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Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

A High Temperature-tolerant and Radiation-resistant In-core Neutron Sensor for Advanced Reactors

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Project Overview

■ Goal and Objectives

To develop a small and reliable gallium nitride (GaN) neutron sensor capable of withstanding high neutron fluences and high temperatures, while isolating gamma background. This project will provide an understanding of the fundamental material properties and electronic response of a GaN semiconductor device in the harsh environment found in nuclear applications.

Participants

Student/Postdoc: Walter Powell; Pat Mulligan; Dr. Jie Qiu

■ Schedule:

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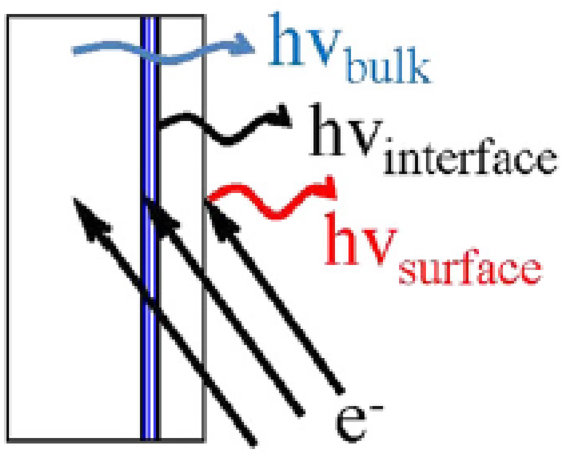
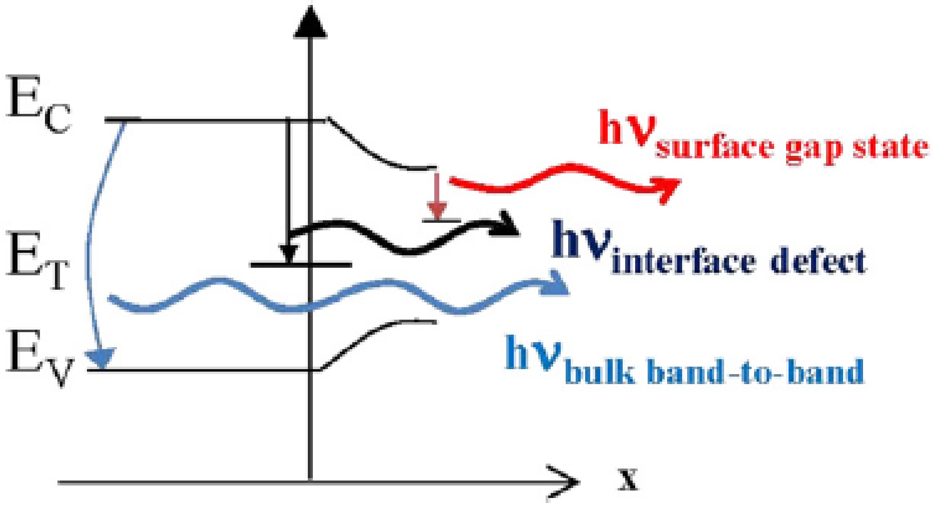
Why GaN?

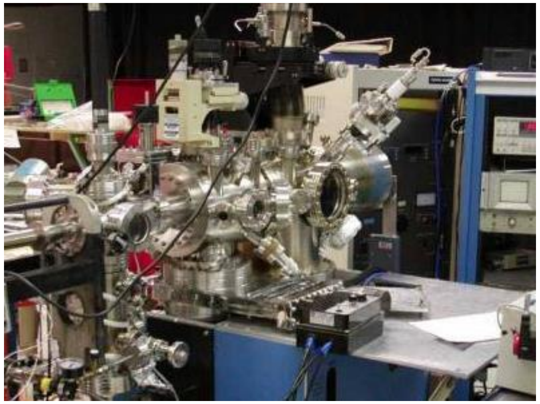
- ❖ Growth technology invented in mid-90
- ❖ GaN is replacing SiC in LED industry. Also for high frequency, high power devices (MOSFETs, HEMTs)
- ❖ Due to its radiation hardness and wide band gap (3.4 eV), GaN is a promising detector in high radiation field.

Optical characterization by depth resolved cathodoluminescence



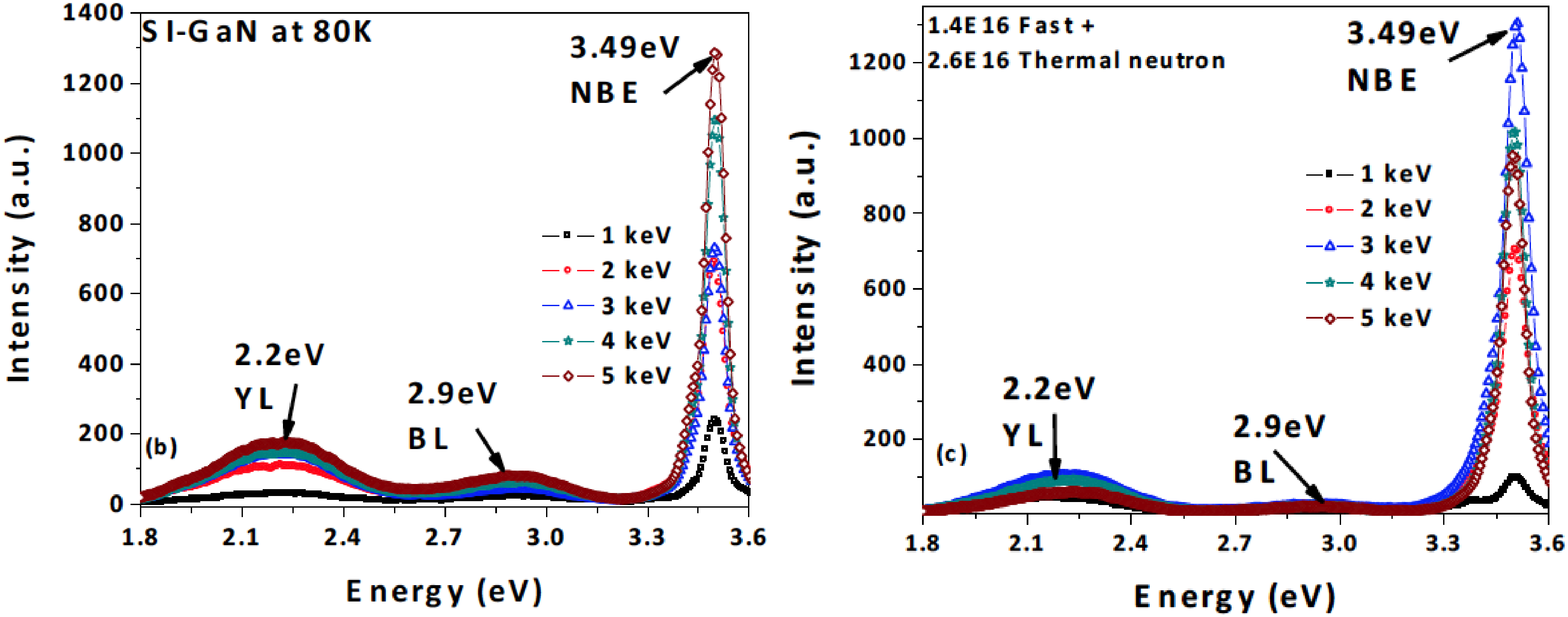
- With increasing electron energies, incident beams can excite above, at, and below interfaces, respectively.
- Luminescence energies correspond to band-to-band, band–to-defect and near-surface electronic material transitions





- **A DRCLS spectroscope**

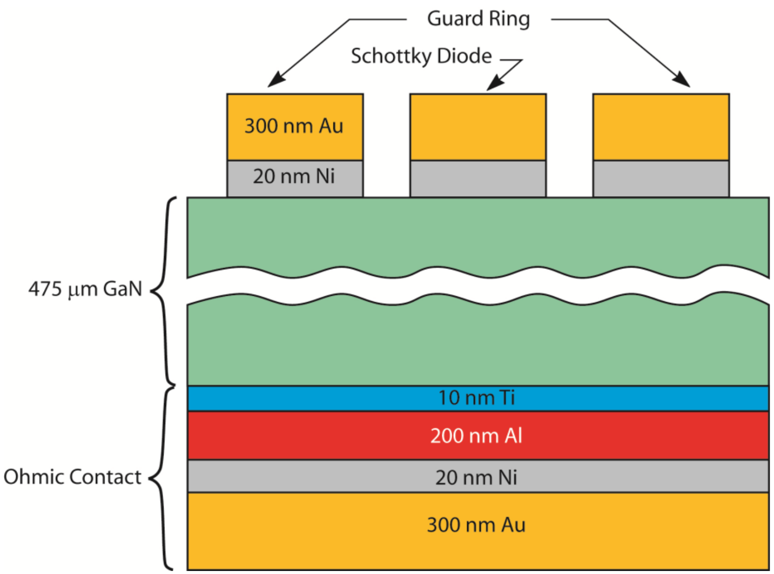
Optical Properties

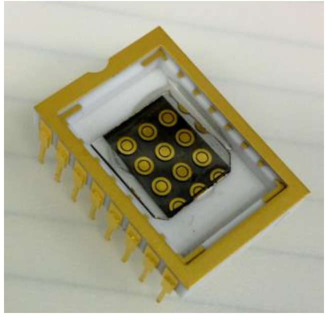


- ❖ NBE band intensity maintained the same level after ~10E16 fast + thermal fluences.
- ❖ Materials' property does not change much after neutron irradiation of this level.

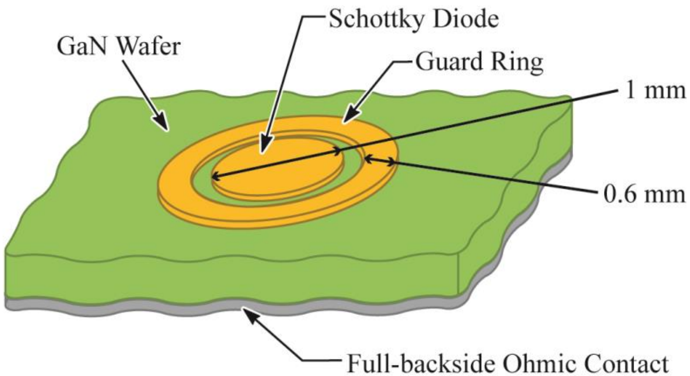
Device Fabrication

- **Freestanding, n-type, Hydride vapor phase epitaxy (HVPE) GaN**
  - 1 cm x 1 cm x 450 µm wafer

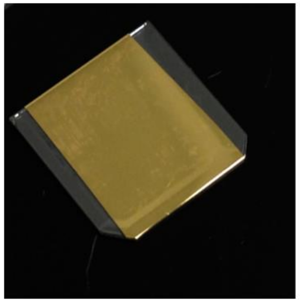




Schottky diodes wire bonded to Dual Inline Package (DIP), Ag paste on bottom



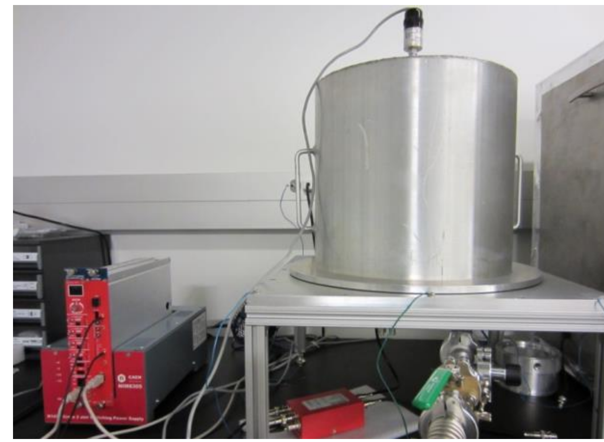
Photomask to deposit 9 Ni/Au Schottky pads with guard rings

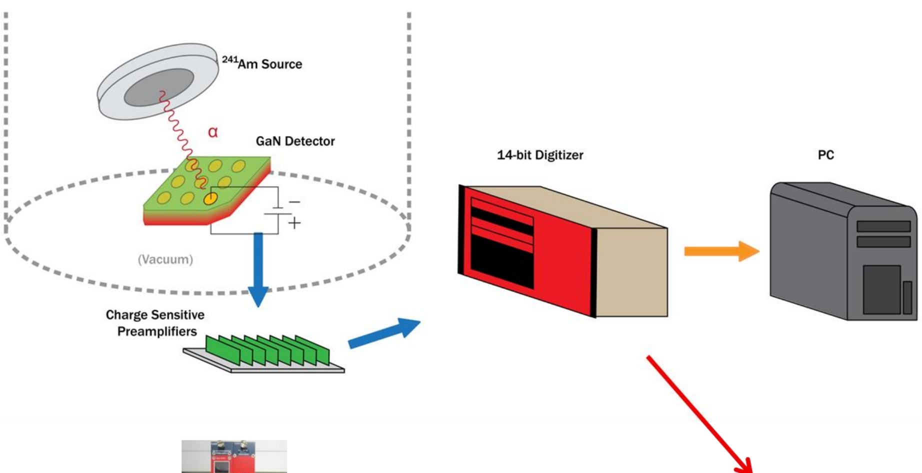


Full-backside Ti/Al/Ni/Au ohmic contact

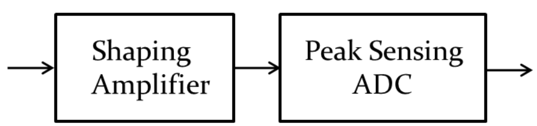
α-particle Detection

- α-particle detection performed using 0.8 µCi ^{241}Am disk source
- Spectrum acquired using digital data acquisition system



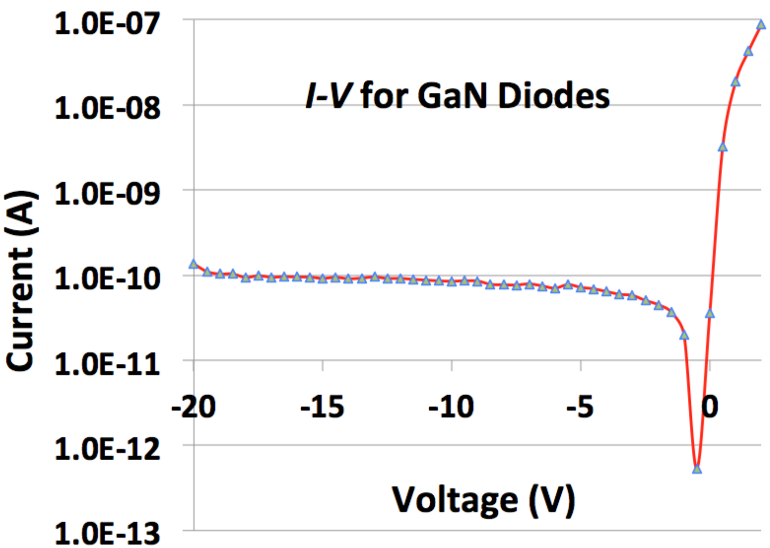


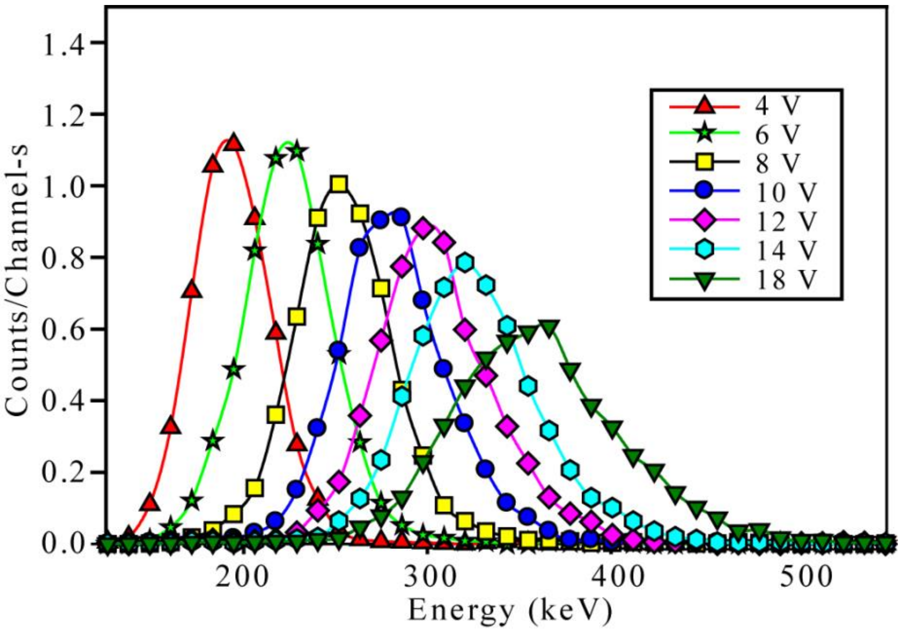
NIM crate housing the digitizer



Electrical Characteristics

- *I-V* measurements show leakage current sufficiently low (0.1 - 10 nA) for GaN sensors





- Detector charge collection efficiency (CCE) investigated by sweeping reverse bias, obtaining ^{241}Am spectrum

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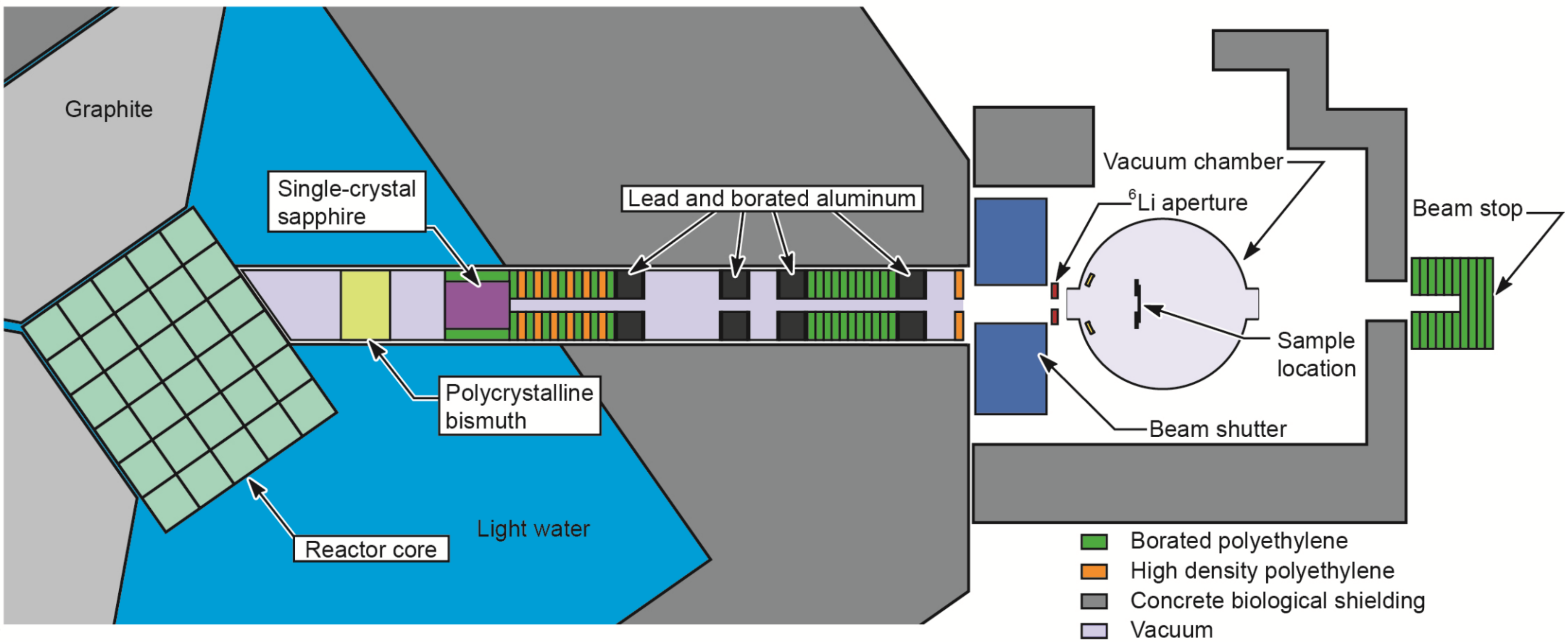
OSU Reactor Beam Facility



P.L. Mulligan, L.R. Cao, D. Turkoglu, Rev. Sci. Instrum. **83**, 073303 (2012).

- Sample position approximately 3.2 m from edge of reactor core
- Flux at sample location is ≈ 8.6×10^6 n/cm^2-s

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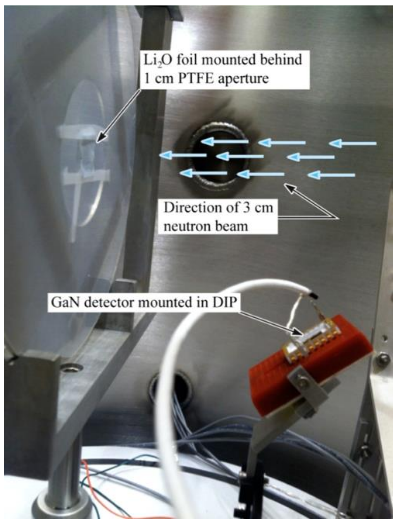
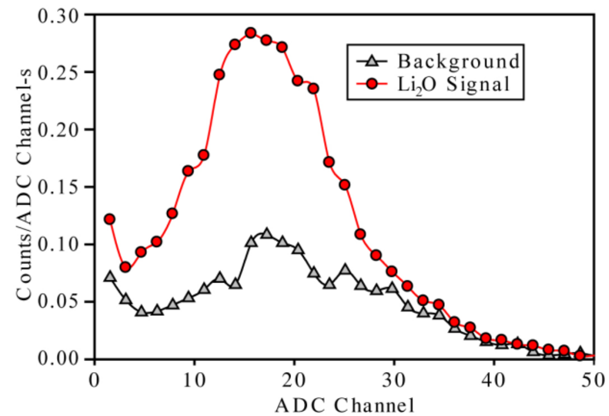
GaN Neutron Detection Schematic

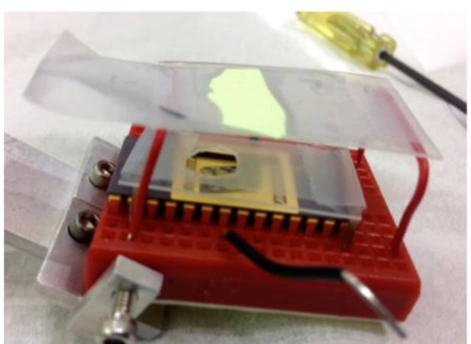
^{6}Li + n -> ^{3}H (2727 kev) + ^{4}He (2055 keV)



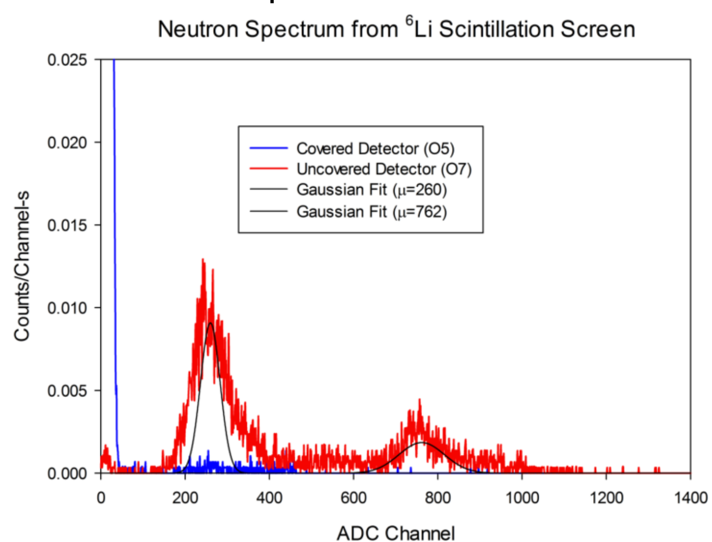
Neutron signal detected by GaN with lithium oxide as convertor



Two peaks detected



LiF film directly mounted in the beam



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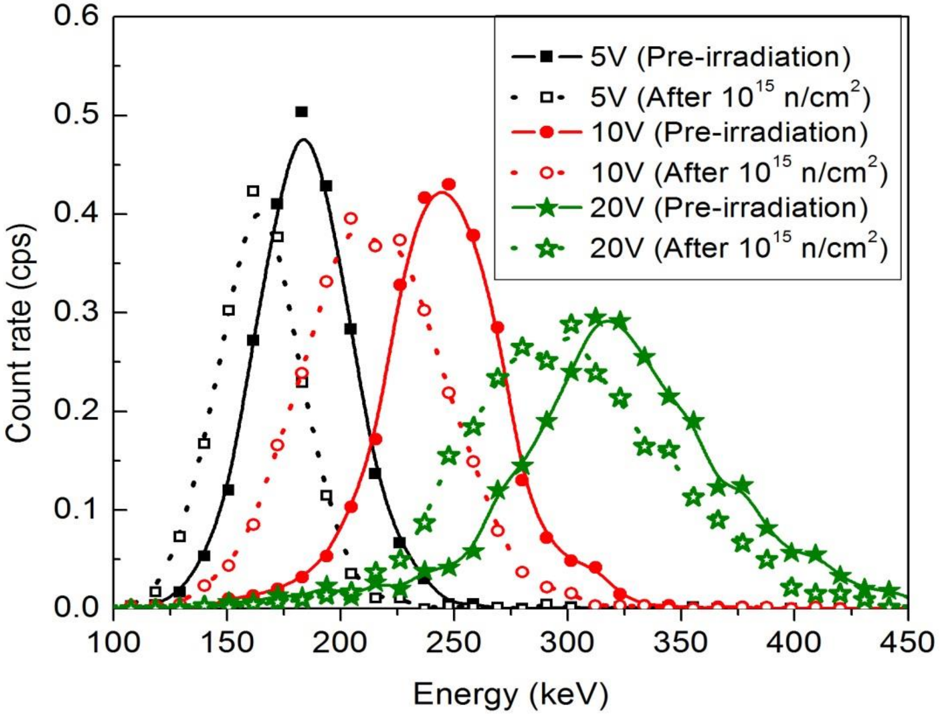
Post-irradiation Device's peformance

- **Spectroscopic response to 5.48 MeV alpha particles from ^{241}Am before and after 10^{15} n/cm^2 neutron irradiation as a function of applied voltage**

- **After 10^{15} n/cm^2 irradiation, the spectra maintained a similar shape but shifted towards lower-energy and broadened**



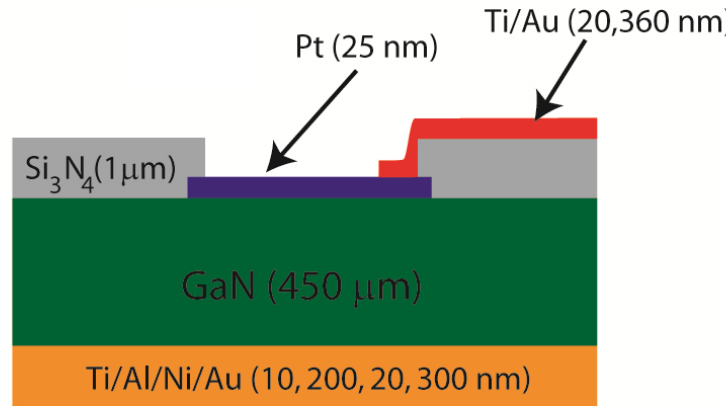
Small degradation in CCE, still a working device

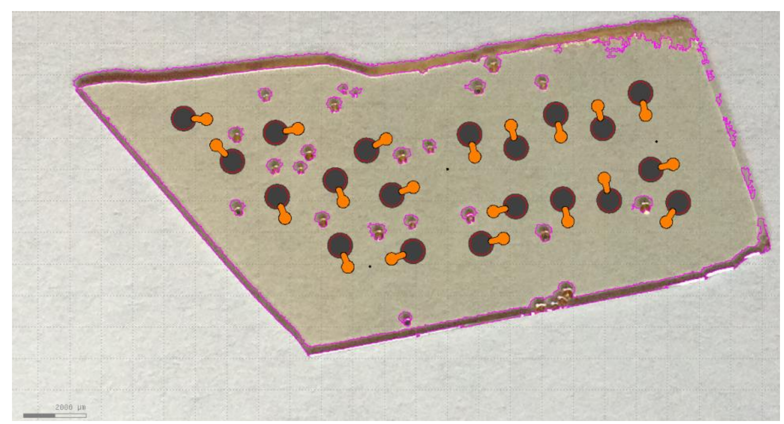
New Fabrication Process for High Temperature

Developed fabrication recipes

- **Thin (25 nm) Pt contact**
  - Minimize dead layer
  - Reduce metal diffusion
- **Si_3N_4 surface passivation**
  - Insulation for wire bonding overlay
- **High temperature anneal after passivation**
- **Lithography with maskless aligner**
  - More working detectors per wafer
- **Ready for deposition of neutron conversion material**

New detector layout optimized for high temperature use





Maskless aligner for customized lithography patterns

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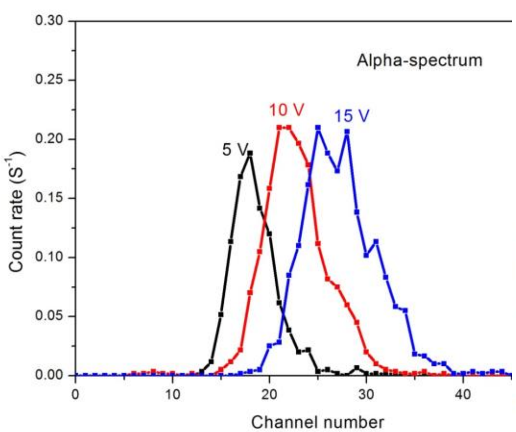
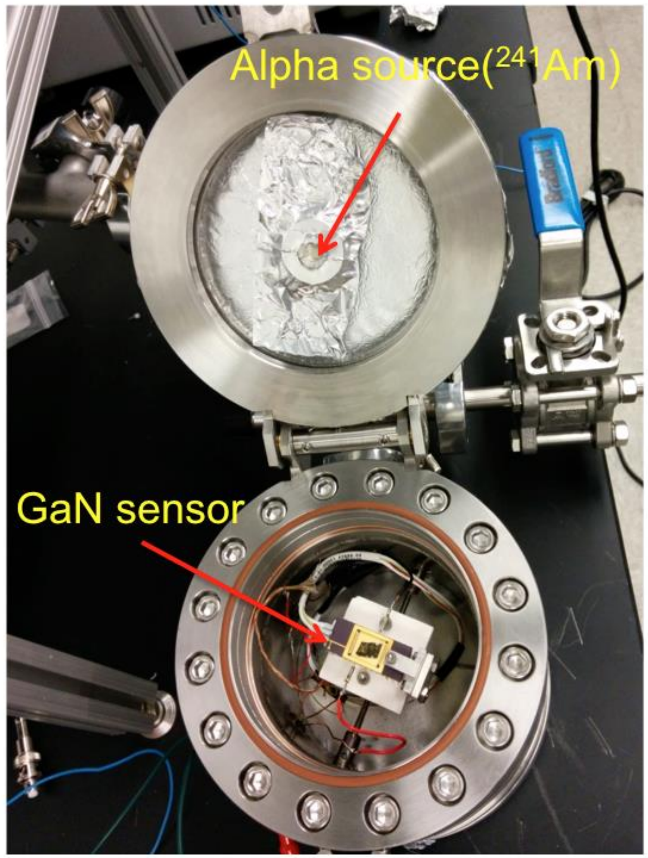
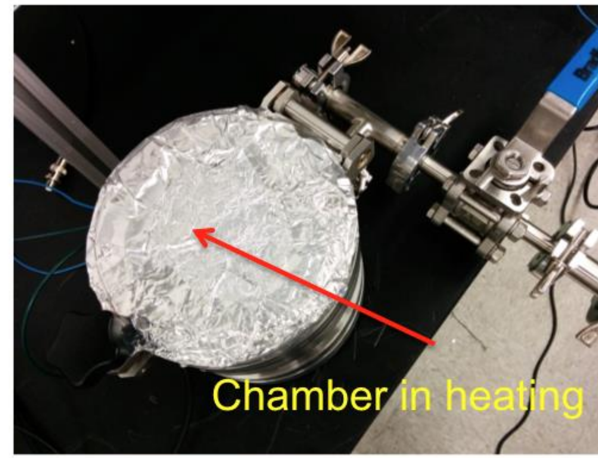
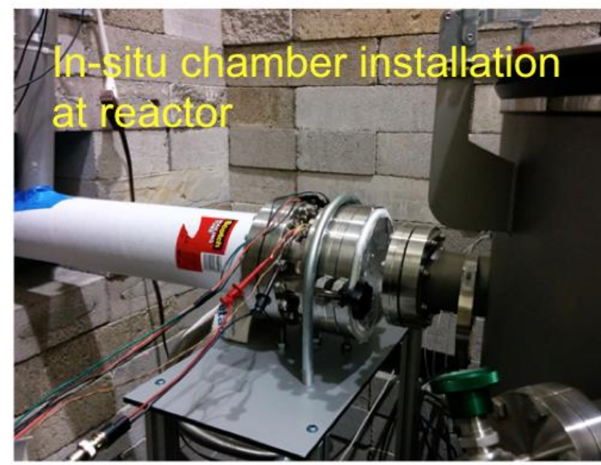
In-situ heated Experiment: high temperature chamber at OSU Research reactor beam line



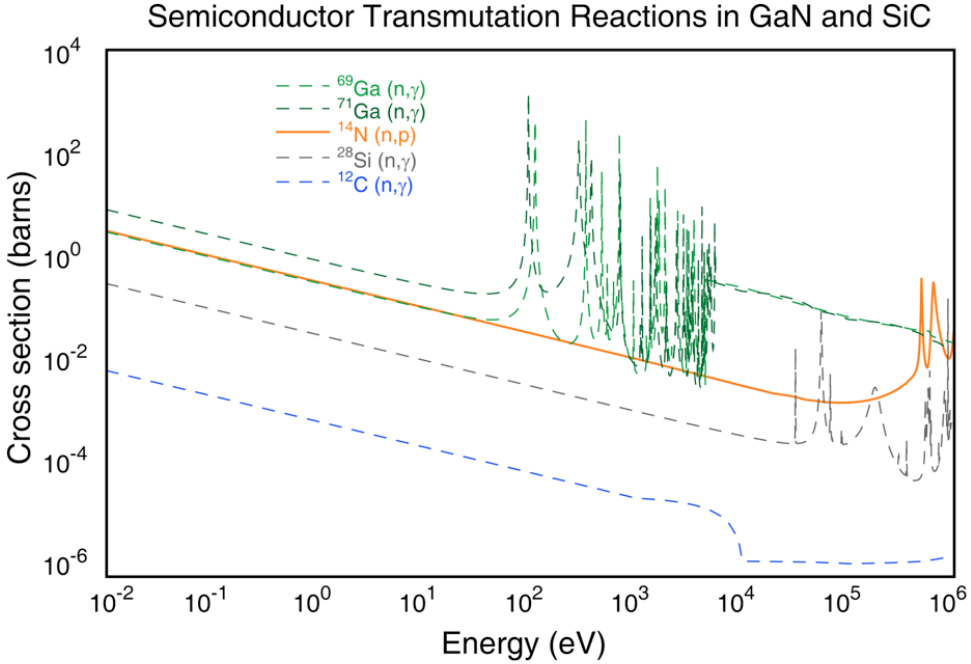
Alpha spectra by GaN at reactor

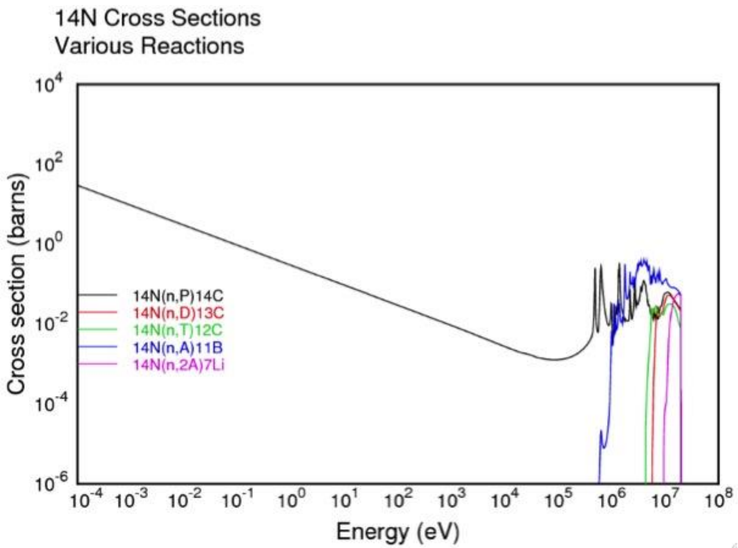


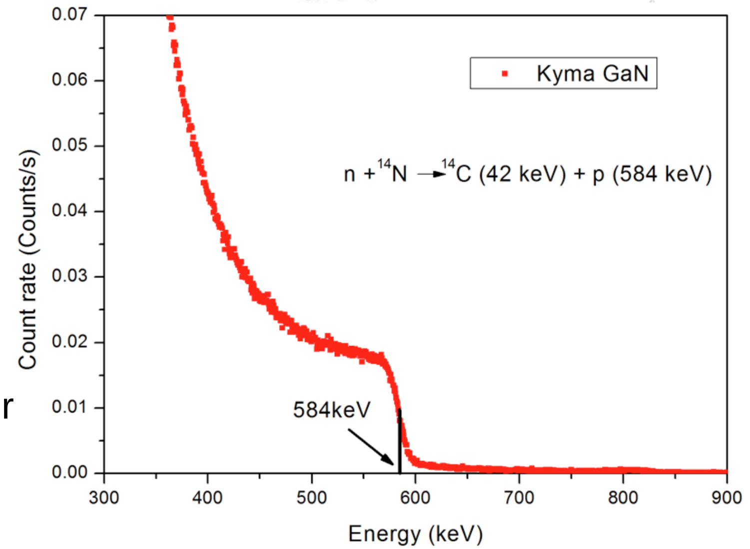




Intrinsic GaN neutron sensitivity







Proton energy spectrum from a GaN wafer following neutron capture by ^{14}N

Outcomes

Delivered working devices; One PhD dissertation and one Master thesis; Nine publications; Two more journal articles in preparation

1.) J. Wang, P. Mulligan L. Cao, “Transient current analysis of a GaN radiation detector by TCAD”, ***Nuclear Instruments and Methods in Physics Research Section A***: Vol. 761, 7-12. 2014. (Published)

2.) Praneeth Kandlakunta, Lei R. Cao. "Neutron-Gamma Separation in a Gadolinium based Semiconductor Neutron Detector." In: Transactions of American Nuclear Society. (Jun 2014). 110 170 – 173 (Published).

3.) Evan. J. Katz, Chung-Han Lin, Jie Qiu, Zhichun Zhang, Umesh K. Mishra, Lei Cao, Leonard J. Brillson “Neutron Irradiation Effects on Metal-Gallium Nitride Contacts”, ***Journal of Applied Physics***, Vol. 115, no. 12. (Mar 2014): 123705 - 123705-9. (Published)

4.) Padhraic Mulligan, Jie Qiu, Jinghui Wang, Lei R. Cao, “Study of Gallium Nitride for High-Level Neutron Field Measurement”, ***IEEE Transactions on Nuclear Science,*** *Vol. 61, no. 4: 2040 - 2044. 2014.* (Published).

5.) Chung-Han Lin, Evan. J. Katz, Jie Qiu, Zhichun Zhang, Umesh K. Mishra, Lei Cao, and Leonard J. Brillson, “Neutron Irradiation Effects on Gallium Nitride-based Schottky Diode”, ***Applied Physics Letters***, vol. 103, issue. 16, 2013 (Published)

6.) Jie Qiu, Evan Katz, Chung-Han Lin, Lei Cao, Leonard J. Brillson, "The Effect of Neutron Irradiation on Semi-insulating GaN". ***Radiation Effects and Defects in Solids***. Vol. 168, 1-9. 2013. (Published)

7.) P. Mulligan, J.H. Wang,L. R. Cao, "Evaluation of Freestanding GaN as an Alpha and Neutron Detector". ***Nuclear Instruments and Methods in Physics Research Section A***:. Vol. 719, 13-16. 2013. (Published)

8.) Jie Qiu, Evan Katz, Lei R. Cao, Leonard J. Brillson. "The Evaluation of GaN for Neutron Detector with Cathodoluminescence Spectroscopy" In: *Transaction* of *American Nuclear Society*, Vol. 107. (2012): 357 - 359. (Published)

9.) J. Ralston, P. Kandlakunta, L. Cao, "Electron Emission Following 157Gd Neutron Capture" In: *Transaction* of *American Nuclear Society,* Vol. 106. (2012): 313 - 315. (Published)

Conclusion

- ❑ Achieved Initial goals for fabrication of a working sensor and demonstrated neutron detection in harsh environment

- ❑ Provided an additional and/or alternative neutron flux monitoring device in light water small modular reactors and high temperature reactors for improved reactor safety

- ❑ Further development to meet other NE program’s needs
  - Sensor in spent fuel salt for pyroprocessing parameter monitoring
  - Intrinsic neutron sensor in high flux environment
  - Disposable flux monitor in photovoltaic mode in accident scenarios