
Bulk damage effects in irradiated silicon detectors due to clustered divacancies, K.Gill et al. Journal of Applied Physics, 82, 126 (1997)

Radiation Damage TCAD Modelling

Radiation Damage Modelling

- Too many physical traps for simulation
- Effective set of traps modelling the measured identified point and cluster defects
- It is assumed that the traps obey SRH statistics (there are doubts at high fluences, needed a parameter tweaking**)
- Parameters are dependent on the simulator (Synopsys Sentaurus, Silvaco Atlas)

Example: 2 trap model, 6 parameter

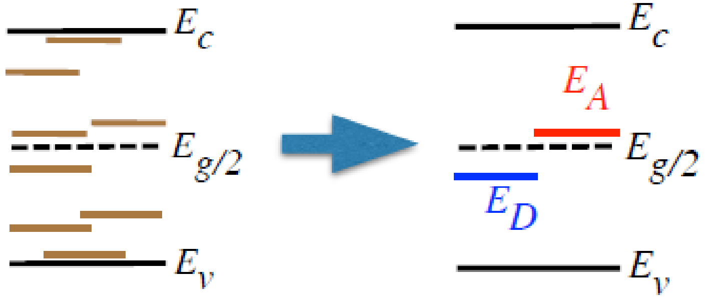
- 1. Concentrations: N_A, N_D
- 2. Cross-sections σ^A_e, σ^A_h, σ^D_e, σ^D_h

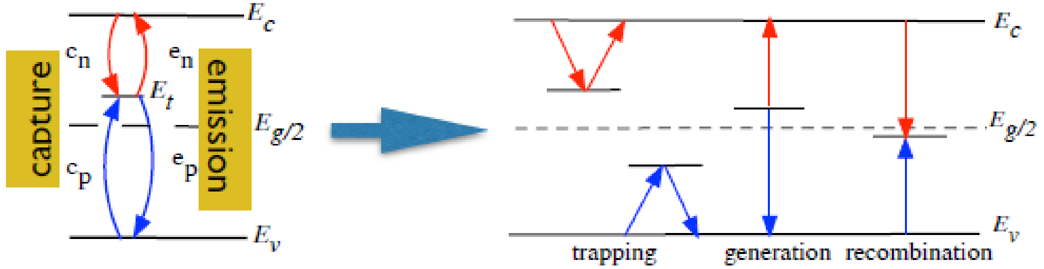
Trap charge density: $\rho_{trap} = q[N_D f_D - N_A f_A]$

Net Recombination Rate:

$$R_{net} = \frac{v_h v_e \sigma_h^D \sigma_e^D N_D (np - n_i^2)}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})} + \frac{v_h v_e \sigma_h^A \sigma_e^A N_A (np - n_i^2)}{v_e \sigma_e^A (n + n_i e^{E_A/kT}) + v_h \sigma_h^A (p + n_i e^{-E_A/kT})}$$

with {





Defect occupancy:

$$f_D = \frac{v_h \sigma_h^D p + v_e \sigma_e^D n_i e^{E_D/kT}}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})}$$

$$f_A = \frac{v_e \sigma_e^A n + v_h \sigma_h^A n_i e^{-E_A/kT}}{v_e \sigma_e^A (n + n_i e^{E_A/kT}) + v_h \sigma_h^A (p + n_i e^{-E_A/kT})}$$

and Trapping rates:

$$\Gamma_h = v_h[\sigma_h^D N_D (1 - f_D) + \sigma_h^A N_A f_A]$$

$$\Gamma_e = v_e[\sigma_e^A N_A (1 - f_A) + \sigma_e^D N_D f_D]$$

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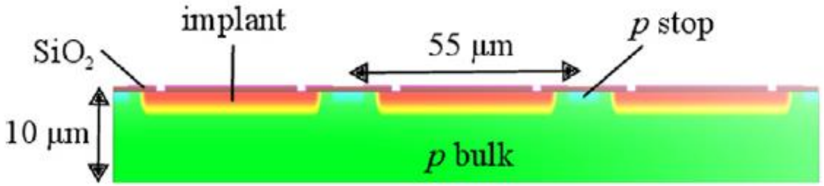
*"Study of point and cluster defects in radiation damaged silicon", E.M.Donegani et al. NIM A 898 pp.15-23 (2018) and J.Schwandt 32th RD50

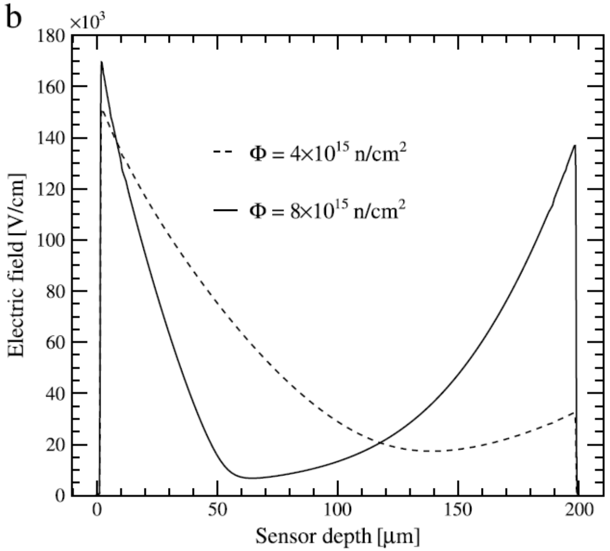
Ad hoc damage models (LHCb 2017)



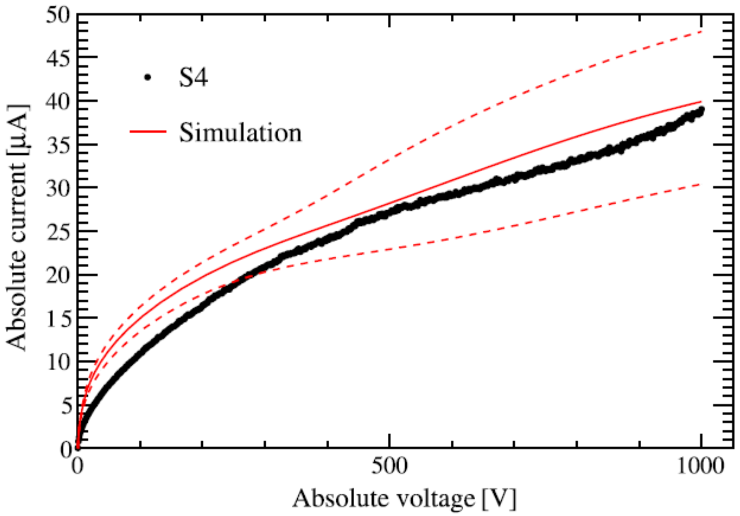
From the classical **EVL model***, one donor and one acceptor level (1 and 2 in the table), they add a third acceptor level. Cross-sections are adjusted to experimental results. Measurements for 200 µm thick n-on-p sensors bump bonded to TimePix3 readout .

Parameters of the proposed radiation damage model. The energy levels are given with respect to the valence band (E_V) or the conduction band (E_C). The model is intended to be used in conjunction with the Van Overstraeten–De Man avalanche model.

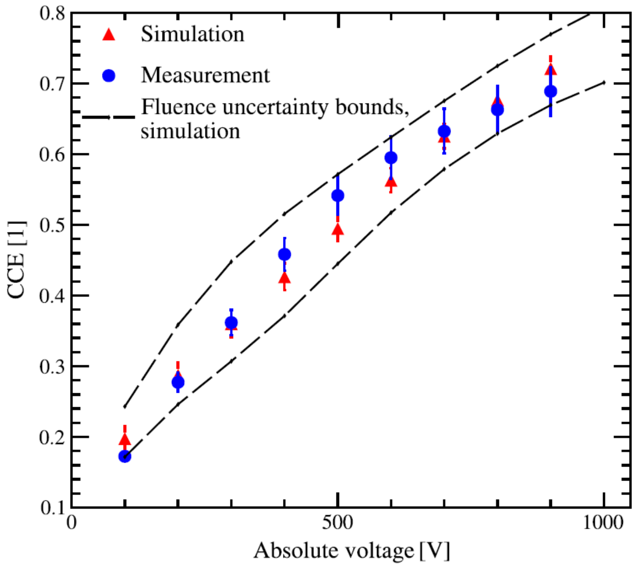
Defect number	Type	Energy level [eV]	σ_e [cm^{-2}]	σ_h [cm^{-2}]	η [cm^{-1}]
1	Donor	$E_V + 0.48$	2×10^{-14}	1×10^{-14}	4
2	Acceptor	$E_C - 0.525$	5×10^{-15}	1×10^{-14}	0.75
3	Acceptor	$E_V + 0.90$	1×10^{-16}	1×10^{-16}	36



Simulated electric field (2D mesh) in pixel centre at 1000V bias for two fluence levels.



Measured and simulated I-V curves (T=-31,1ºC) after uniform proton irradiation to Φ=4e15 MeV n$_{eq}$/cm^2.



Measured and simulated CCE as a function of voltage at Φ=4e15 MeV n$_{eq}$/cm^2.

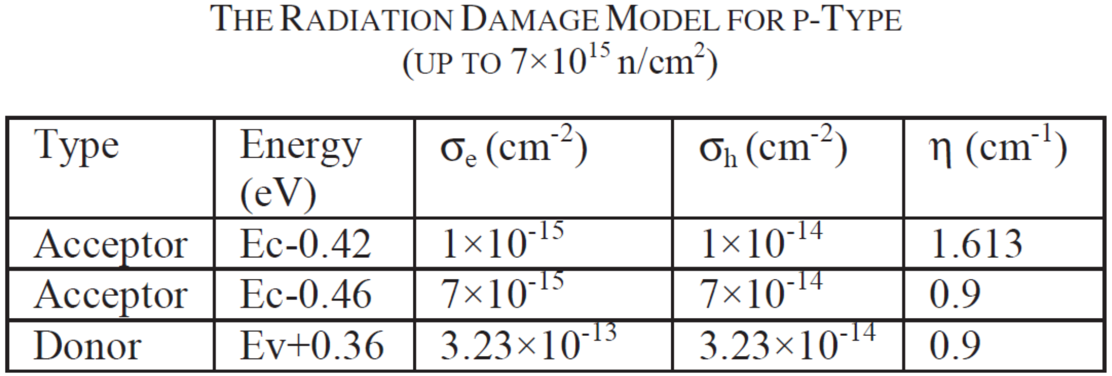
The model captures the transition from a linear electric field/saturating I-V curve to a double junction electric field/non-saturating I-V curve, as a consequence of avalanche generation in the high-field regions of doublé junctions. For pixel center hit, the CCE is aceptable.

"Development of a silicon bulk radiation model for Sentaurus TCAD", A. Folkestad et al., NIM A 874, pp.94-102, 2017

*"Double peak electric field distortion in heavily irradiated silicon strip detectors", Eremin et al. NIM A 535 pp.622-631, 2004

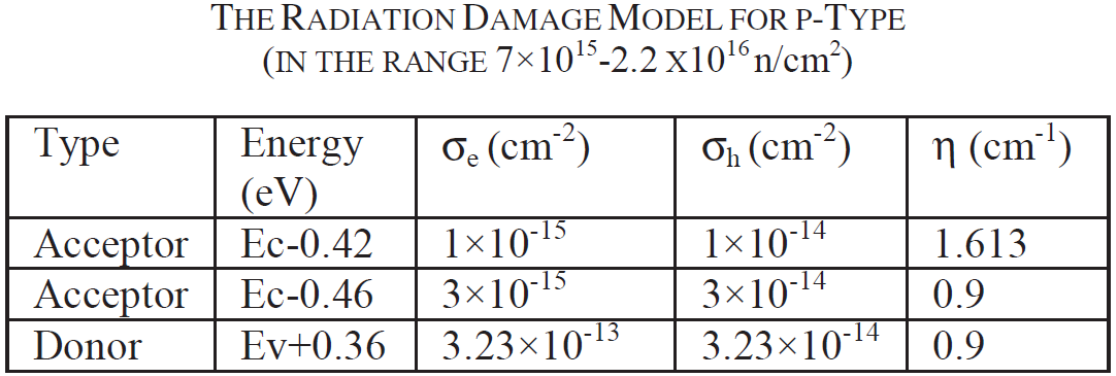
“New Perugia” Model (2015)

The High Luminosity Large Hadron Collider, HL-LHC, implies higher fluences than in LHC so new radiation damage models up to 2.2e16 neq/cm2 are needed. The first one was the “New Perugia Model”: it comprises a modelling of bulk and also surface damage in the Si-SiO2 interface (in case of microelectronics or AC coupled detectors)



THE RADIATION DAMAGE MODEL FOR P-TYPE
(UP TO 7×10^{15} n/cm^2)

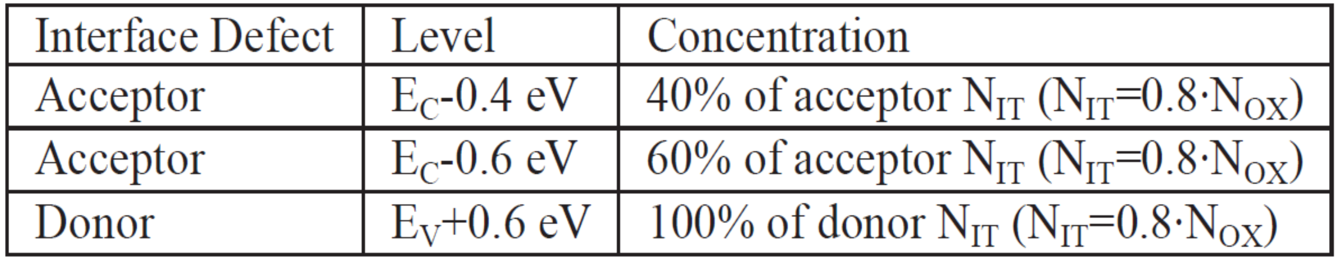
Type	Energy (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η (cm^{-1})
Acceptor	Ec-0.42	1×10^{-15}	1×10^{-14}	1.613
Acceptor	Ec-0.46	7×10^{-15}	7×10^{-14}	0.9
Donor	Ev+0.36	3.23×10^{-13}	3.23×10^{-14}	0.9



THE RADIATION DAMAGE MODEL FOR P-TYPE
(IN THE RANGE 7×10^{15}-2.2 x10^{16} n/cm^2)

Type	Energy (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η (cm^{-1})
Acceptor	Ec-0.42	1×10^{-15}	1×10^{-14}	1.613
Acceptor	Ec-0.46	3×10^{-15}	3×10^{-14}	0.9
Donor	Ev+0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

Bulk Damage New Perugia Model



Interface Defect	Level	Concentration
Acceptor	E_C-0.4 eV	40% of acceptor N_{IT} ($N_{IT}=0.8\cdot N_{OX}$)
Acceptor	E_C-0.6 eV	60% of acceptor N_{IT} ($N_{IT}=0.8\cdot N_{OX}$)
Donor	E_V+0.6 eV	100% of donor N_{IT} ($N_{IT}=0.8\cdot N_{OX}$)

Interface Damage New Perugia Model (oxide charge density,N_{ox}; interface trap density, N_{it})

- The Surface model comes from experimental measures on gated diodes and MOS capacitors, p-type substrate after γ irradiations (10-500 Mrad).
- The avalanche generation effect at high fluences has to be considered (Van Overstraeten-De Man model is the default model, other models change CCE by 3-4%)
- Bulk model comes from the “old Perugia model” and a literature survey made by the Perugia group

“Measurements and TCAD simulations of Bulk and Surface Radiation Damage Effects in Silicon Detectors”, F.Moscatelli et al., 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)

The Hamburg Pentatrap Model, HPTM (2018)

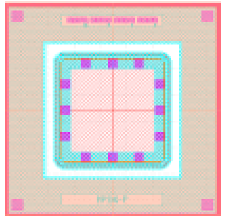
High-Luminosity LHC radiation level for the 1st pixel layer after 3000 fb^{-1}: Φ_{eq}~2.3e16 n_{eq}/cm^2, dose~12 MGy

Intends to describe I-V, C-V and CCE measurements on pads diodes simultaneously for fluences > 1e15 n_{eq}/cm^2 protons 24 GeV/c

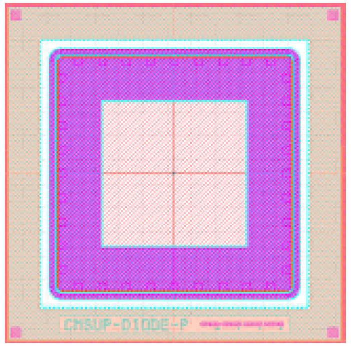
Defect	Type	Energy	g_{int} [cm^{-1}]	σ_e [cm^2]	σ_h [cm^2]
E30K	Donor	E_C-0.1 eV	0.0497	2.300E-14	2.920E-16
V_3	Acceptor	E_C-0.458 eV	0.6447	2.551E-14	1.511E-13
I_p	Acceptor	E_C-0.545 eV	0.4335	4.478E-15	6.709E-15
H220	Donor	E_V+0.48 eV	0.5978	4.166E-15	1.965E-16
C_iO_i	Donor	E_V+0.36 eV	0.3780	3.230E-17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

- Trap concentration of defects: $N = g_{int}\,\Phi_{neq}$
- Simulations for the optimization performed at -20ºC with
  - Slotboom band gap narrowing
  - Impact Ionisation (van Overstaeten-de Man)
  - TAT Hurkx with tunnel mass=0.25 m_e (default value: 0.5 m_e) in the case of Ip
  - Relative permitivitty of silicon 11.9 (default value 11.7)
- Both cross sections for E30K and the electron cross section for CiOi fixed
  - 12 free parameter
- Optimization done with the non-linear simplex method

Diode 2mm x 2mm



Diode 5mm x 5mm



- Measurements on pad diodes, p-type (p-stop, p-spray)
- Thinned float zone FTH2000 (200 μm thick)
- MCz, Epi, Deep diffused FZ
- Electrical characterization after 80min@60ºC

annealing, at T=-20ºC, I-V up to 1000V (reverse) and up to current limit of 0.5 mA (forward)

C/G-V with 100 Hz-2 MHz

TCT with 670nm (red) and 1064 nm (IR) laser

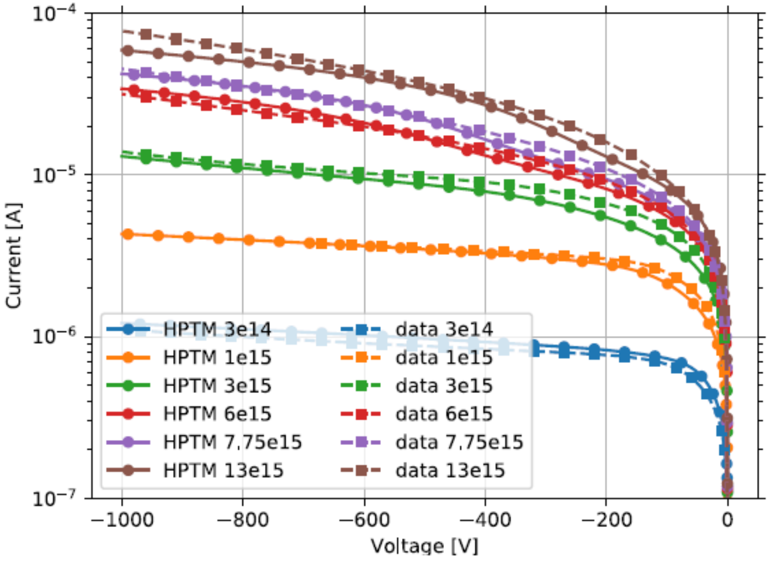
J.Schwandt, 32th RD50 presentation.

"A new model for the TCAD simulation of the silicon damage by high fluence proton irradiation", Joern Schwandt et al., 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC).

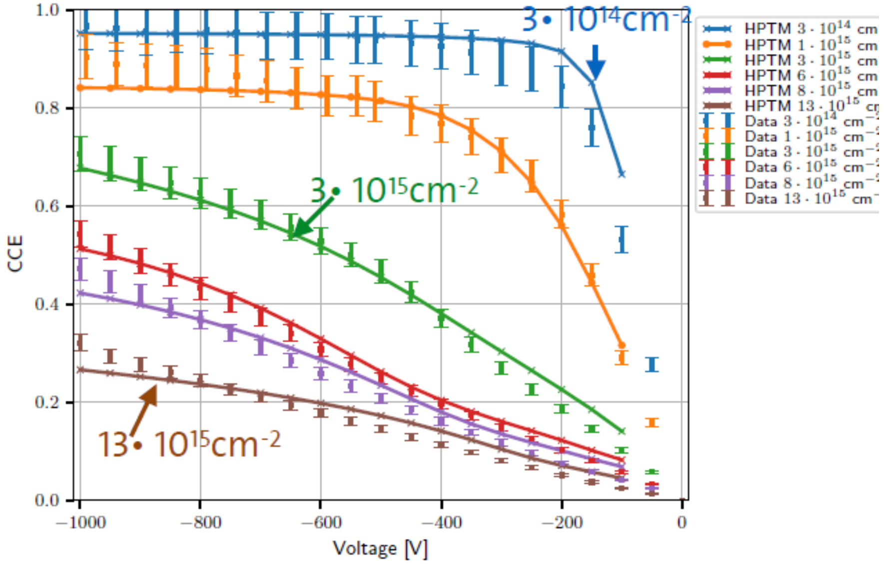
The Hamburg Pentatrap Model (2)

Parameter tuned to I-V, C-V and CCE-IR (laser) at T=-20ºC for 24 GeV/c protons in the range Φ_{eq}= 0.3 … 13e15 n_{eq}/cm^2

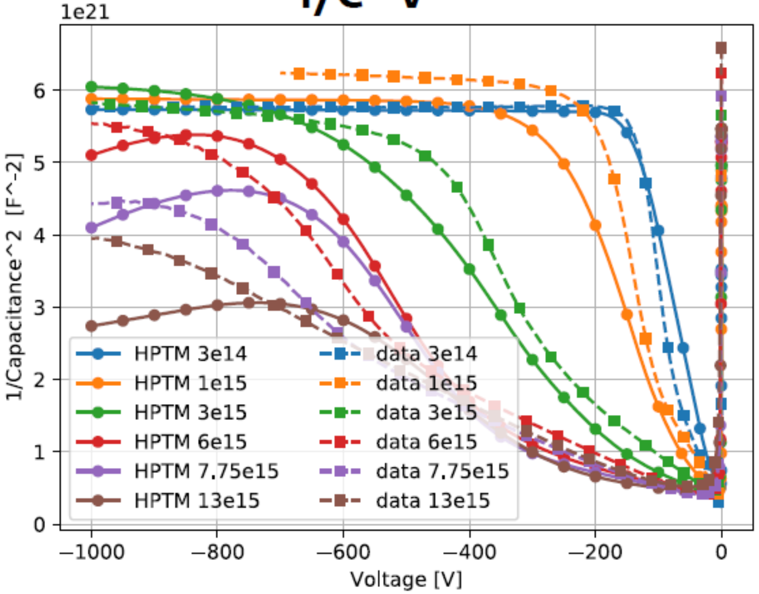
I-V



CCE-V



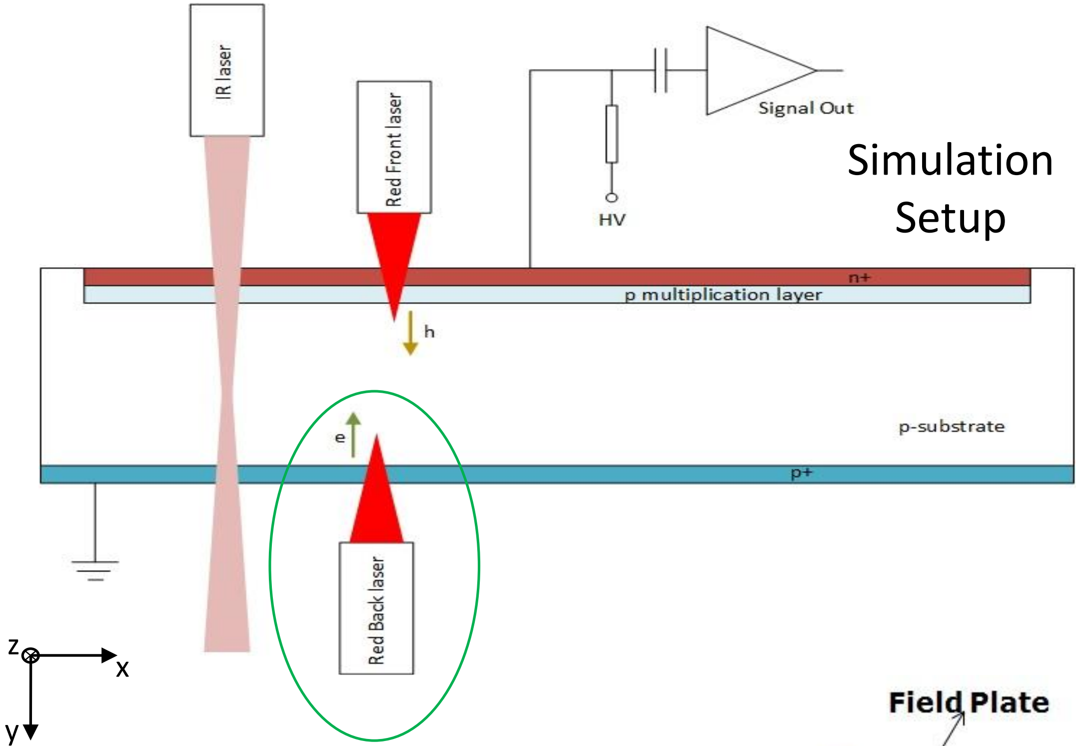
1/C²-V

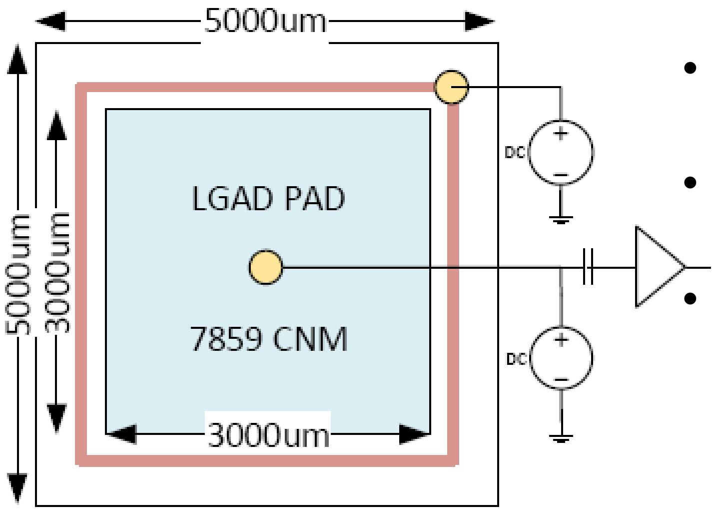


- The simulations for 0.3 and 1e5 n_{eq}/cm^2 are extrapolations and the 7.75e15 n_{eq}/cm^2 is a interpolation (not included in the optimization)
- The simulations of I-V /C-V agrees with the measurements within 20% for all fluences and voltages
- The simulations of CCE-V agrees with the measurements within 20% for all fluences and high voltages

J.Schwandt, 33th RD50

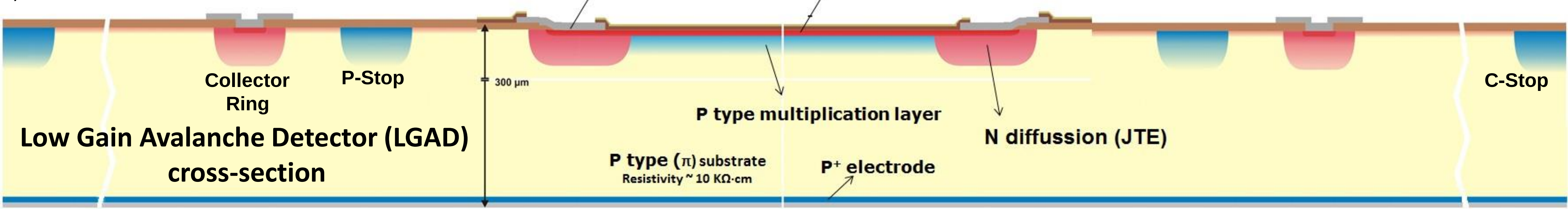
Acceptor Removal: LGAD family





Simulation Setup:

- **Red Pulsed Laser: 670 nm, 10 μm spot, 50W/cm^2, 200 ps,**
- **BackIllumination at Device Center**
- **2D detector model: 1 μm in Z direction, 5 mm in X direction, 300 μm in Y direction)**



Low Gain Avalanche Detector (LGAD) cross-section

Simulation of Acceptor Removal and Radiation Damage in LGAD devices, 30th RD50 Workshop 2017 Krakow

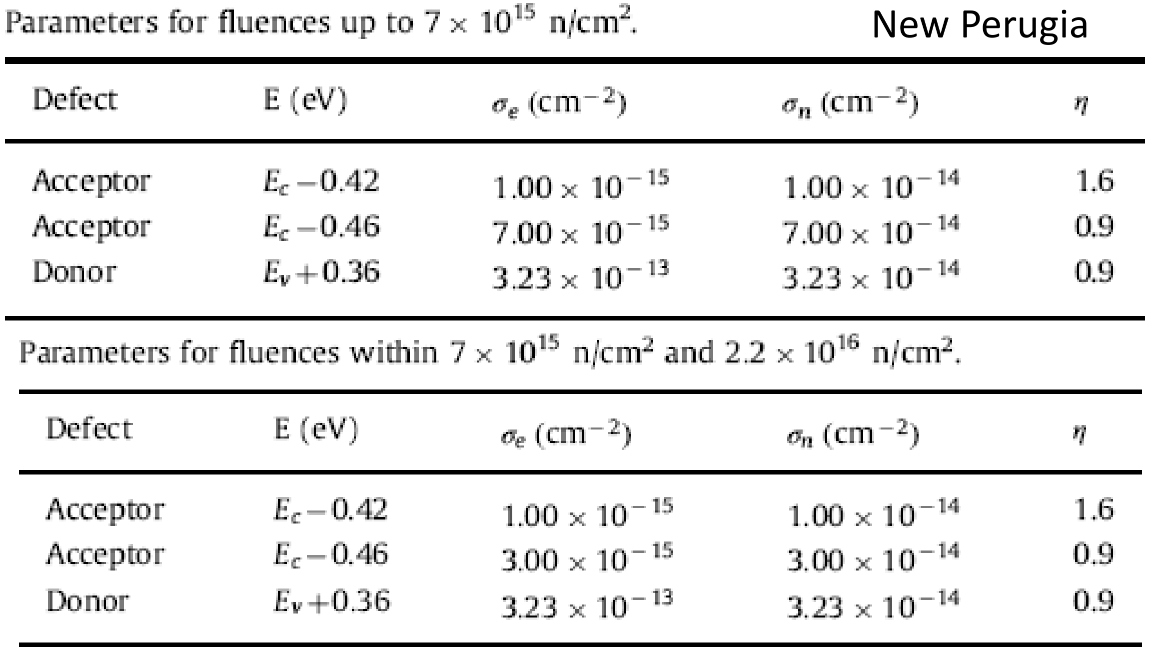
Doping profiles under confidenciality rules

From 29th RD50: Radiation Damage Models

Four damage models

1. Pennicard Model ϕ =1e12 up to 1e14 n_{eq}/cm^2
2. CMS Proton and Neutron model ϕ = 1e14-1e15 n_{eq}/cm^2
3. Two Level Model Proton ϕ = 1e14-1e15 n_{eq}/cm^2
4. New Perugia Model ϕ =1e12 up to 2e16 n_{eq}/cm^2

New Perugia



Parameters for fluences up to 7×10^{15} n/cm^2.

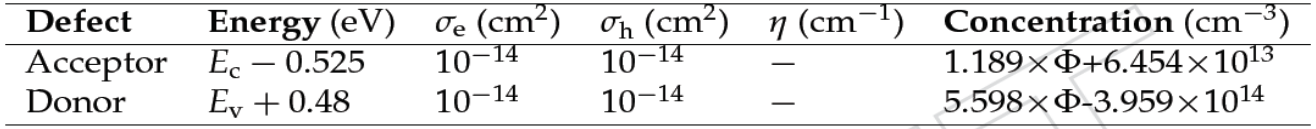
Defect	E (eV)	σ_e (cm^{-2})	σ_n (cm^{-2})	η
Acceptor	$E_c - 0.42$	1.00×10^{-15}	1.00×10^{-14}	1.6
Acceptor	$E_c - 0.46$	7.00×10^{-15}	7.00×10^{-14}	0.9
Donor	$E_v + 0.36$	3.23×10^{-13}	3.23×10^{-14}	0.9

Parameters for fluences within 7×10^{15} n/cm^2 and 2.2×10^{16} n/cm^2.

Defect	E (eV)	σ_e (cm^{-2})	σ_n (cm^{-2})	η
Acceptor	$E_c - 0.42$	1.00×10^{-15}	1.00×10^{-14}	1.6
Acceptor	$E_c - 0.46$	3.00×10^{-15}	3.00×10^{-14}	0.9
Donor	$E_v + 0.36$	3.23×10^{-13}	3.23×10^{-14}	0.9

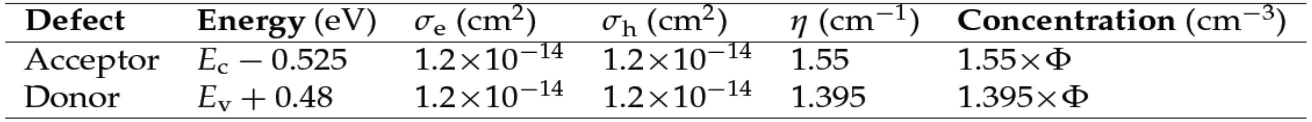
Modeling of radiation damage effects in silicon detectors at high fluences HL-LHC with Sentaurus TCAD, D.Passeri et al, NIMA 824 (2016), 443-445

CMS Proton Model



Defect	**Energy** (eV)	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})	**Concentration** (cm^{-3})
Acceptor	$E_c - 0.525$	10^{-14}	10^{-14}	–	$1.189\times\Phi+6.454\times10^{13}$
Donor	$E_v + 0.48$	10^{-14}	10^{-14}	–	$5.598\times\Phi-3.959\times10^{14}$

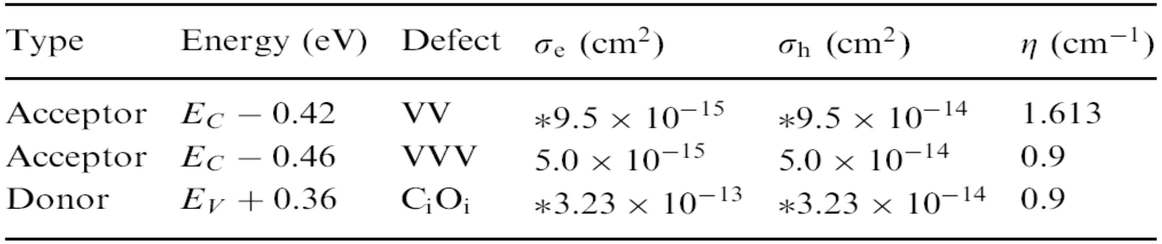
CMS Neutron Model



Defect	**Energy** (eV)	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})	**Concentration** (cm^{-3})
Acceptor	$E_c - 0.525$	1.2×10^{-14}	1.2×10^{-14}	1.55	$1.55\times\Phi$
Donor	$E_v + 0.48$	1.2×10^{-14}	1.2×10^{-14}	1.395	$1.395\times\Phi$

Simulation of Silicon Devices for the CMS Phase II Tracker Upgrade CMS Note 250887

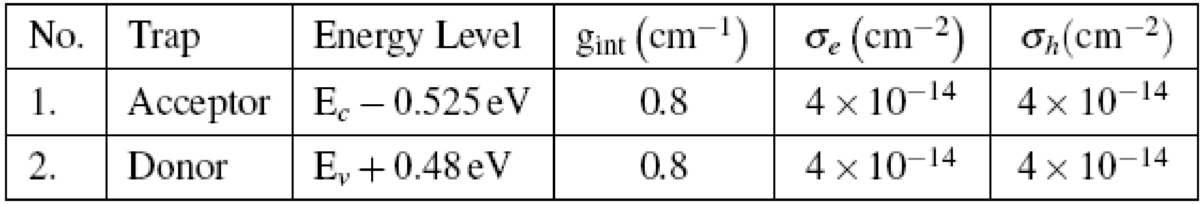
Pennicard Model $N(cm^{-3})=\eta_{int} \times \phi$



Type	Energy (eV)	Defect	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	$E_C - 0.42$	VV	$*9.5 \times 10^{-15}$	$*9.5 \times 10^{-14}$	1.613
Acceptor	$E_C - 0.46$	VVV	5.0×10^{-15}	5.0×10^{-14}	0.9
Donor	$E_V + 0.36$	C_iO_i	$*3.23 \times 10^{-13}$	$*3.23 \times 10^{-14}$	0.9

Simulations of radiation-damaged 3D detectors for the Super-LHC, D.Pennicard et al. NIMA 592(1-2), 2008, pp16-25

Eremin et al two level model* $N(cm^{-3})=g_{int} \times \phi$

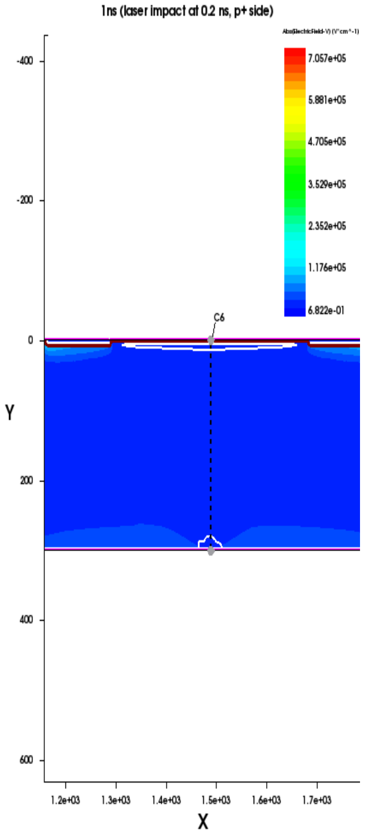


No.	Trap	Energy Level	g_{int} (cm^{-1})	σ_e (cm^{-2})	σ_h(cm^{-2})
1.	Acceptor	$E_c - 0.525$ eV	0.8	4×10^{-14}	4×10^{-14}
2.	Donor	$E_v + 0.48$ eV	0.8	4×10^{-14}	4×10^{-14}

Combined effect of bulk and Surface damage on strip insulation properties of proton irradiated n+-p silicon strip sensors, R.Dalal et al. JINST 2014 9 P04007

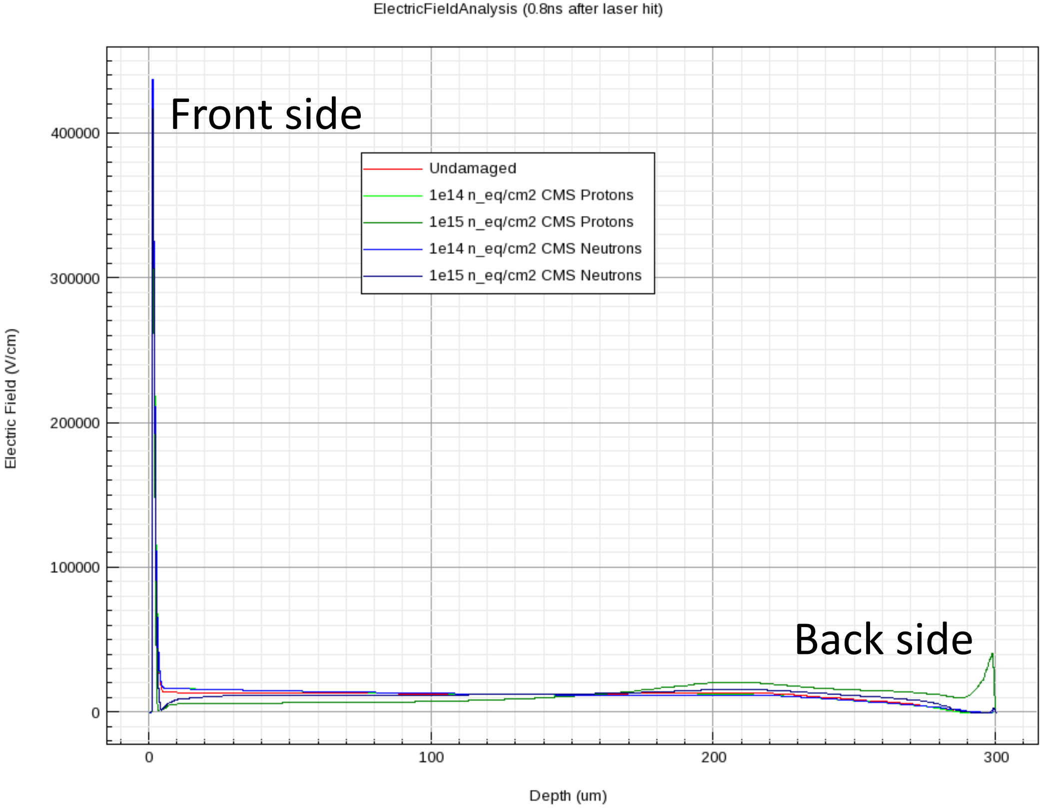
*The origin of double peak electric field distribution in heavily irradiated silicon detectors, V.Eremin, E.Verbitskaya, Z.Li, NIMA 476 (2002) 556-564

From 29th RD50 LGAD: All Models show a similar panorama, for example: CMS Model



Electric Field Profiling

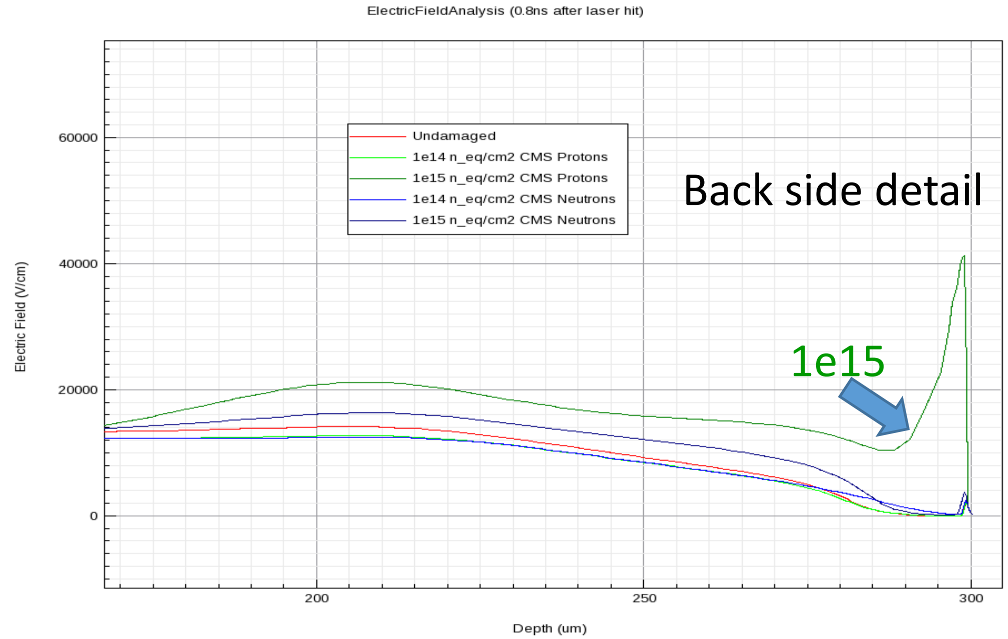
Electric Field along Y axis



Front side

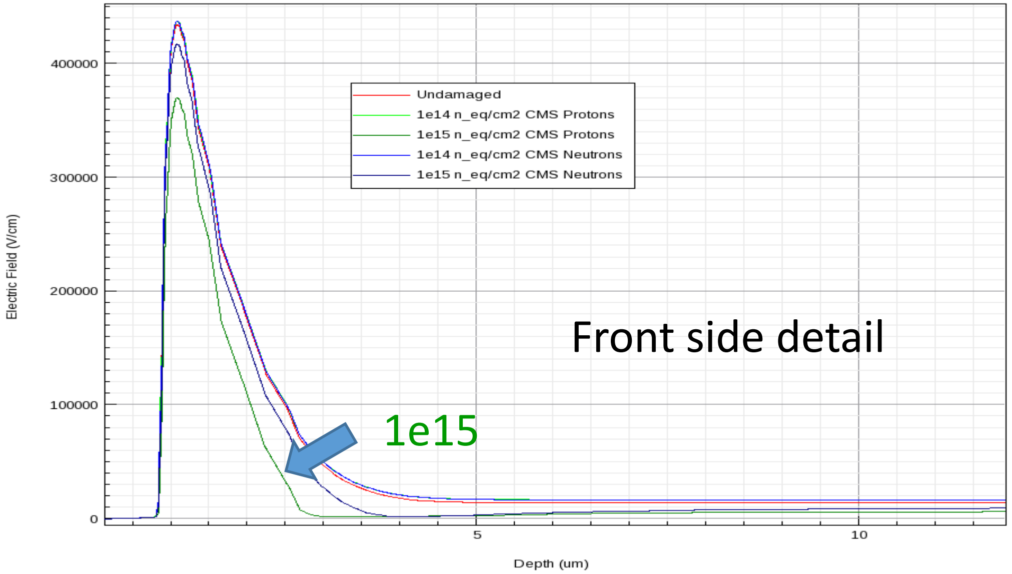
Back side

At 1e15 a double junction appears at P+ volumen (device back side)



Back side detail

1e15



Front side detail

1e15

LGAD Acceptor Removal

$$\frac{dN_T^0}{dt} = -eN_T^0 \; ; \; e = \frac{\sigma v N_c T^2}{g}\exp\left(\frac{-E_a}{k_b T}\right) \; ; \; N_T^0 = N_T\exp(-et).$$

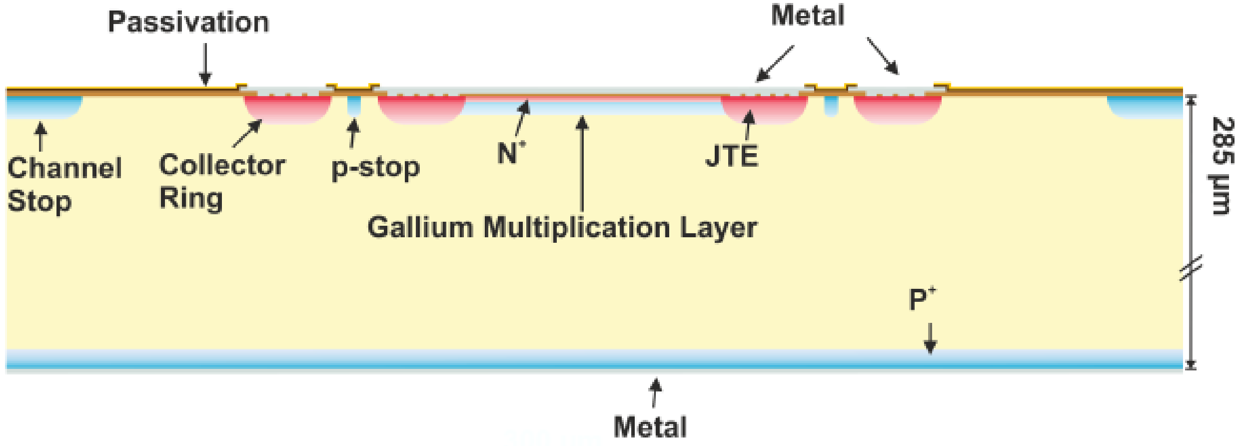
(1998 Yamaguchi)

$$N_A = N_A e^{-cA\phi}$$

(1999 Yamaguchi)

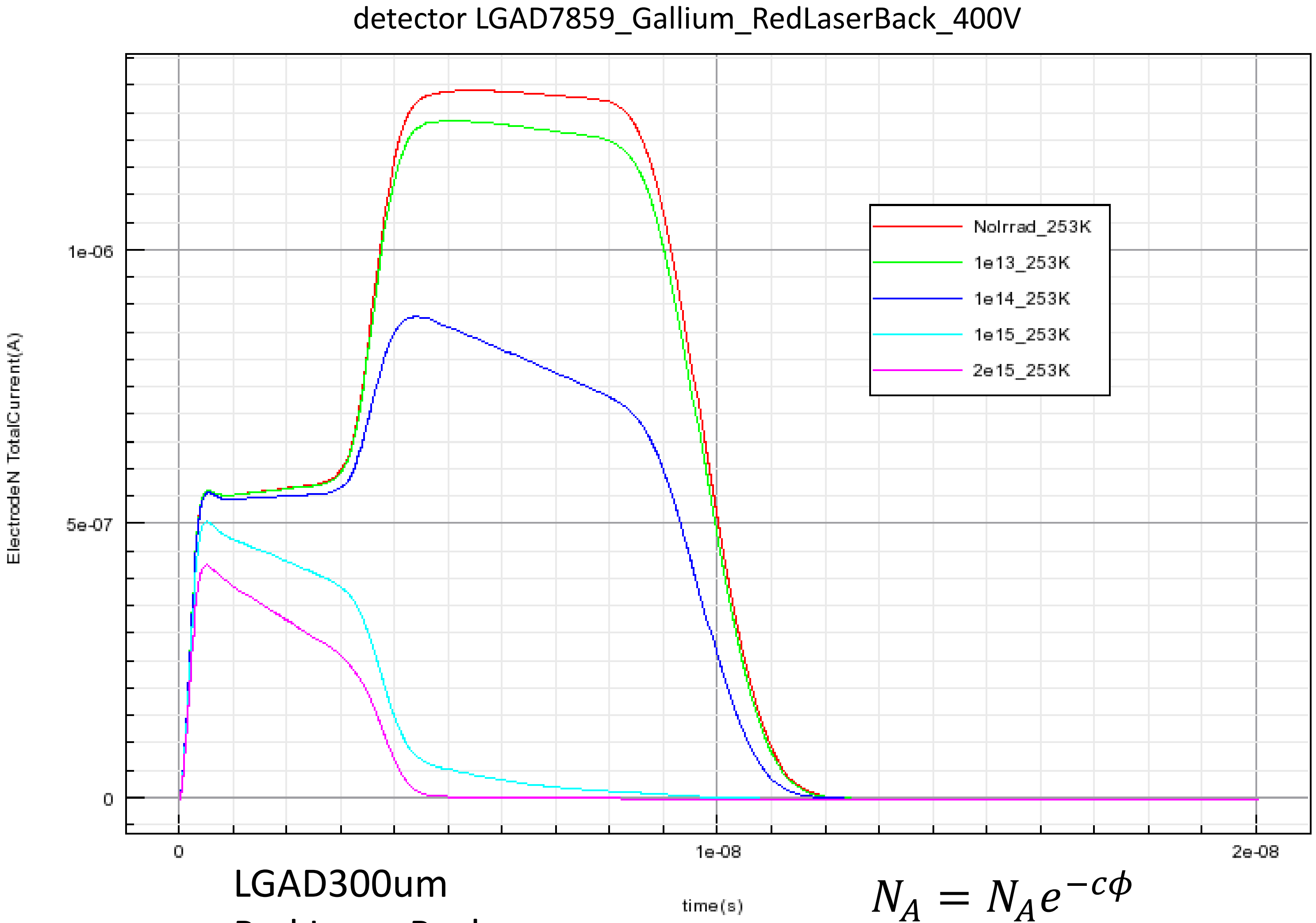
- We consider the acceptor removal model from literature (Watkins’ removal mechanism)
- From Mar Carulla Trento 2017 we extrapolate C_A=4e-16 cm^2 for a Kramberger’s Paper type Gallium LGAD device, no T dependence as a first approach (also 2003 Kahn)
- We consider also the trap model (new Perugia)
- Simulation of Red Laser Back Transient
- Maximum fluence damage 2e15 n_{eq}/cm^2 compatible with CMS ETL (Endcap Timing Layer)

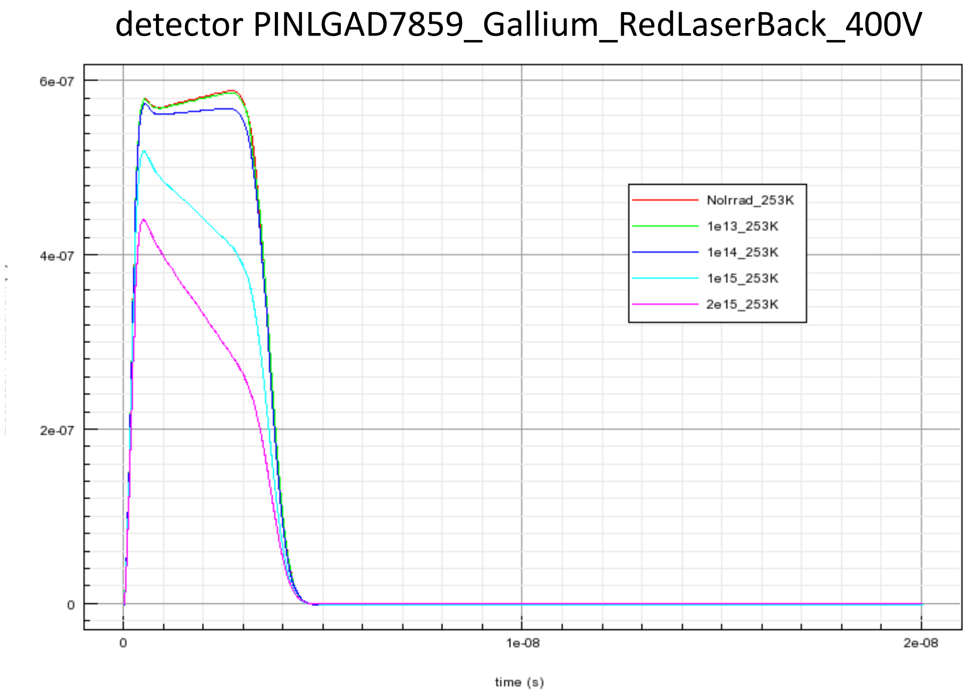
	Dopant	Doping(cm^{-3})	C_A (cm^2)
Wafer9 (Mar)	Ga	2,25E+16	6,90E-16
Kramb. Paper(2015)	B	5,00E+16	9,10E-16
Wafer10 (Mar)	Ga	1,00E+17	1,00E-16
Wafer11 (Mar)	Ga	2,30E+17	3,30E-16
Wafer14 (Mar)	B	3,00E+18	2,00E-17



- Explanation for carrier removal and type conversión in irradiated silicon solar cells, T.Yamaguchi et al. Applied Physics Letters 72(10), 1998
- A detailed model to improve the radiation resistance of Si space solar cells, T.Yamaguchi et al. IEEE Trans on Electron Devices,46(10), 1999
- Strategies for improving radiation tolerance of Si space solar cells, A.Kahn et al. Solar Energy Materials & Solar Cells, 75, 271-276, 2003
- Defects in Semiconductors, L.Romano, V.Priviera, C.Jagadish, 2015 AP Elsevier publishers
- Radiation effects in Low Gain Avalanche Detectors after hadron irradiations, G.Kramberger et al., JINST 2015 10 P07006
- Last measurements and developments on LGAD detectors, Mar Carulla et al., 12th “Trento” Workshop February 2017

Acceptor Removal+Trap Model (New Perugia)





LGAD300um
Red Laser Back
400V Bias 253K
1e13-2e15 n_{eq}/cm^2

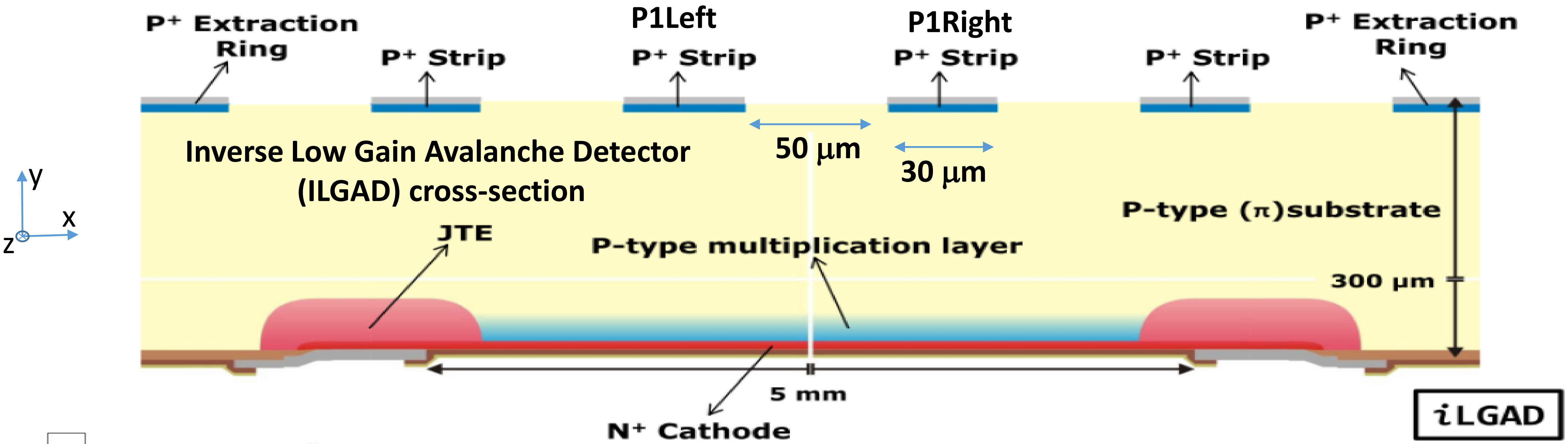
$$N_A = N_A e^{-c\phi}$$

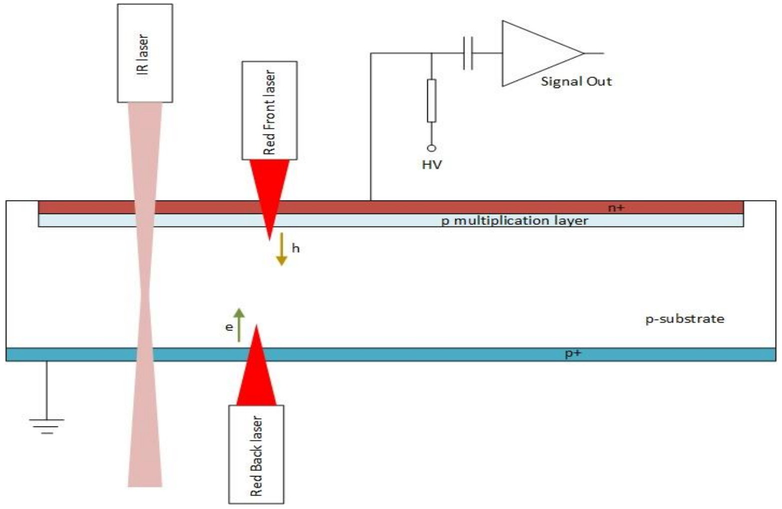
$c=4x10e^{-16}\ cm^{-2}$

New Perugia Trap Model

Fluence n/cm²	Charge LGAD (C)	Charge PIN (C)	Gain Q_{lgad}/Q_{pin}
NoIrrad	9,86e-15	2,01e-15	4,91
1e13	9,46e-15	2,00e-15	4,72
1e14	6,77e-15	1,95e-15	3,46
1e15	1,74e-15	1,22e-15	1,42
2e15	1,28e-15	1,19e-15	1,08

ILGAD Simulations





Doping profiles under confidenciality rules

Simulation Setup:

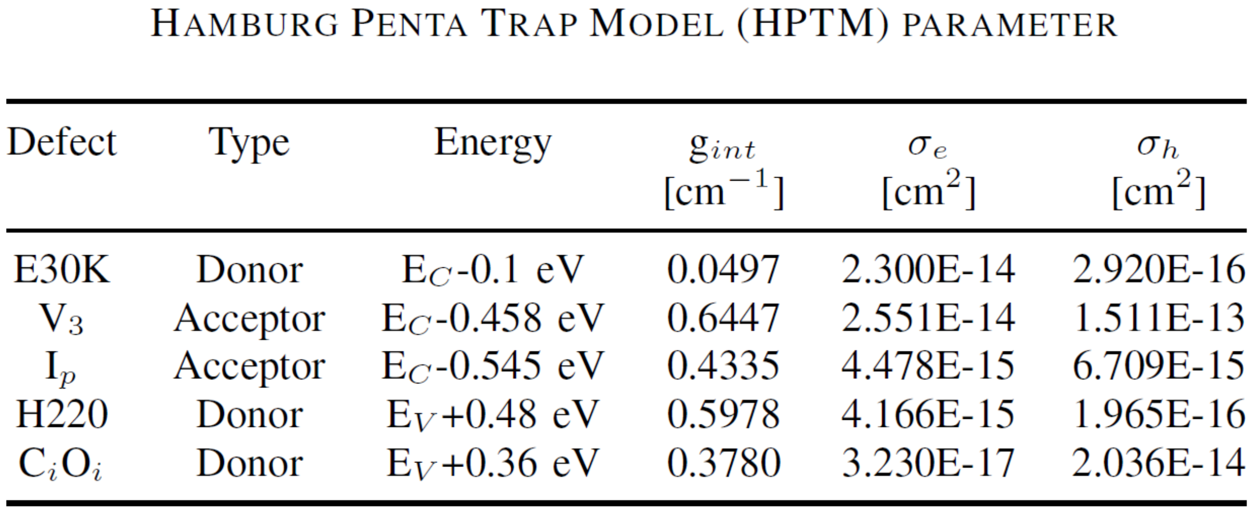
- Red Pulsed Laser: 670 nm, 10 µm spot, 50W/cm^2, 200 ps,
- BackIllumination at P1 Right
- FrontIllumination aligned with P1 Right
- IR Pulsed Laser: 1064nm, 30W/cm^2,10 mm spot, 30W/cm^2, 200 ps at P1 Right
- 2D detector model: 1 µm in Z direction, 5 mm in X direction, 300/50 µm in Y direction)

From 32th RD50 Workshop, Hamburg, 2018

Radiation Damage Models for ILGAD

One damage model, Traps+Acceptor Removal

1. New Perugia Model (300K)ϕ =1e15 up to 7,5e15 n_{eq}/cm^2
2. Hamburg Penta Trap model (253K) ϕ =1e15 up to 7,5e15 n_{eq}/cm^2
3. No interface trap model because the ILGAD is DC coupled
4. Acceptor Removal $N_A = N_A e^{-c\phi}$ c=10e^{-16} cm^{-2}

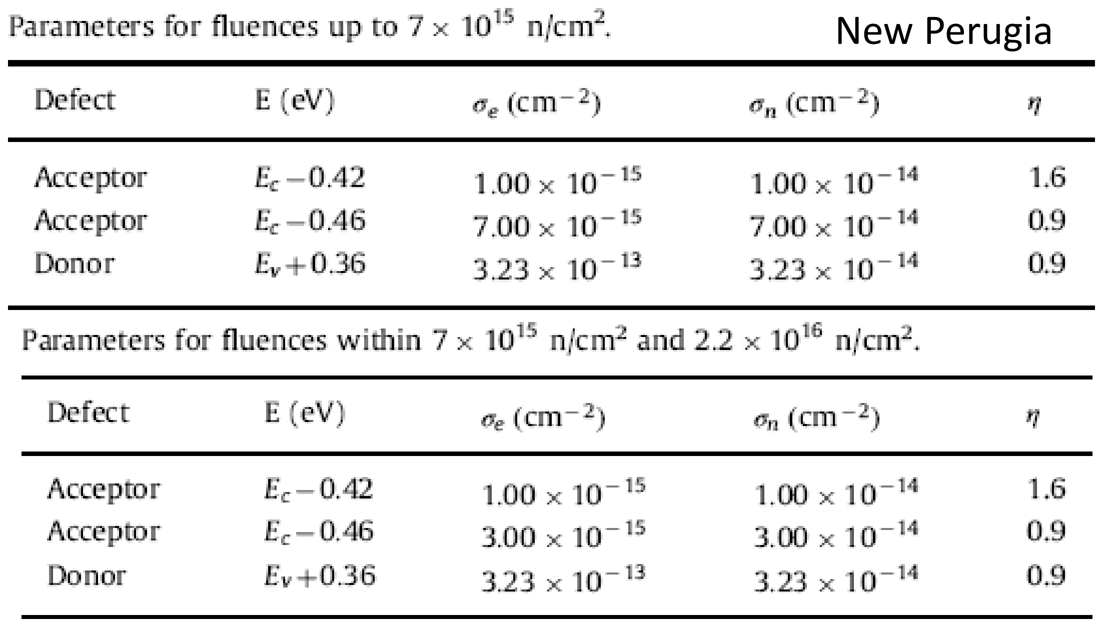


HAMBURG PENTA TRAP MODEL (HPTM) PARAMETER

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

"A new model for the TCAD simulation of the silicon damage by high fluence proton irradiation", Joern Schwandt et al., 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC)

From 32th RD50 Workshop, Hamburg, 2018



New Perugia

Parameters for fluences up to 7×10^{15} n/cm^2.

Defect	E (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η
Acceptor	$E_c-0.42$	1.00×10^{-15}	1.00×10^{-14}	1.6
Acceptor	$E_c-0.46$	7.00×10^{-15}	7.00×10^{-14}	0.9
Donor	$E_v+0.36$	3.23×10^{-13}	3.23×10^{-14}	0.9

Parameters for fluences within 7×10^{15} n/cm^2 and 2.2×10^{16} n/cm^2.

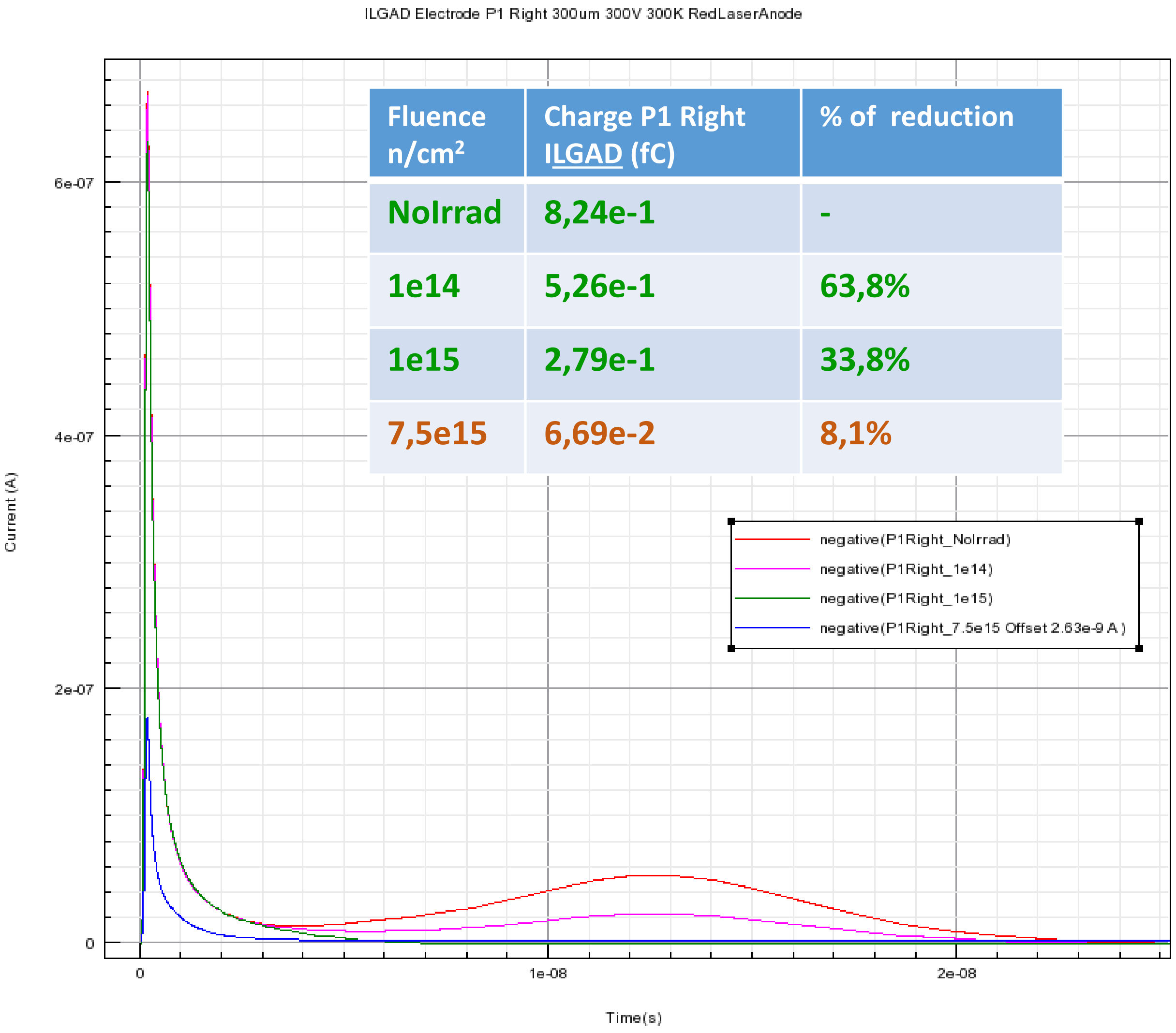
Defect	E (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η
Acceptor	$E_c-0.42$	1.00×10^{-15}	1.00×10^{-14}	1.6
Acceptor	$E_c-0.46$	3.00×10^{-15}	3.00×10^{-14}	0.9
Donor	$E_v+0.36$	3.23×10^{-13}	3.23×10^{-14}	0.9

Modeling of radiation damage effects in silicon detectors at high fluences HL-LHC with Sentaurus TCAD, D.Passeri et al, NIMA 824 (2016), 443-445

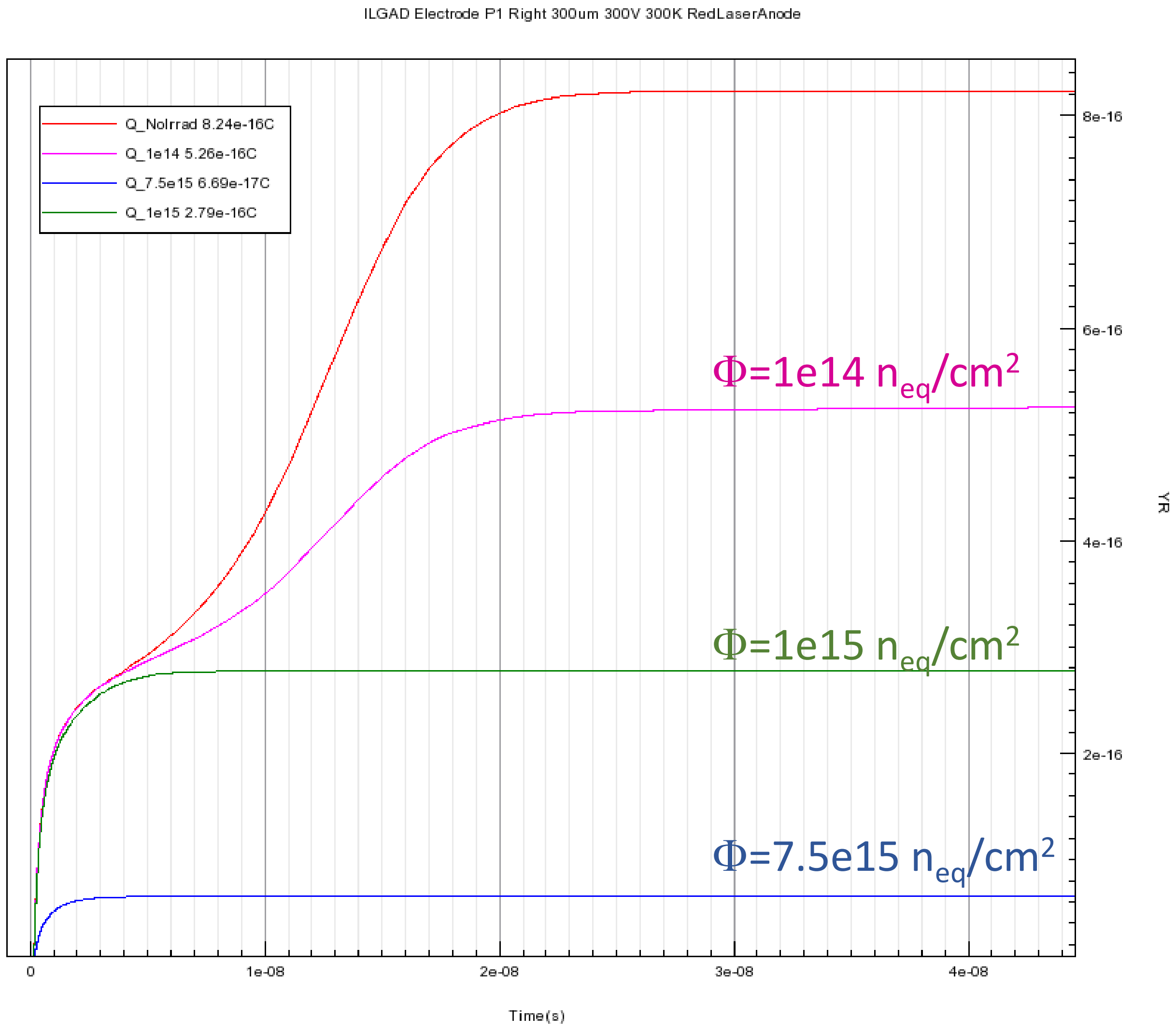
$$\frac{dN_T^0}{dt} = -eN_T^0 \quad ; \quad e = \frac{\sigma \nu N_c T^2}{g} \exp\left(\frac{-E_a}{k_b T}\right) \quad ; \quad N_T^0 = N_T \exp(-et)$$

Explanation for carrier removal and type conversión in irradiated silicon solar cells, T.Yamaguchi et al. Applied Physics Letters 72(10), 1998
Radiation effects in Low Gain Avalanche Detectors after hadron irradiations, G.Kramberger et al., JINST 2015 10 P07006

ILGAD 300 V_{bias}, 300 um RedLaserBack 300K Irradiation P1 Right

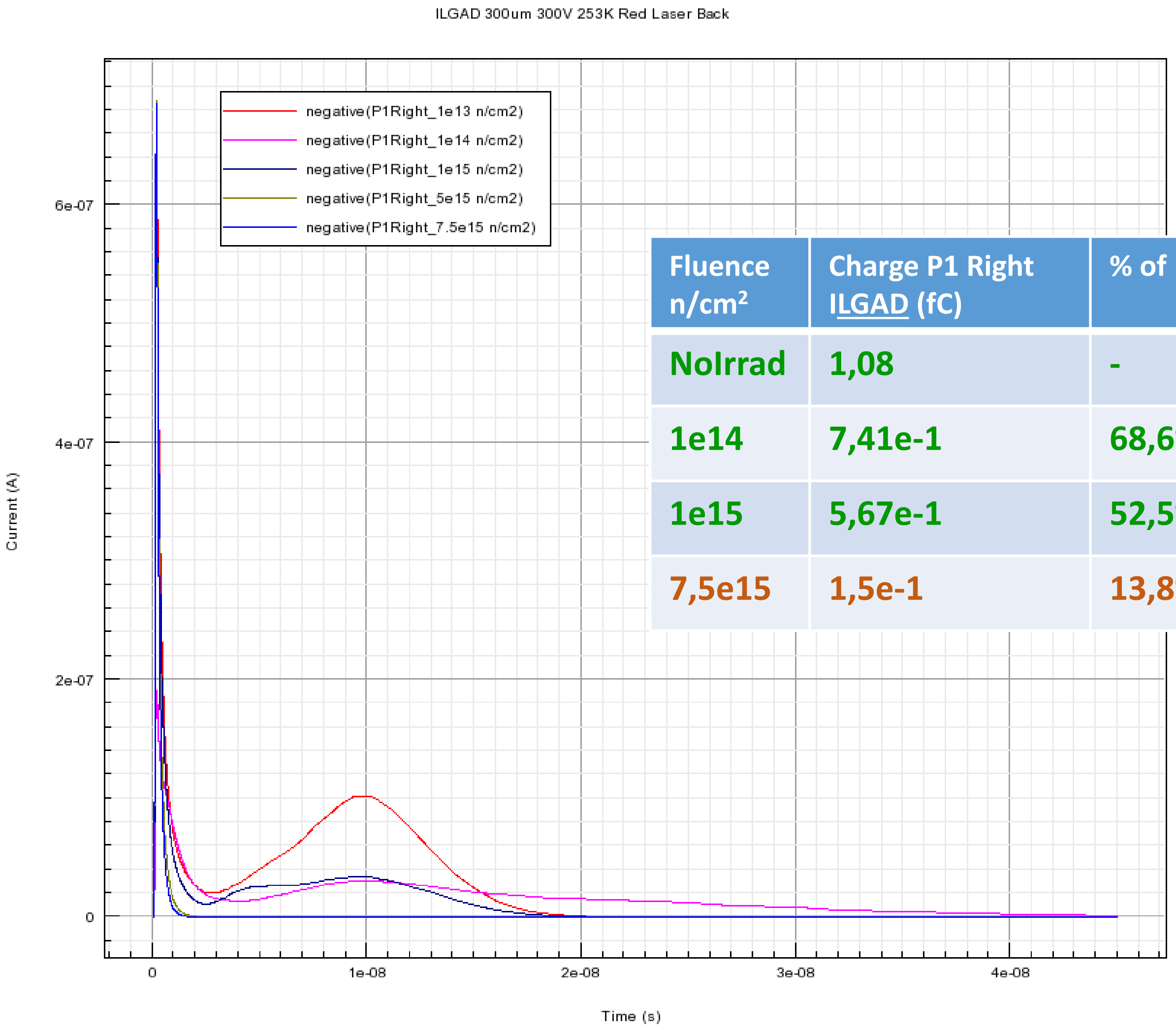


Fluence n/cm^2	Charge P1 Right ILGAD (fC)	% of reduction
NoIrrad	**8,24e-1**	**-**
1e14	**5,26e-1**	**63,8%**
1e15	**2,79e-1**	**33,8%**
7,5e15	**6,69e-2**	**8,1%**

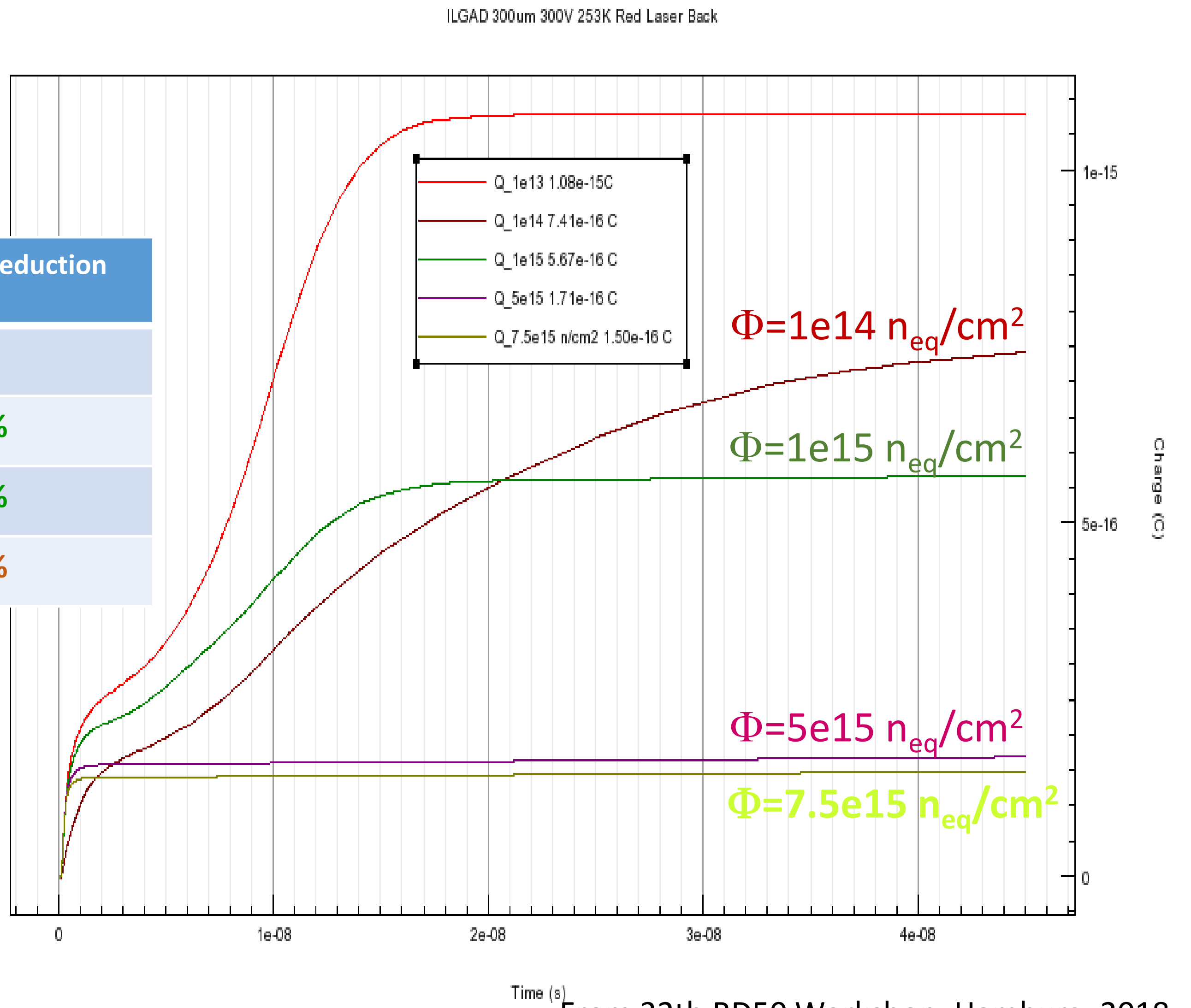


From 32th RD50 Workshop, Hamburg, 2018

ILGAD 300 V_{bias}, 300 um RedLaserBack <u>253K</u> Irradiation P1 Right Hamburg PentaTrap Model

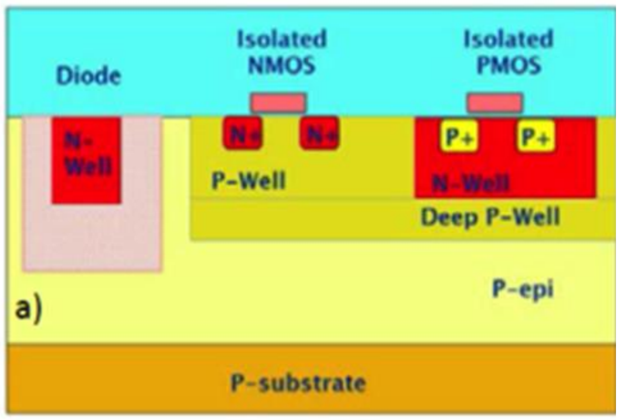


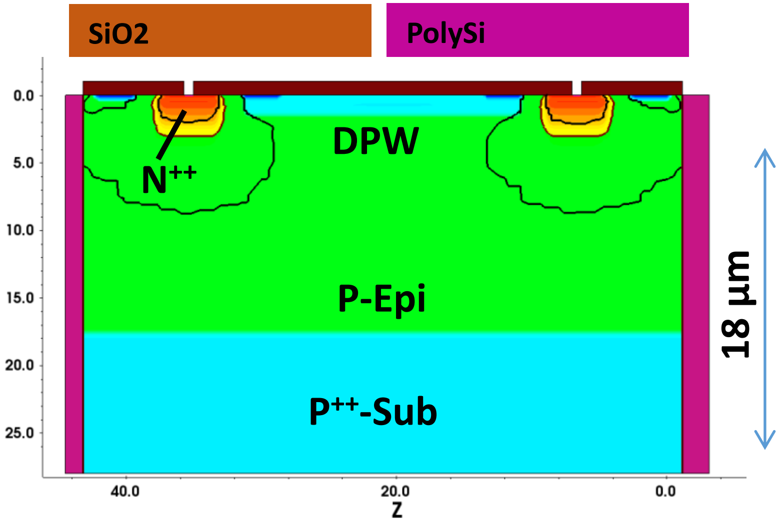
Fluence n/cm²	Charge P1 Right ILGAD (fC)	% of reduction
NoIrrad	1,08	-
1e14	7,41e-1	68,6%
1e15	5,67e-1	52,5%
7,5e15	1,5e-1	13,8%



From 32th RD50 Workshop, Hamburg, 2018

Monolithic detectors (MAPS): OVERMOS project



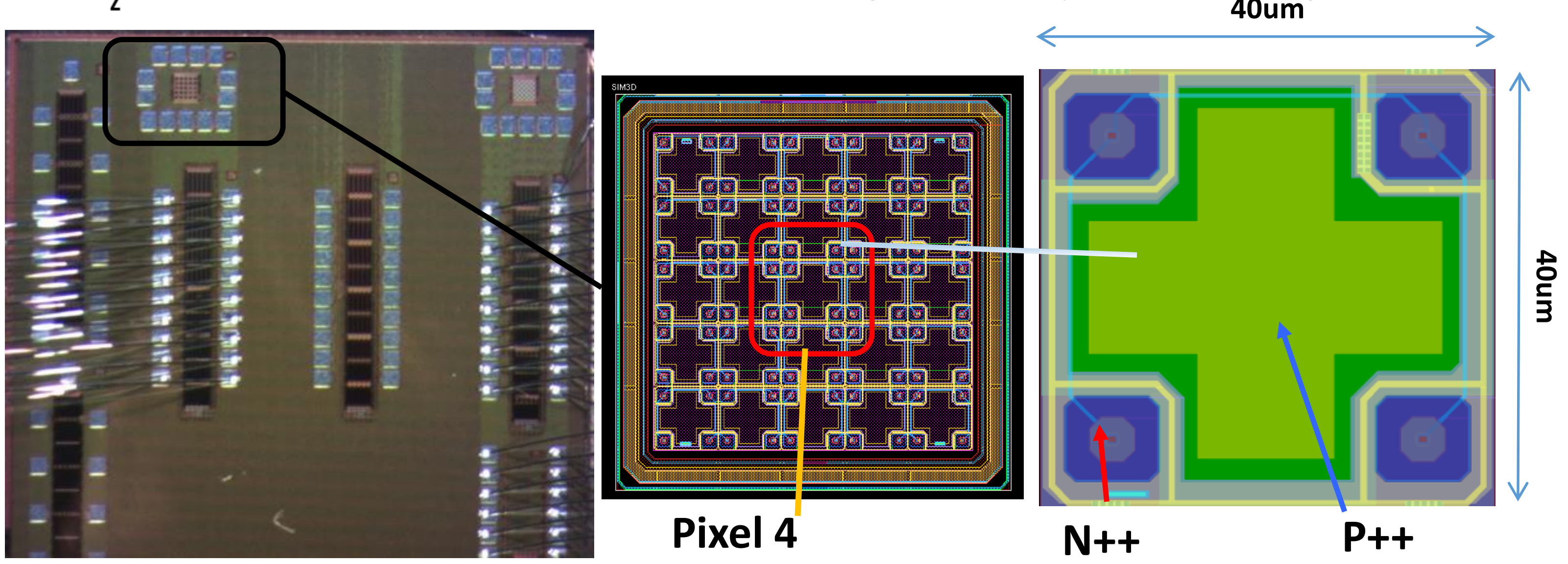


TCAD simulation

- For DC studies only ¼ pixel is simulated
- For CCE 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-Silicide (NS) regions (will implement silicide growth next)

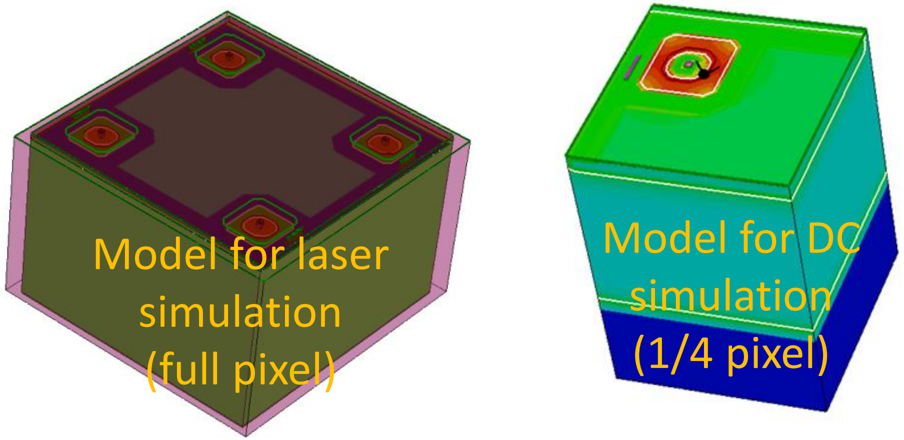
OVERMOS is a **CMOS MAPS (Monolithic Active Pixel Sensor)** project demonstrator fabricated using:

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



“TCAD Processes and device simulations of OVERMOS, a CMOS 180nm MAPS detector”, E.G.Villani, 34th RD50 Workshop, Lancaster University, UK, 12-14 June 2019

OVERMOS Monolithic detectors (MAPS) TCAD Simulations



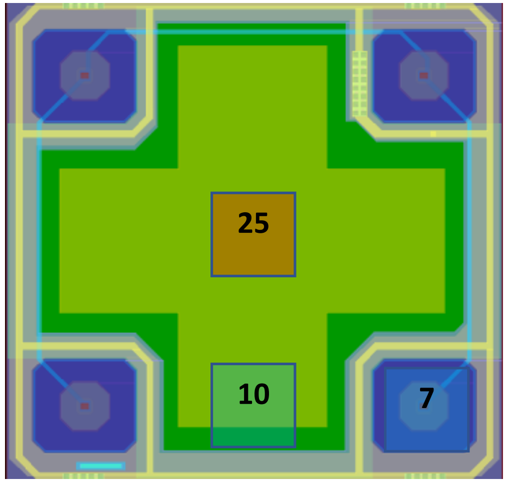
Physics models: SDEVICE parameters for mobility and recombination

- 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 3D simulations using a simplified device obtained using SPROCESS. The SPROCESS scripts allow simulation of devices fabricated using TowerJazz 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%



Laser Transient Simulation with hits at regions 25, 10 (SiO2-CoSi2 interface) and 7 (SiO2) to consider dielectric attenuation of transmitted light.

OVERMOS Monolithic detectors (MAPS) Radiation Models

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

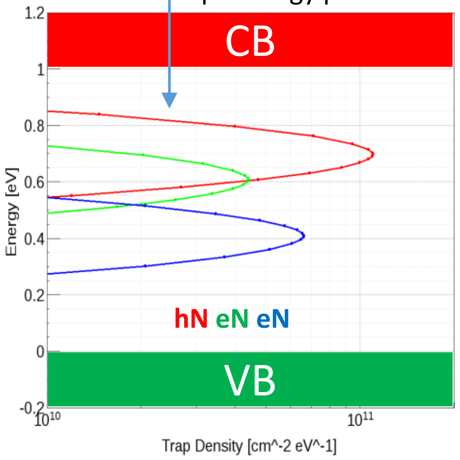
- Trap concentration of defects: **$N = g_{int} \cdot \Phi_{neq}$**
- Simulations for the optimization have been performed at **T= -20 °C** with:
  1. Slotboom band gap narrowing
  2. Impact ionisation (van Overstaeten-de Man)
  3. TAT Hurkx with tunnel mass = **$0.25\ m_e$** (default value: $0.5\ m_e$) 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

Interface effects considered

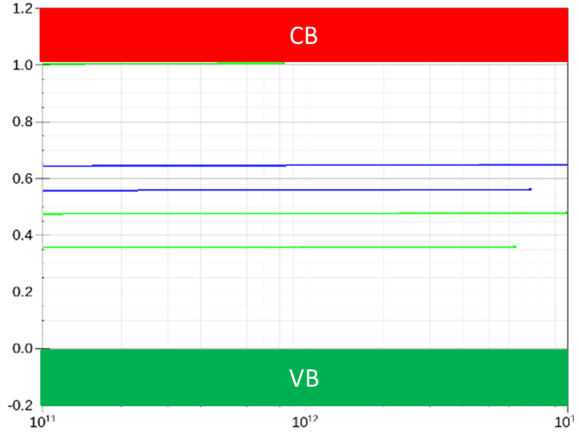
- Fixed oxide-charge (**Oxch**) density and interface traps (**Oxint**) included
- Interface traps distributed among 3 energy levels, Gaussian , σ = 70meV
- Ratio Oxint/Oxch ~ 0.9
- Simulations 1.2e11 Oxch
- Xsection 1E-15 cm^-2

DLN=30 (by default, energy discretization of traps in TCAD is 13 for the Gaussian distribution)

Interface traps energy plot



Bulk traps energy plot

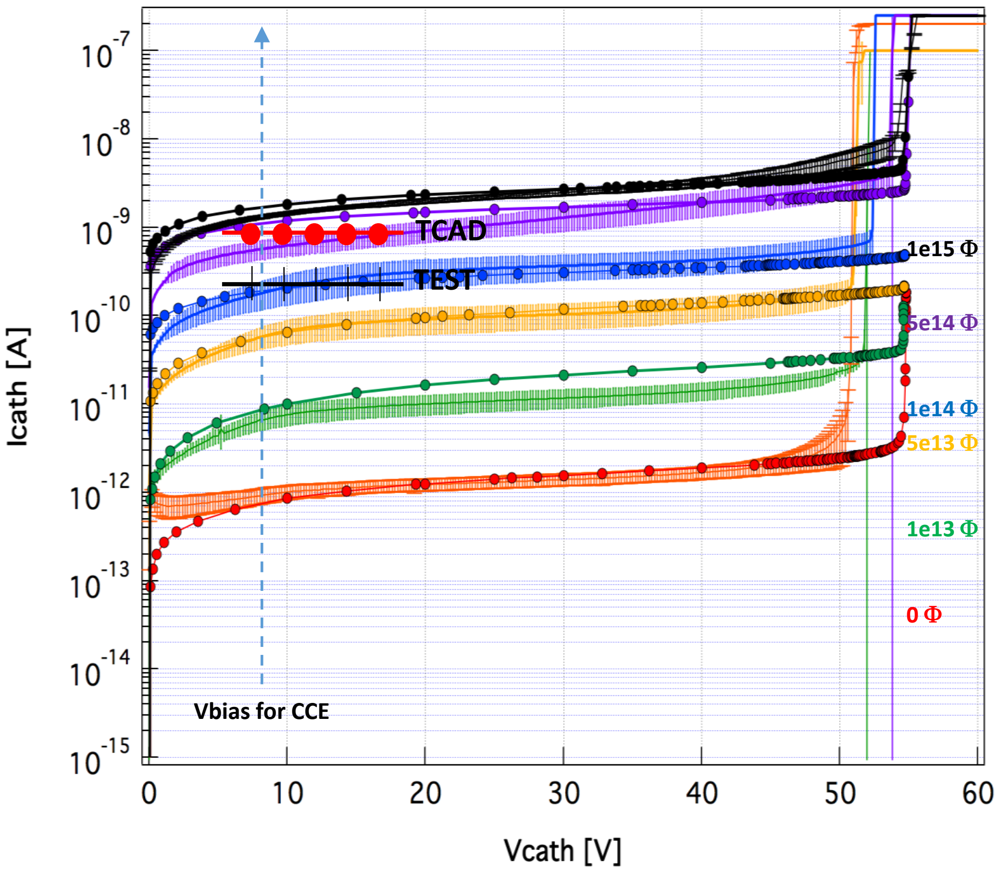


Interface Defect	Level	Concentration	σ
Acceptor	E_C-0.4 eV	40% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Acceptor	E_C-0.6 eV	60% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Donor	E_V+0.7 eV	100% of donor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV

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

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

OVERMOS MAPS TCAD Simulation I-V (3/5)



DC IV plots up to BV

<IV>[10] measured OVERMOS + σ

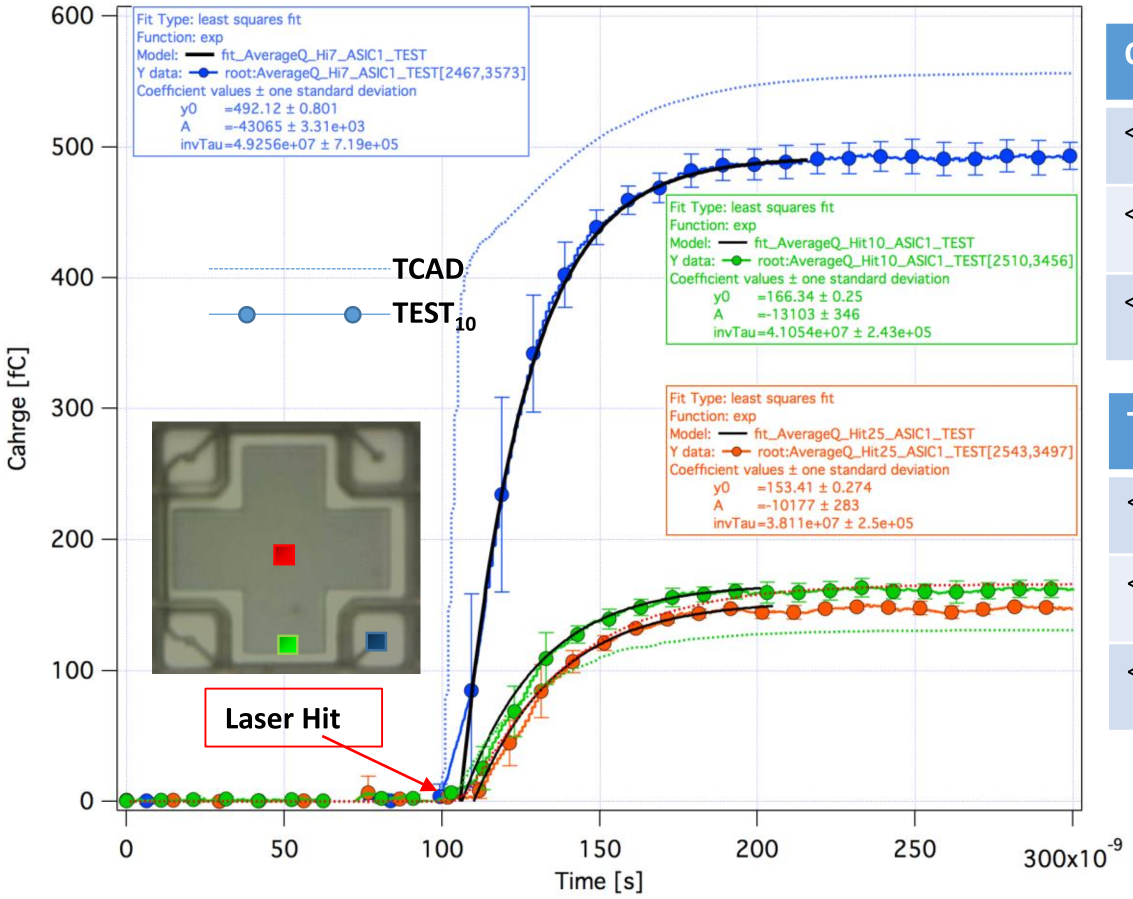
IV TCAD Oxch 1.2e11, OxINT 1.1e11

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: $(\Delta I/\Delta V)_{max}$

- The models seems to predict leakage current for the Tower Jazz 180nm SL CMOS process.
- Breakdown Voltage (BV) needs improvement.

OVERMOS MAPS TCAD Simulation CCE (4/5)



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

$T_{coll10\text{-}90}$	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 Charge Amplifier delay substraction: 9.1%
[b]hit10 with CA delay subs: 17.7%
[c]hit25 with CA delay subs: 23.3%

SiO2: For normal incidence
And transmitted: 1- R @ λ = 1064 nm, n_2=1.4469 R = 3.3%, T =96.6%, only real refractive index considered (k=0 in TCAD model)
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)

$$R = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2$$

SDEVICE Optical Generation parameters:

- 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

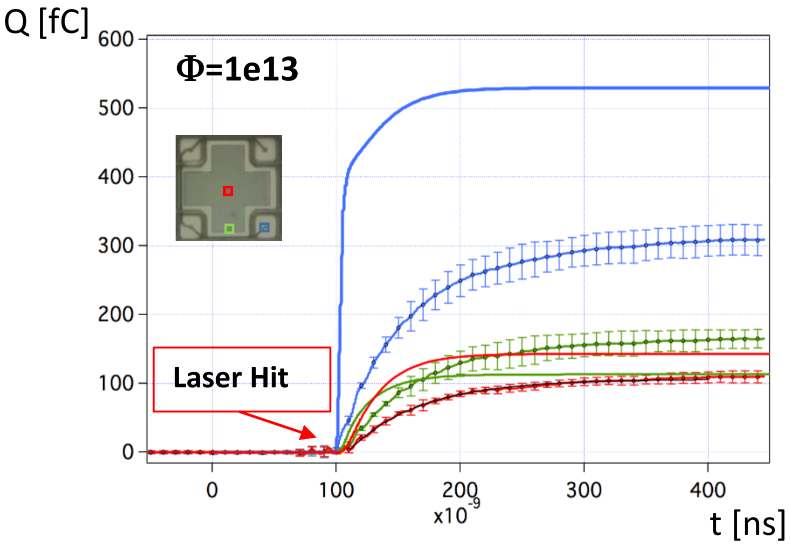
- Wavelength= 1.064 * Incident light wavelength [um]
- Intensity= @<20000.0*exp(-0.036*@Silicide_Thick@)*0.966>@ PolarizationAngle= 0 Theta= 90 Phi = 0

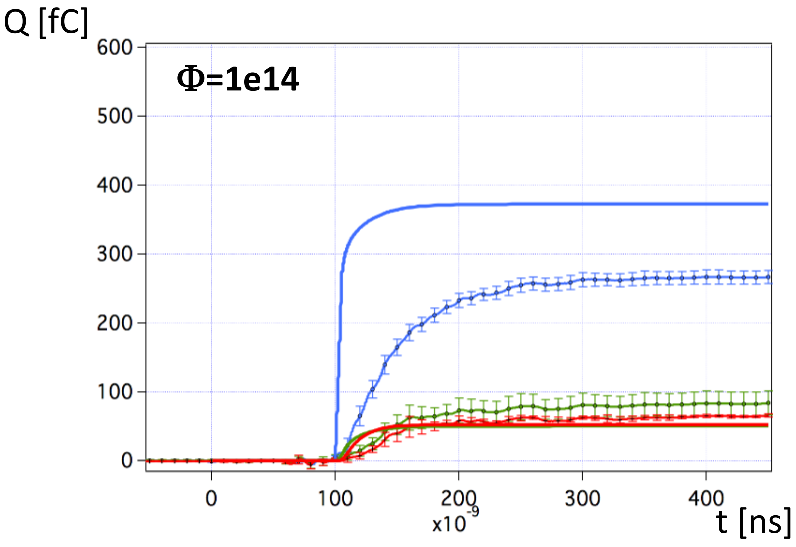
➢ Manually estimated expected charge from

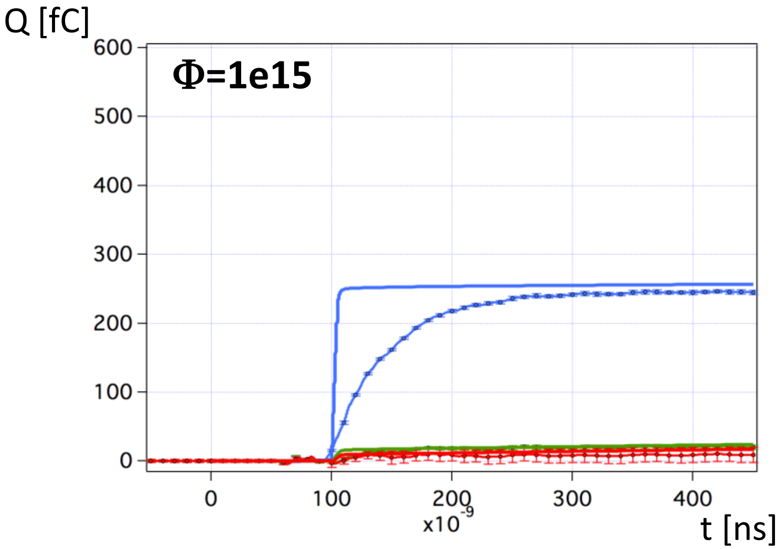
$$n = (1 - R)(1 - e^{-\alpha z max})\frac{P}{h\nu z_{max}} \sim 416fC$$

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

OVERMOS Irradiated MAPS CCE TCAD Simulations







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

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

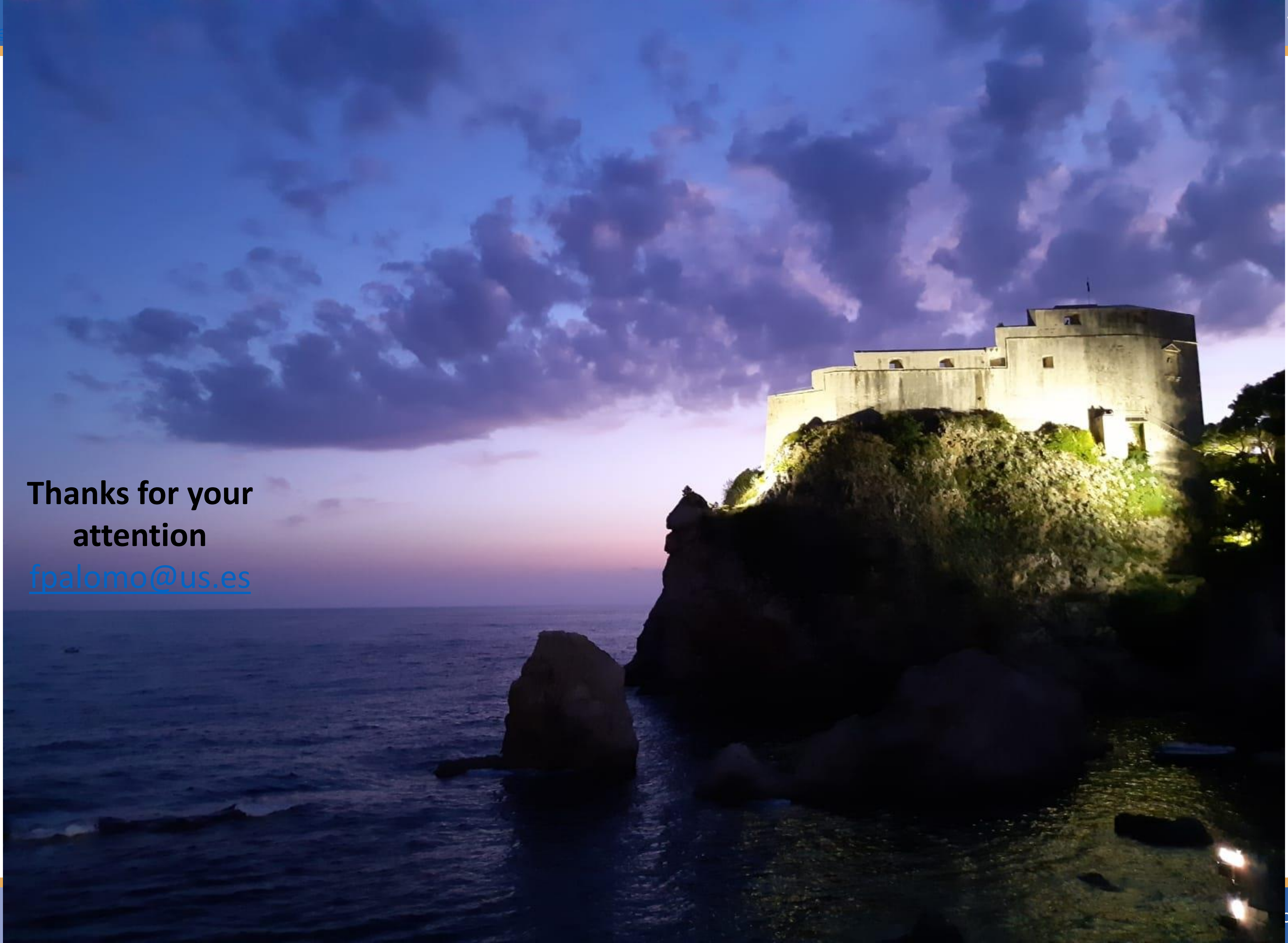
Q_{coll}	Test	TCAD	Δ%
<Qh7>	246	257	**-4**
<Qh10>	21	24	**-14**
<Qh25>	10	17	**70**

Neutron Irradiation simulated for different fluences Φ. CCE, using laser injection for irradiated structures gives decent results with respect to TCAD predictions but discrepancies are bigger than $I_{leakage}$.

"TCAD Processes and device simulations of OVERMOS, a CMOS 180nm MAPS detector", E.G.Villani, 34th RD50 Workshop, Lancaster University, UK, 12-14 June 2019

Conclusions

- From tailor-made to generic defects models, a bumpy road
- Every device needs specific defect modeling (LGADs for example, prone to acceptor removal)
- Reality is hard, simulation is only a tool
- TCAD defect modeling is a tool but not the “definitive” tool
- RD50 is actively working to improve predictive power of our models, much needed for the HL-LHC radiation environment



Thanks for your attention

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