Presentation for admission to the 3rd year

PhD Program of National Interest in
“Technologies for fundamental research in Physics and Astrophysics”
(Curriculum: Detectors, Lasers and Optics)

UNIVERSITÀ DEGLI STUDI DI PADOVA

Istituto Nazionale di Fisica Nucleare

Dr. Tommaso Croci
PhD TECH-FPA, XXXIX cycle, A.Y. 2024/2025
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Perugia, 19/09/2025

Outline

- Research topic, objectives and overall planning
- Research activities and achievements
  - ❑ 2nd academic year
  - ❑ 3rd academic year (planning)
- Courses, exams and other training activities
  - ❑ 2nd academic year
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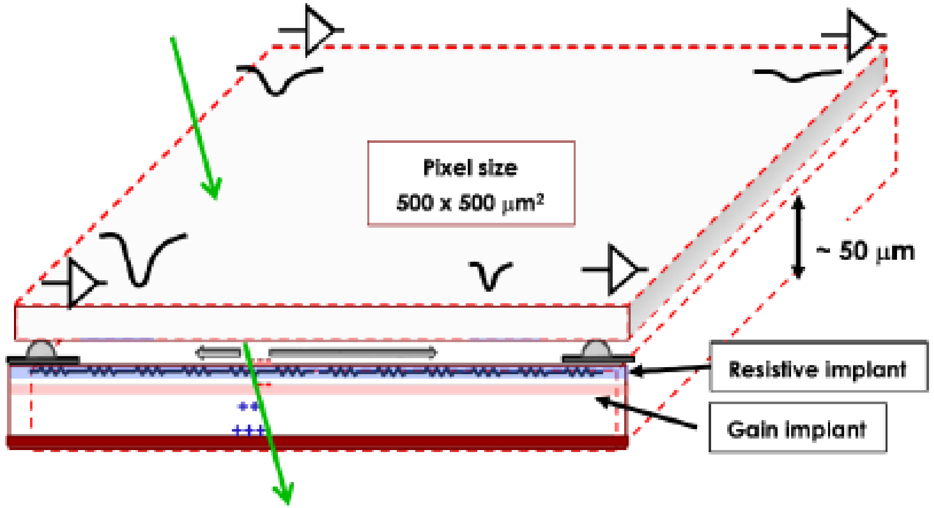
Research topic

- Development of **methodologies** and **numerical models** for the study, design, and optimisation of **innovative radiation-hard silicon particle detectors** for **4D tracking** in future **high-energy physics experiments**, e.g. Future Circular Collider (FCC) at CERN, Geneva, Switzerland.

- **Target**: silicon sensor-based 4D tracking detectors for future colliders (*****)
  - ❑ high **temporal** (~10-20 ps) and **position** (10 μm) **resolution**
  - ❑ large **area coverage** (~m^2)
  - ❑ low **power budget** (0.1-0.2 W/cm^2)
  - ❑ low **material budget** (100 μm or less)
  - ❑ high **radiation tolerance** (> 10^{17} 1 MeV n_{eq}/cm^2)

- **LGAD-based** DC-coupled Resistive Silicon Detectors (**DC-RSD**)



(*****) "The 2021 ECFA detector research and development roadmap", ECFA Detector R&D Roadmap Process Group, DOI: 10.17181/CERN.XDPL.W2EX

Objectives & overall planning (1/2)

- Development of **methodologies** and **numerical models** for the study, design, and optimisation of **innovative radiation-hard silicon particle detectors** for **4D tracking** in future **high-energy physics experiments**, e.g. Future Circular Collider (FCC) at CERN, Geneva, Switzerland.

- **Objectives** → **Activities**

❑ Development of **Technology-CAD** (**TCAD**) **simulation methodologies** and **models** for **particle sensors** and **radiation-induced damage effects** at extreme fluences (10^{16}-10^{17} 1 MeV n_{eq} cm^{-2}) → **TCAD simulation**

❑ **Electrical characterisation** and **beam test** of the **available sensor samples** by means of proper test equipment and accelerator centre facilities, **before** and **after irradiation** → **Experimental measurements**

❑ **Irradiation** of the **available sensor samples** by means sources and irradiation facilities → **Irradiation**

❑ **Calibration** and **validation** of the **developed TCAD simulation methodologies** and **models** based on the agreement between simulation and experimental data → **Model validation**

❑ **Dissemination** of the research activities at **conferences**, through the publication of **articles** and the production of the **final thesis** → **Dissemination**

Objectives & overall planning (2/2)

- Development of **methodologies** and **numerical models** for the study, design, and optimisation of **innovative radiation-hard silicon particle detectors** for **4D tracking** in future **high-energy physics experiments**, e.g. Future Circular Collider (FCC) at CERN, Geneva, Switzerland.

Activities	M6	M12	M18	M24	M30	M36
TCAD simulation	■	■	■	■	■	
Experimental measurements	■		■	■	■	
Irradiation	■			■		
Model validation	■			■	■	
Dissemination	■	■	■		■	■

M6-M12 (**1st A.Y.**), M18-M24 (**2nd A.Y.**), M30-M36 (**3rd A.Y.**), A.Y. (academic year).

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  - ❑ 2nd academic year
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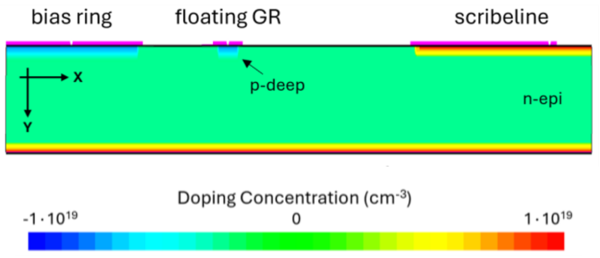
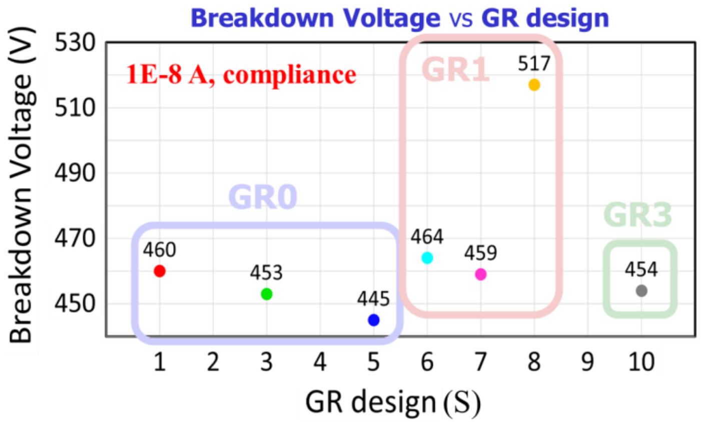
Research activities and achievements (1/6)

TCAD simulation – 2nd academic year

- Guard Ring (**GR**) protection structures in thin p-i-n and LGAD silicon detectors on **n-doped substrates**. [T. Croci et al., NIM, A 1080 (2025) 170753]

Layout of a GR structure (e.g. GR1)

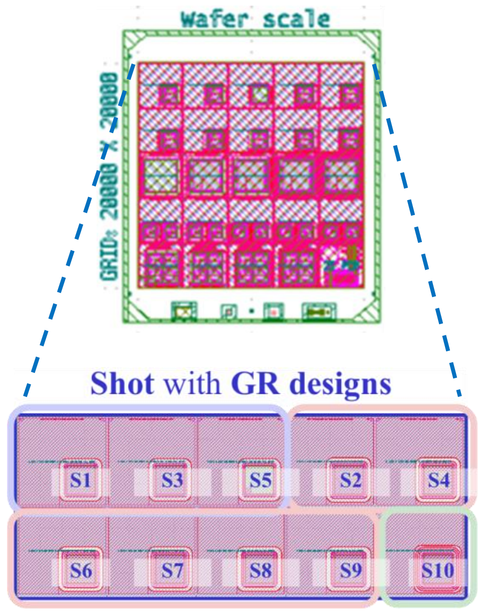




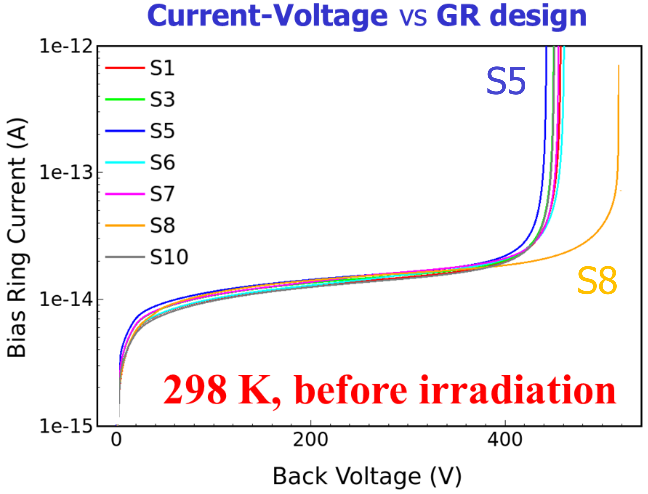
$V_{BD,S3} \approx V_{BD,S7} \approx V_{BD,S10}$
$V_{BD,S1} \approx V_{BD,S6}$

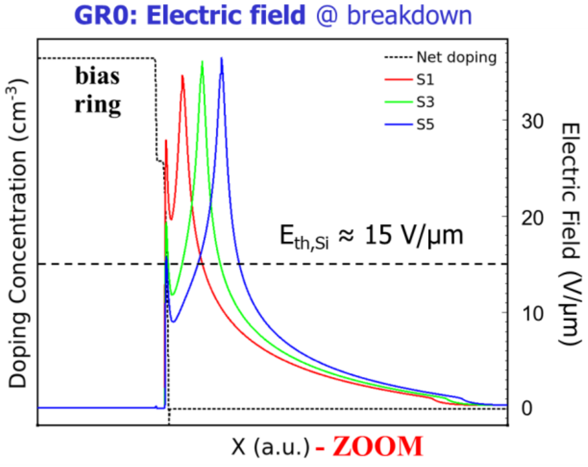
GR0 ≈ GR1 ≈ GR3
S5 worst GR design
S8 best GR design

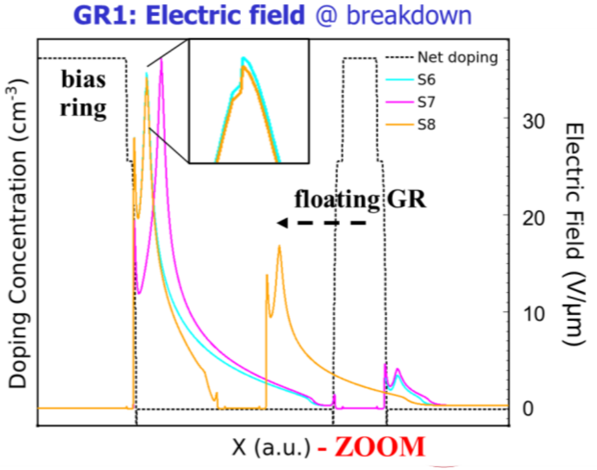
"NLGAD" R&D batch, FBK
(ongoing production)



- ✓ **GR0: no floating GRs**, varying
  - metal *overhang*
- ✓ **GR1: 1 floating GR**, varying
  - floating GR *position*
  - metal *overhang*
- ✓ **GR3: 3 floating GRs**, using of:
  - single *p-deep* implant







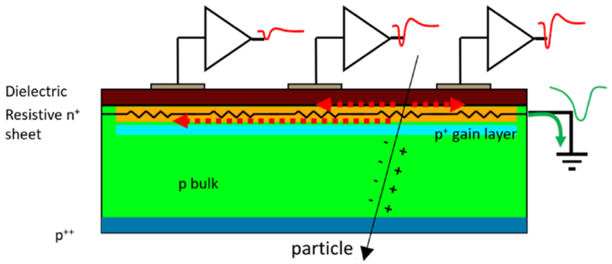
Research activities and achievements (2/6)

TCAD simulation and Beam Test – 2nd academic year

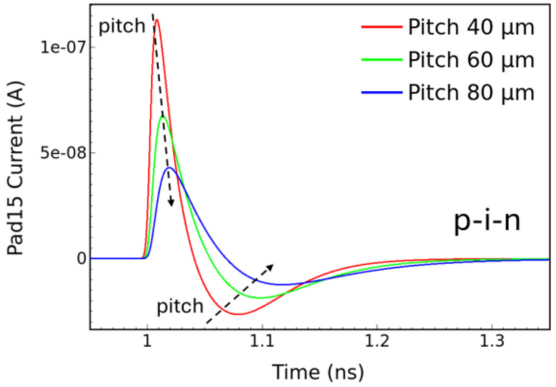
- LGAD-based AC-coupled Resistive Silicon Detector (**RSD**) architectures ("RadHard AC-LGAD" R&D production).
- **Beam test** of LGAD-based DC-coupled RSD ("DC-RSD1" R&D production) at DESY, Hamburg, Germany (9-16 Dec '24).

Simulation plan

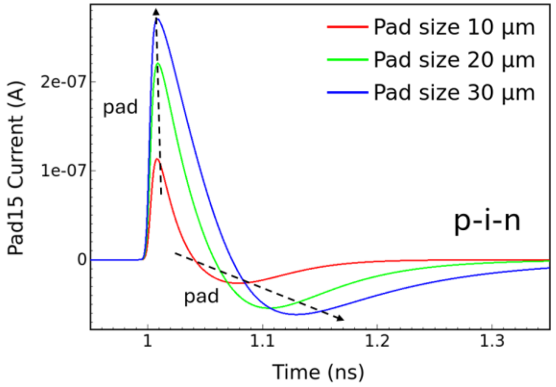
Parameter (or variable) **space**
1. Pitch
2. Pad size
3. C_{ox} (= $\varepsilon_{ox}\,\varepsilon_0\,A_{pad}/t_{ox}$)
4. $R_{sh,n+}$ (= $\rho_{Si,n+}/t_{Si,n+}$)

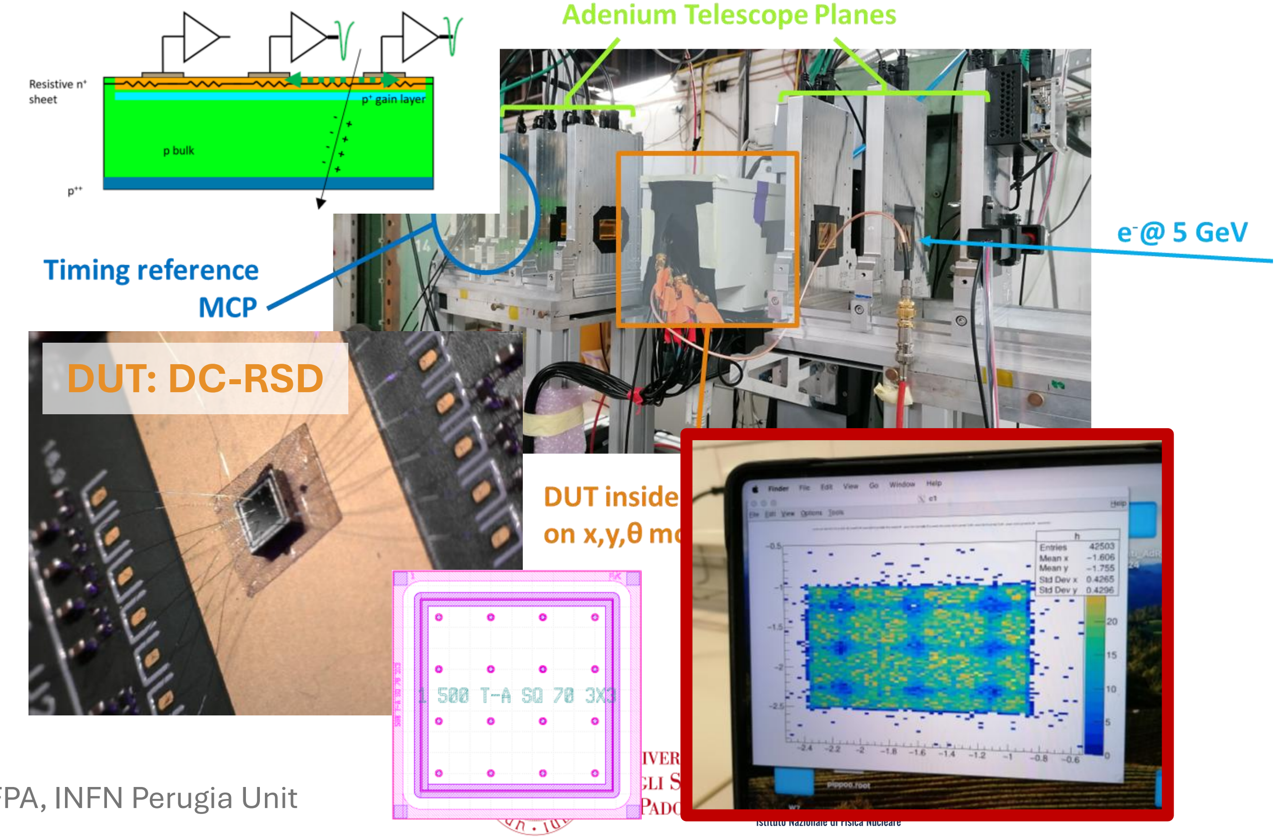


Current vs. Time (**I-t**) vs **Pitch** - ZOOM



Current vs. Time (**I-t**) vs **Pad size** - ZOOM

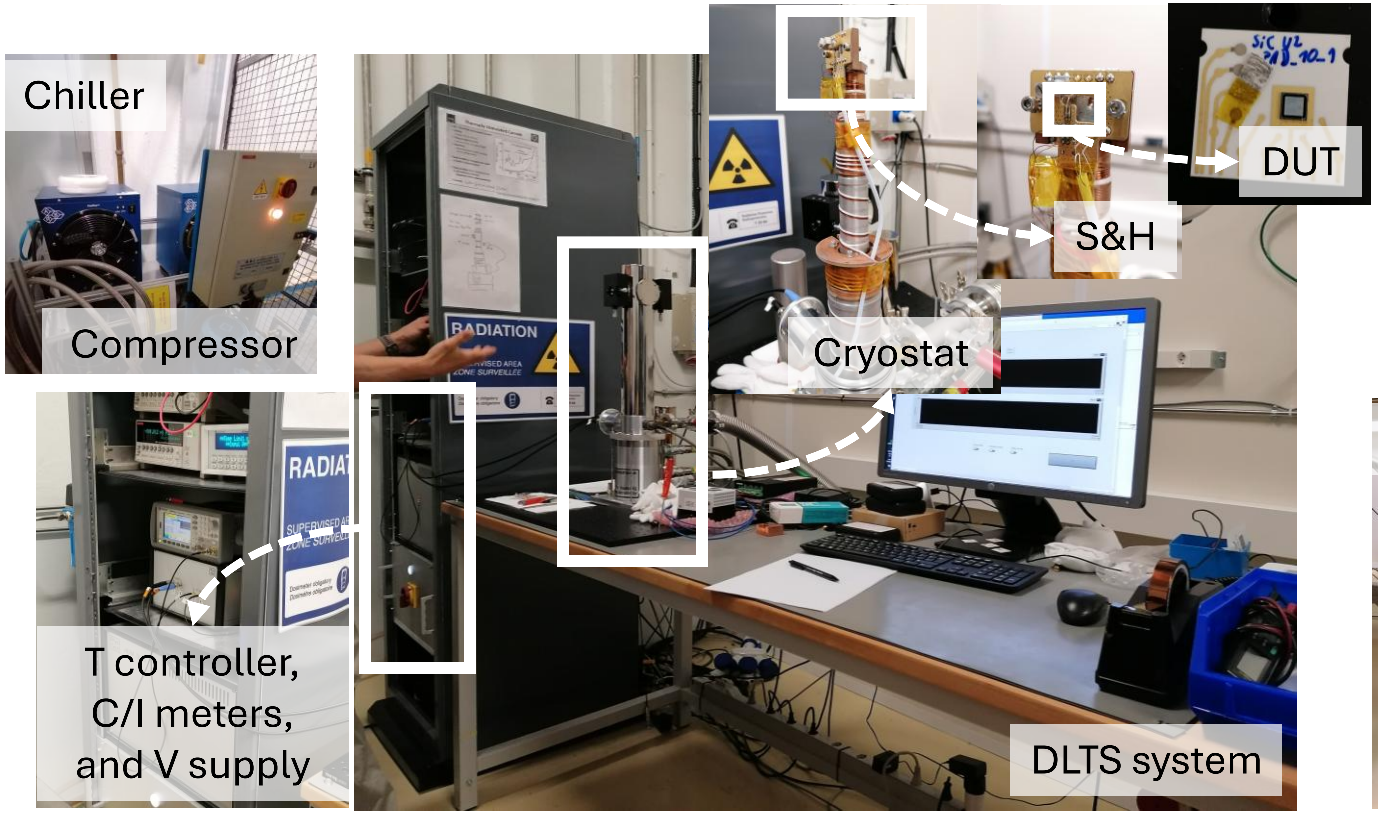


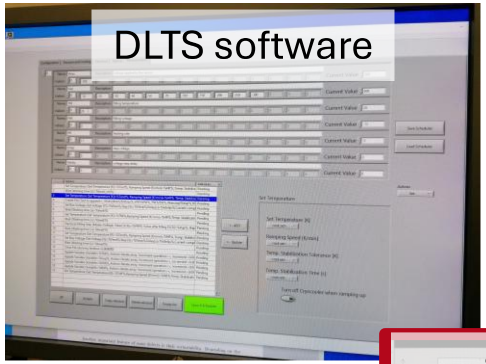


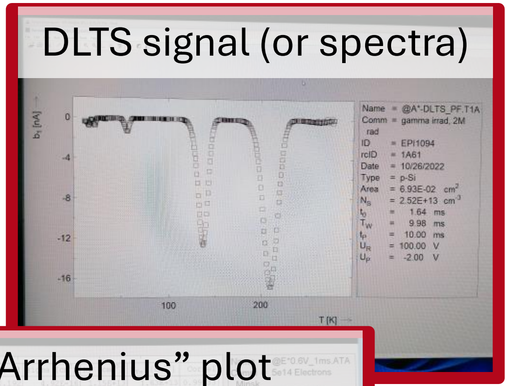
Research activities and achievements (3/6)

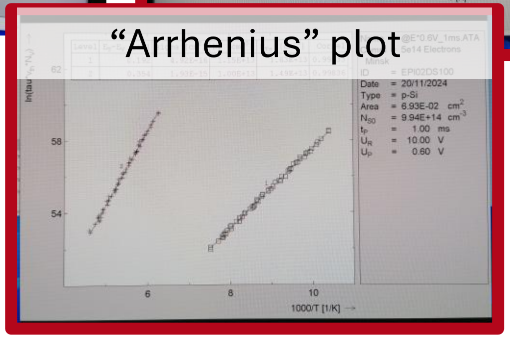
Experimental measurements – 2nd academic year

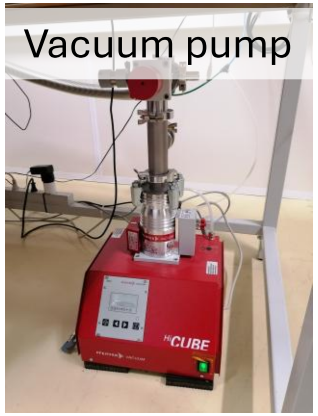
- **Defect spectroscopy**: setup, training and measurements at Deep Level Transient Spectroscopy (**DLTS**) system – SSD Lab, CERN EP-DT group (April-September ’25).











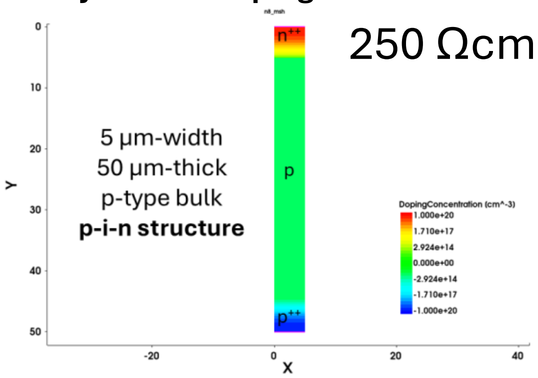
Defect parameters:
N_t, E_a and $\sigma_{e,h}$

Research activities and achievements (4/6)

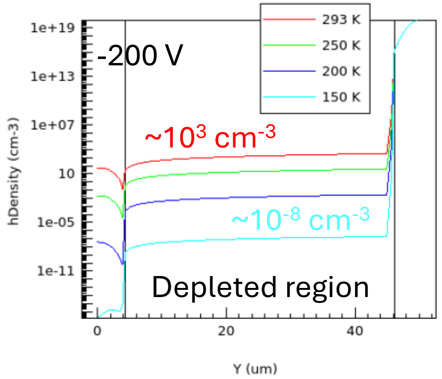
TCAD simulation – 2nd academic year

- **Development** of a **TCAD simulation framework** capable of **reproducing** the **DLTS measurement results** – SSD Lab, CERN EP-DT group (April-September ’25).

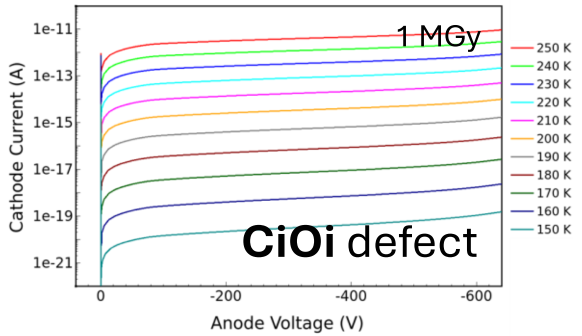
Layout and Doping Concentration



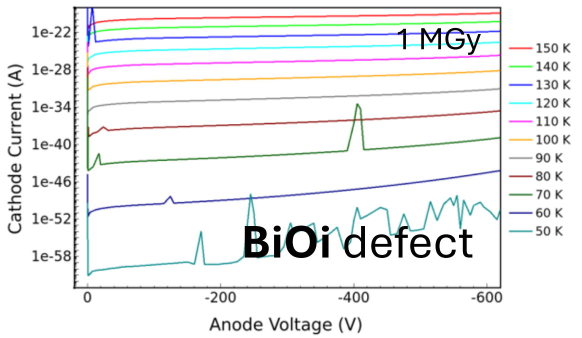
Majority Carrier Density



Current-Voltage (I-V)

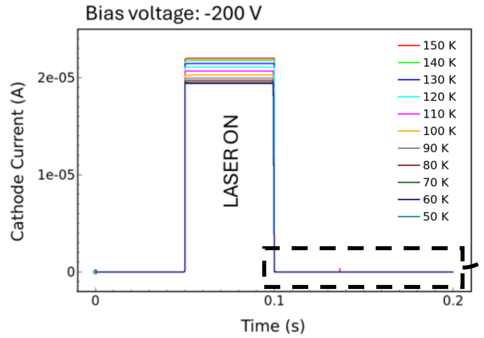


Current-Voltage (I-V)

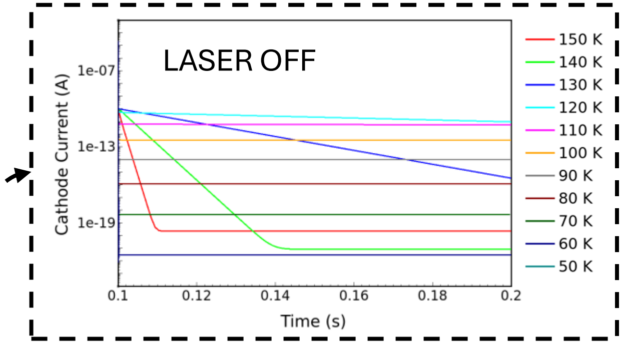


Example: BiOi defect **@ 1 MGy**

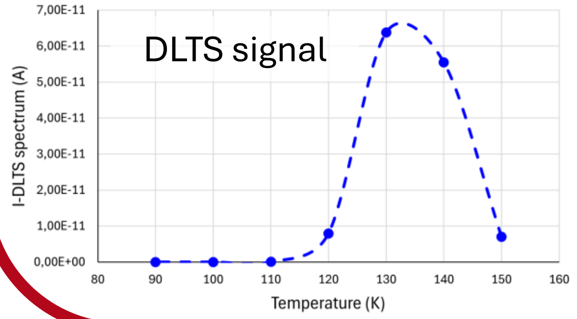
Current-Time (I-t)



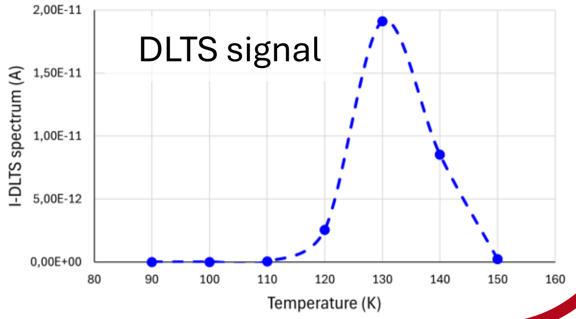
ZOOM



“Double Boxcar” Method



“Correlator Function” Method



Research activities and achievements (5/6)

Dissemination – 2nd academic year

- **Presentation at conference**:
  - *Poster*: “Enhancing guard-ring protection structures for the next generation of radiation-hard thin silicon particle detectors”, 17th Vienna Conference on Instrumentation - VCI2025, **17-21 February 2025**, Vienna University of Technology, Wien, Austria.
- **Publications** (Corresponding Author):
  - T. Croci et al., "Enhancing guard-ring protection structures for the next generation of radiation-hard thin silicon particle detectors", Nuclear Inst. and Methods in Physics Research A, Volume 1080, **November 2025**, 170753. DOI: 10.1016/j.nima.2025.170753.
  - T. Croci et al., "Measurements and TCAD simulations of guard-ring structures of thin silicon sensors before and after irradiation", Nuclear Inst. and Methods in Physics Research A, Volume 1069, **December 2024**, 169801. DOI: 10.1016/j.nima.2024.169801.
- **Publications** (Co-Author):
  - A. Fondacci, T. Croci et al., "Compensated LGAD optimisation through van der Pauw test structures", Nuclear Inst. and Methods in Physics Research A, Volume 1080, **November 2025**, 170800. DOI: 10.1016/j.nima.2025.170800.
  - F. Moscatelli, A. Morozzi, T. Croci et al., "TCAD modeling of bulk and surface radiation damage effects in silicon devices", Journal of Instrumentation, Volume 20, **September 2025**, C09006. DOI: 10.1088/1748-0221/20/09/C09006.
  - A. Fondacci, T. Croci et al., "Design and optimisation of radiation resistant AC- and DC-coupled resistive LGADs", Journal of Instrumentation, Volume 20, **June 2025**, C06016. DOI: 10.1088/1748-0221/20/06/C06016.
  - A. Morozzi, A. Fondacci, T. Croci et al., "Thin silicon sensors for extreme fluences: a doping compensation strategy", Nuclear Inst. and Methods in Physics Research A, Volume 1069, **December 2024**, 169904. DOI: 10.1016/j.nima.2024.169904.
  - A. Fondacci, T. Croci et al., "TCAD investigation of Compensated LGAD sensors for extreme fluence", Nuclear Inst. and Methods in Physics Research A, Volume 1068, **November 2024**, 169811. DOI: 10.1016/j.nima.2024.169811.

Research activities and achievements (6/6)

Dissemination – 2nd academic year

- **Publications** (Co-Author):
  - A. R. Altamura et al., "Radiation-resistant thin LGADs for enhanced 4D tracking", Nuclear Inst. and Methods in Physics Research A, Volume 1081, **January 2026**, 170799. DOI: 10.1016/j.nima.2025.170799.
  - R. Arcidiacono et al., "Innovative DC-coupled resistive silicon detector for 4D tracking", Nuclear Inst. and Methods in Physics Research A, Volume 1080, **November 2025**, 170796. DOI: 10.1016/j.nima.2025.170796.
  - M. Da Rocha Rolo et al., "ARCADIA Fully-Depleted CMOS MAPS development with LFoundry 110nm CIS", Frontiers in Sensors, Volume 6, **August 2025**, 1603755. DOI: 10.3389/fsens.2025.1603755.
  - V. Sola et al., "Thin LGAD sensors for 4D tracking in high radiation environments: state of the art and perspective", Frontiers in Sensors, Volume 6, **August 2025**, 1648102. DOI: 10.3389/fsens.2025.1648102.
  - L. Lanteri et al., "Characterization of the FBK-LGAD devices manufactured at an external foundry for large-volume productions", Journal of Instrumentation, Volume 20, **July 2025**, C07039, DOI: 10.1088/1748-0221/20/07/C07039.
  - M. Centis Vignali et al., "Development and wafer-level characterization of the first production of DC-RSD sensors at FBK", Journal of Instrumentation, Volume 20, **July 2025**, C07037. DOI: 10.1088/1748-0221/20/07/C07037.
  - M. Durando et al., "Thin LGADs as radiation-resilient sensors for 4D tracking", Journal of Instrumentation, Volume 20, **July 2025**, C07028. DOI: 10.1088/1748-0221/20/07/C07028.
  - M. Ferrero et al., "Compensated LGAD – an innovative design of thin silicon sensors for very high fluences", Journal of Instrumentation, Volume 20, **July 2025**, C07023. DOI: 10.1088/1748-0221/20/07/C07023.
  - M. Menichelli et al., "Hydrogenated Amorphous Silicon Charge-Selective Contact Devices on a Polyimide Flexible Substrate for Dosimetry and Beam Flux Measurements", Sensors, Volume 25, **February 2025**, 1263. DOI: 10.3390/s25041263.
  - G. Mazza et al., "Cleopatra: a 12-channel recycling integrator ASIC for the readout of hydrogenated amorphous silicon detectors in radiotherapy dosimetry", Journal of Instrumentation, Volume 20, **January 2025**, C01034. DOI: 10.1088/1748-0221/20/01/C01034.
  - R. S. White et al., "Characterisation of the FBK EXFLU1 thin sensors with gain in a high fluence environment", Nuclear Inst. and Methods in Physics Research A, Volume 1068, **November 2024**, 169798. DOI: 10.1016/j.nima.2024.169798.

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Research activities and achievements (1/2)

3rd academic year (planning)

- **TCAD simulation**
  - ❑ **Set-up** and **validation** of the **TCAD simulation** and **design workflows**, both before and after irradiation, focused on
    - **GR** protection **structures** in thin p-i-n and LGAD silicon detectors on **n-doped substrate**
    - LGAD-based **RSD architectures** under different occupancy conditions.
  - ❑ **Assessment** and **benchmarking** of the **TCAD-based DLTS simulation framework** for defect spectroscopy in silicon particle detectors.

- **Experimental measurements**
  - ❑ **Electrical characterization** and **study** of the "**popcorn**" **noise** of the different **GR** design **strategies** for thin p-i-n and LGAD detectors on **n-type substrate** ("NLGAD" R&D production), both before and after irradiation.

Research activities and achievements (2/2)

3rd academic year (planning)

- **Dissemination**

❑ **Presentations at conferences/workshops**:

- "4th DRD3 week on Solid State Detectors R&D", **10-14 Nov 2025**, CERN, Geneva, Switzerland.
- "21st Trento Workshop on Advanced Silicon Radiation Detectors" - TREDI2026 (work in progress), **Feb 2026**, Perugia, Italy.
- ... (intentionally left blank)

❑ **Publications** (Corresponding Author):

- *Article*: "A TCAD-based DLTS simulation framework for defect spectroscopy in silicon particle detectors".
- *Article*: "Guard-Ring protection structures for radiation-hard thin silicon particle detectors: design, test, and performance".
- ... (intentionally left blank)

❑ **Production** of the **final** PhD **thesis**

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- Courses, exams and other training activities
    - ❑ 2nd academic year
    - ❑ 3rd academic year (planning)

Courses, exams and other training activities (1/2)

2nd academic year

- **Courses and exams**:
  - ❑ "Machine Learning Programming in Physics", **1 Oct-5 Nov 2024**, INFN and University of Bari, course held online, 2.5 CFU.
  - ❑ "Design of readout integrated circuits for particle detectors", **4-19 Nov 2024**, INFN and University of Bari, course held online, 2.5 CFU.
  - ❑ "Numerical simulation of electronic devices with TCAD tools for HEP applications", **9-11 Jun 2025**, INFN and University of Perugia, course held in presence, 2.5 CFU.
- **Workshops**:
  - ❑ "2nd DRD3 week on Solid State Detectors R&D", **2-6 Dec 2024**, CERN, Geneva, Switzerland.
  - ❑ "6th Allpix Squared User Workshop", **7-9 May 2025**, online attendance.
- **Seminar**:
  - ❑ "Advanced UK Instrumentation Training 2025", **6 May-27 Jun 2025**, lectures held online.

Courses, exams and other training activities (2/2)

3rd academic year (planning)

- **Schools**:
  - ❑ "Events" of the TECH-FPA National PhD course (national days/guided tours)
  - ❑ ... (intentionally left blank)
- **Workshops**:
  - ❑ "4th DRD3 week on Solid State Detectors R&D", **10-14 Nov 2025**, CERN, Geneva, Switzerland.
  - ❑ "21st Trento Workshop on Advanced Silicon Radiation Detectors" - TREDI2026 (work in progress), Feb 2026, Perugia, Italy.
  - ❑ ... (intentionally left blank)
- **Seminars**:
  - ❑ ... (intentionally left blank)

THANKS FOR YOUR ATTENTION!

UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN Istituto Nazionale di Fisica Nucleare

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BACKUP

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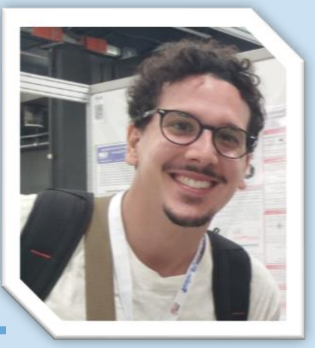

- **Current position within the *PhD TECH-FPA***
  - ❑ Hosting institution: National Institute for Nuclear Physics (INFN), Perugia Unit
  - ❑ Supervisors: Dr. *Arianna Morozzi*, Prof. *Daniele Passeri*, Prof. *Pisana Placidi*
  - ❑ Curriculum: Detectors, Lasers and optics
  - ❑ A.Y.: 2024/2025

PHD TECH-FPA (link)

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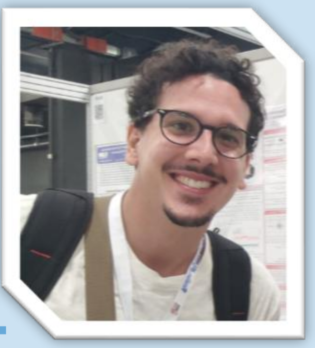
UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN Istituto Nazionale di Fisica Nucleare

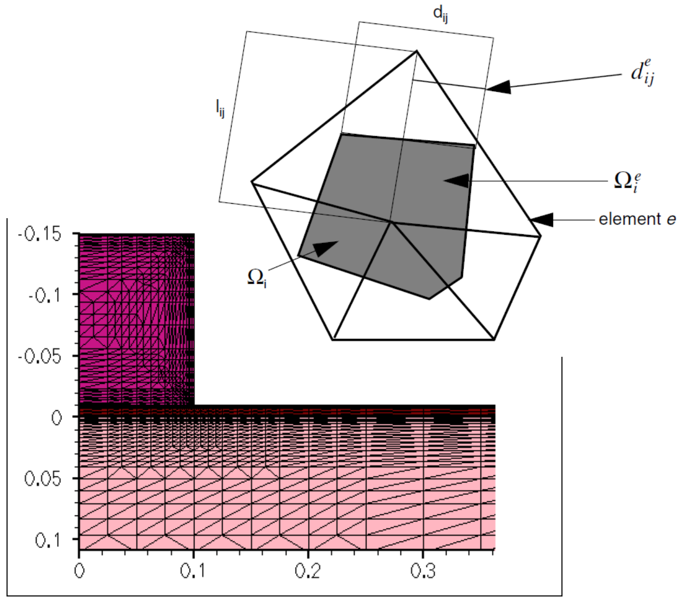


- **Educational background** @ University of Perugia (UNIPG), Department of Engineering (DI) - Perugia, Italy
  - Bachelor's Degree in *Computer Science and Electronic Engineering* (curriculum: *Electronics*)
  - Master's Degree in *Electronic and Telecommunication Engineering* (curriculum: *Electronics and Radio Frequencies*)
- **Research and work experience** @ INFN Perugia Unit & DI UNIPG

  Development of technologies for radiations and particles detection, with a special focus on the field of sensors and their related readout electronics.
  - **TCAD simulation** and **design** (Synopsys Sentaurus)
    - DC-coupled Resistive Silicon Detector (**DC-RSD**): development of a hybrid approach (TCAD + Spice), design and optimization in terms of spatial resolution and reconstruction of the particle impact positions.
    - Low-Gain Avalanche Diode (**LGAD**): design and optimization of the gain layers of thin LGAD detectors and the related guard-ring protection structures (radiation hardness and high voltage operations).
  - **Development** and **validation** of the **surface and bulk radiation damage numerical model** ("University of Perugia" TCAD model)
  - **Experimental measurements** (i.e., electrical characteristics and response to radiation stimuli - laser and β source) in **laboratory** of p-i-n and LGAD devices, before and after irradiation.
  - **VLSI design**, **simulation** and **verification** (Cadence Virtuoso, Synopsys Custom Compiler)
    - Monolithic Active Pixel Sensors (**MAPS**) in 110 nm LFoundry CMOS technology
    - integrated 10 µm-pitch Active Pixel Sensor (**APS**) arrays in standard CMOS technology (LFoundry 110 nm).
  - **PCB design** (KiCAD EDA) of an **acquisition system** (based on the Arduino platform) for the measurement of analog signals generated by active pixel test structures.

Technology-CAD (TCAD) simulations

- **TCAD simulation tools** solve fundamental, physical partial differential equations, such as *diffusion* and *transport* equations for *discretized geometries* (finite element meshing).
- This deep physical approach gives TCAD simulation **predictive accuracy**.
- **Synopsys© Sentaurus TCAD**



$$\begin{cases} \nabla \cdot (-\varepsilon_s \nabla \phi) = q \ (N_D^+ - N_A^- + p - n) & \text{Poisson} \\ \dfrac{\partial n}{\partial t} - \dfrac{1}{q} \nabla \cdot \vec{J}_n = Un & \text{Electron continuity} \\ \dfrac{\partial p}{\partial t} + \dfrac{1}{q} \nabla \cdot \vec{J}_p = Up & \text{Hole continuity} \end{cases}$$

$\vec{J}_n, \vec{J}_p$

$$U_{n,p} = G - R$$

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Simulation setup

Physical models

- ✓ **Standard drift-diffusion model**
  - => Fermi-Dirac statistics
- ✓ **Generation/Recombination rate**
  - => Shockley-Read-Hall (SRH)
  - => Band-To-Band Tunneling (BTBT)
  - => Auger
  - => Massey impact ionization model
- ✓ **Carriers mobility variation**
  - => doping and field dependent
- ✓ **Bandgap narrowing model**
  - => OldSlotboom
- ✓ **Physical parameters**
  - => s_0 = 0 cm/s (surface recomb. velocity)
  - => $\tau_n = \tau_p$ = 1E-3 s (e-/h+ recomb. lifetime)

Radiation damage model

- ✓ **"New University of Perugia"**
  - => combined **surface** and **bulk** damage scheme

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

surface

	Acceptor-like	Donor-like
Energy (eV)	$E_C - 0.56 \le E_T \le E_C$	$E_V \le E_T \le E_V + 0.60$
Width (eV)	0.56	0.60
D_{IT} (eV^{-1}cm^{-2})	$D_{IT_{acc}}(\phi)$	$D_{IT_{don}}(\phi)$
N_{IT} (ϕ) (cm^{-2})	$N_{IT_{acc}}(0) + \Delta N_{IT_{acc}}(\phi)$	$N_{IT_{don}}(0) + \Delta N_{IT_{don}}(\phi)$
$\sigma_{electrons}$ (cm^2)	1.00×10^{-16}	1.00×10^{-15}
σ_{holes} (cm^2)	1.00×10^{-15}	1.00×10^{-16}

	Fixed oxide charge
Q_{OX} (ϕ) (cm^{-2})	$Q_{OX}(0) + \Delta Q_{OX}(\phi)$

Pre-irradiation values

$Q_{OX}(0) = 8.0 \times 10^{+10}$

$N_{IT_{acc}}(0) = 7.0 \times 10^{+09}$

$N_{IT_{don}}(0) = 7.0 \times 10^{+09}$

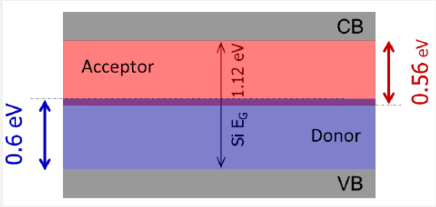
Extension of the “UNIPG” Rad. Dam. TCAD Model

“PerugiaModDoping”[1]

“**New University of Perugia**” Radiation Damage Model [2]

Surface damage ($+ Q_{ox}$)

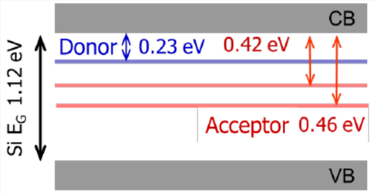
Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \le E_T \le E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \le E_T \le E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$



+

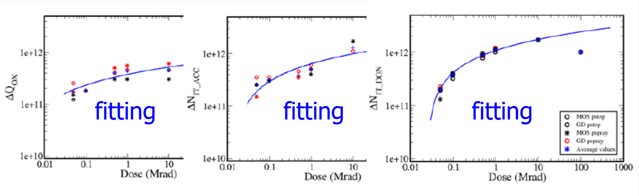
Bulk damage

Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
Donor	E_C - 0.23	0.006	2.3×10^{-14}	2.3×10^{-15}
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}



- ✓ **Bulk damage** → **Traps concentrations** dependence upon the introduction rate **η** (defects concentration) and the **fluence** (**~ η×Φ**)
- ✓ **Surface damage** → **Traps** (N_{IT} interface trap density) and **oxide charge** (**Q_{OX}**) **concentrations** dependence upon the **fluence** as follow:

$$Q_{OX}(\phi) = Q_{OX}(0) + \Delta Q_{OX}(\phi)$$
$$N_{IT_{acc}} = N_{IT_{acc}}(0) + \Delta N_{IT_{acc}}(\phi)$$
$$N_{IT_{don}} = N_{IT_{don}}(0) + \Delta N_{IT_{don}}(\phi)$$



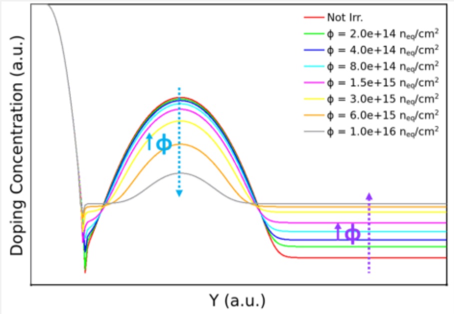
(a) ΔQ_{OX} (b) ΔN_{IT_ACC} (c) ΔN_{IT_DON}

+

Torino analytical parameterisations [3]

- **Gain Layer** (Acceptor Removal)

$$N^{peak}_{A,GL}(\Phi) = N_{A,GL}(0) \cdot e^{-c \cdot \Phi}$$

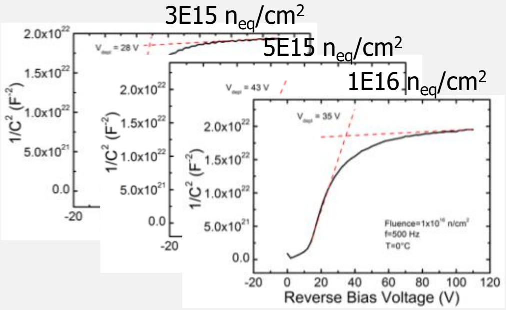


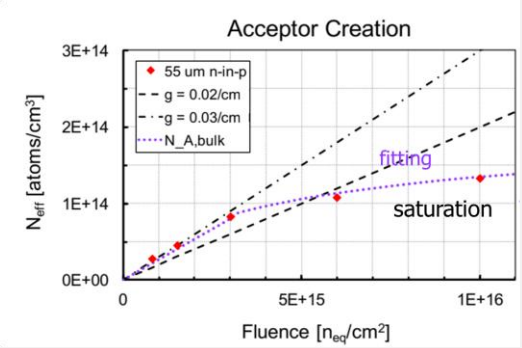
- **Bulk** (Acceptor Creation)
  - ✓ if $0 < \Phi \le 3e15\ n_{eq}/cm^2$

$$N_{A,bulk}(\Phi) = N_{A,bulk}(0) + g_c \cdot \Phi$$

  - ✓ if $\Phi > 3e15\ n_{eq}/cm^2$

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





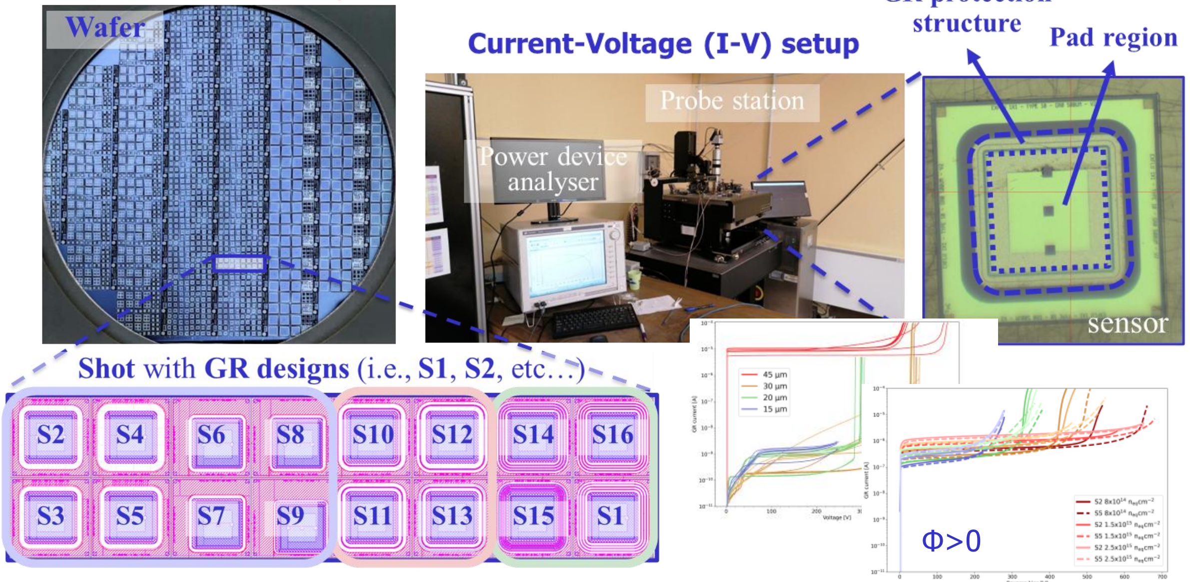
[1] P. Asenov et. al, NIM. A 1040 (2022) 167180; **[2]** A. Morozzi et. al, PoS (Vertex2019) 050; **[3]** M. Ferrero et. al, CRC Press (2021).

Optimisation studies of Guard-Ring (GR) protection structures

for thin **p-type substrates** (45, 30, 20 and 15 µm) up to high fluences (2.5×10^{15} 1 MeV n_{eq}/cm^2)

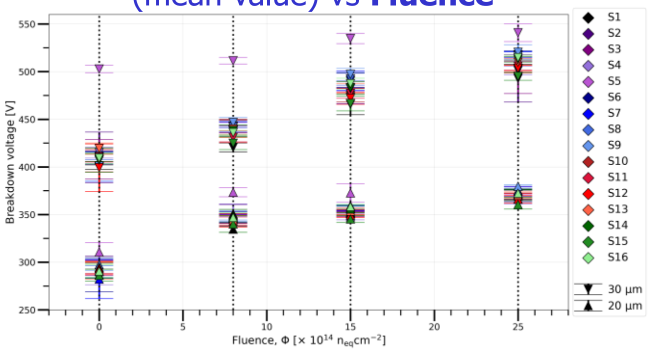
- Extensive test campaign on the different GR structures contained in the "EXFLU1" R&D batch (FBK)

"EXFLU1" R&D batch, FBK

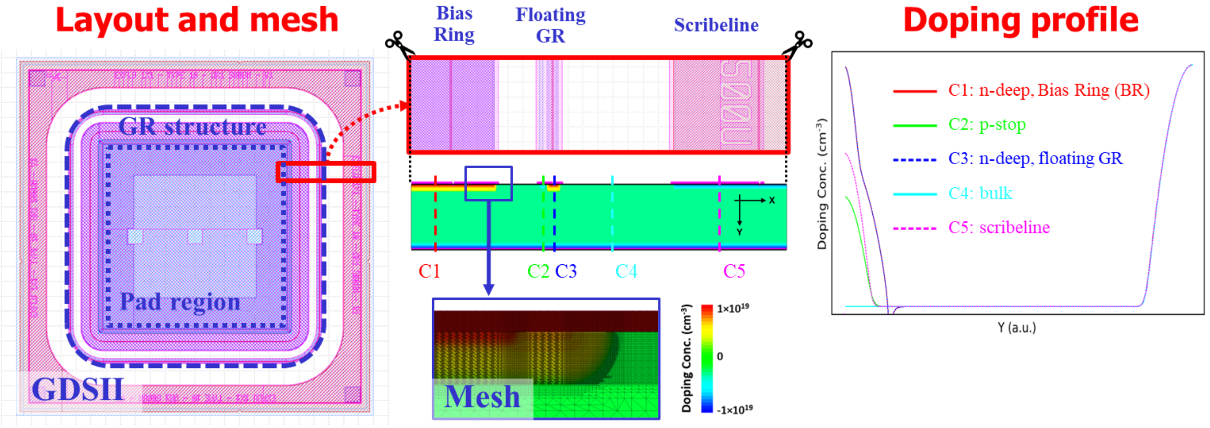


- ✓ **GR0**: **no floating GRs**, varying
  - *edge* region size
  - *void* region size (i.e., scribeline)
  - metal *overhang*
- ✓ **GR1**: **1 floating GR**, varying
  - floating GR *position*
- ✓ **GR3**: **3 floating GRs**, using one or both of:
  - single *n-deep* implant
  - single *p-stop* implant

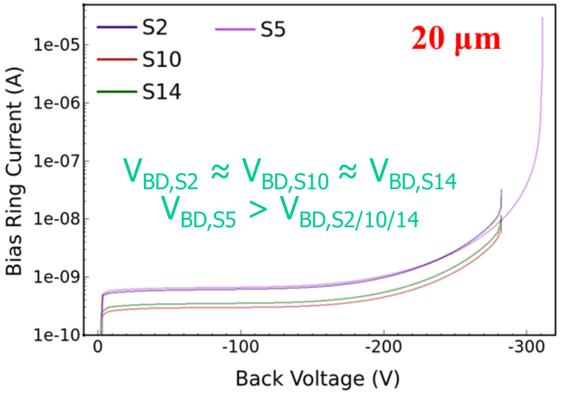
Breakdown voltage (mean value) vs **Fluence**



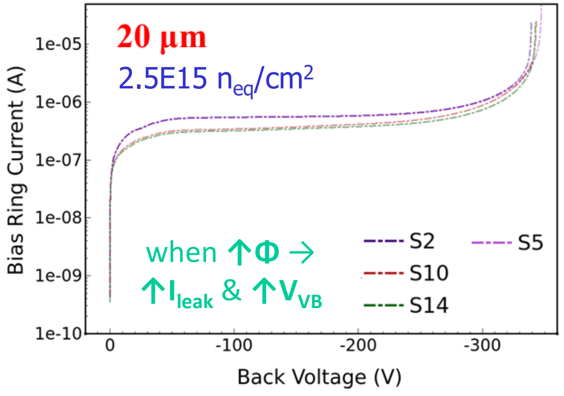
- Ad-hoc TCAD modelling of the different GR design strategies, accounting for the radiation-induced damage effects [1]



Current-Voltage @ 298 K



Current-Voltage @ 273 K



GR0 ≈ GR1 ≈ GR3, & S5 best GR design

[1] P. Asenov *et al.*, NIM, A 1040 (2022) 167180.

C-DLTS *transient analysis* (1/)

(from Michael Moll's PhD thesis, Ch. 4, Para. 4.4, pp. 81-88)

capacitance transient

$$C(t) = \Delta C_0 \times \exp\left(-\frac{t+t_0}{\tau_e}\right) + C_R \qquad (4.15)$$

amplitude

characteristic time constant

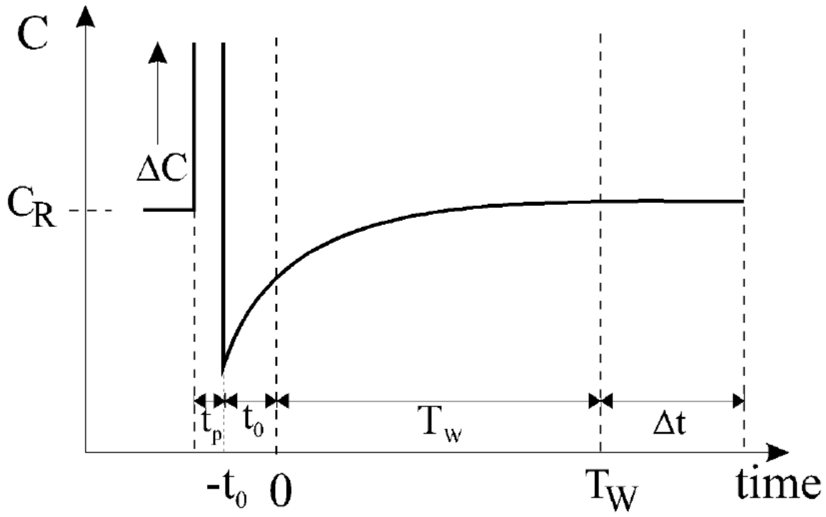


Figure 4.8: Time axis used for analysis of capacitance transients. A delay period t_0 has to be included due to the pulse overload recovery of the capacitance bridge.

Questions:

- How the defect parameters (i.e. concentration, activation energy and cross section) are obtained from the measured capacitance transients?
- How the DLTS spectra are generated?

Assumptions: exponential behaviour for the capacitance transient (Eq. 4.15) and definition of the time axis as displayed in Fig. 4.8

Methods for analysing transient signal:

- Double boxcar (integrator)
- Lock-in (amplifier?)
- Correlator functions
- Fourier transformation (DLTFS)
- Laplace transformation

C-DLTS *transient analysis: Double boxcar method* (1/)

(from Michael Moll's PhD thesis, Ch. 4, Para. 4.4, pp. 81-88)

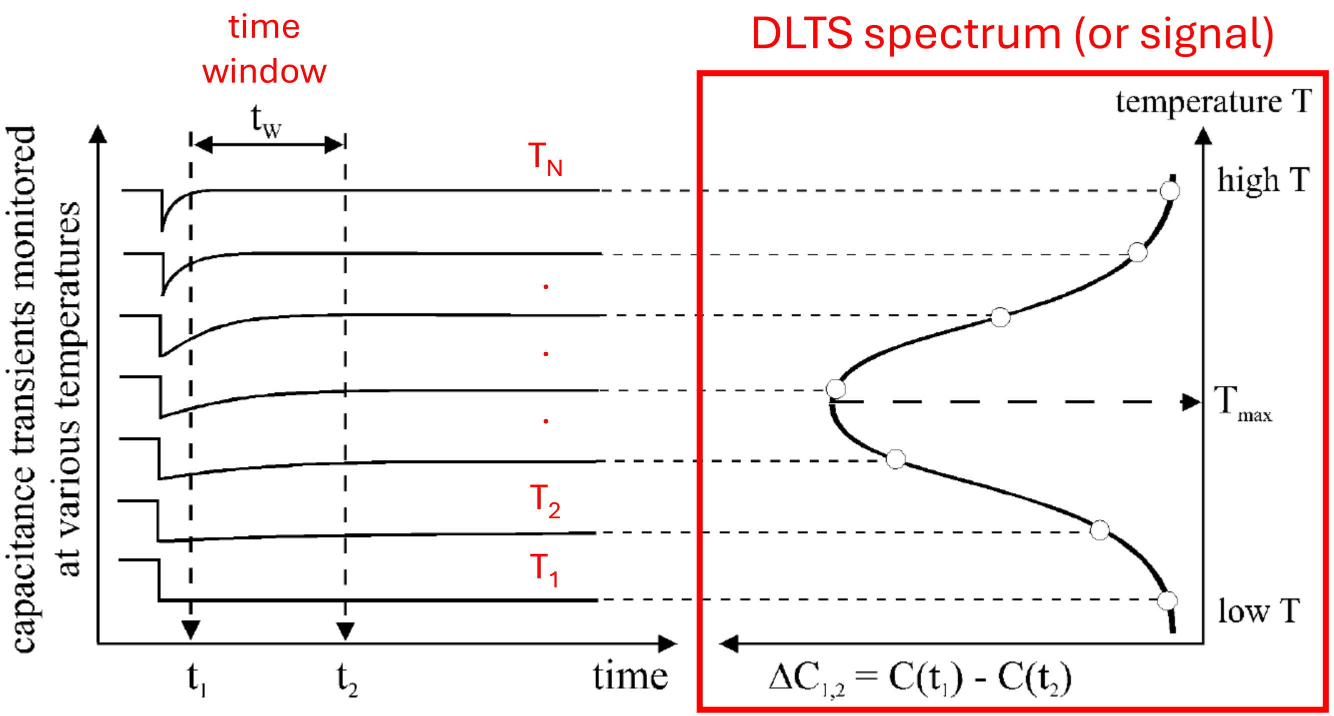


Figure 4.9: The left-hand side shows capacitance transients at various temperatures, while the right-hand side shows the corresponding DLTS signal resulting from using the double boxcar to display the difference between the capacitance at time t_1 and the capacitance at time t_2 as a function of temperature (after [Lan74]). **NB**: after filling pulse, t_p, and delay period t_0

Emission time constant, τ_e, at the **peak maximum temperature**, T_{max}, in the DLTS spectrum **@ time window**

$$\tau_e(T_{max}) = \frac{t_1 - t_2}{\ln\left(\frac{t_1}{t_2}\right)}. \qquad (4.16)$$

Double boxcar integrator method: consists of taking the difference between the measured capacitance, **$\Delta C_{1,2} = C(t_1) - C(t_2)$**, at two precise moments (t_1 and t_2), **NB**: **after** the filling pulse, **t_p**, **and** the delay period, **t_0** (see previous slide).

DLTS spectrum: difference **$\Delta C_{1,2} = C(t_1) - C(t_2)$** plotted **versus** the temperature, **T**.

- **Zero** @ T_{low} & T_{high} where the emission process is too slow and too fast, respectively.
- **Max** @ T_{max} where the emission time constant, $\tau_e(T_{max})$, fits the chosen time window, t_W, depending on t_1 and t_2 (Eq. 4.16).

Arrhenius plot: can be constructed from a set of data ($T_{max,i}$, $\tau_e(T_{max,i})$) obtained performing several temperature scans with different time windows.

Drawback: the outcoming DLTS signal is fully influenced by the behaviour of the transient signal at the two sampling points.

C-DLTS *transient analysis: Correlator functions* (1/2)

(from Michael Moll's PhD thesis, Ch. 4, Para. 4.4, pp. 81-88)

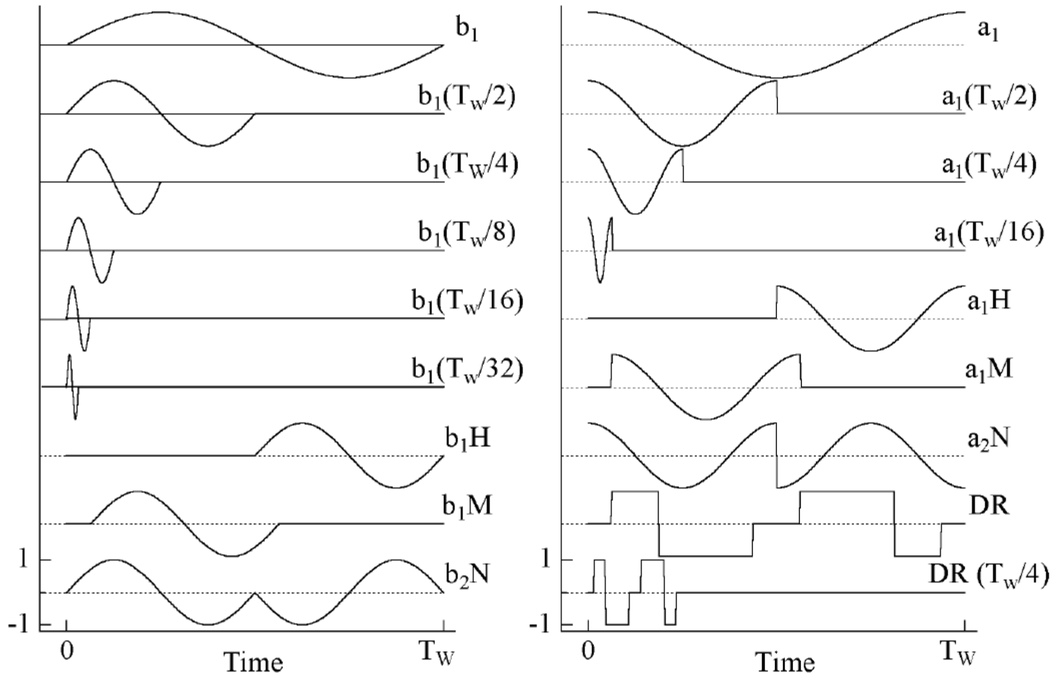


Figure 4.10: The 18 correlator functions used for the *maximum evaluation*.

$$b_1 = \frac{2\,\Delta C_0}{T_W} \int_0^{T_W} \exp\left(-\frac{t+t_0}{\tau_e}\right) \sin\left(\frac{2\pi}{T_W}t\right) dt \qquad (4.17)$$

$$\tau_e(T_{max}) = 0.43 \times T_W. \qquad (4.18)$$

<u>Correlator function</u>: the **complete capacitance transient** is used by **folding** it with a **correlator function**, e.g. a sine, namely by doing the **convolution** between the **measured signal** and a **known function**, called **correlator**. The result is a correlator function, e.g. b_1 (Eq. 4.17), where T_W is the time window.

<u>DLTS spectrum</u>: correlator, e.g. $\mathbf{b_1}$, plotted **versus** the temperature, **T**. NB: in this case, the **emission time constant**, $\tau_e(T_{max})$, can only be **calculated numerically** (Eq. 4.18), where 0.43 corresponds to 512 time bins.

<u>Arrhenius plot</u>: can be constructed from **18 pairs** $(T_{max,i}, \tau_e(T_{max,i}))$ **for each time window** (usually 20, 200 and 2000 ms), by using in total **18 different correlator** functions (Fig. 4.10). See **example** in the next slide.

C-DLTS *transient analysis: Correlator functions* (2/2)

(from Michael Moll's PhD thesis, Ch. 4, Para. 4.4, pp. 81-88)

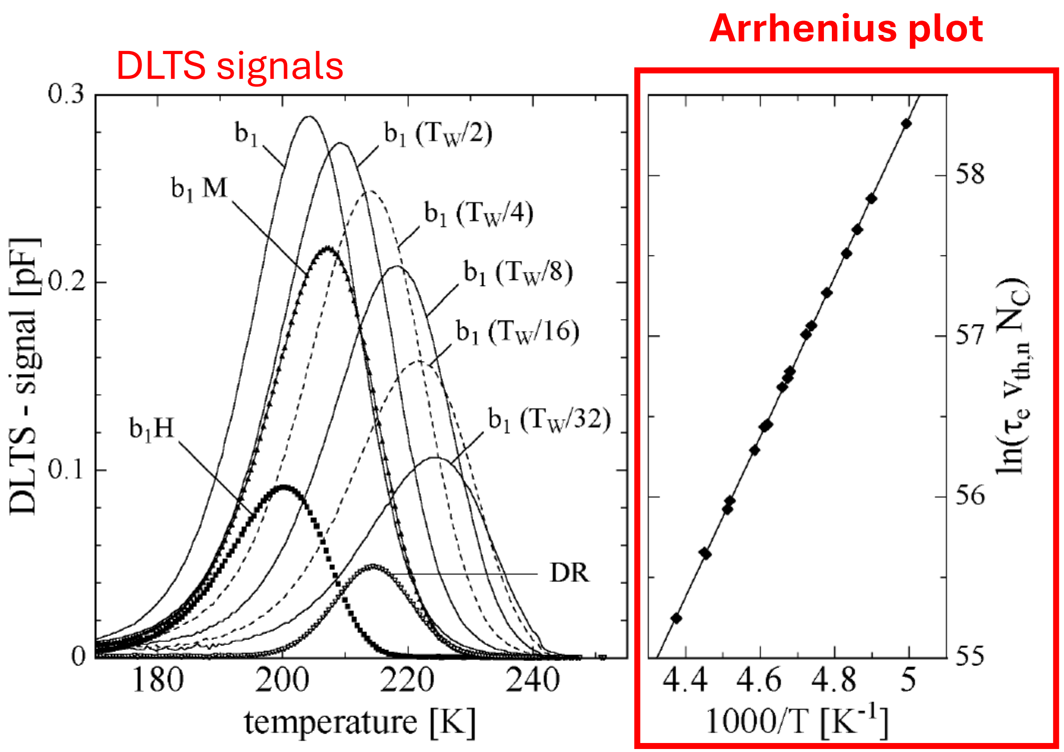


Figure 4.11: DLTS spectra obtained with various different correlators (see Fig. 4.10). For better visibility not all of the 18 used correlators are shown. However, the Arrhenius plot on the right-hand contains the data obtained with all 18 correlators. (transition: $VV^{(-/0)}$, sample M21009, $V_R = -10\,\mathrm{V}$, $V_P = 0\,\mathrm{V}$, $T_W = 200\,\mathrm{ms}$, $t_0 = 6\,\mathrm{ms}$, ^{60}Co-γ-irradiated: 107 kGy)

Example:
DLTS signals corresponding to 9 different correlators (on the left) and an **Arrhenius plot** (on the right).

This **method** is called ***maxima evaluation***.

Usually, **three different time windows** T_w of 20, 200 and 2000 ms used **during one temperature scan**.

NB: the **measured temperature dependence** of the **characteristic emission time constant** of the capacitance transient, $\boldsymbol{\tau_e}$, can be used to establish an **Arrhenius plot** to determine the **capture cross-section**, $\sigma_{n,p}$, and the **activation energy**, $\Delta H'_{n,p}$, of the defect from the **intercept with the ordinate** and from the **slope**, respectively.