17th (Virtual) "Trento" Workshop on Advanced Silicon Radiation Detectors

ISTITUTO OFFICINA DEI MATERIALI

INFN

UPO
UNIVERSITÀ DEL PIEMONTE ORIENTALE

A.D. 1308 unipg
UNIVERSITÀ DEGLI STUDI DI PERUGIA

Sensitivity analysis of parameters characterizing the bulk radiation damage on silicon devices

Patrick Asenov[1,2], Roberta Arcidiacono[3,4], Nicolo Cartiglia[3], Tommaso Croci[2, 5], Marco Ferrero[3,4], Alessandro Fondacci[5], Arianna Morozzi[2], Francesco Moscatelli[1,2], Daniele Passeri[2,5], Valentina Sola[3]

[1]Istituto Officina dei Materiali (IOM), Italian National Research Council (CNR), Perugia, Italy

[2]INFN Sezione di Perugia, Perugia, Italy

[3]INFN Sezione di Torino, Torino, Italy

[4]Universitá del Piemonte Orientale, Vercelli, Italy

[5]Università di Perugia, Perugia, Italy

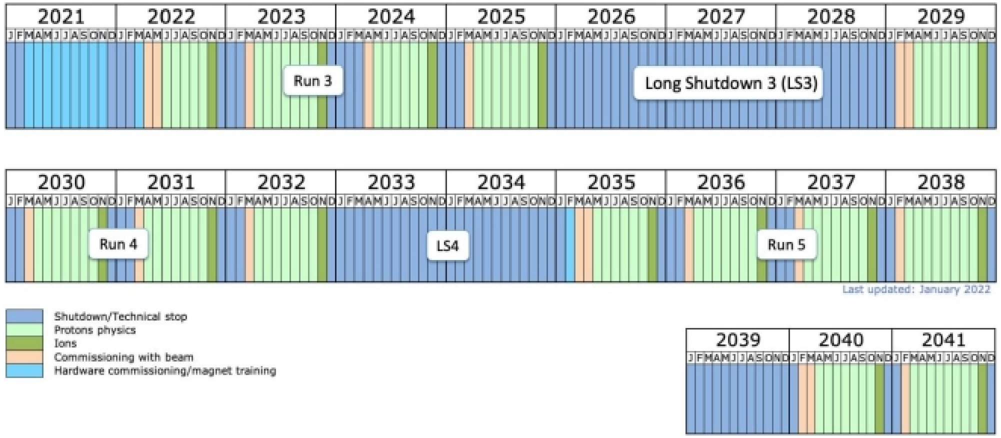
The High-Luminosity era

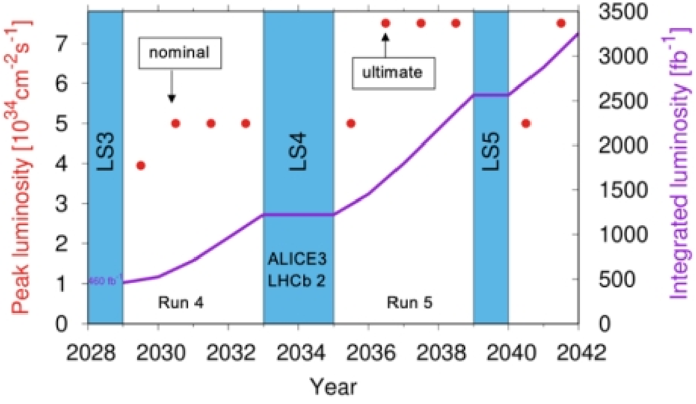
- High Luminosity LHC: fluences > 2×10^{16} 1 MeV n_{eq}/cm^2; doses > 1 Grad for innermost layers of the big LHC detectors → tight constraints in terms of radiation hardness for Si detectors

- Si detectors → a need for optimization → inter-electrode isolation and charge collection efficiency; Low-Gain Avalanche Diodes (LGAD): promising devices for coping with the high spatial density of particle hits and for better measuring the time of interaction of MIPs (thin active volume) → **current study: simulation of PIN diodes and LGADs**

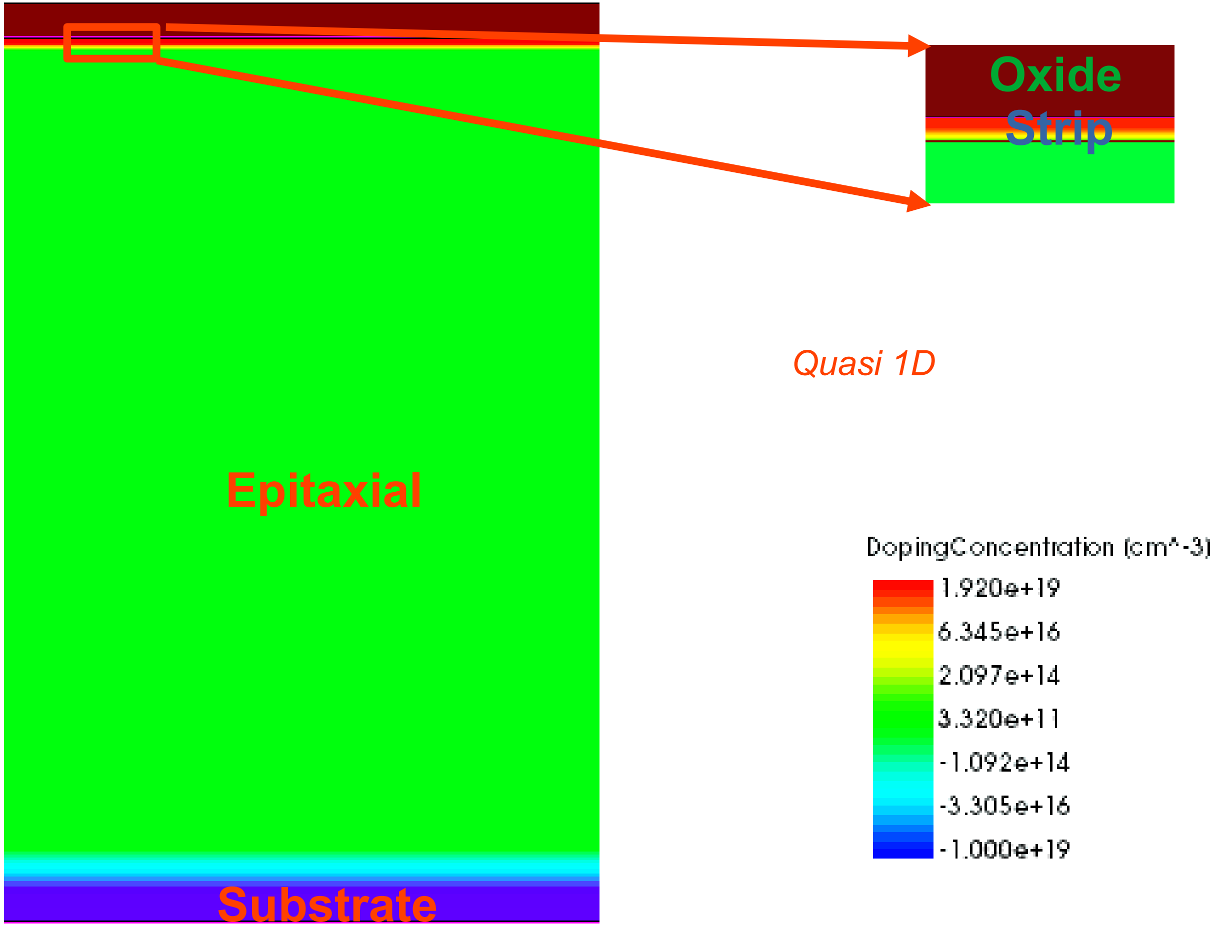
- Simulation tools (e.g. TCAD) → to study different technology and design options → a need for a combined radiation damage model describing both surface and bulk damage effects in silicon devices

Provisional long-term schedule





Geometry of a PIN diode



A diode with a wide, undoped intrinsic semiconductor region between a heavily-doped p-type semiconductor and a heavily-doped n-type semiconductor

Silicon

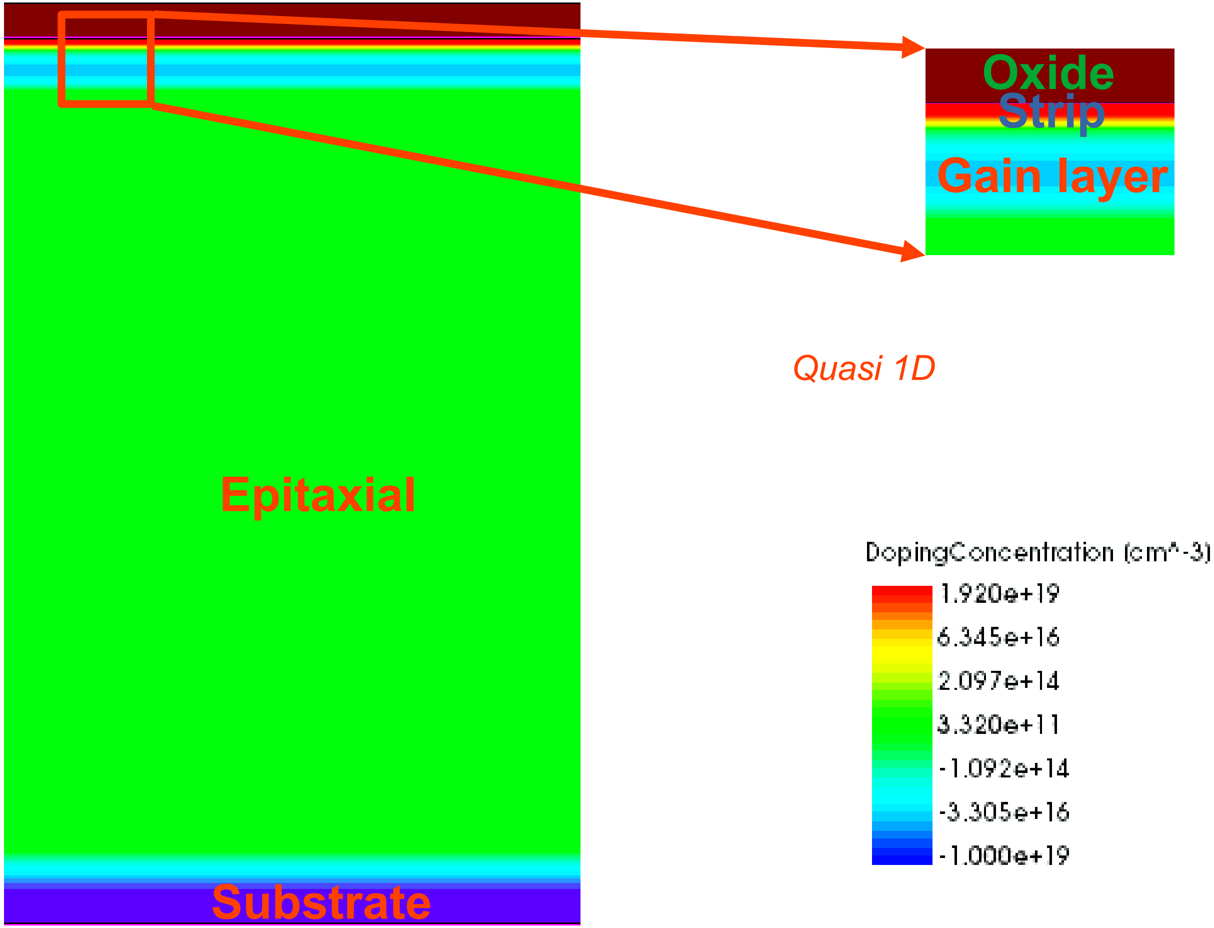
- Width: 20 μm
- Thicknesses: a) 25; b) 35; c) 55 μm
  - Epitaxial layer: a) 24.5; b) 34.5; c) 50 μm
  - Substrate: a) 0.5; b) 0.5; c) 5 μm

Silicon oxide

- Width: 18 μm
- Thickness: 1 μm

Simulated structures: based on sensors produced at Fondazione Bruno Kessler (FBK), Trento, Italy. Electrical measurements performed by the Turin and Perugia groups.

Geometry of an LGAD



The same as the PIN (for cases (a) and (b)), but with a p-doping implant serving as a Gain Layer (GL)

- Depletion: high-electric-field region in the GL close to the detector surface → avalanche due to impact ionization
- Low gain values → low noise levels due to the controlled charge multiplication in silicon

Simulated structures: based on sensors produced at Fondazione Bruno Kessler (FBK), Trento, Italy. Electrical measurements performed by the Turin and Perugia groups.

The baseline Perugia Surface and Bulk model

MODEL ***Perugia0***

Surface

	energy (eV)	Interface trap state density ($eV^{-1}cm^{-2}$)	Integrated interface trap density (cm^{-2})	eXsect (cm^2)	hXsect (cm^2)
Acceptor	E_C-0.56	Function of φ	Function of φ	1.0e-16	1.0e-15
Donor	E_V+0.60	Function of φ	Function of φ	1.0e-15	1.0e-16

Fixed oxide charge:

Function of φ

Bulk

	energy (eV)	intr. rate (cm^{-1})	eXsect (cm^2)	hXsect (cm^2)
Donor	E_C-0.23	0.006	2.3e-14	2.3e-15
Acceptor	E_C-0.42	1.6	1.0e-15	1.0e-14
Acceptor	E_C-0.46	0.9	7.0e-14	7.0e-13

- A starting point for the work presented here: fully implemented within the Synopsys Sentaurus Technology CAD (TCAD) tool
- Goal: description of the surface and bulk damage effects induced by radiation in silicon sensors → relying on a limited number of parameters relevant for physics
- Integrated interface trap density and oxide charge density: determined before and after X-ray irradiation with doses ranging from 0.05 to 100 Mrad (SiO_2), for different foundries and technologies → model tested with FBK, HPK, IFX devices
- Next objective: to optimize the reproduction of the bulk damage effects

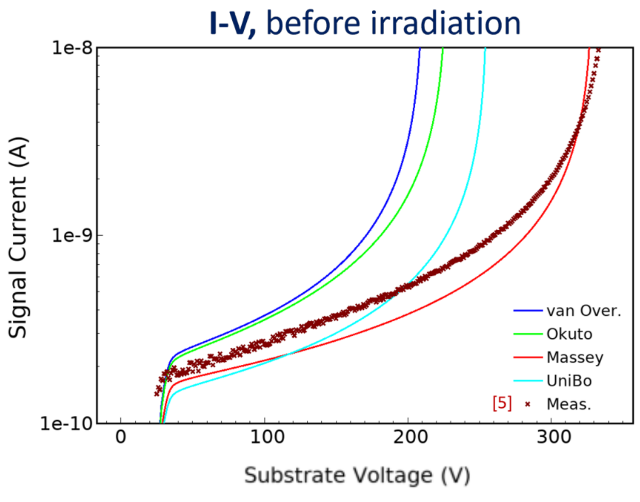
Morozzi A, Moscatelli F, Croci T and Passeri D (2021) TCAD Modeling of Surface Radiation Damage Effects: A State-Of-The-Art Review. Front. Phys. 9:617322. doi: 10.3389/fphy.2021.617322

Characteristics of the simulations

- CV simulations: 300 K; IV simulations, damage factor: 253 K and scaled using Chilingarov's formula (A Chilingarov 2013 JINST 8 P10003): $I(T) \propto T^2 \exp(-1.21\,eV/2k_B T)$

- Area Factor (AF) = 50000 for (c)/84500 for (a) and (b); f = 1 kHz

- Physical models: Shockley-Read-Hall (SRH), Band-To-Band Tunneling, Auger for the generation/recombination rates; e/h mobility; Massey avalanche model **only for IV**; a series of *New University of Perugia* models (for surface and bulk damage modeling) including a trap generation mechanism



Temperature **300 K.** Electrical contact area **1mm²**

D. J. Massey, J. P. R. David and G. J. Rees, *IEEE Trans. Electron Devices*, vol. 53, no. 9, pp. 2328-2334, 2006.

- Other impact ionization models, such as the van Overstraeten-de Man, Okuto-Crowell, and University of Bologna models also examined for the avalanche generation → all of them underestimate the breakdown voltage of the devices → the Massey model allows the most faithful reproduction of the experimental data → T. Croci et al 2022 JINST **17** C01022

PerugiaModDoping models

	etaA1 (cm^-1)	etaA2 (cm^-1)	etaD (cm^-1)	EmidA1 (eV)	EmidA2 (eV)	EmidD (eV)	hxA1 (cm^2)	hxA2 (cm^2)	exD (cm^2)
Case 1	1.6	0.9	0.006	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 2	1.6	0.9	0.006	0.42	0.545	0.23	1.00E-14	1.00E-14	2.30E-14
Case 3	1.6	0.9	0.2	0.42	0.545	0.23	1.00E-14	1.00E-14	2.30E-14
Case 4	1.6	0.9	0.2	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 5	1.6	0.9	0.02	0.42	0.545	0.23	1.00E-14	1.00E-14	2.30E-14
Case 6	1.6	0.9	0.02	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 7	1.6	0.9	0.01	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 8	1.6	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 9	1.6	0.9	0.015	0.42	0.46	0.23	1.00E-14	1.40E-12	2.30E-14
Case 10	1.6	0.9	0.015	0.42	0.46	0.23	5.00E-14	7.00E-13	2.30E-14
Case 11	1.6	1.5	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 12	2	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 13	2.5	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 14	3	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 15	5	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 16	10	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 17	10	0.9	0.015	0.42	0.46	0.23	1.00E-14	4.00E-13	2.30E-14
Case 18	10	1.2	0.015	0.42	0.46	0.23	1.00E-14	4.00E-13	2.30E-14

Always two acceptor levels and one donor level → all E calculated from E_C

eta: introduction rate; Emid: mid-energy level of uniformly distributed band of traps; hx/ex: capture cross sections for holes/electrons; exA = hxA/10, hxD = exD/10

The **best** case: the one for which the sum of squares of relative differences between simulated and experimental values of all important parameters is minimized

A sensitivity analysis of the simulation parameters

Change of parameter	Current-related damage factor	Charge collection efficiency	IV	$1/C^2$ - V
etaD ↑	↓	↓	→; breakdown at high values	←
etaA1 ↑	↓ then ↑	-	↑	→
etaA2 ↑	↓	↑	-	→; slope ↓
hXA1 ↑	↓	↑	↓	←
hXA2 ↑	↑	-	↑	→; slope ↓

A study of the effects/trends of outputs caused by the modification of various simulation parameters → a sensitivity analysis

Best case 18 summarized below:

Defect number	Type	Energy level	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
1	Donor	$E_C - 0.23$ eV	2.3e-14	2.3e-15	0.015
2	Acceptor	$E_C - 0.42$ eV	1.0e-15	1.0e-14	10
3	Acceptor	$E_C - 0.46$ eV	4.0e-14	4.0e-13	1.2

In the original Perugia0: σ_e = 7.0e-14 cm^2, σ_h = 7.0e-13 cm^2, η_D = 0.006 cm^{-1}, η_{A1} = 1.6 cm^{-1}, η_{A2} = 0.9 cm^{-1}

An analytical parameterization

- Torino analytical Bulk parameterization (Acceptor Creation):

✓ if not irradiated

$$N_{A,bulk} = 5e12\ cm^{-3}$$

✓ if $0 < \phi \leq 3e15\ n_{eq}/cm^2$

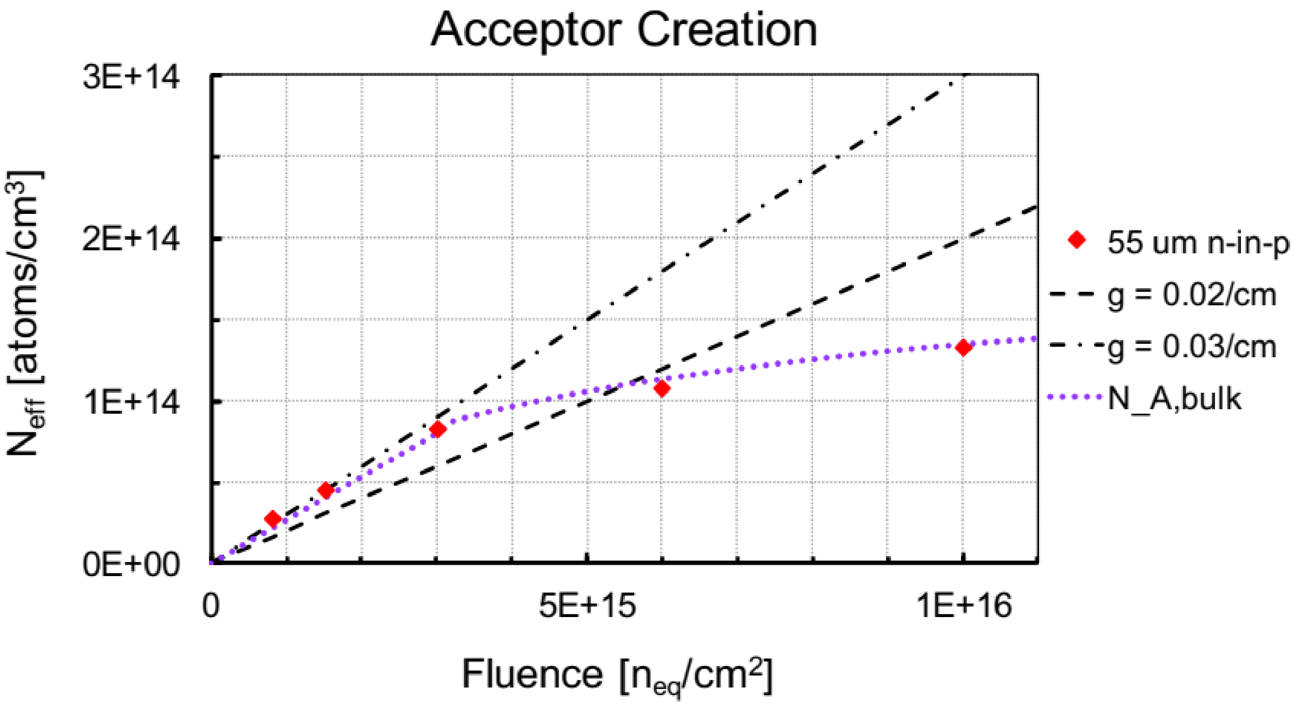
$$N_{A,bulk}(\phi) = N_{A,bulk}(0) + g_c{*}\phi$$

$$g_c = 2{,}37e\text{-}2\ cm^{-1}$$

✓ if $\phi > 3e15\ n_{eq}/cm^2$

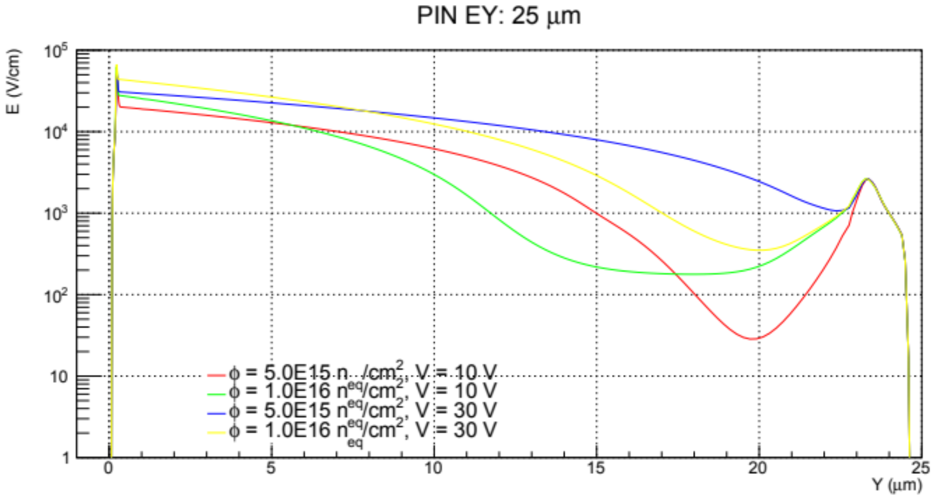
$$N_{A,bulk}(\phi) = 4{,}17e13{*}\ln(\phi) - 1{,}41e15$$

All results presented here: for a modified version of *Perugia 2019* where the doping concentration is a branching function → *PerugiaModDoping*
The model: fine-tuned with PIN diodes ans subsequently validated for **LGADs** → absolute values for all magnitudes



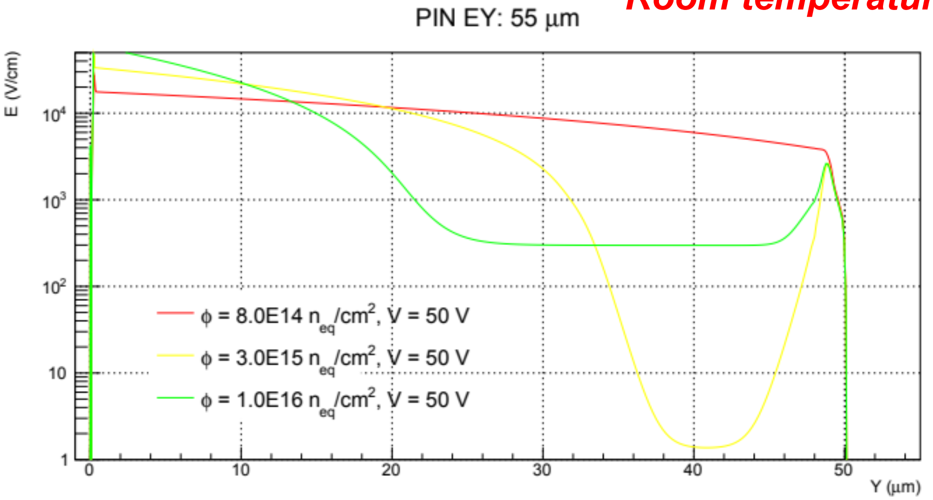
M. Ferrero et al., *A summary of the radiation resistance of carbonated gain implants*, TREDI Workshop, Online, 16-18 February 2021

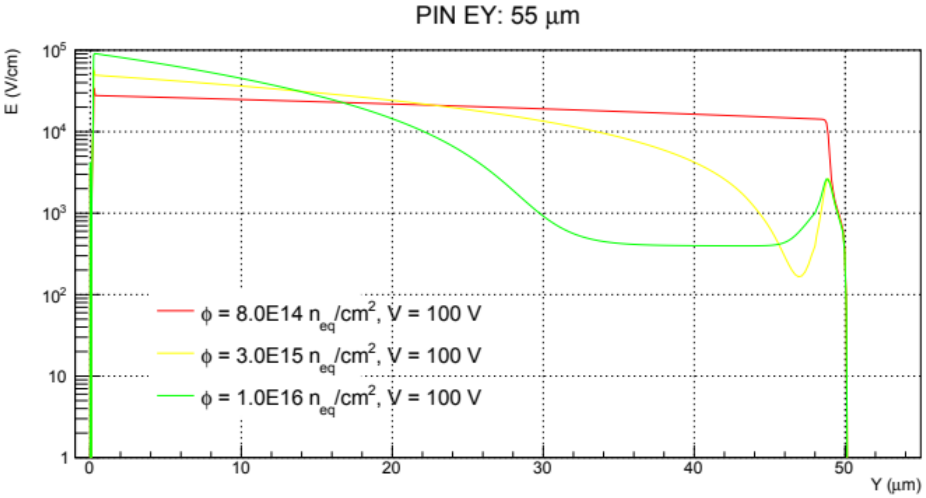
Best case 18, PIN: electric field vs. Y



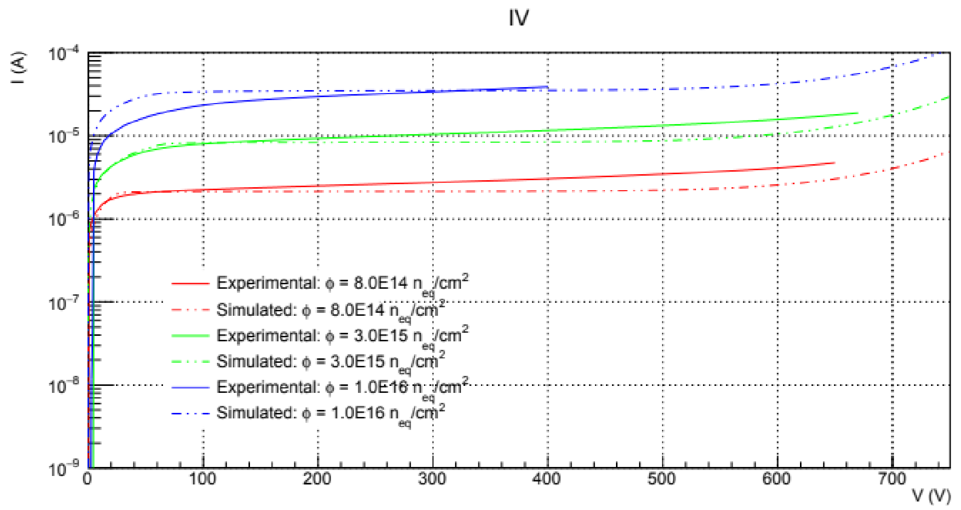
Defect number	Type	Energy level	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
1	Donor	$E_C - 0.23$ eV	2.3e-14	2.3e-15	0.015
2	Acceptor	$E_C - 0.42$ eV	1.0e-15	1.0e-14	10
3	Acceptor	$E_C - 0.46$ eV	4.0e-14	4.0e-13	1.2

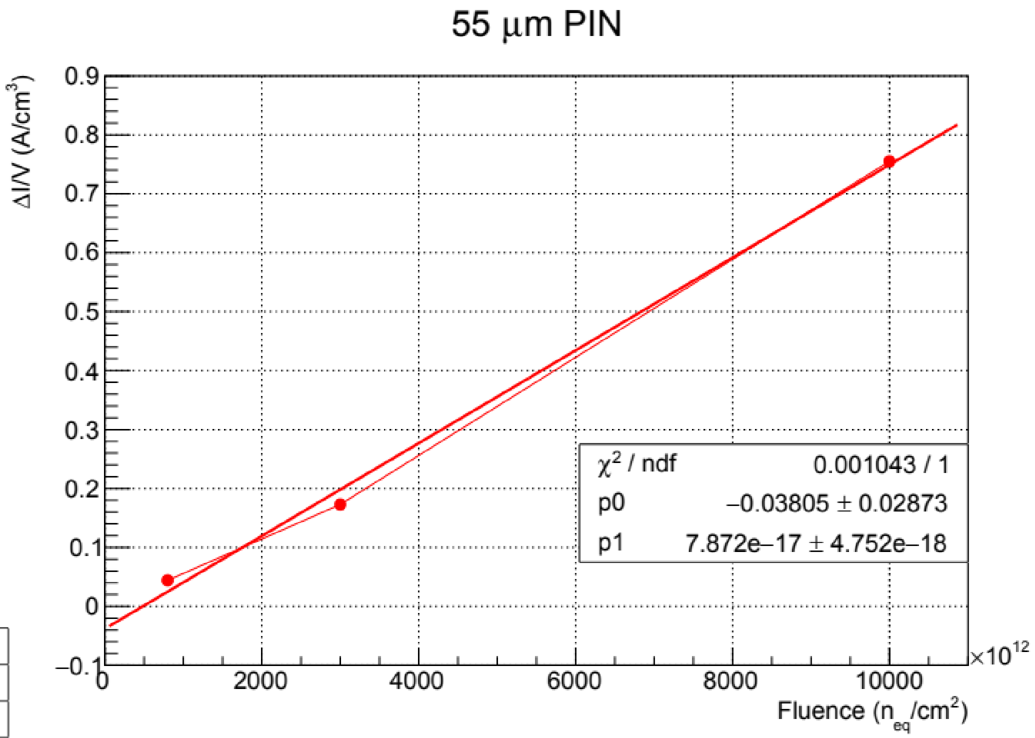
Room temperature; Y: thickness coordinate





Best case 18, 55 µm PIN: IV and current-related damage factor α

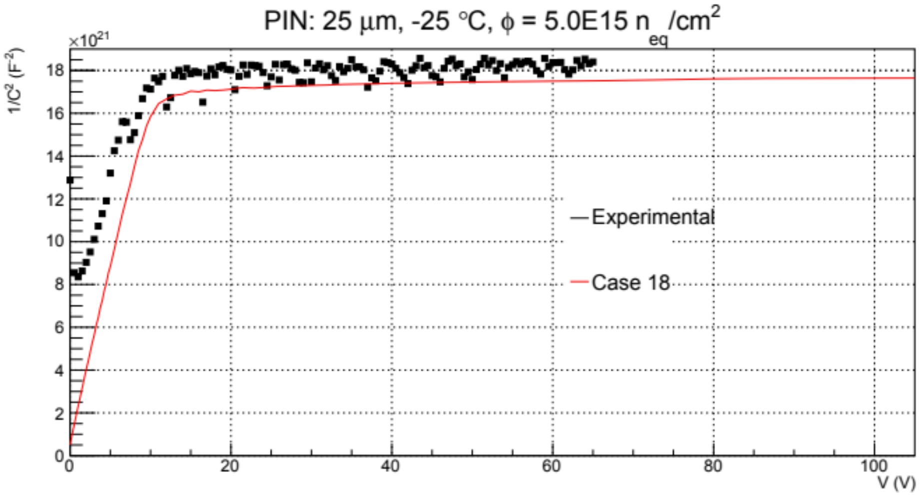


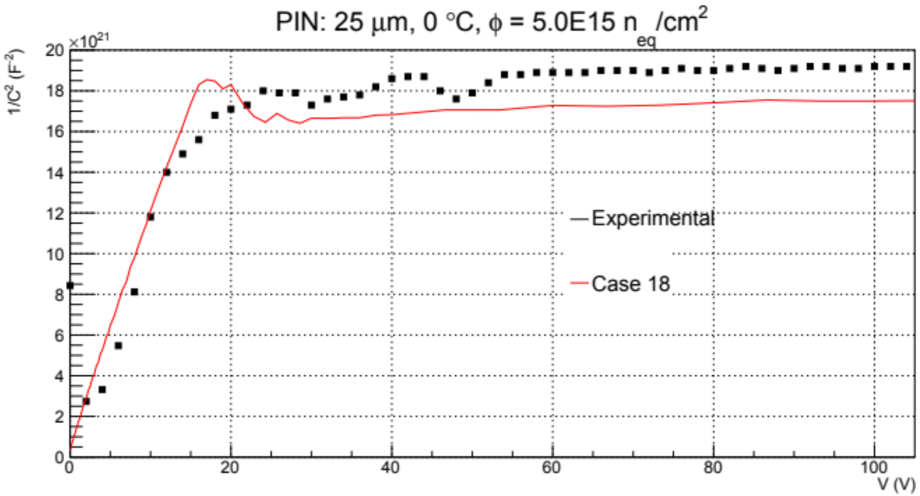


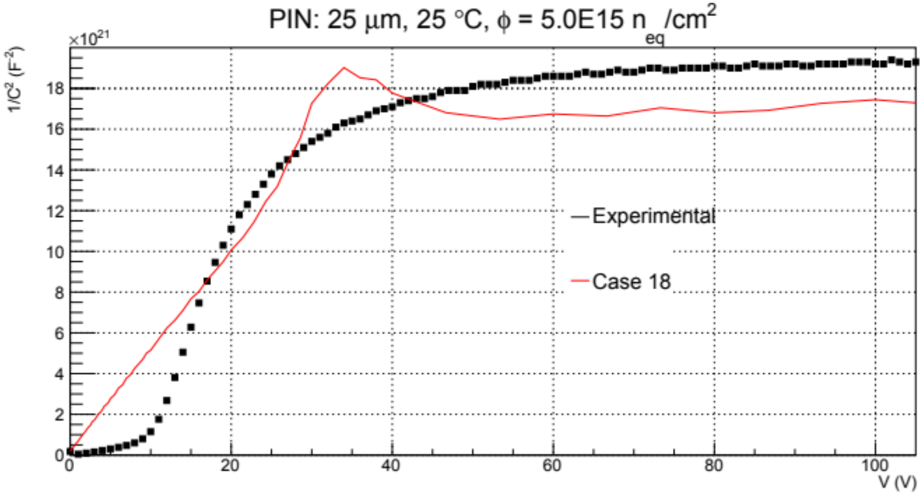
Defect number	Type	Energy level	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
1	Donor	$E_C - 0.23$ eV	2.3e-14	2.3e-15	0.015
2	Acceptor	$E_C - 0.42$ eV	1.0e-15	1.0e-14	10
3	Acceptor	$E_C - 0.46$ eV	4.0e-14	4.0e-13	1.2

Simulation executed at 253 K → results scaled using Chilingarov's formula.
Best case 18: α = 7.872e-17 A/cm
Perugia0 original (Perugia 2019 Surface): α = 6.942e-17 A/cm
Perugia0ModDoping: α = 6.031e-17 A/cm

25 μm PIN, $1/C^2$-V

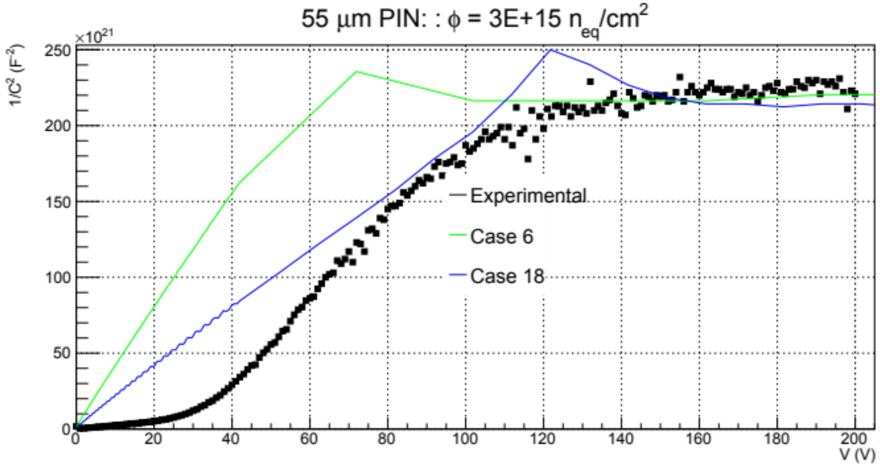


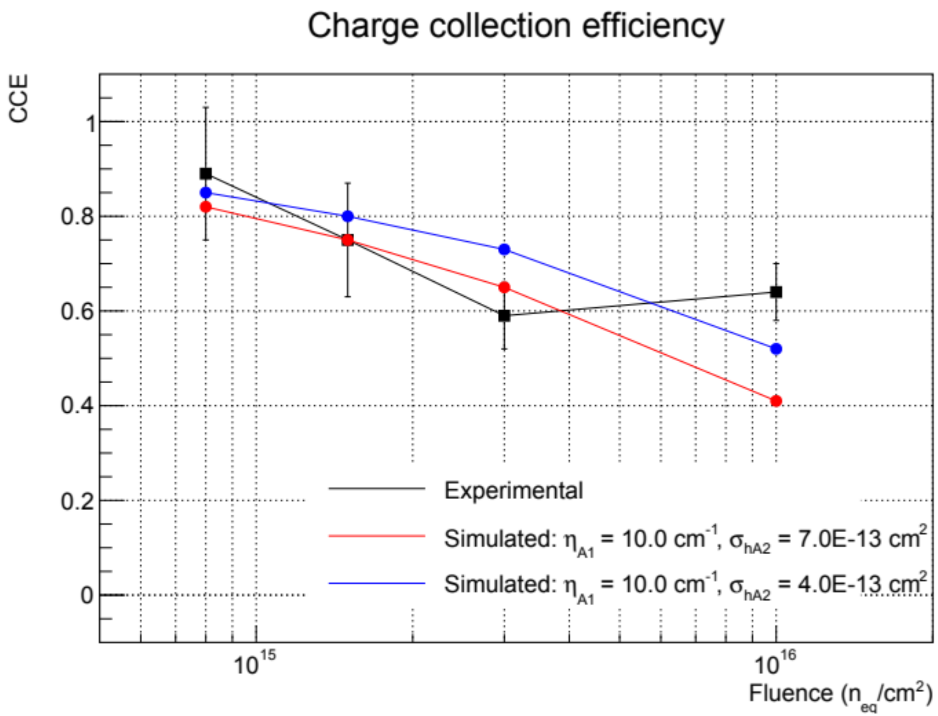




Defect number	Type	Energy level	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
1	Donor	$E_C - 0.23$ eV	2.3e-14	2.3e-15	0.015
2	Acceptor	$E_C - 0.42$ eV	1.0e-15	1.0e-14	10
3	Acceptor	$E_C - 0.46$ eV	4.0e-14	4.0e-13	1.2

55 µm PIN: 1/C²-V, charge collection efficiency





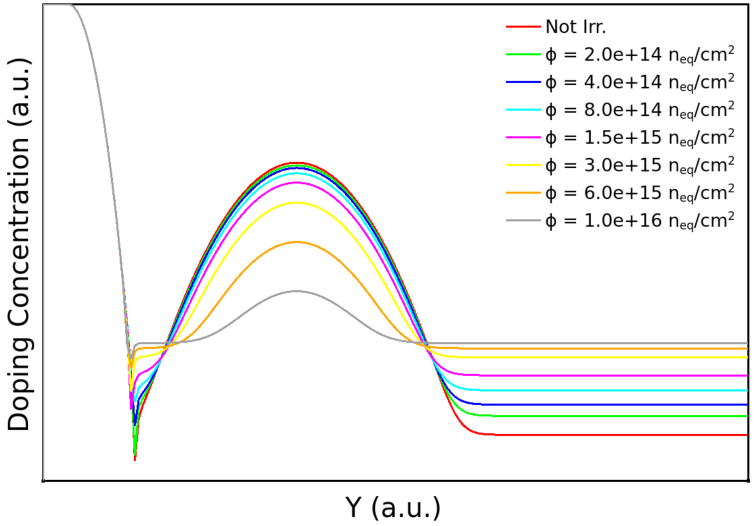
Blue: best case 18

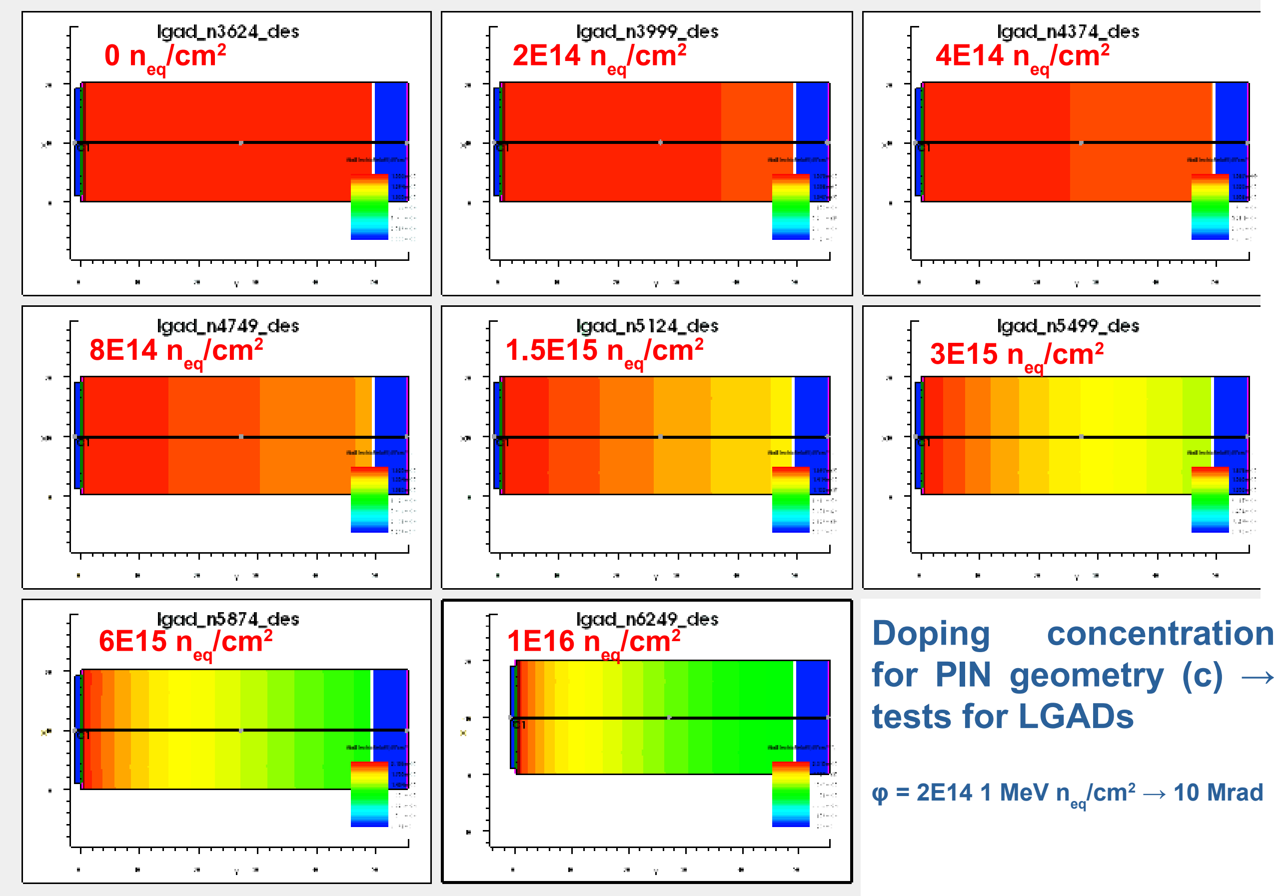
CCE = 1 for fluence = 0

	etaA1 (cm^-1)	etaA2 (cm^-1)	etaD (cm^-1)	EmidA1 (eV)	EmidA2 (eV)	EmidD (eV)	hxA1 (cm^2)	hxA2 (cm^2)	exD (cm^2)
Case 6	1.6	0.9	0.02	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 18	10	1.2	0.015	0.42	0.46	0.23	1.00E-14	4.00E-13	2.30E-14

LGAD: evolution of the acceptor doping concentration

- $N_{GL}(\varphi) = N_A(0)e^{-c\varphi}$
  - N_{GL} is the doping concentration of the gain layer, φ is the fluence, c is the acceptor removal coefficient



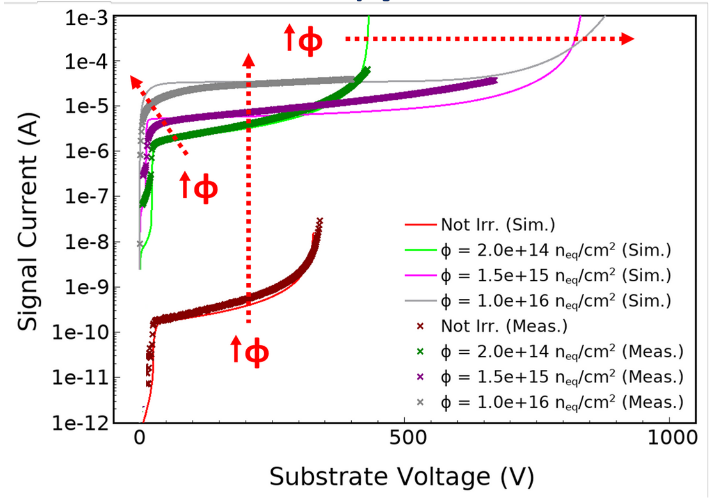


Doping concentration for PIN geometry (c) → tests for LGADs

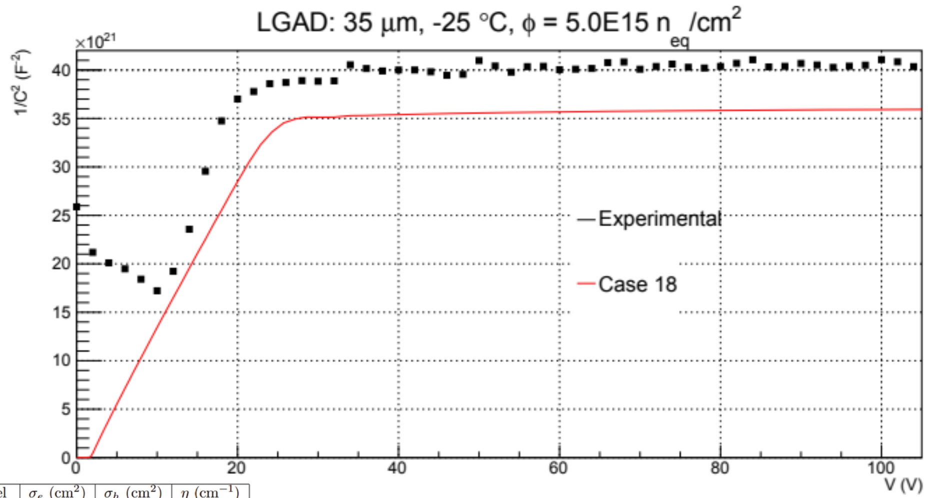
φ = 2E14 1 MeV n_{eq}/cm^2 → 10 Mrad

Testing Case 18 on LGADs

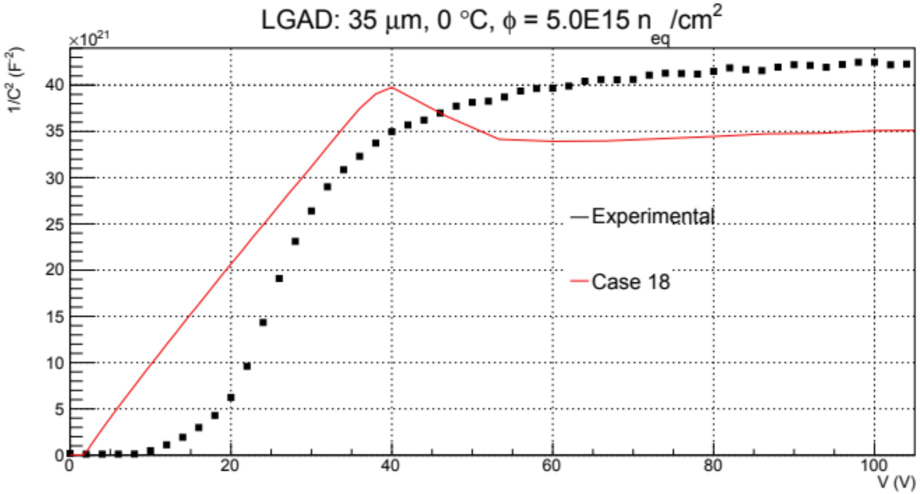
I-V

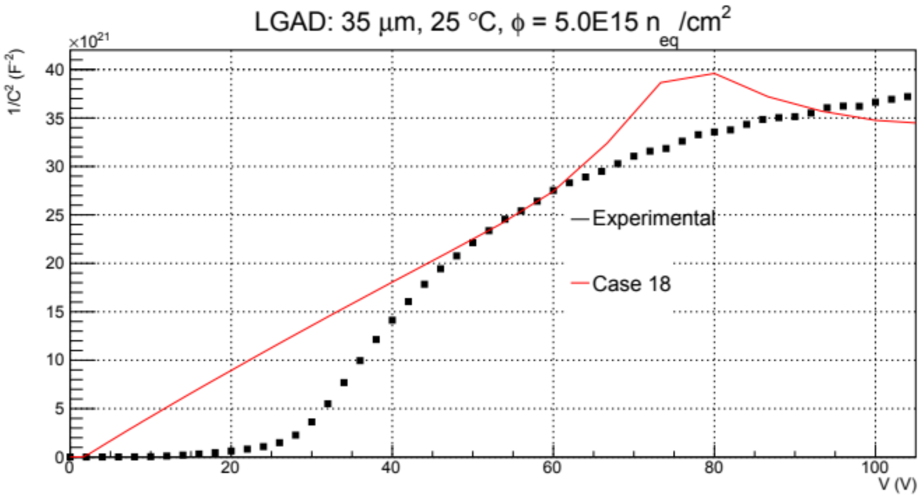


T. Croci et al 2022 JINST **17** C01022



Defect number	Type	Energy level	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
1	Donor	$E_C - 0.23$ eV	2.3e-14	2.3e-15	0.015
2	Acceptor	$E_C - 0.42$ eV	1.0e-15	1.0e-14	10
3	Acceptor	$E_C - 0.46$ eV	4.0e-14	4.0e-13	1.2





Conclusions

- The behavior of FBK PIN diodes simulated with a new series of Perugia models
- Measurements in Turin: a change in the acceptor doping concentration value *N* with fluence → a novel parameterization
- Impact of the variation of some input parameters of the model (electron/hole cross sections and acceptor/donor introduction rates) on the changes in leakage current, full depletion voltage, charge collection efficiency and damage factor *α*
- An optimal case → very good agreement between simulated and experimental results in terms of IV, $1/C^2$ – V, CCE calculation, *α* calculation
- PerugiaModDoping tested for various thicknesses and temperatures, and for fluences up to 1E16 1 MeV n_{eq}/cm^2
- PerugiaModDoping, using the Torino parameterization → subsequent validation for LGADs
- Future: fine-tune the model to match the experimental data at even higher fluences; perform more electrical measurements at high fluences; use the model during the design phase of future LGADs

Acknowledgements

- We would like to thank Fondazione Bruno Kessler (FBK) for the devices provided.

- This project has received funding from the European Union's Horizon 2020 Research and Innovation program with the project AIDA-2020 under Grant Agreement no. 654168 and PRIN Project 2017 2017L2XKTJ 4DInSiDe.

- Additionally, we would like to thank INFN CSN5 for further financial support as part of the eXFlu research project.

- *See also talks by L. Menzio and V. Sola*

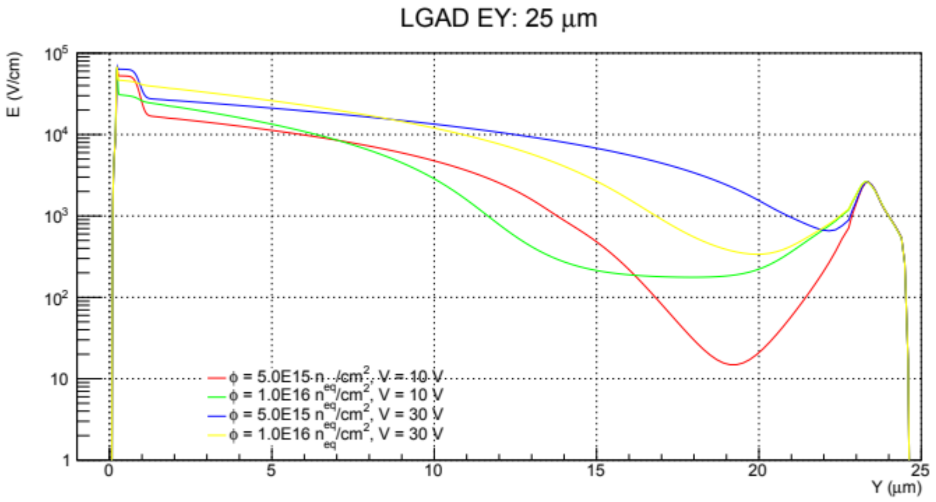
Backup

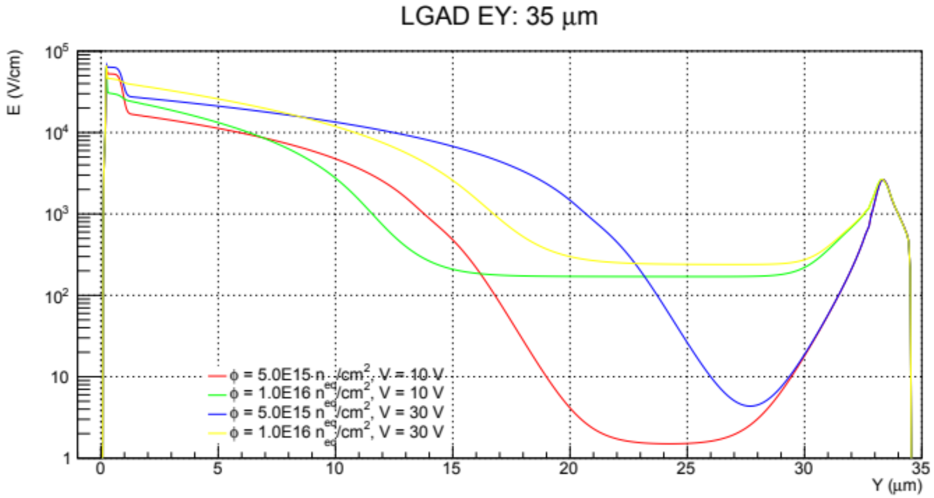
Methodology

- Methodology steps for the simulations:

1) DC/AC analysis: static DC biasing (with the n-cathode grounded and the p-anode sweeped) → small-signal AC biasing (for each DC bias step, superimposition of a sinusoid)
2) Transient analysis: a Time-Variant (TV) simulation of an impinging MIP following the *HeavyIon* model in TCAD (for each DC bias step)
3) Calculation of outputs: e.g. current, capacitance, Charge Collection Efficiency (CCE), current-related damage factor α (a figure of merit of the device)

Best case 18: 25/35 μm LGAD, electric field vs. Y





Room temperature
Y: thickness coordinate

Calculation of the full depletion voltage V_{fd}

- $1/C^2$ – V: intersection of two lines $y = a + bx$, $y = c + dx$, where b and d represent two different slopes → $V_{fd} = (a - c)/(d - b)$

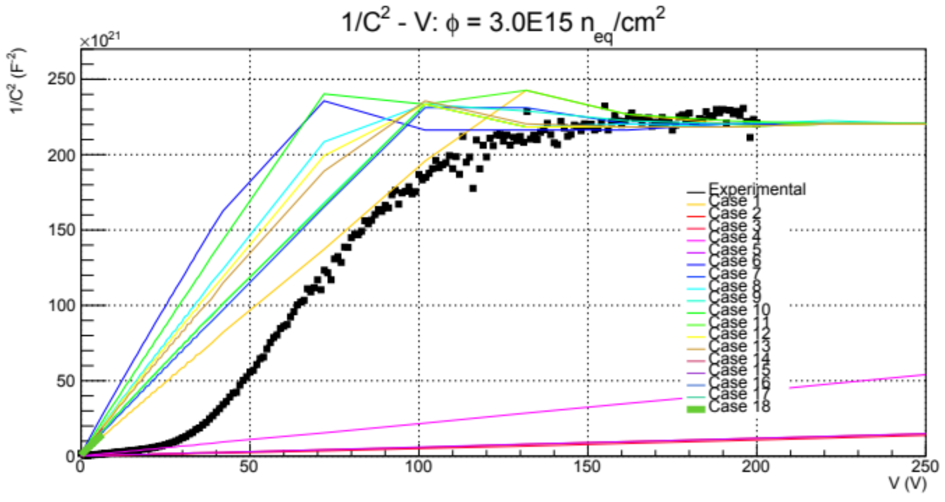
- We compare two average values:
  - Simulated average
  - Experimental average (from multiple wafers)

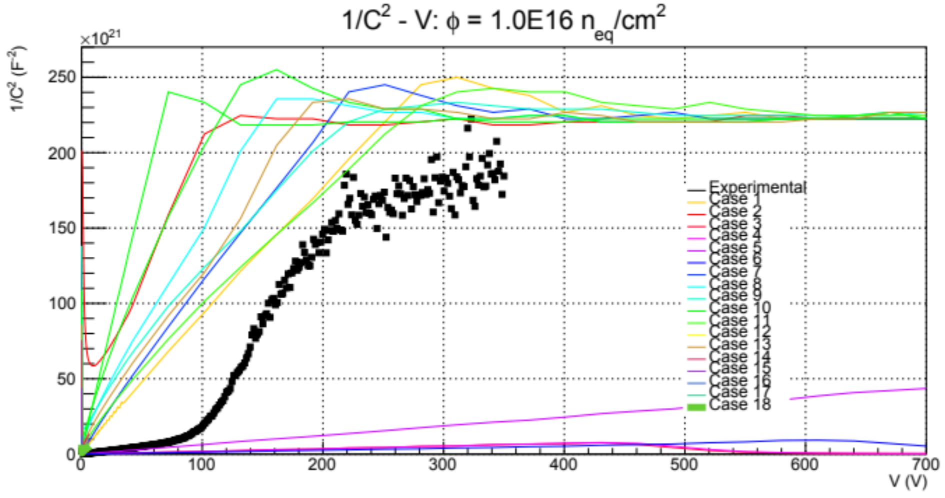
- ROOT calculates the error of each parameter: δa, δb, δc, δd
  - $(\delta Vd)^2 = (\partial Vd/\partial a)^2(\delta a)^2 + (\partial Vd/\partial b)^2(\delta b)^2 + (\partial Vd/\partial c)^2(\delta c)^2 + (\partial Vd/\partial d)^2(\delta d)^2$

- We examine here the case of 150 Mrad, 55 μm PIN
  - Simulated: V_{fd} = (116.81 ± 5.63) V
  - Experimental for average C: V_{fd} = (109.29 ± 4.44) V
  - Experimental Sample 1: V_{fd} = (115.96 ± 7.04) V
  - Experimental Sample 2: V_{fd} = (110.20 ± 6.94) V
  - Experimental Sample 3: V_{fd} = (100.82 ± 14.68) V → noisy, a visible dispersion here!
  - Experimental Sample 4: V_{fd} = (109.84 ± 5.63) V
  - V_{fd} from 4 samples: Average: 109.21 V; Standard deviation: 5.42 V

  - All of the above were calculated with the same ROOT program and are **not** the values from the exp. sheet. Only V_{fd} for Sample 3 is significantly different.

All models: 55 µm PIN, 1/C² – V





All models: 55 µm PIN, IV