DRD3 Work Package Project template

Title: Development of radiation-hard GaN devices for MIP detection

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Project description

Gallium nitride (GaN) semiconductors are now commonly found in optoelectronic and high-power devices, e.g., light-emitting diodes (LEDs), lasers and high electron mobility transistors (HEMTs). GaN can also be used for detecting ionizing radiation under extreme radiation conditions due to its properties such as a wide bandgap (3.39 eV), large displacement energy (theoretical values averaging 109 eV for N and 45 eV for Ga), and high thermal stability (melting point: 2500 ^{0}C). Compared to narrower band-gap semiconductors such as silicon, GaN can operate at higher temperatures; while a comparison with other wide band-gap semiconductors, such as SiC, demonstrates GaN’s higher electron mobility and potential for better carrier transport properties. In the proposal below, we provide the outline of a project that aims to exploit recent developments in GaN fabrication processes aiming at robust performances at harsh environments, e.g. high temperatures, and assess the potential of GaN as a meterial for the fabrication of radiation hard devices for MIP detection.

Project phases:

The project is organized in two main phases. The firt phase (Phase-I) is essentially the proof-of-principle that GaN is indeed a radiation-hard material and that fabrication of a monolithically integrated device is possible. Phase-I will also provide the necessary infrastructure for device modelling and device performance characterization. Phase-II will only commence after the successful completion of Phase-I and will mainly focus in demonstrating large scale production capabilities of fully integrated detector devices. Both phases are organized in work packages which represent the major deliverables of each phase.

1. **Phase-I, complete by end of 2030**
    a. **Work Package 1: Develop material quality appropriate for applications in harsh environments such as radiation-hard MIP detectors – requires close collaboration with vendors (growers)**
        - Low non-intentional (residual) doping concentration <10^{15} cm^{-3} demonstrated, reduce by >1 order of magnitude
        - Demonstrate low threading dislocation density ~10^5 cm^{-2}
        - Further develop epitaxial GaN growth on bulk SiC or GaN substrate:
            - Increase thickness of epitaxial GaN layer that displays low concentration of uncompensated donors to >10μm and preferably to >15μm
        - Develop/implement techniques for device performance characterization:
            - Fabricate test devices (diodes, HEMTs) to study performance
            - Assess bulk electrical properties (IV/CV), depletion depth
            - Measure charge collection efficiency using optical (laser) and radiation sources
            - Measure electron mobility
        - Microscopically measure GaN material growth quality:
            - Perform systematic study of electric and deep trap spectra, estimate concentrations, trap energies and cross-sections.
            - Develop appropriate techniques for such measurements portable to high-resistivity and potentially high defect concentration material
    b. **Work Package 2: Demonstrate and improve on radiation hardness at larger than HL-LHC fluences (>10^{16} n_{eq}/cm^2)**
        - Fabricate test devices for irradiation campaigns (Schottky diodes, transistors) also appropriate for device simulation
        - Perform irradiations with protons/neutrons/gammas
        - Measure bulk electrical properties, compare to those before irradiation
            - Depletion depth, high-current breakdown characteristics
            - Induced leakage current, noise level
            - For transistors, obtain transfer curves, gate currents
        - Measure radiation induced trapping defects
        - Investigate charge collection efficiency, establish level of signal deterioration
        - Improve fabrication process to address any potential performance and/or reliability gaps at large radiation fluences
    c. **Work Package 3: Develop infrastructure for device simulation**
        - Device modelling that adequately reproduces measured pre-irradiation characteristics
        - Design optimization
        - Implement microscopically measured pre-irradiation point and cluster defects in TCAD (Sentaurus/Silvaco) models
        - Charge propagation/trapping modelling (Allpix^2)
        - Introduce radiation damage defects – model
    d. **Work Package 4: Study high-temperature operation – understand signal-to-noise**
        - Develop infrastructure to study high-temperature operation
        - Measure bulk electrical properties, depletion depth
        - Evaluate temperature dependence of bulk/surface defects – improvements
    e. **Work Package 5: Study ageing**
        - Assess stability of electrical characteristics (leakage current, CCE,…)

    - Investigate defect evolution with time
    - Effects of annealing
  f. **Work Package 6: Implement process to fabricate a GaN transistor-sensor device integrated on the same die**
    - Develop Process Design Kit (PDK) including compact modeling
    - Develop TCAD device model – optimize design parameters
    - Full characterization of device electrical properties before/after irradiation as in work packages (1), (2) above – compare to model
    - Assess the capability of fabrication of large area GaN pixel devices
      - Investigate power aspects
      - Costs, yields, large quantities production feasibility
    - Undertake engineering runs on GaN sensor devices and on transistor-sensor integrated on the same die

2. **Phase-II, after 2030 (outlook) – assumes that phase-I is successfully completed**
  a. **Work Package 1:** Improve understanding of interaction of radiation defects with dislocations and dopants, and the effect of defect transformation upon increasing irradiation temperature and upon annealing; identify main radiation defects to develop effective modeling of radiation damage in GaN.
  b. **Work Package 2:** Develop radiation damage model, combine with GEANT4 simulation of particle interaction with matter; develop signal process simulation, understand signal-to-noise.
  c. **Work Package 3:** Increase wafer size to >50mm with high uniform yield – assess large scale GaN wafer fabrication.
  d. **Work Package 4:** Investigate industrial partnerships; large scale production capabilities.
  e. **Work Package 5:** Demonstrate LGAD GaN device.
  f. **Work Package 6:** Assess GaN devices as potentially high-rate (>5 GHz/cm^2), high timing precision (<100ps) devices.

In the current proposal we focus on the research program outlined for Phase-I. This is summarized in table 1 below. Each work package represents a major deliverable of the project. The column marked 'x' indicates the expected completion of the deliverable.

	Timeline of major deliverables					
		2025	**2026**	**2027**	**2028-2029**	**2030**
	WP1: Improve material quality; GaN growth on bulk GaN substrate; increase thickness of epitaxial GaN layer			x		
	WP2: Demonstrate radiation hardness to protons/neutrons at >10^{16} neq/cm^2				x	
	WP3: Improve existing infrastructure for TCAD modeling					x
	WP4: Study high-temperature operation	x				
	WP5: Study ageing			x		
	WP8: Monolithically integrate transistors and sensors on same substrate					x

Table 1: Timeline of major deliverables for Phase-I

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In table 2 below, a more detailed breakdown of the main deliverables (aligned to the work packages presented above), as well as the most important milestones within each deliverable, as presented. The corresponding work package is shown under the column “WP project #”. Under “Lead” the lead institutes are listed. The column labelled “Type” indicates the form of the final deliverables provided for each milestone within the work package. The due dates shown in the last column of the table are aligned to the ones shown in Table 1 above but are now broken down according to the main milestones within the work package. This provides a more detailed timeline and at the same time the means to track the progress of each work package individually.

Number	**Deliverable/Milestone Title**	**WP project #**	**Lead**	**Type**	**Dissemination Level**	**Start Date**	**End Date**
D-Project#-1	***Improve material quality***	WP1	NRC/Carleton Vilnius, FZU, Birmingham +others +suppliers	Prototypes	Publication	Q4 2024	Q4 2027
	Milestone#-1.1 *Epitaxial GaN growth on bulk GaN substrate*			Prototypes	Publication	Q4 2024	Q4 2027
	Milestone#-1.2 *Device performance characterization infrastructure*			Reports	Publication	Q3 2024	Q2 2025
	Milestone#-1.3 *Microscopically measure GaN material quality*			Reports	Publication	Q4 2024	Q4 2025
D-Project#-2	***Establish radiation hardness at $>10^{16}$ neq/cm^2***	WP2	RAL, FZU, Vilnius, JSI, Birmingham +others	Reports	Publication	Q4 2024	Q4 2028
	Milestone#-2.1 *Perform Irradiations* *Measure bulk electrical properties*					Q4 2024	Q3 2028
	Milestone#-2.2 *Measure radiation induced trapping defects*					Q1 2025	Q4 2028
D-Project#-3	***Develop Device simulation***	WP3	RAL +others	Modelling SW	Publication	Q4 2024	Q2 2030
	Milestone#-3.1 *Implement microscopically measured point and cluster defects in TCAD models*					Q2 2025	Q2 2027
	Milestone#-3.2 *Introduce radiation damage defects*					Q1 2026	Q3 2030
D-Project#-4	***High Temperature Operation***	WP4	NRC/Carleton +others	Prototype	Publication	Q1 2025	Q4 2025
D-Project#-5	***Ageing Effects***	WP5	NRC/Carleton FZU, Vilnius +others	Reports	Publication	Q1 2026	Q4 2027
D-Project#-6	***Monolithically integrate transistors and sensors on same substrate***	WP8	NRC/Carleton CNM +others	Prototype	Publication	Q1 2026	Q4 2030

Table 2: Summary of milestones and deliverables

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- **Collaborative work:**
    - WG activities involved:
        - WG3 – radiation hardness studies
        - WG4 – TCAD modelling of GaN devices and radiation damage
        - WG5 – Irradiation campaigns, test beams
        - WG6 – Wide bandgap material quality, monolithic integration, high-timing precision devices characterization
- **Participants:**
    - Ottawa consortium – National Research Council of Canada (NRC), Carleton University
    - CNM – Barcelona
    - STFC – RAL, Particle Physics Department
    - FZU – Institute of Physics of the Czech Academy of Sciences
    - Oxford University
    - Vilnius University, Institute of Photonics and Nanotechnology
    - JSI – Jozef Stefan Institute
    - University of Birmingham

FA/Institute	**NRC-Carleton**				**CNM-Barcelona**				**STFC-RAL**			
	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs
D-Project#-1												
D-Project#-2												
D-Project#-3												
D-Project#-4												
D-Project#-5												
D-Project#-6												
D-Project#-7												
D-Project#-8												
Total												

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FA/Institute	**FZU – Institute of Physics**				**Oxford University**				**Vilnius University**			
	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs
D-Project#-1												
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D-Project#-4												
D-Project#-5												
D-Project#-6												
D-Project#-7												
D-Project#-8												
Total												

FA/Institute	**JSI**				**University of Birmingham**							
	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs	Funding (kCHF)	FTE/year Physicists	FTE/year Ph.D. Students	FTE/year Engineers/Techs
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D-Project#-7												
D-Project#-8												
Total												

- **Resources needed**
    - 100k CHF fabrication costs – assumes 1+1 fabrication runs (Schottky diodes, HEMTs), includes costs for consumables and technical personnel
    - 55k CHF for material – 12, 4” wafers on SiC substrate
    - HQP (physicists – RAs, graduate students) for measurements
        - 1 RA and 1 Ph.D. student at Carleton/NRC for 3 years, 60k CHF/year
        - Other institutes?
- **Project structure**
    - TBD