NRC·CNRC

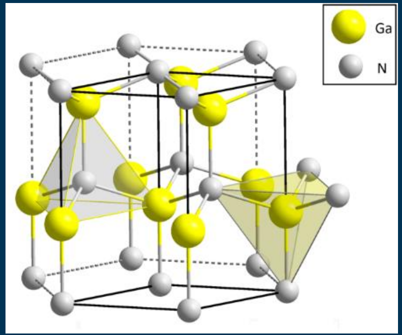
Development of radiation-hard GaN devices for MIP detection - Phase I

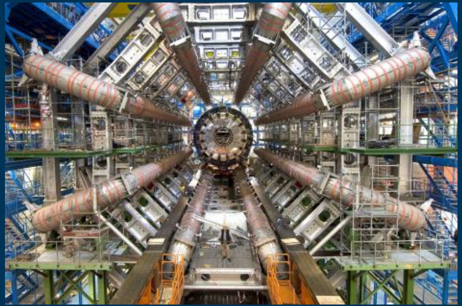
Alex Walker, *et al.*, NRC
Thomas Koffas, *et al.*, Carleton University
Joan-Marc Rafi, *et al.*, CNM
Giulio Villani, RAL
Marcela Mikeštíková, *et al.*, Czech Academy of Science

Wide bandgap material R&D for extreme fluences

GaN overcoming Si in high-power, high-temperature switching applications

- Bandgap of 3.4 eV, atomic bond energy of ~9 eV/atom
- High breakdown fields
- High electron mobilities in HEMTs
- Broad range of suppliers producing high volume, reliable GaN technologies albeit on sapphire, SiC and Si substrates
  - *No clear path toward viable, low cost GaN substrates…*
- Potential in extreme fluence applications such as FCC-hh



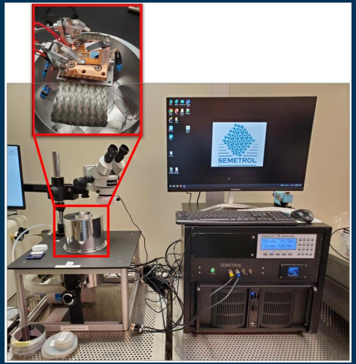


ECFA roadmap includes WBG materials

Diamond, SiC, … and GaN!

Focus for GaN on:

- Material quality and epitaxial improvements on native GaN substrates
  - Targeting low threading dislocation densities <1E6 cm^{-2}
- Understand device leakage and sensitivity before and after irradiation
  - Characterizing traps (eg. DLTS)
- Development of improved TCAD capabilities
- Access to larger wafer sizes with high yields for reasonable costs
  - Collaborate with vendors such as NTT, Kyma, …
- Opportunities for monolithically integrating transistors and sensors
- Assess devices with high-rate, high timing precision



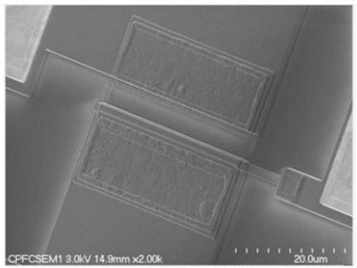


Figure 5-1: SEM of A Field Plated GaN500 HFET without Air-Bridges

Collaborative Environment

Previous research proposal (*RD50-2021-02*) within RD50 included NRC, Carleton University, RAL, CNM on first generation GaN Schottky device fabrication & testing

Collaboration opportunities within:

- WG3: Radiation hardness studies
- WG4: TCAD modeling
- WG5: Irradiation campaigns, test beams
- WG6: Wide bandgap material quality, monolithic integration, high timing precision device characterization

National Research Council of Canada

- 2,229 scientists, engineers, technicians, including 272 SME technology advisors
- 179 buildings in 22 lab locations
- $839M in funding programs, with $293M funding to SMEs
- $155M in revenue

We work with:

- **9,349** SMEs
- **1,000** companies (R&D)
- **150** hospitals
- **70** colleges and universities
- **35** federal departments
- **39** provincial/municipal governments
- **36** countries

SME: small-medium enterprises

Quantum and Nanotechnologies Research Centre Capabilities

QN'S CORE CAPABILITIES

QUANTUM SCIENCE

- NRC's quantum ambitions hinge on core capabilities (e.g., ultrafast laser physics, emerging materials, advanced microscopy, nanomechanical devices, HPC, etc.).

MATERIALS DEVELOPMENT

- Materials capabilities at QN are broad (e.g., nanomaterials, polymer chemistry, organic electronics, nano-engineered metamaterials, compound semiconductors, emerging materials).

MATERIALS CHARACTERIZATION

- Materials characterization extends over all three sites. QN has expertise in determining the properties of our advanced materials.

FABRICATION

- QN has expertise and access to fabricate a range of devices and incorporate them into prototypes. Increased automation is key.

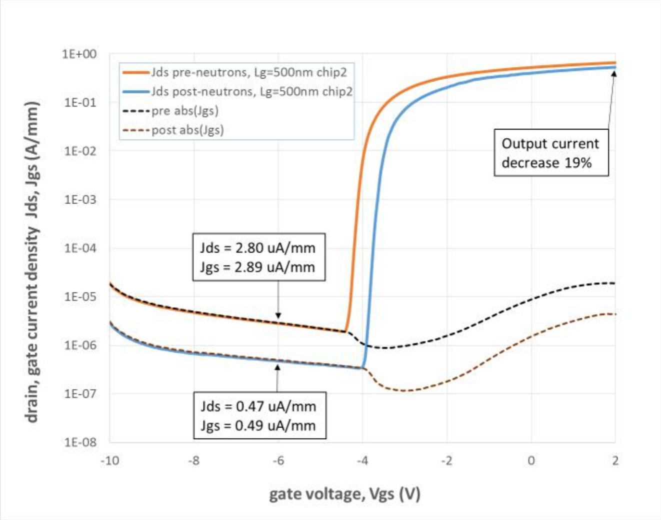
DEVICE DESIGN AND TEST

- QN has expertise in designing and testing proof-of-concept experiments and devices for specific applications.

Current State of GaN at NRC

Gallium Nitride HEMTs for Extreme Environments

- First group to demonstrate measurement and modelling of RF HEMTs at 500°C
- Preliminary data on HEMT degradation at 10^{16} 1-MeV n_{eq}/cm^2 with ~19% output current decrease, and +0.4 V threshold shift
- Next-generation devices have been fabricated and irradiation campaign being planned



Schottky Diode Sensors

- Fabricating second generation GaN Schottky sensors
- Comparing two different GaN on GaN suppliers, process optimization and in-depth device characterization

NRC facilities: material growth to device testing

Epitaxy of III-V semiconductors:

- MBE of GaAs, GaSb;
- CBE of InP

Organic materials

- Printing: ink formulation, inkjet, aerosol, roll-to-roll (flexo, gravure, offset)
- Organic and polymer film deposition

Materials characterisation

- SEM, TEM and AFM microscopies
- SIMS, NanoAuger and XPS spectroscopies
- Optical and e-beam lithography
- PECVD of aSi, SiO_x, SiN, sputtering of optical filters
- RIE etching tools for GaAs, InP, GaN and Si
- Metal evaporation and RTAs

Advanced Technologies Fabrication (ATF)

- Optical and e-beam lithography
- PECVD of aSi, SiO_x, SiN, sputtering of optical filters
- RIE etching tools for GaAs, InP, GaN and Si
- Metal evaporation and RTAs

Assembly and packaging, prototype integration

Device design and simulation

Device testing

- DC to RF characterization (PA, automated probing)
- Photonic device testing: lasers, detectors, couplers, waveguides

Testing facilities (1)

Full wafer testing (-60 to 200 °C)

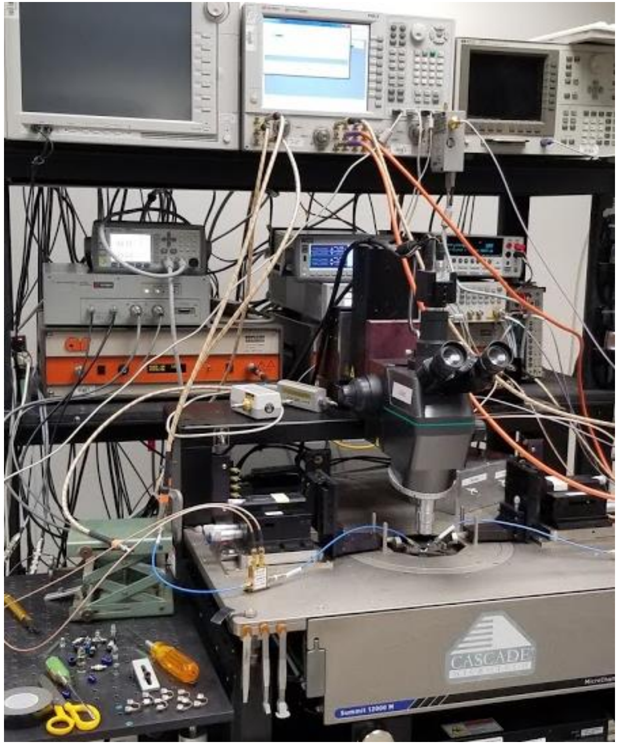
Two Cascade Summit 12000 semi-auto probe stations

- 2” to 8”
- Automated with “move and measure” using custom software
- DC and RF (Up to 50 GHz)
- Statistical analysis software written
  - Transfer curves, output curves, multi-biased S-params

Testing facilities (2)

Instrumentation

- Auriga AU-5 Pulsed-IV (In procurement)
- Keysight N4245B PNA-X
- Keysight B1500A (With atto-sense and CV)
- Keysight B1505A (With MCMV 1 kV/10 A expander)
- Keysight B2902 SMUs
- HP 4284/4285 LCR meters
- HP Impedance analyzer
- Mini-Circuits ZHL-16W-43-S+ power amplifier (1.8 to 4 GHz)



Software

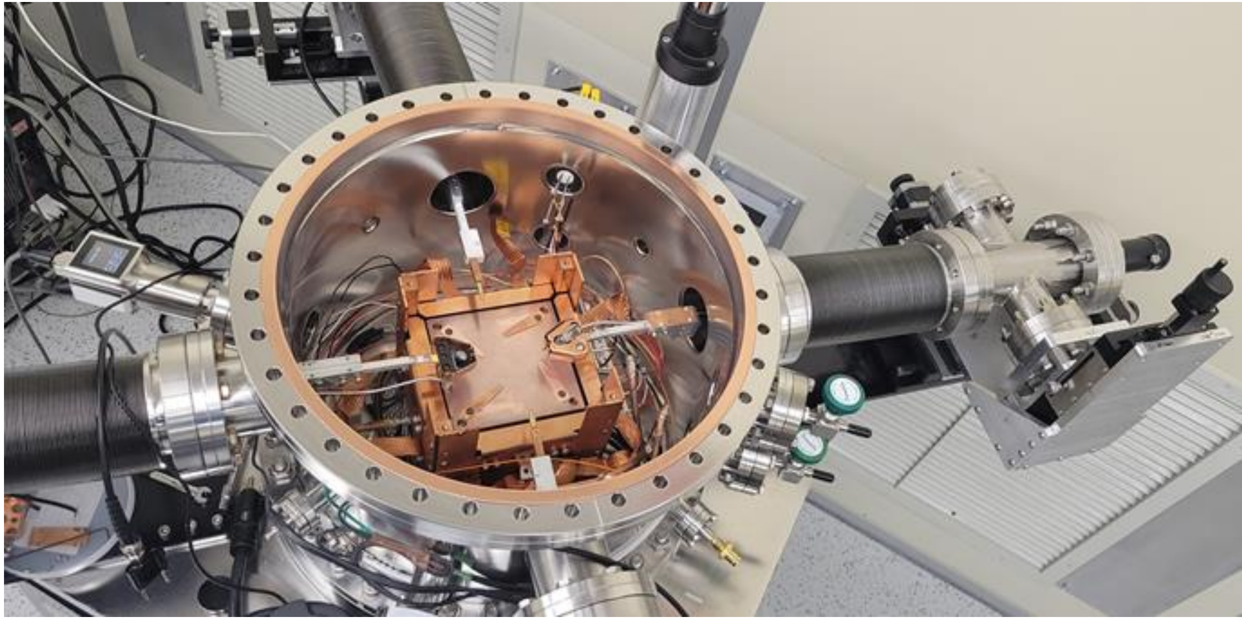
- Synopsys Sentaurus TCAD and Silvaco ATLAS & ATHENA
- Keysight IC-CAP & ADS

Testing facilities (3)

High-temperature probing

MicroXact CPS-HT

- Vacuum chamber system
- Rated to 700 °C
- 2 DC, 2 RF probes
- Up to 4” wafers



IP Protection

Enabling industry innovation

Telecommunications
· Security
· Data communications
· Quantum sensing/communications
· Automotive light detection and ranging (LiDAR)
· Aerospace (photonic gyro)
· Environmental and physical sensing
· AI

Critical Service Supply Chain

· First or second source
· Non competitive supplier
· Partial processing for critical steps

Leading edge technology development

· Buried Heterojunction Device
· Quantum dot
· Semiconductor optical amplifier
· Photonic integrated circuit

North America’s only InP pure play commercial compound semiconductor III-V foundry

· Offering unique solutions toexactly meet client needs
· 20+ years experience
· High electron mobility transistor (HEMT)
· Indium phosphide (InP)
· Gallium arsenide (GaAs)

Canadian Photonics Fabrication Centre (CPFC)

End-to-end fabrication

· Design
· Growth process
· Test and characterization
· Commercial grade prototyping
· Scaling to volume

One-stop shop

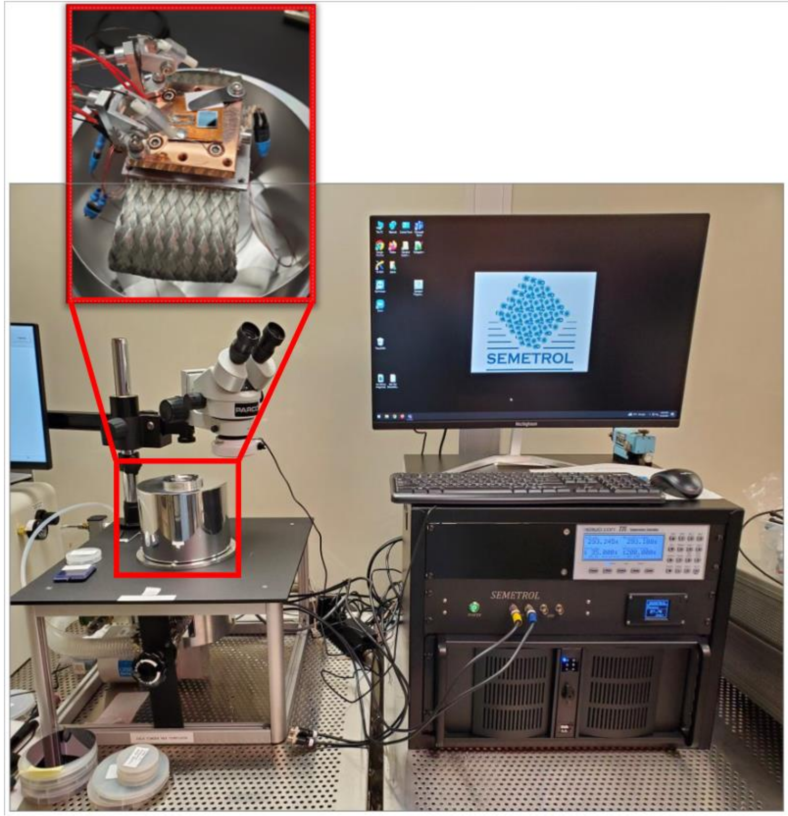
· Research & development
· Scale services: full technology readiness level to manufacturing readiness level
· Expert led process development for new product introduction
· Manufacturing services

Impact to Canada

· Supporting innovation
· Improving time to market
· Enabling SMEs & MNEs
· Improved market insight
· Supporting SME growth and local job creation

Carleton University Microfabrication Facility

- Deep-level transient spectroscopy
- Bruce Model BDF-8 furnace bank (100 mm)
- LPCVD, PECVD
- Various metal deposition systems (e-beam, thermal, sputtering)
- Karl Suss MA-6 contact mask aligner resolves to 0.8 μm
- In-house mask-making on photographic emulsion plates
- e-beam direct write lithography with modified SEM
- Reactive Ion Etching (RIE); Planar Plasma
- Multiwavelength ellipsometry



Institute of Microelectronics of Barcelona

Clean Room Facilities

> 150 process tools
- Thermal processes & CVD
- Ion implantation
- PVD
- Photolithography
- Cleaning & wet etching
- Dry etching (RIE)
- Microsystems
- Nano-fabrication
- On-line characterization

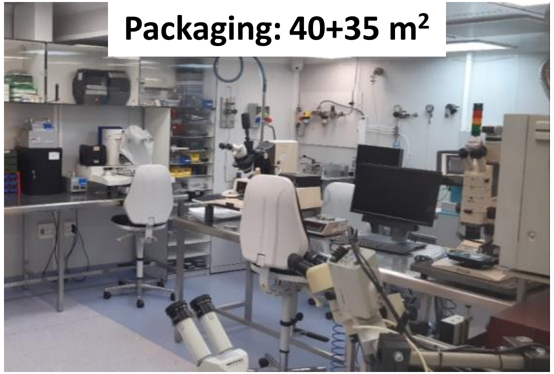
150 mm, 100 mm Wafers & Dies
2 lines: CMOS & Non-CMOS
Self-service & Per assignment

Clean Room virtual tour

Integrated cleanroom: 1500 m^2

100-10000 class

Packaging: 40+35 m^2



Associated laboratories

Electrical characterization

Printed electronics

+ Reverse engineering

Institute of Microelectronics of Barcelona

Centre Nacional de Microelectrònica IMB

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Radiation Detectors activities (~10 Permanent researchers, ~8 postdocs, ~7 students, ~2.5 technical support)

Available equipment

Electrical characterization: (IV, CV, ...): probe stations (manual, automatic, T-controlled (-60°C-300°C))
Physical characterization: SEM, FIB, EDX, AFM, 3D-Profilometer
Laser based characterization tools (TCT standard: infrared, blue and UV lasers) for timing 2D scanning
MIP setup for timing and CCE measurement with strontium-90 and alpha sources
X-ray tube for irradiation and characterization
TCAD Synopsis Sentaurus license and computing infrastructure
Alibava and Alivata setup
Mechanical workshop (wire bonder, 3D printer, PCB prototypes, etc.)

Current project proposal close-related **background** and **interests**

GaN devices **fabrication** IMB-CNM past capabilities:
"A HfO_2 based 800V/300℃ Au-free AlGaN/GaN-on-Si HEMT Technology" https://doi.org/10.1109/ISPSD.2012.6229017
Electrical **characterization** and **irradiation effects** on WBG (SiC) radiation detectors:
37th RD50 Workshop (Zagreb - online), contribution #28, extended work: https://doi.org/10.1109/TNS.2020.3029730
Last (43rd) RD50 Workshop (CERN), contribution #63, extended work: https://doi.org/10.1109/TNS.2023.3307932

MSCA-COFUND Doctoral Programme (**PhD student** to start July 2024):
"Advanced Wide Band Gap Semiconductor Devices for Particle Detection in High Energy Physics and Space Applications"

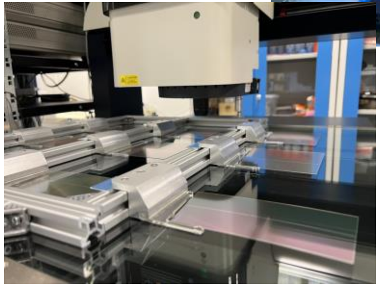
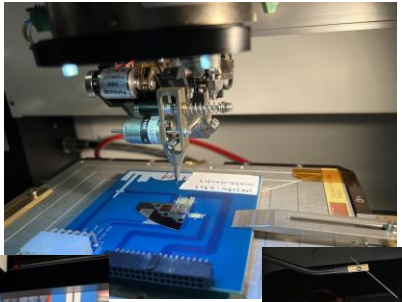
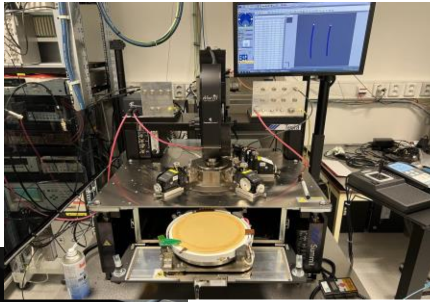
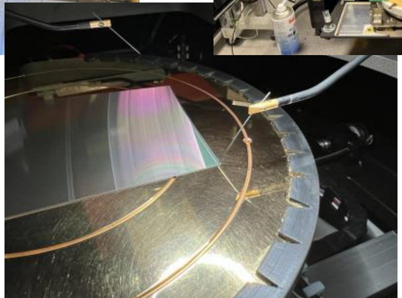
DocFam+

"This project has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska Curie grant agreement No. 10181337"

Institute of Physics of the Czech Academy of Sciences (FZU)

- 20+ year of experience with testing of silicon sensors - both R&D and production testing
  - ATLAS SCT
  - ATLAS ITk strip (currently QC/QA testing of production sensors for half of the end-cap)

- Members of the RD50 collaboration for many years
  - focused of investigation of radiation hardness of silicon sensors

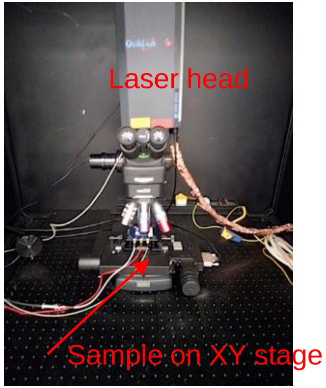
RAL Laser In Particle Physics Dept. (PPD) for detector R&D

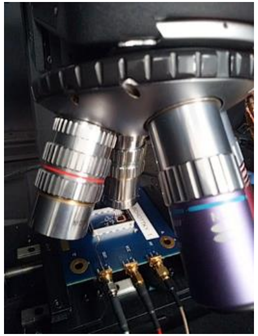
Manufacturer: NewWave Research
Model: QuikLaze Trilite,
Characteristics:

- Type: Nd:YAG
- Wavelength: 1064, 532,355 nm
- Power: 500 uJ max
- Class: IIIb
- Pulse width: 4.5ns
- Firing rate max: 50 Hz

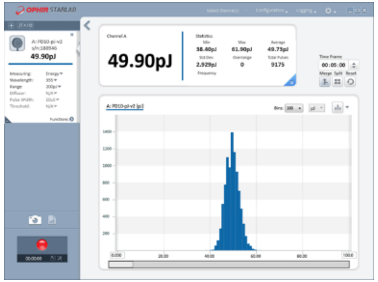
The system consists of a laser coupled to a microscope with 4 different optics – up to x100 magnification. Variable shutter size [0, 2.5] mm, optics dependent. NDA filters can be inserted in the optical path to attenuate the Laser intensity

Stage 1um resolution, 114 x 75 mm

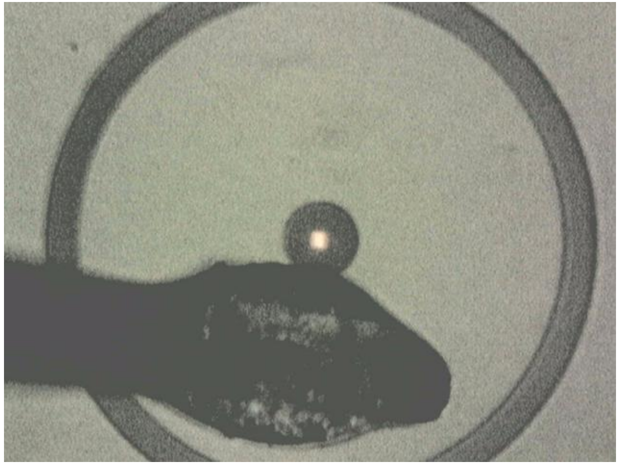


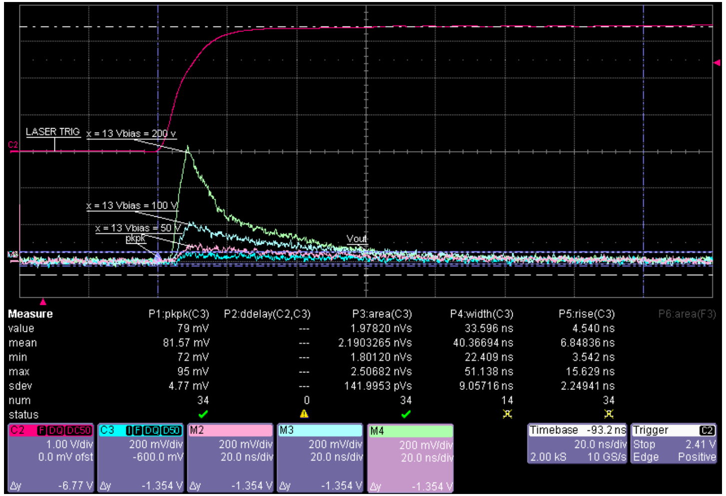


4 optics –
x5/x20/x50/x100
On Z stage



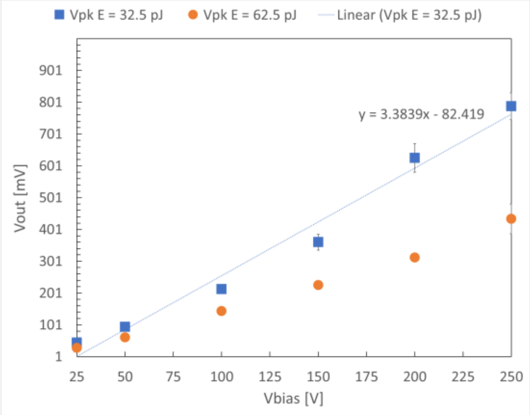
First Gen – CCE Test Results at STFC-RAL

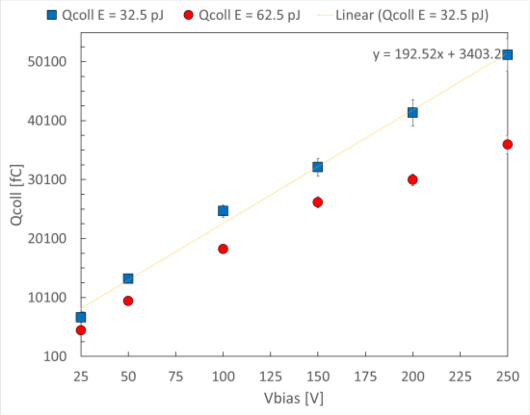


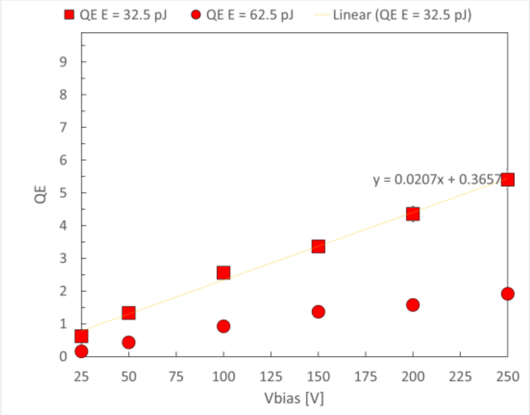


- GaN Schottky bonded on a TIA COLA board of 50 dB gain, approx. 316, > 1 GHz bandwidth
- The signal from the GaN+COLA feeds a LeCroy Waverunner Scope (20 ns timescale, 200 mV vertical scale, 50 Ohm input)
- The area is calculated over 140 ns (i.e. gating from the Laser trigger for the next 140 ns, at 10 GS/s)
- The beam is focused on the middle point of the cathode and the bias voltage is stepped [25,250]V, for two different values of Laser energy
- The signal increases in magnitude with bias voltage
- The transient lasts around 50 ns (probably there is some charge diffusion from the centre to the edges)

First Gen – CCE Test Results at STFC-RAL







- **The output pk-pk signal, collected charge and QE (collected charge in e- / injected photons) increase with applied detector bias. A linear fit seems to describe the process reasonably well**
- **Increasing the delivered energy (i.e. Increasing the injected charge) seems to decrease the signal**
- **Assuming a defect concentration 5e15 cm^{-3}, the estimated maximum field vs. bias is approximately 6e5 V/cm but not sufficient to ignite impact ionisation https://pubs.aip.org/aip/apl/article/117/25/252107/1061381/On-impact-ionization-and-avalanche-in-gallium**
- **The IV plot shows the device is still rectifying but the reverse leakage current is high after illumination**

Timeline: Milestones and major deliverables

#	Milestone | Year (20xx)	24	25	26	29	>30		Group
1	Understand material quality; GaN growth on native GaN substrate; increase thickness of epitaxial GaN layer >10 microns			X			|	NRC, Carleton, Suppliers
2	Improve existing infrastructure for TCAD modelling				X		|	RAL, NRC, +
3	Establish radiation hardness to protons/neutrons at $>10^{16}$ 1-MeV n_{eq}/cm^2			X			|	CNM, +
4	Establish radiation hard HEMT fabrication process; electron mobility			X			|	NRC, Carleton, CNM, +

Timeline: Milestones and major deliverables

#	Milestone | Year (20xx)	24	25	26	29	>30		Group
5	Monolithically integrate transistors and sensors on same substrate				X		|	NRC, Carleton, CNM, +
6	Assess GaN devices as high-rate, high timing precision devices			X			|	RAL, +
7	Industrial partnerships – large scale production					X	|	
8	Demonstrate LGAD GaN device(?)					X	|	

THANK YOU

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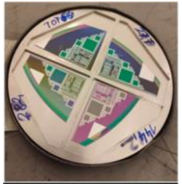
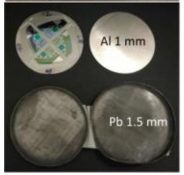
Ottawa, ON, Canada

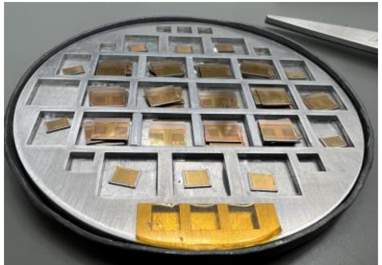
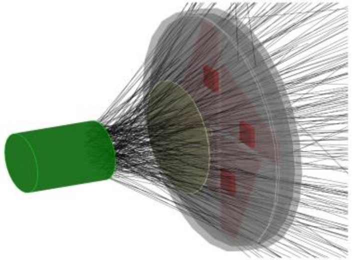
Irradiations of semiconductor components

^{60}Co irradiations at UJP Praha, a.s.

- max. dose rate typically around 20 krad/min
- irradiations in charge particle equilibrium box
- regular irradiations for ATLAS ITk strip project + R&D irradiation campaigns

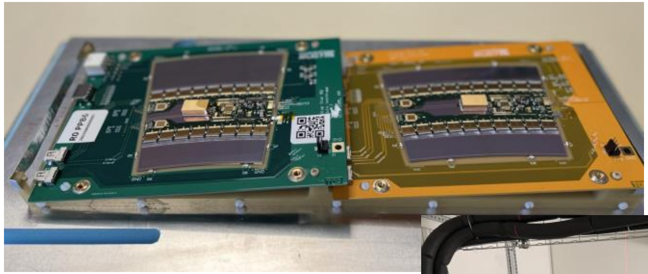
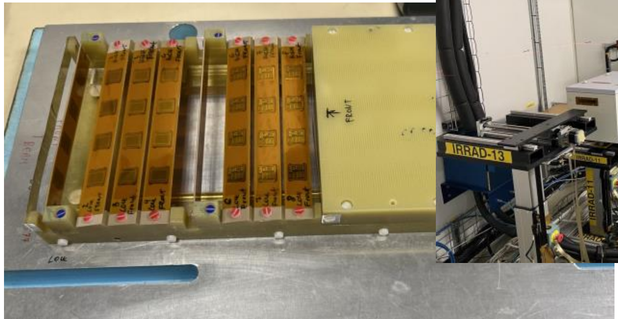





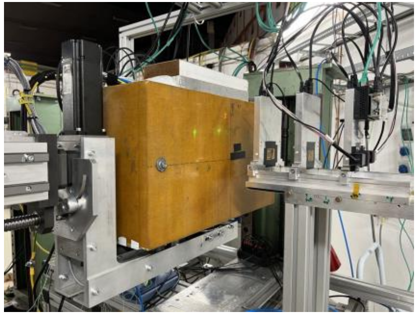
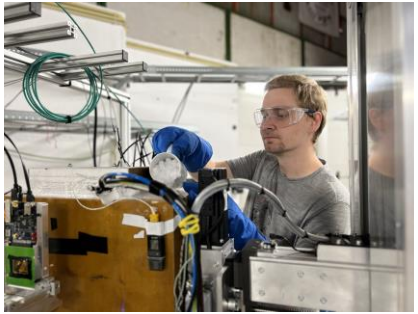
Proton irradiations at CERN IRRAD

- irradiation campaigns for ATLAS ITk strip project
- active (readout) and passive irradiations of ITk strip sensors and modules

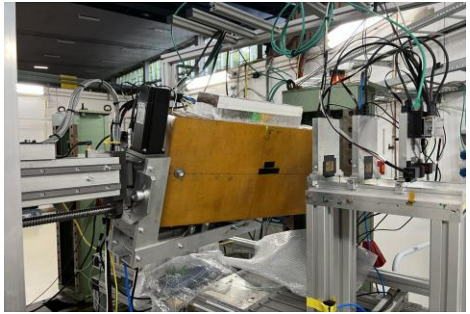




Testbeam activities at DESY II and CERN SPS

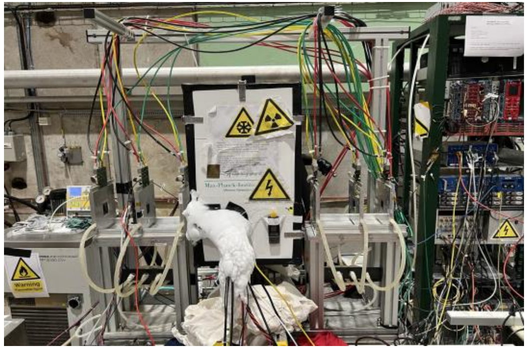
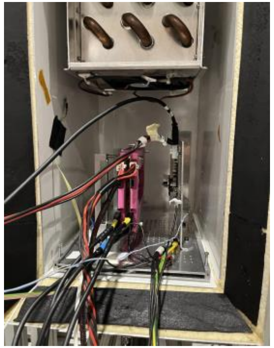
DESY II testbeam facility
- 5 GeV electrons, Alpide telescope

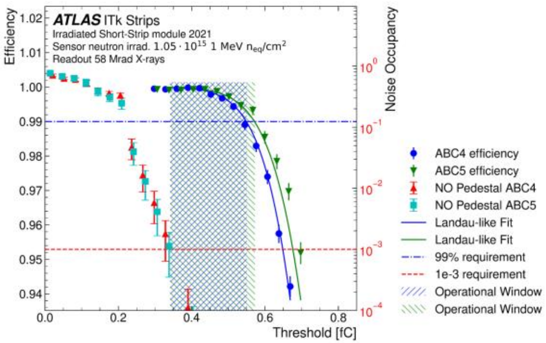
FZU designed and built moving stages for precise positioning of DUTs into the particle beam

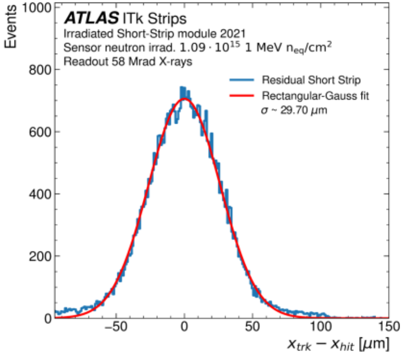



CERN SPS testbeam facility
- 120 GeV charged hadrons, Mimosa/Alpide

Testbeam results represent critical part of all ITk strip reviews (FDRs, PRRs, …)





Clean laboratory and measurement setups

- Semiconductor components are studied in clean laboratory: ISO-7, completely ESD safe, reasonable T/RH stability + 2nd non-clean laboratory in preparation
- Tesla 200mm automatic probe station: triax chuck with temp. control (-55˚C,+300˚C), triax probes, shielding for measurement of very low currents, HV 5000 V compatible
- Karl Suss 200mm probe station for manual testing at room temperature
- F&S Bondtec Series 58 (automatic wire bonding station) with standard wedge-wedge 5830 and deep-access wedge-wedge 5832 bondheads
- Environmental chamber Binder MK56 (-40˚C,+180˚C)
- OGP SmartScope CNC 500
- Top/Edge-TCT setup with infrared and red lasers (large scanning TCT from Particulars)
- Sample storage: MP Dry cabinets (with patch panels), laboratory freezers
- Specific setups: long-term leakage current stability setup (space for 16 samples), intensive UV-A/C source, ATLAS ITk strip sensor QA testing setup, …

New laboratory and measurement setups for R&D activities

- Laboratory has its own air-conditioning system with filters, but currently not clean for certification (ESD protections equivalent to our clean lab)
- Measurement equipment planned to be purchased and installed in coming months
  - Manual probe station with temperature control of chuck
  - Current TCT setup extended by the UV laser
  - Beta source setup with reasonably active beta source
  - Powerful chiller(s) for cooling of samples in TCT, Beta, …
  - Environmental chamber with T/RH control
  - Dry storage cabinet with temperature control
  - Standard measurement units: SMUs, LCR meters, picoammeters, high-R meters, DMMs, oscilloscope, LV power supplies, …