PhD course of National Interest in Technologies for Fundamental Research in Physics and Astrophysics

Annual report

Name and surname: Tommaso Croci
Cycle and a.a.: XXXIX cycle, a.y. 2024/2025
Supervisors: Dr. Arianna Morozzi, Prof. Daniele Passeri, Prof. Pisana Placidi

• Research activity carried out during the year

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

During the second year of the doctoral program, **Technology-CAD** (**TCAD**) **simulations** were carried out to explore different **design strategies** for **Guard Ring** (**GR**) **protection structures** in thin p-i-n and Low-Gain Avalanche Diode (LGAD) detectors fabricated on **n-doped** silicon **substrates** ("NLGAD" R&D production). In parallel, **TCAD simulations** and **design studies** continued on various LGAD-based **AC-coupled Resistive Silicon Detector** (**RSD**) **architectures**, aimed at optimising 4D tracking performance under different occupancy conditions ("RadHard AC-LGAD" R&D production).

A **beam test** of LGAD-based **DC-coupled Resistive Silicon Detectors** ("DC-RSD1" R&D production) was conducted at the **DESY accelerator centre** (German Electron Synchrotron) in Hamburg, Germany, from 9 to 16 December 2024, in the framework of the INFN CSN5 "4DShare" R&D project. The main **challenges** were setting up the experiment to ensure **precise alignment between** the **device under test** and the **beam telescope**, **configuring** and **operating** the various **instrumentation components** (e.g., oscilloscope, digitizers, amplifiers, voltage supply, DAQ system), **managing** the **data acquisition** process, and performing **track reconstruction** and **analysis**.

Defect spectroscopy measurements – specifically **Deep Level Transient Spectroscopy** (**DLTS**) – were performed, along with the **development** of a **TCAD simulation framework** capable of reproducing the experimental results (i.e., DLTS spectra). These activities were carried out during a **six-month international internship** at the Solid-State Detectors Laboratory (**SSD**) of the **CERN EP-DT group**, under the supervision of Dr. Michael Moll (Leader of the SSD and Deputy Group leader of the CERN EP-DT group), from April to September 2025.

The **design** and **simulation activities** were conducted using the state-of-the-art **Synopsys Sentaurus TCAD suite**, supported by dedicated **high-performance workstations** (e.g., DELL PowerEdge R640 Server with 80 cores and 128 GB RAM). One of the **main challenges** encountered during these activities was ensuring **simulation convergence** at **cryogenic temperatures** (below 250 K), as required by the operating conditions of the DLTS climate chamber. In this regime the **concentration** of **charge carriers** in the depleted volume of a silicon sensor becomes **extremely low** (e.g. ~10^{-10} cm^{-3} at 100 K compared to ~10^{3} cm^{-3} at room temperature), making it nearly impossible to solve the fundamental physical equations – such as diffusion and transport equations – on the discretised geometries, even when simulating a simple one-dimensional p-n junction. To overcome these software limitations, various **numerical strategies** were **adopted**, including **tuning mathematical parameters** that govern convergence behavior (e.g., number of Newton iterations, extended precision floating-point arithmetic, error criteria), as well as **specific workarounds**, such as **artificially increasing** the **charge carrier generation rate** to mimic charge injection from an optical stimulus (e.g., laser illumination).

As part of the **defect spectroscopy activities**, I underwent **supervised training** on the **DLTS system**, which **comprises multiple interconnected instruments**, including a cryostat, temperature controller, vacuum pump, compressor and chiller, capacitance and current meters, and voltage supply units. The main **challenge** was **managing** such a **complex setup** from both **hardware** and **software** perspectives, which requires the adoption of a **systematic approach**, treating the system as a set of functional sub-blocks to facilitate **troubleshooting** and **problem-solving**.

- ## List of attended courses and passed exams

o “Machine Learning Programming in Physics”, **1 Oct-5 Nov 2024**, INFN and University of Bari, course held online, 2.5 CFU.

o “Design of readout integrated circuits for particle detectors”, **4-19 Nov 2024**, INFN and University of Bari, course held online, 2.5 CFU.

o “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.

- **List of attended conferences, workshops and schools, with mention of the presented talks**

o Presentations at conferences:

- Poster: “Enhancing guard-ring protection structures for the next generation of radiation-hard thin silicon particle detectors”, 17th Vienna Conference on Instrumentation - VCI2025 (https://vci2025.hephy.at/), **17-21 Feb 2025**, Vienna University of Technology, Wien, Austria.

o Workshops:

- “2nd DRD3 week on Solid State Detectors R&D” (https://indico.cern.ch/event/1439336/), **2-6 Dec 2024**, CERN, Geneva, Switzerland.
- “6th Allpix Squared User Workshop” (https://indico.cern.ch/event/1489052/), **7-9 May 2025**, online attendance.

o Seminars:

- “Advanced UK Instrumentation Training 2025” (https://indico.global/event/14484/), **6 May-27 June 2025**, lectures held online.

List of published papers/proceedings

o 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.

o 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.

- 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.
- 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.
- 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.
- 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.
- 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.

- 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.
- 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.
- 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.

- **Thesis title (even temporary)**

"Development of methodologies and numerical models for the design and optimisation of innovative radiation-hard silicon particle detectors for 4D tracking in future high-energy physics experiments"

Date, 12 September 2025 **Signature**

Seen, the supervisor

Arianna Morozzi

Daniele Passeri

Pisana Placidi