Title: GaN as Neutron Detector
EE701: Introduction to MEMS
Instructor: Prof. Siddharth Dutta Gupta

Submitted By: Jatin Kumar (22B3922)

1. Introduction

Gallium Nitride (GaN) has emerged as a promising material for neutron detection due to its wide bandgap, radiation hardness, and thermal stability. These properties make it suitable for use in high-radiation environments such as nuclear reactors, space missions, and national security applications. The global shortage of Helium-3 (^{3}He) has driven the search for alternative neutron detection materials, with GaN standing out due to its superior mechanical robustness and ability to operate at lower voltages compared to traditional gas detectors.

2. Working Principle

GaN-based neutron detectors operate by exploiting the interaction between neutrons and nitrogen-14 (^{14}N) in the GaN crystal lattice. When a thermal neutron is absorbed by ^{14}N, it undergoes a (n, p) reaction, converting to carbon-14 (^{14}C) and emitting a proton. This reaction can be represented as:

$$^{14}\mathrm{N} + n \rightarrow ^{14}\mathrm{C} + p$$

The emitted proton generates charge carriers within the GaN material, leading to scintillation, which is then detected by a photodetector such as a photomultiplier tube (PMT) or an avalanche photodiode (APD). The addition of neutron conversion layers, such as Lithium Fluoride (^{6}LiF) or Gadolinium (Gd) doping, enhances the sensitivity by capturing neutrons and emitting high-energy alpha particles, which further ionize the GaN. The detection efficiency (η) of the neutron detector can be expressed as:

$$\eta = \frac{N_{\text{detected}}}{N_{\text{incident}}}$$

where N_{detected} is the number of neutrons detected and N_{incident} is the number of neutrons incident on the detector.

3. Material and Technology Used

GaN for neutron detection is typically grown using Metal-Organic Chemical Vapor Deposition (MOCVD) or Hydride Vapor Phase Epitaxy (HVPE). MOCVD-grown GaN films are often doped with Silicon (Si) or Gadolinium to enhance scintillation efficiency and gamma discrimination. Freestanding GaN wafers, grown via HVPE, are also explored for their potential in high-efficiency charged particle detection. The detectors are fabricated as Schottky diodes, with Ni/Au contacts forming the detection interface.

4. Fabrication Process

The fabrication process begins with the growth of GaN films on sapphire substrates using MOCVD, followed by doping and the addition of neutron conversion layers. The GaN films are then patterned into Schottky diodes using standard photolithography techniques. The freestanding GaN detectors are prepared by slicing and polishing bulk GaN wafers. Contacts are deposited using electron beam evaporation, and the diodes are mounted on dual inline packages for radiation testing.

5. Applications

GaN-based neutron detectors have significant applications in fields requiring robust, high-temperature, and radiation-resistant detection systems. These include nuclear reactor monitoring, space exploration, and national security for detecting illicit nuclear materials. The ability of GaN detectors to discriminate between gamma and neutron radiation makes them particularly valuable in mixed radiation fields.

6. Results and Performance Evaluation

GaN detectors demonstrate promising neutron detection capabilities, with Si-doped GaN showing excellent gamma discrimination. When coupled with a ^{6}LiF conversion layer, these detectors exhibit a linear response to reactor power, making them suitable for high-flux environments. The detection efficiency (η) in high-flux environments can be modeled as:

$$\eta = \alpha \cdot e^{-\beta\Phi}$$

where α and β are constants determined experimentally, and Φ is the neutron flux.

Freestanding GaN detectors also show high charge collection efficiency (CCE) for alpha particles, confirming their potential for charged particle detection. The CCE is given by:

$$\mathrm{CCE} = \frac{Q_{\mathrm{collected}}}{Q_{\mathrm{generated}}}$$

where $Q_{\mathrm{collected}}$ is the charge collected by the detector and $Q_{\mathrm{generated}}$ is the total charge generated by the ionizing event.

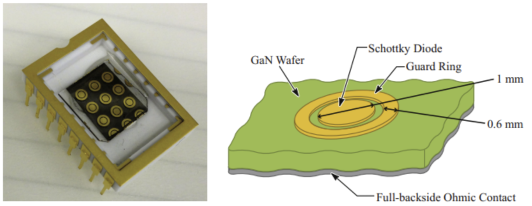

Figure 1: GaN wafer with nine Schottky diodes deposited on the Ga-face, including a schematic of a single GaN Schottky diode and guard ring.

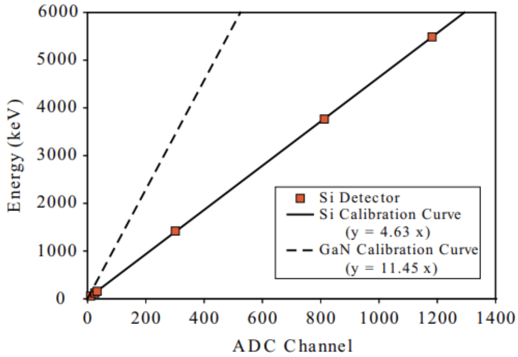

Figure 2: Energy calibration curve of reference Si detector and inferred calibration curve for GaN detector.

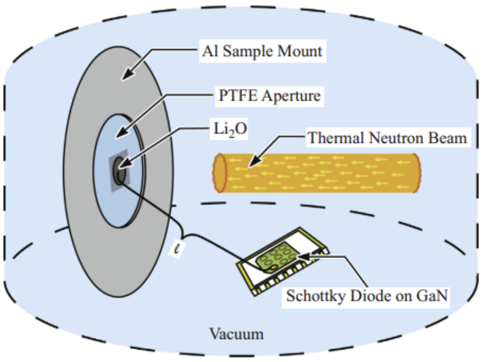

Figure 3: Simplified schematic of neutron detection experiment.

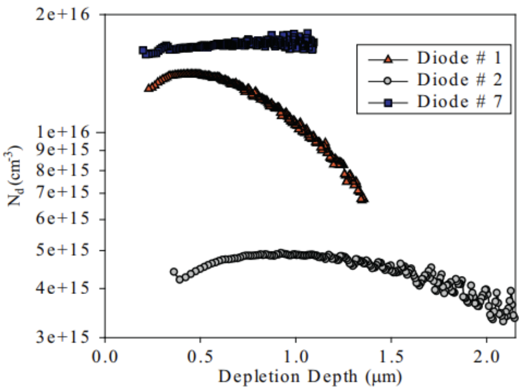

Figure 4: Residual carrier concentration vs. depletion depth of several Schottky diodes on GaN wafer at 300 K.

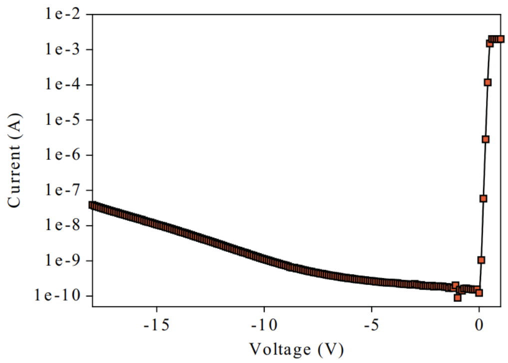

Figure 5: I-V curve of the GaN detector, showing leakage current at different reverse bias voltages.

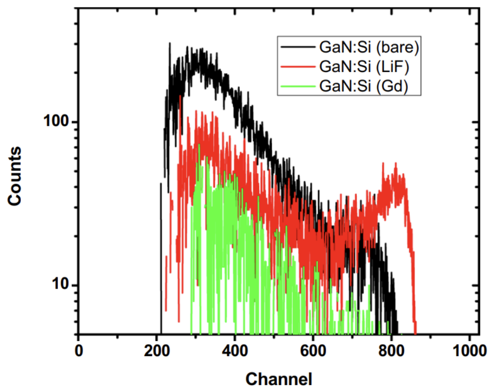

Figure 6: Neutron-induced scintillation spectra produced by 6LiF-coated Si-doped GaN scintillator.

7. Conclusion

GaN is a viable material for developing high-performance neutron detectors. Its intrinsic neutron sensitivity, coupled with enhanced performance through doping and conversion layers, positions GaN as a strong candidate for next-generation radiation detectors. Further optimization in fabrication and material processing could lead to even more efficient and robust detectors suitable for a wide range of applications.

References

1. Zhou, C., et al. (2019). *Neutron detection performance of gallium nitride-based semiconductors. Scientific Reports*, 9(1), 17551.

2. Mulligan, P., Wang, J., & Cao, L. (2013). *Evaluation of freestanding GaN as an alpha and neutron detector. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *708*, 7-12.

3. Zhu, Z., Sun, Z., Zou, J., et al. (2020). *Fabrication and performance evaluation of GaN thermal neutron detectors with 6LiF conversion layer. Chinese Physics B*, *29*(10), 106102.