PhD Open Days

Impact of Swift Heavy Ion Irradiation on the Structural and Optical Properties of GaN and AlGaN Semiconductors

PHD PROGRAMME IN TECHNOLOGICAL PHYSICS ENGINEERING

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Motivation

- GaN and AlGaN combine high energy efficiency with intrinsic radiation tolerance. Their tunable bandgap (3.4–6.2 eV) makes AlGaN well suited to high electron mobility transistors (HEMTs) in power electronics and space.
- The impact of high-energy heavy ions on AlGaN's crystal structure and optical properties remains unclear, requiring ongoing research.
- Aim: to determine the structural and optical response of $Al_xGa_{1-x}N$ (x=0 to x=1) to uranium-ion irradiation at different fluences.

Space radiation environment

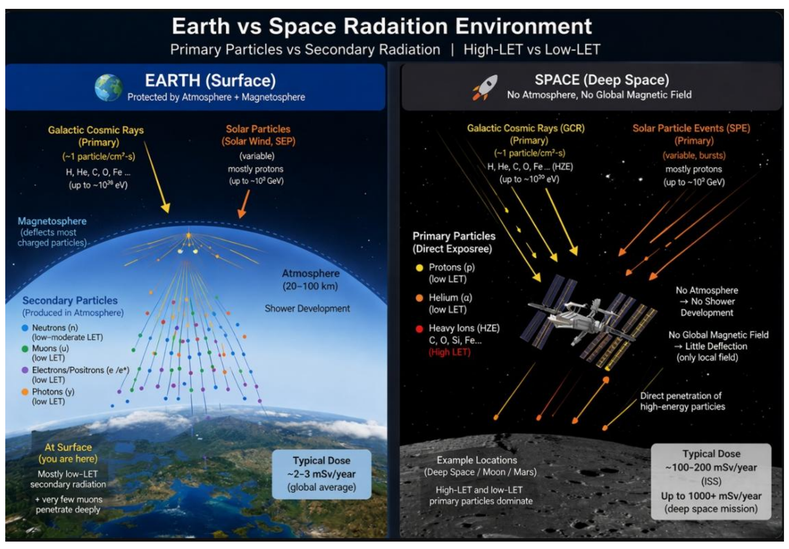


Figure 1: Earth's surface vs deep space: primary vs secondary particles, high-LET vs low-LET. Illustrative diagram based on NASA data (nasa.gov/hrp/radiation).

- Galactic cosmic rays (GCR): highly energetic heavy ions, hundreds of MeV/u.
- Swift heavy ions (SHI): about 1% of the flux, yet a cause of catastrophic failures in semiconductors.
- Ground simulation: 238U at 3.78 MeV/u mimics the deep-space "thermal spike".

Swift heavy ion physics

- **Stopping power**: energy loss is dominated by the electronic stopping power S_e.

$$-\frac{dE}{dz} = S_e + S_n$$

- **Thermal spike**: energy deposited in the electronic system produces a localised, transient melt.
- **Latent tracks**: cylindrical structural defects form along the ion trajectory.

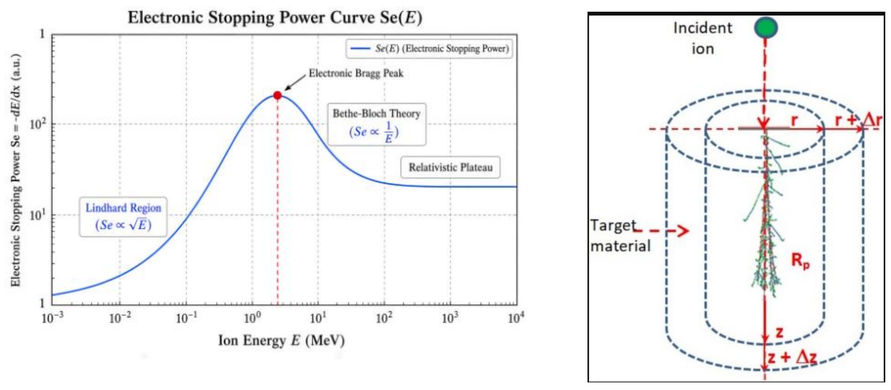


Figure 2: Electronic stopping power Se(E) and ion-track schematic (after S. Mammeri, 2025).

Materials, irradiation and methods

- $Al_xGa_{1-x}N$ films (x = 0, 0.19, 0.77 and 1), 3 µm thick, wurtzite, grown on c-plane sapphire.
- **Irradiation at GANIL**: 238U at 3.78 MeV/u (0.9 GeV), fluences from 5×10^{10} to 1×10^{12} $ions/cm^2$ .The ions cross the film and stop inside the substrate.
- **HRXRD:** Bruker D8 Discover, Cu $K_{\alpha 1}$, symmetric ω-2θ scans of the (004) reflection; lattice parameters by the Bond method. UV–Vis: Shimadzu UV-1800, 190–1100 nm.

Structural analysis: HRXRD results

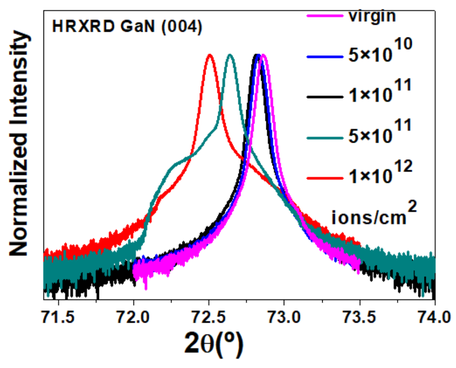


Figure 3: GaN vs fluence

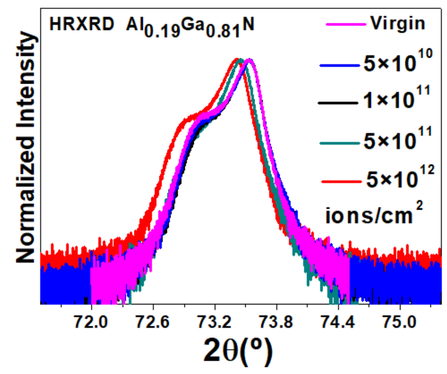


Figure 4: $Al_{0.19}Ga_{0.81}N$ vs fluence

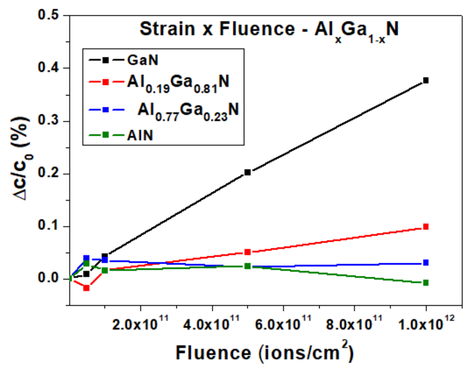


Figure 5: Lattice strain $\Delta c/c_0$ vs fluence (Bond method).

- **GaN Strain Response:** Pure GaN exhibits large 2θ peak shifts and the highest lattice strain $\Delta c/c_0$, indicating strong structural disorder at higher fluences.
- **Role of Aluminum:** Increasing Al content (x) in $Al_xGa_{1-x}N$ significantly suppresses peak shifts and lattice deformation.
- **Structural Resilience:** Al-rich alloys $Al_{0.19}Ga_{0.81}N$, $Al_{0.77}Ga_{0.23}N$, and AlN show enhanced structural stability compared to GaN under swift heavy ion irradiation.

Optical response

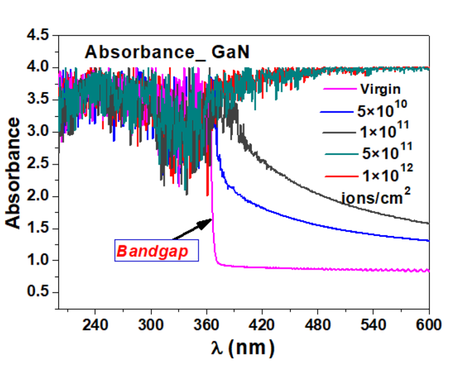


Figure 6a: GaN vs fluence

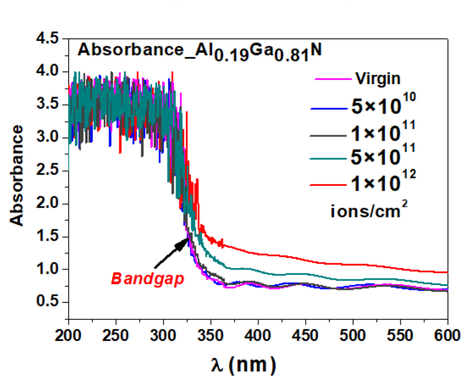


Figure 6b: $Al_{0.19}Ga_{0.81}N$ vs fluence

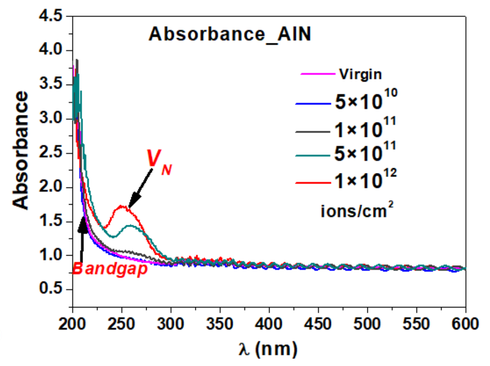


Figure 6c: AlN vs fluence

- Figures 6a–c show absorption rising with fluence across the UV–visible range, far less in AlGaN than in GaN ("grey absorption").
- Irradiated AlN shows a distinct band at ~260 nm (~4.73 eV), linked to nitrogen vacancies (V_N) or carbon centres.

Conclusions

- Radiation resilience increases progressively with aluminium content.
- Tensile strain: SHI irradiation expands the lattice along the c-axis, most strongly in GaN.
- Optical stability: GaN degrades strongly; Al-containing alloys stay more transparent.
- AlN signature: a unique optical band at ~4.73 eV.
- Application: Al-rich nitrides are promising for electronics and sensors in aerospace and nuclear environments.

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