Response of Wide-Bandgap Semiconductors to Swift Heavy-Ion Irradiation:

Single Ion and Broadbeam Experiments

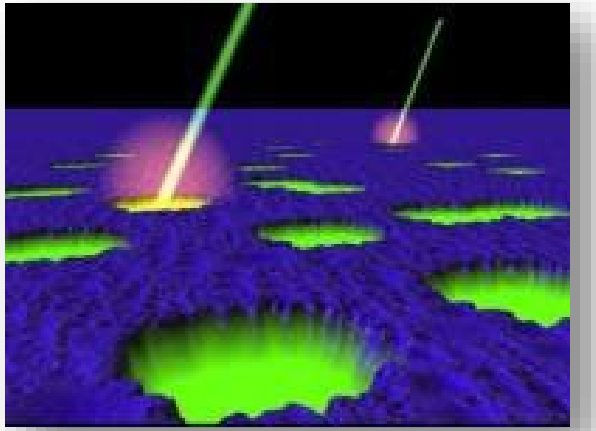
Maik Lang

mlang2@utk.edu

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Department of Nuclear Engineering

Interaction of Swift Heavy Ions with Matter



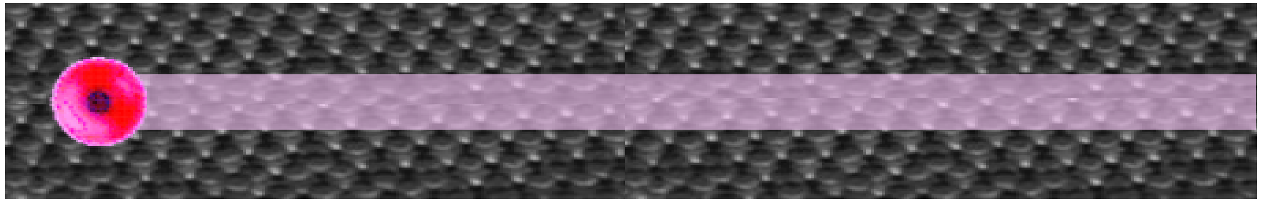
Swift Heavy Ions

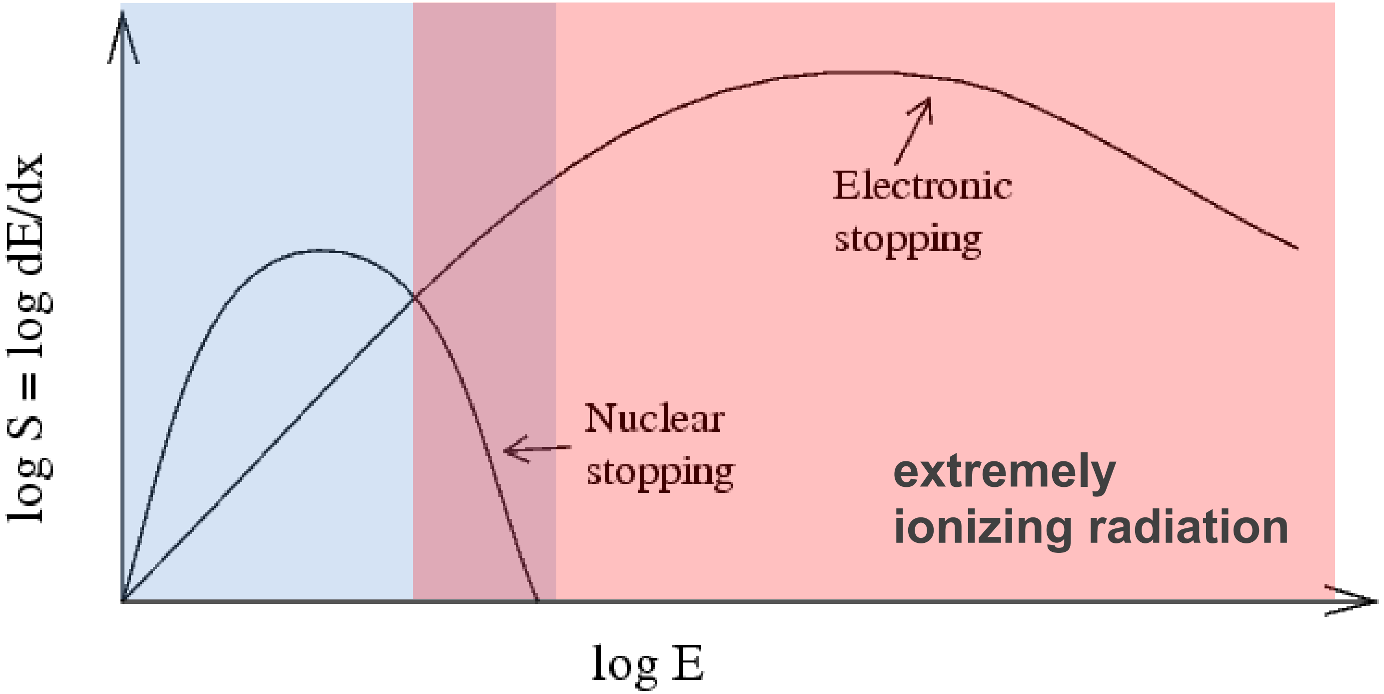
⇨ highly charged atoms

⇨ travelling at very high velocities ($v/c \geq 10\%$)

⇨ large penetration depth (µm – cm)

⇨ example: $^{28+}$Au 950 MeV (4.8 MeV/u)

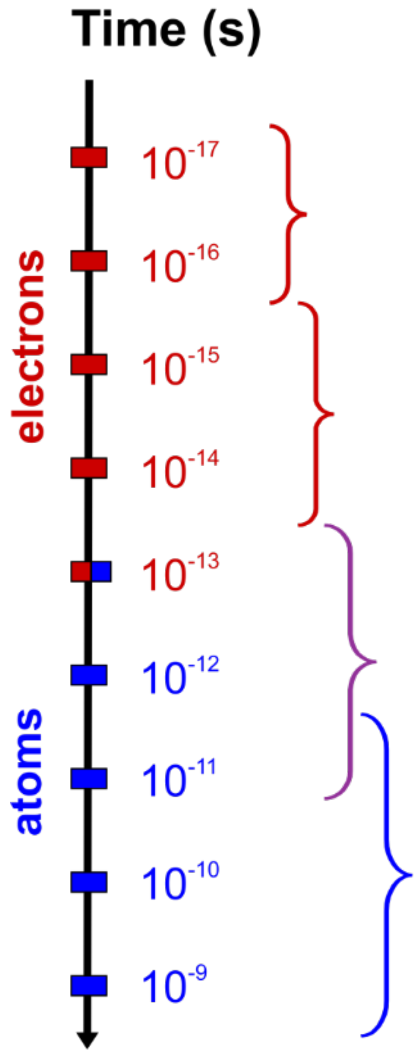




elastic collisions projectile – target atom

inelastic processes projectile – target electrons

Interaction of Swift Heavy Ions with Matter



Stage 1 (10^{-17} – 10^{-16} s)

ionization and formation of δ-electrons

Stage 2 (10^{-15} – 10^{-14} s)

electron cascade

$$C_e(T_e)\frac{\partial T_e}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK_e(T_e)\frac{\partial T_e}{\partial r}\right) - g\cdot(T_e - T) + A(r,t)$$

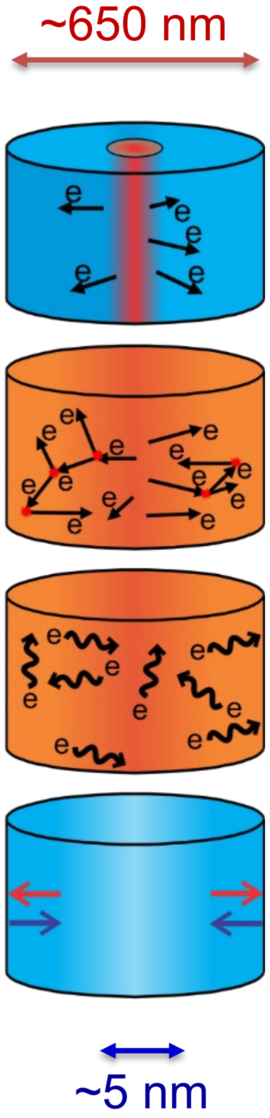
Stage 3 (10^{-14} – 10^{-12} s)

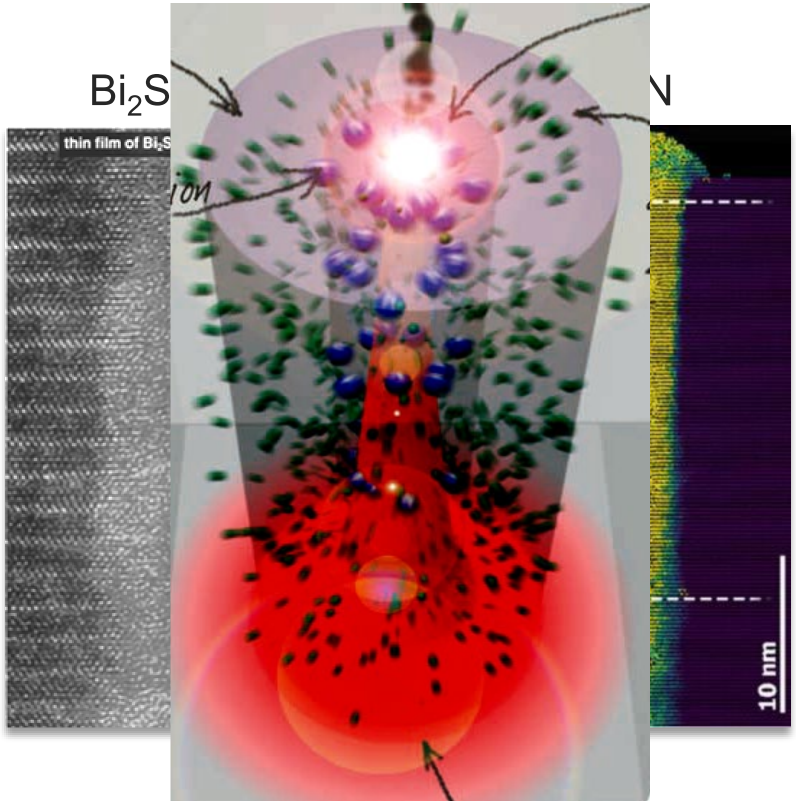
electron-phonon coupling

$$C(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK(T)\frac{\partial T}{\partial r}\right) + g\cdot(T_e - T)$$

Stage 4 ($>10^{-12}$)

lattice processes, thermal spike, quenching and defect formation

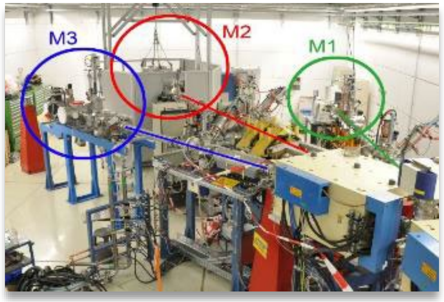


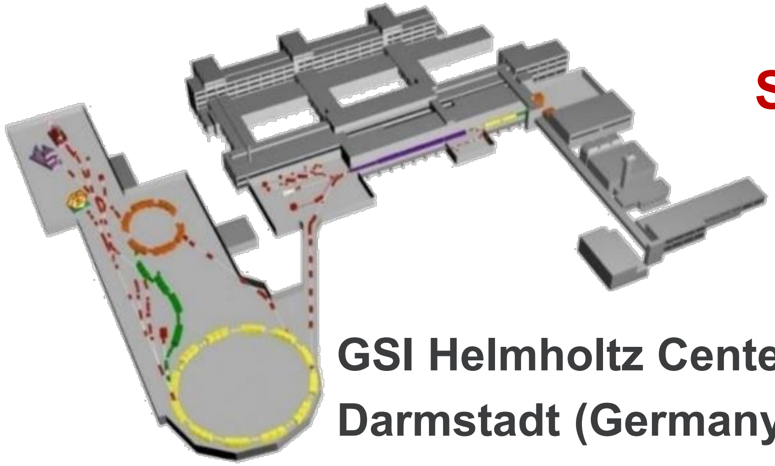


extremely fast and nanoscale

Beamtimes Accomplished in Spring 2024 at GSI

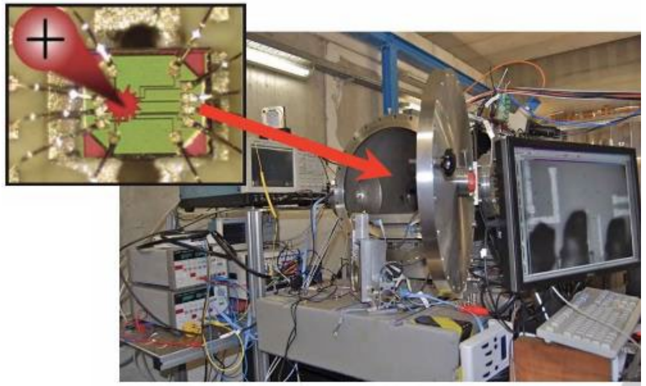
Broadbeam Experiments





GSI Helmholtz Center Darmstadt (Germany)

Single Ion Beam Experiments



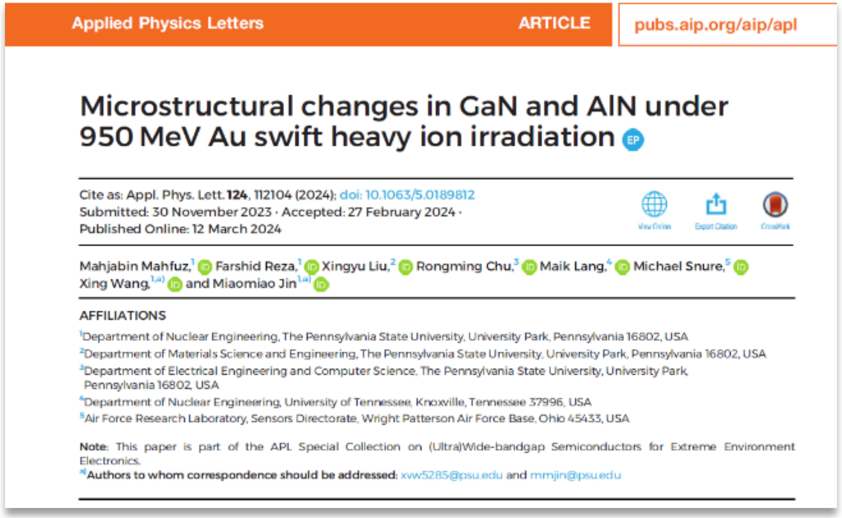
March 2024 (950 MeV ^{197}Au – 72.4 MeV/(mg/cm^2)

April 2024 (192 MeV ^{40}Ar – 10.8 MeV/(mg/cm^2)

- ⇨ AlGaN sample series (AFRL)
- ⇨ AlN, GaN, and Ga_2O_3 based device irradiations (Rongming Chu's team and Aaron Arehart's team)
- ⇨ Capacitance measurements before/after irradiation
- ⇨ Fluence series on AlN, GaN, and SiC powder samples

- ⇨ Single-events testing
- ⇨ Established ion-beam scanning routines and correlation to data acquisition
- ⇨ Tested various devices for several groups:
  - Adam Neal (Ga_2O_3-based transistors)
  - Rongming Chu (GaN-based JFET/ PN diodes)
  - Aaron Arehart (GaN-based diodes)

Motivation: AlGaN Series Broadbeam Irradiation Experiments


Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

Microstructural changes in GaN and AlN under 950 MeV Au swift heavy ion irradiation

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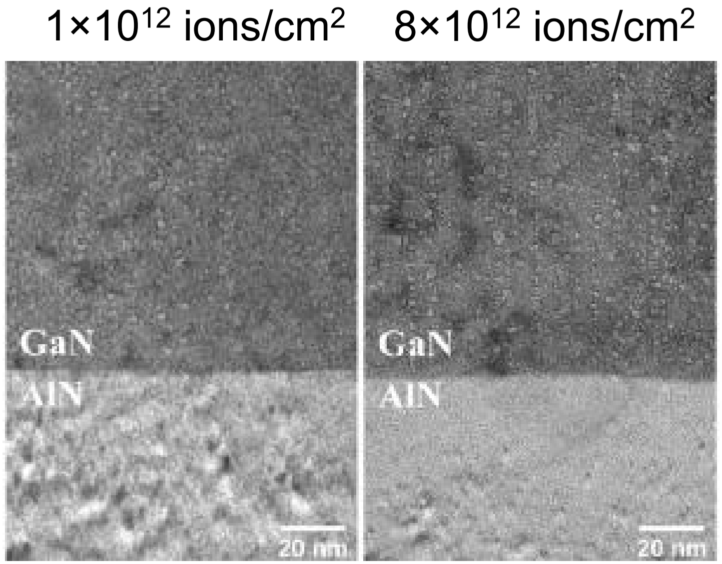
Mahjabin Mahfuz,[1] Farshid Reza,[1] Xingyu Liu,[2] Rongming Chu,[3] Maik Lang,[4] Michael Snure,[5] Xing Wang,[1,a)] and Miaomiao Jin[1,a)]

AFFILIATIONS

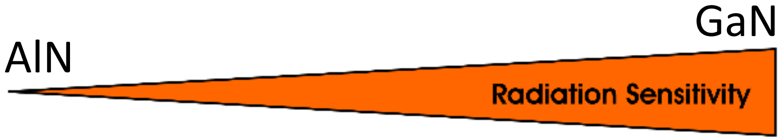
[1]Department of Nuclear Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA
[2]Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA
[3]Department of Electrical Engineering and Computer Science, The Pennsylvania State University, University Park, Pennsylvania 16802, USA
[4]Department of Nuclear Engineering, University of Tennessee, Knoxville, Tennessee 37996, USA
[5]Air Force Research Laboratory, Sensors Directorate, Wright Patterson Air Force Base, Ohio 45433, USA

Note: This paper is part of the APL Special Collection on (Ultra)Wide-bandgap Semiconductors for Extreme Environment Electronics.

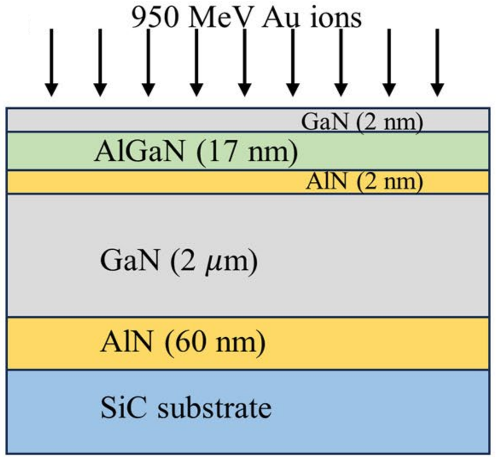
[a)]Authors to whom correspondence should be addressed: xvw5285@psu.edu and mmjin@psu.edu

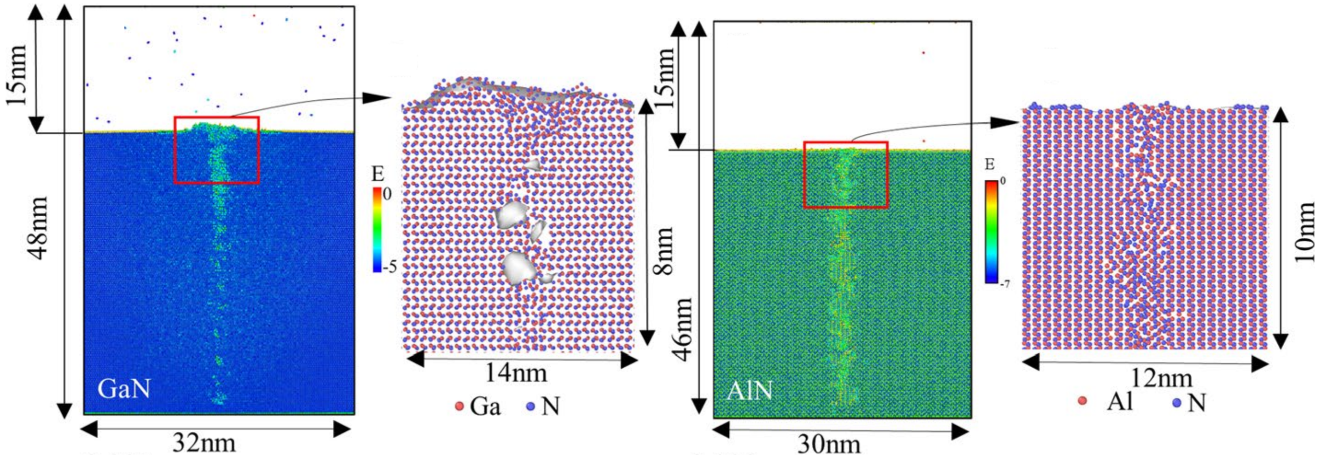


- ⇨ TEM: Cavities of ~2 nm size in GaN
- ⇨ Much smaller features in AlN
- ⇨ MD confirms enhanced resistance of AlN to energetic heavy ions



Gradual change or critical Al-content?





Sample Synthesis: AlGaN Series Broadbeam Irradiation Experiments

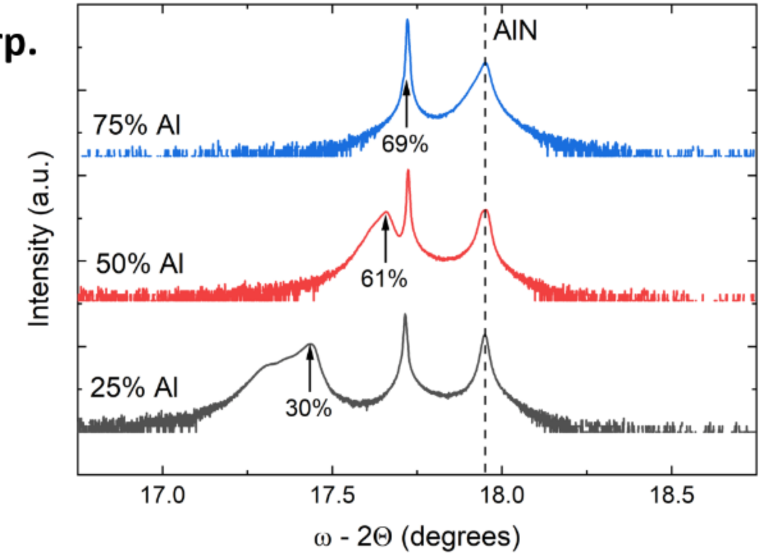
MBE Growth of AlGaN Sample Series

AFRL

Dr. Alex Chaney, AFRL, Azimuth Corp.
Dr. Tadj Asel, AFRL

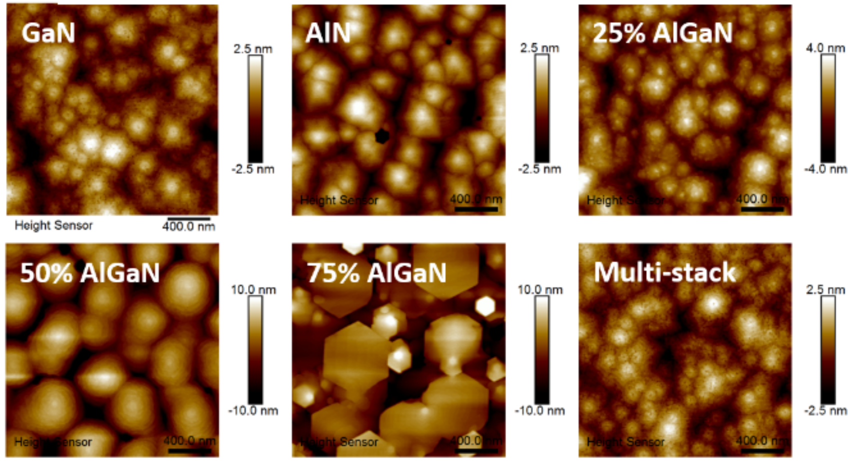
Composition Series

- 1 µm X % Al_xGaN
- 1 µm AlN
- SiC

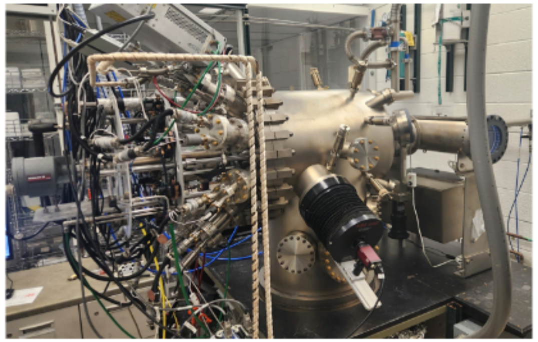


Multi-stack Sample

- 90 nm GaN
- 10 nm 25% Al_xGaN
- 90 nm GaN
- 10 nm 50% Al_xGaN
- 90 nm GaN
- 10 nm 75% Al_xGaN
- 90 nm GaN
- 10 nm 50% Al_xGaN
- 90 nm GaN
- 10 nm 25% Al_xGaN
- 700 nm GaN
- 600 nm AlN
- SiC



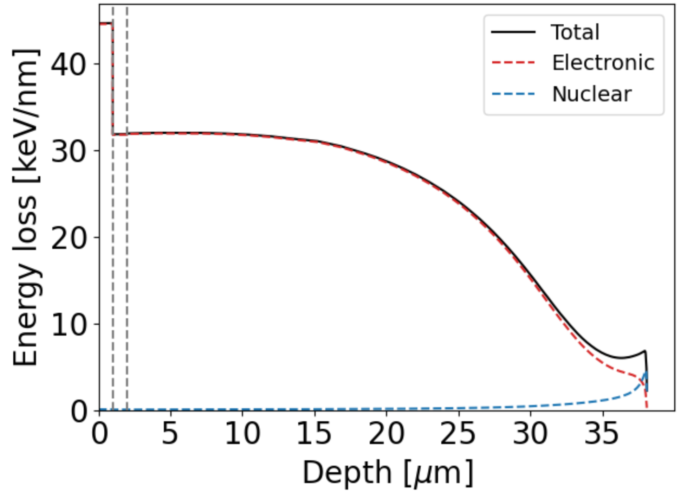
Growth done in Gen II

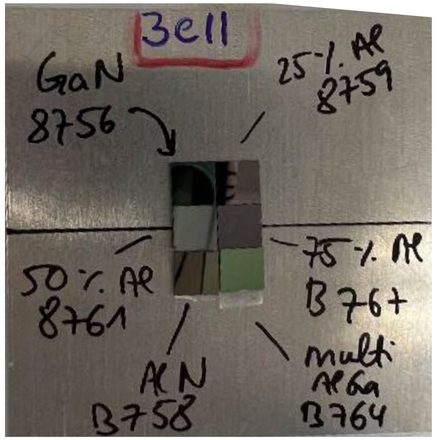


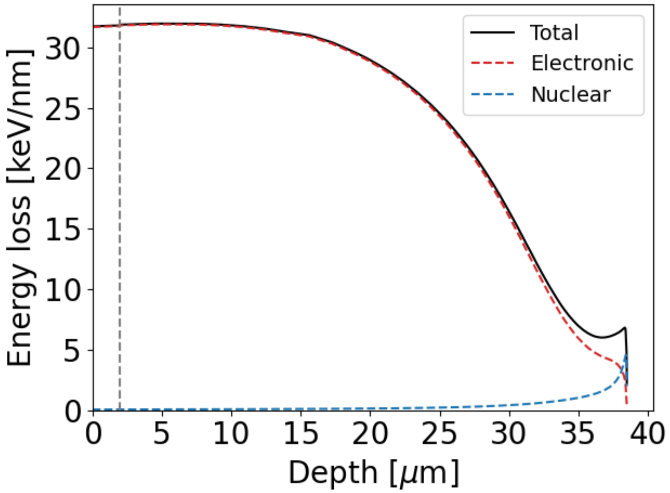
- Ga flux modulated during growth to limit metal buildup
- 3 Al compositions investigated along with GaN & AlN control samples
- Thick AlGaN layers resulted in a shift in Al% from target values
- Additional multi-stack sample with thin AlGaN layers grown to combat this issue

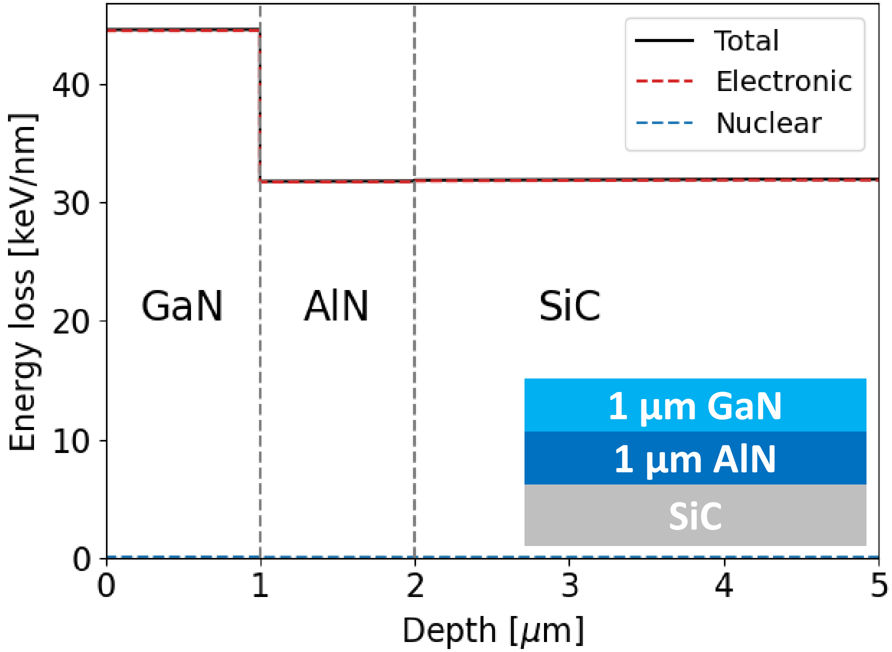
THE AIR FORCE RESEARCH LABORATORY

AlGaN Series Broadbeam Irradiation Experiments

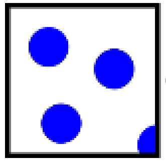




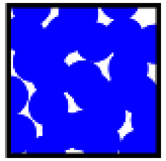




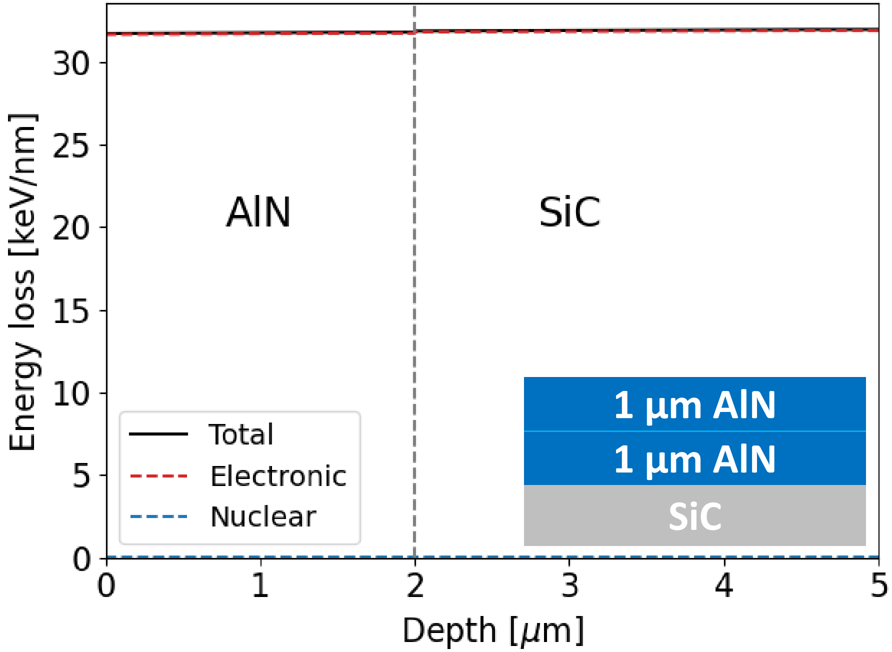
- ⇨ 946 MeV $^{+28}$Au ions
- ⇨ Sample size: 5x5 mm^2
- ⇨ Simultaneously irradiated



3×10^{11}



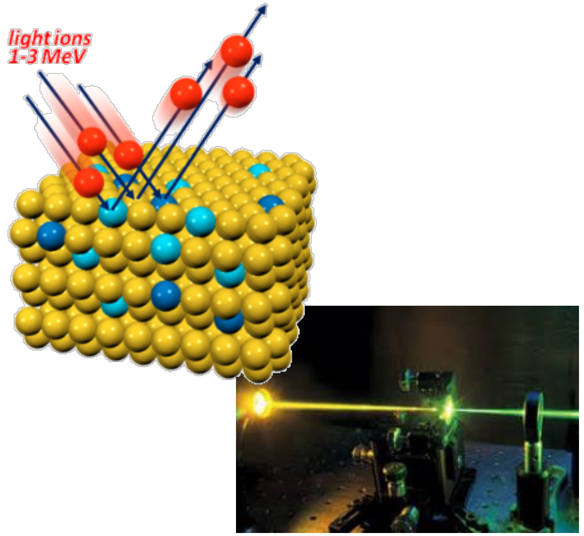
8×10^{12} cm^{-2}



Complementary Characterization of Irradiated AlGaN Series

NUCLEAR ENGINEERING
THE UNIVERSITY OF TENNESSEE KNOXVILLE

Eric O'Quinn, Miguel Crespillo, and Maik Lang *et al*.



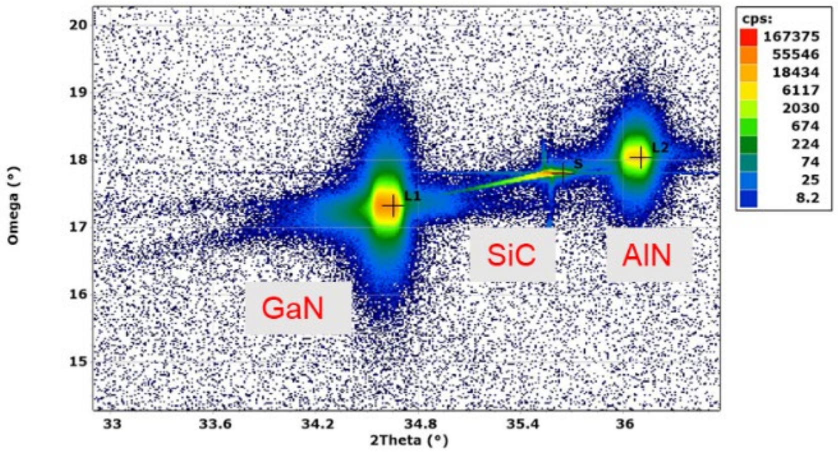
Raman Spectroscopy

Ion-Beam Analysis

(RBS and Ionoluminescence)

Carnegie Mellon University

Swetha Kumar and Reeja Jayan *et al*.



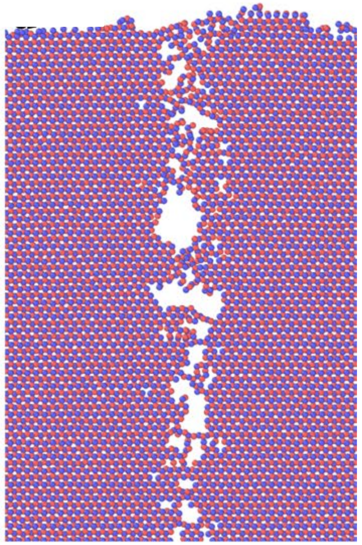
Reciprocal Space Maps (RSM)

(X-ray scattering)

PennState

Xing Wang and Mia Jin *et al*.

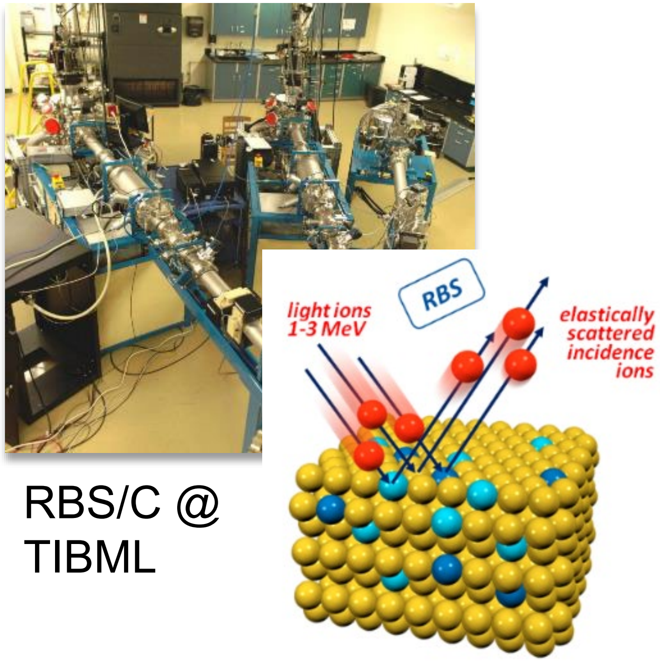
https://www.jeol.com



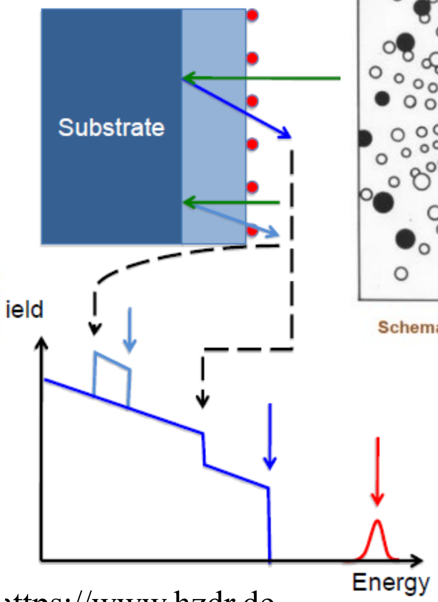
Transmission Electron Microscopy

Molecular Dynamics Simulations

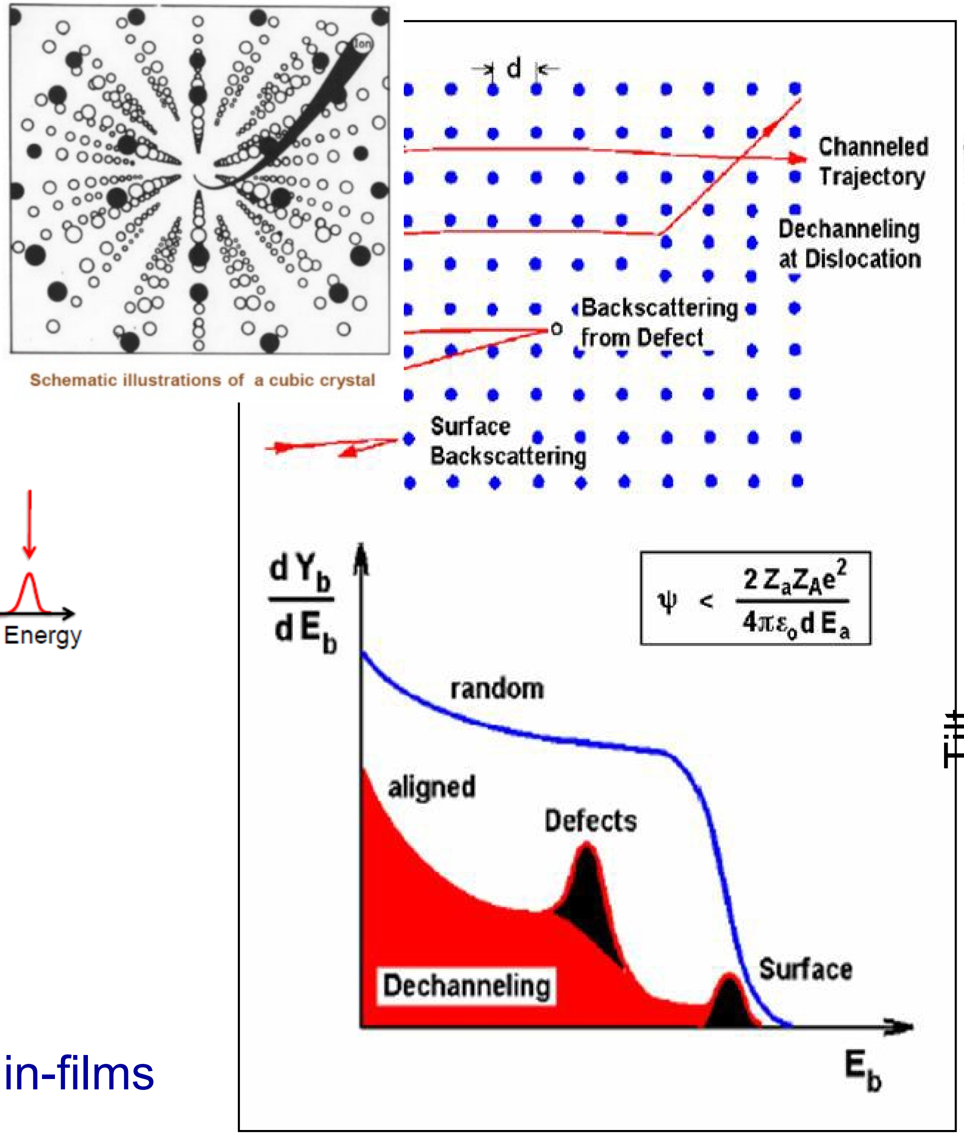
Channeling Rutherford Backscattering Spectrometry (RBS)

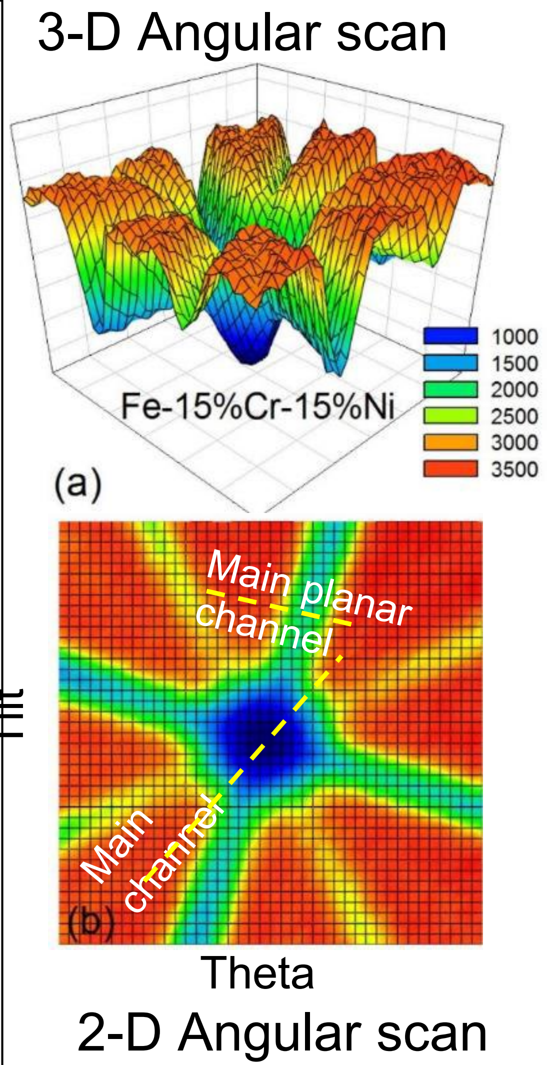


RBS/C @ TIBML



https://www.hzdr.de



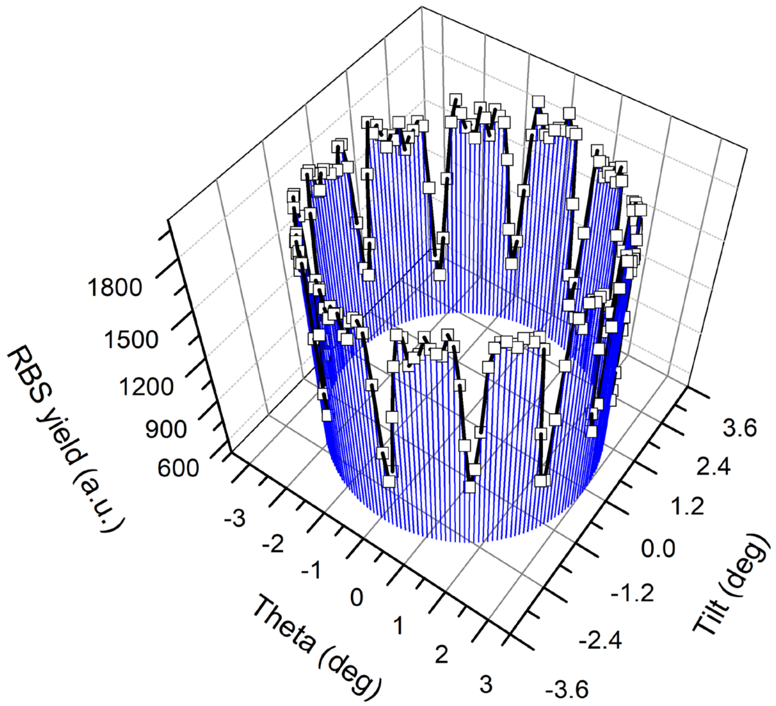


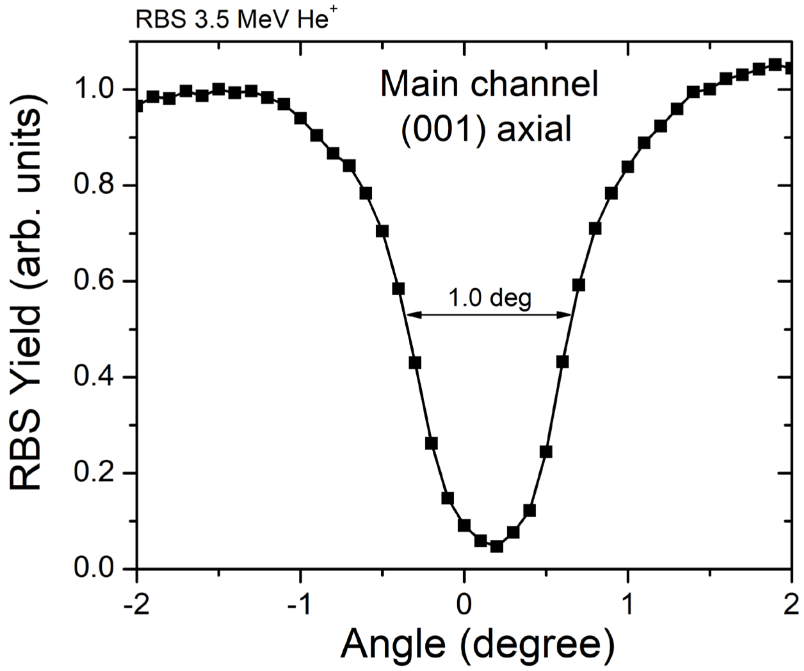
Rutherford Backscattering (RBS)

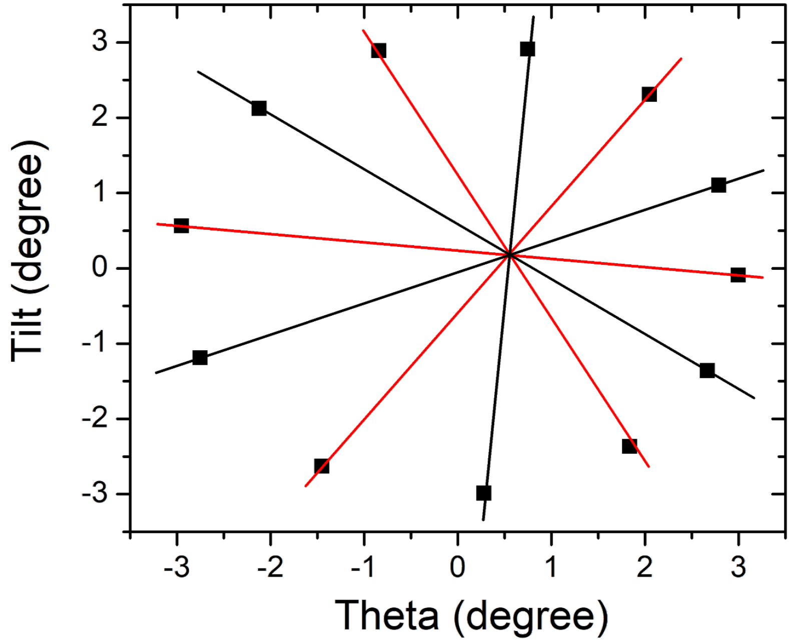
- ⇨ Information on as-prepared thin films
- ⇨ Dopants/impurities, interfaces, surfaces
- ⇨ ppm sensitivity with nm-scale resolution
- ⇨ Channeling-RBS for defect analysis in thin-films

Y. Zhang, *et al.*, "New Ion Beam Materials Laboratory for Materials Modification and Irradiation Effects Research." NIM B **338**, 19-30 (2014)

Channeling RBS: Pristine GaN

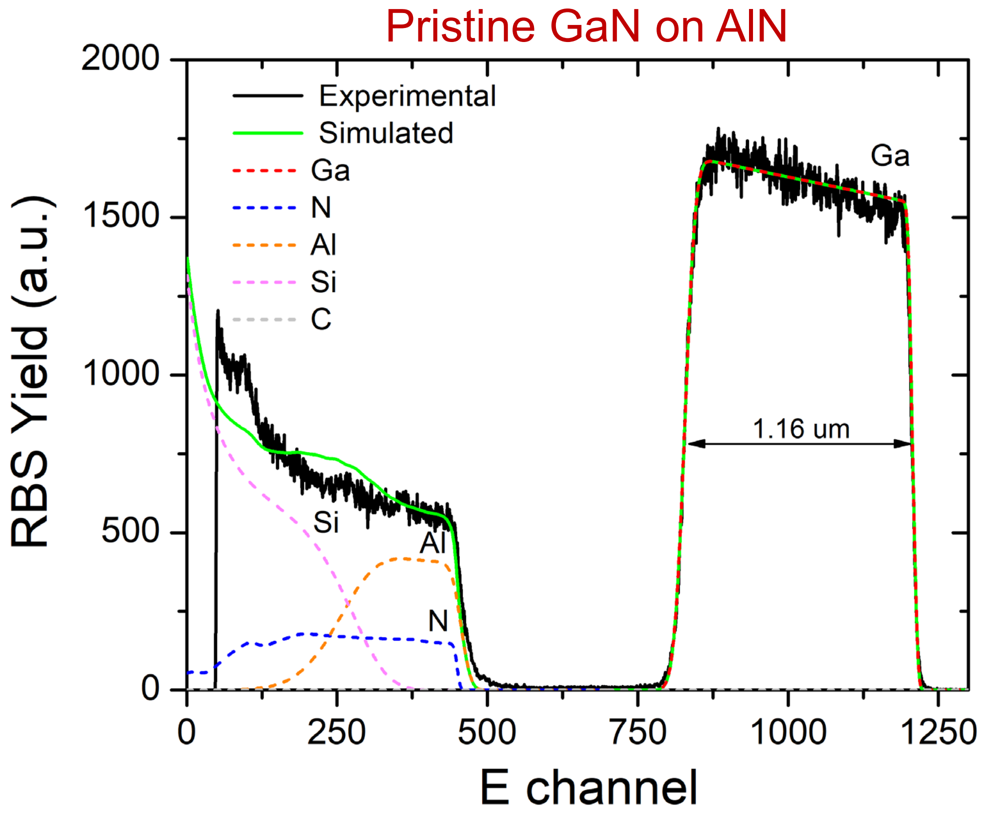


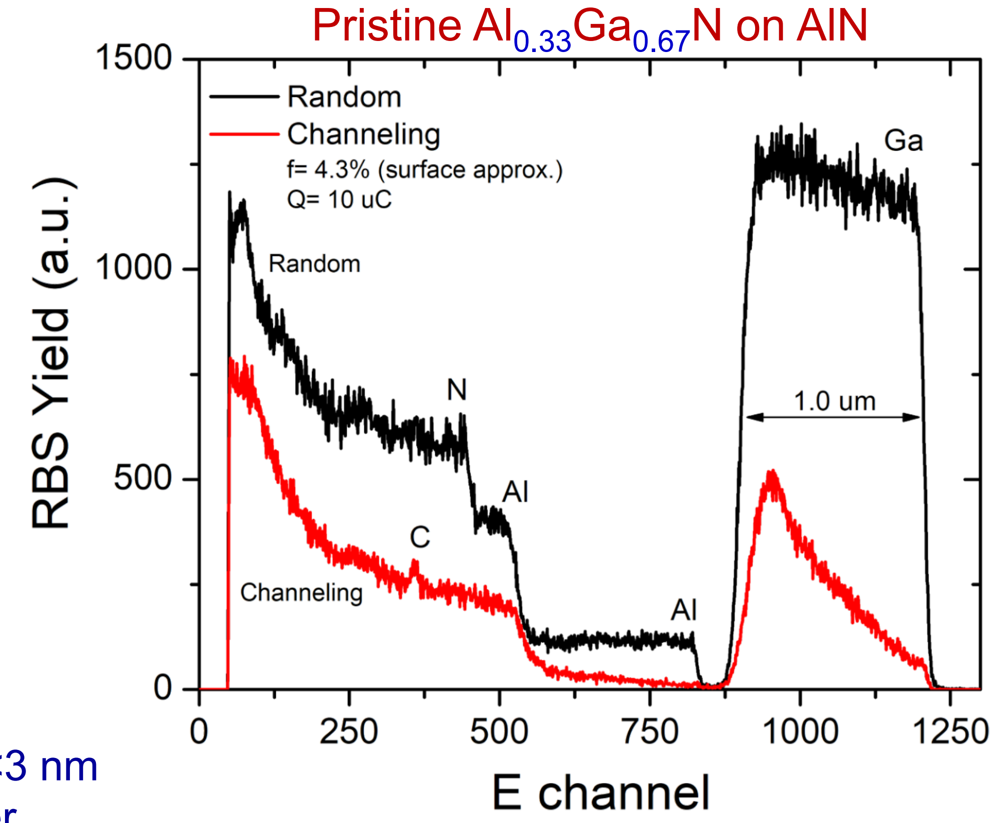




- ⇨ RBS/C channeling scan of pristine GaN with 3.5 MeV He^+ ions
- ⇨ Wurtzite crystal structure ($P6_3mc$) with 6-fold screw rotation around c-axis
- ⇨ Narrow, untwisted, and well-aligned channel along (001)
- ⇨ Similar high quality for entire AlGaN series

Channeling RBS: Pristine GaN and 25%AlGaN





surface roughness: <3 nm
5 nm carbon layer

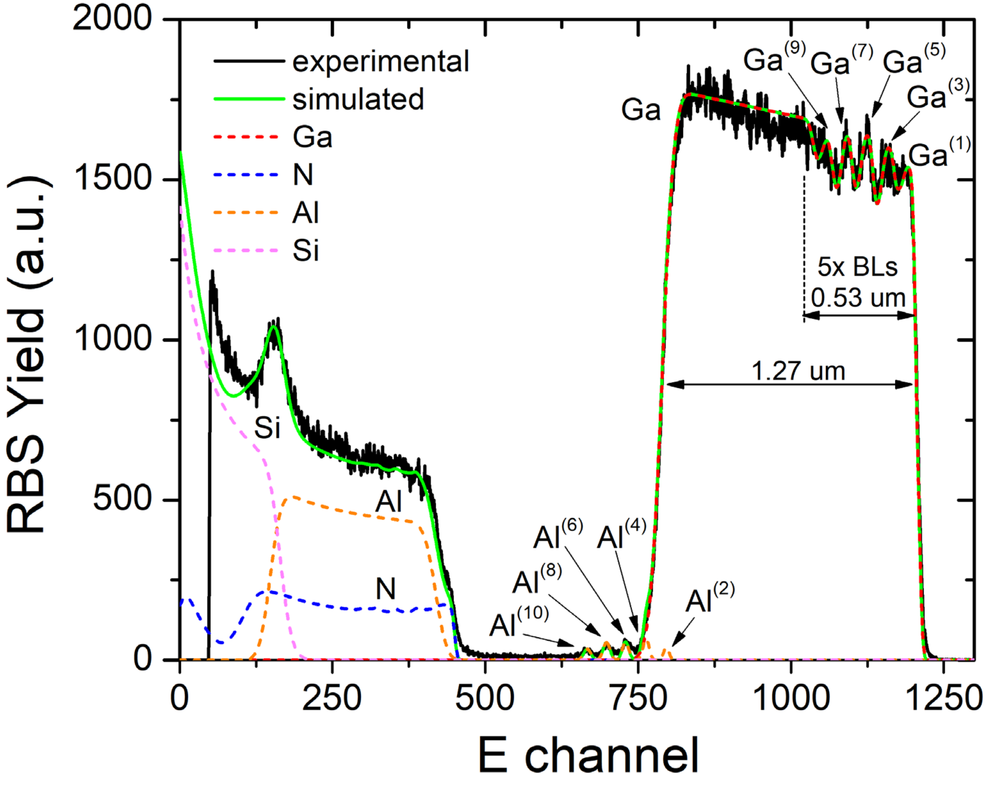
interface roughness: 67.8 nm

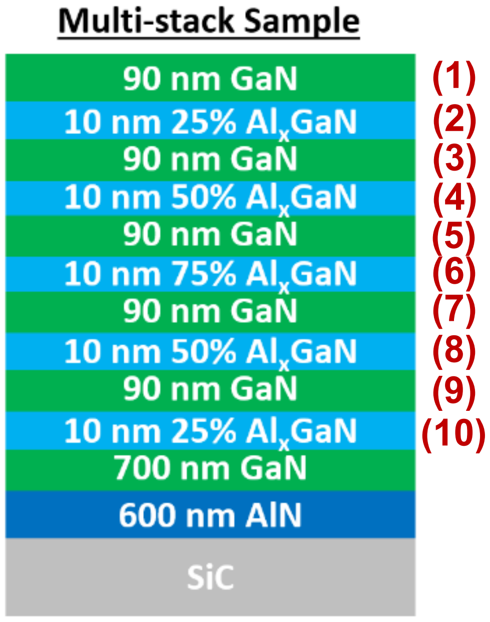
interface roughness: 418 nm

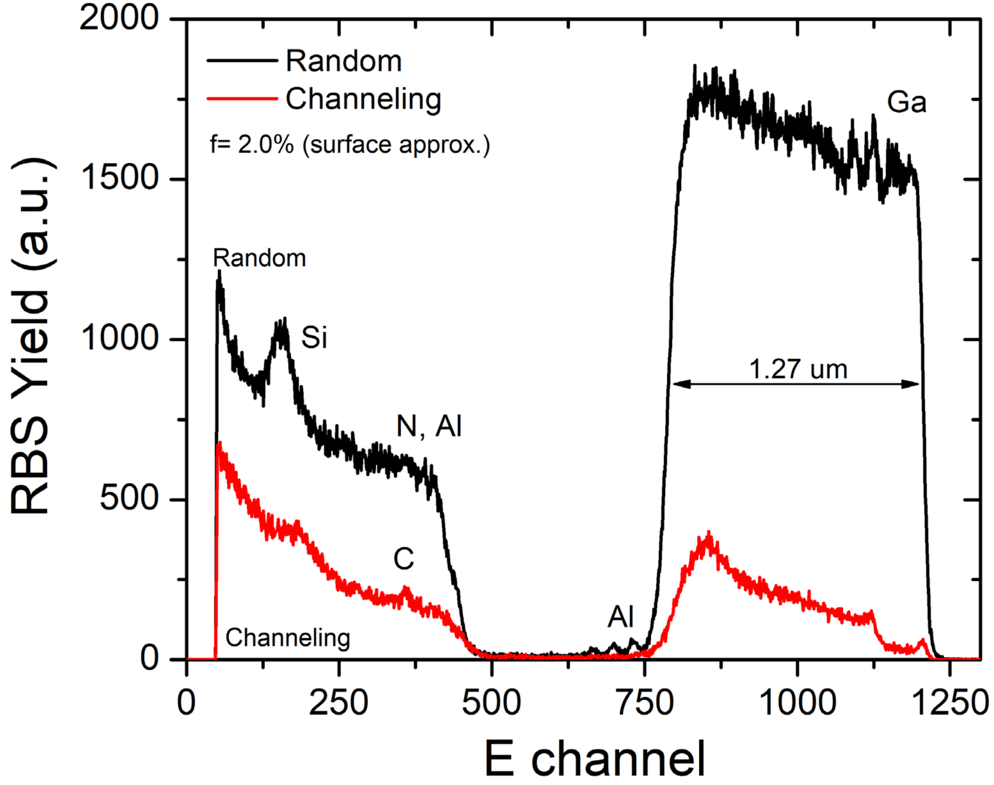
1.16 µm thickness, 2.3% pre-existing disorder

730 nm thickness

Channeling RBS: Pristine Multi-Stack Sample







(1) 46.0% Ga, 54.0% N, 97.7 nm

(2) 17.0% Al, 33.0% Ga, 50.0% N, 15.4 nm

(3) 48.5% Ga, 51.5% N, 96.0 nm

(4) 26.5% Al, 23.5% Ga, 50.0% N, 17.1 nm

(5) 50.0% Ga, 50.0% N, 97.2 nm

(6) 37.5% Al, 12.5% Ga, 50.0% N, 10.6 nm

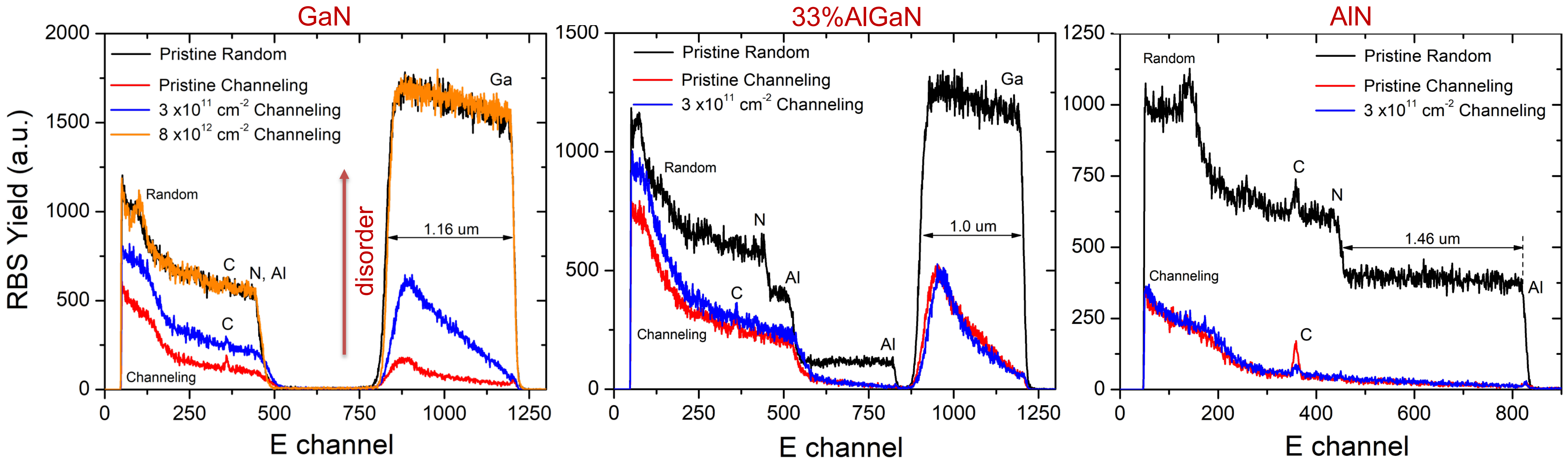
(7) 50.0% Ga, 50.0% N, 88.2 nm

(8) 25.5% Al, 24.0% Ga, 50.5% N, 16.1 nm

(9) 48.5% Ga, 51.5% N, 88.7 nm

(10) 26.0% Al, 27.0% Ga, 47.0% N, 10.5 nm

Channeling RBS: Irradiated GaN, 33%AlGaN, and AlN



3.5 MeV He ions (analysis)

1 µm GaN
1 µm AlN
SiC

946 MeV Au ions (irradiation)

1 µm 33%AlGaN
1 µm AlN
SiC

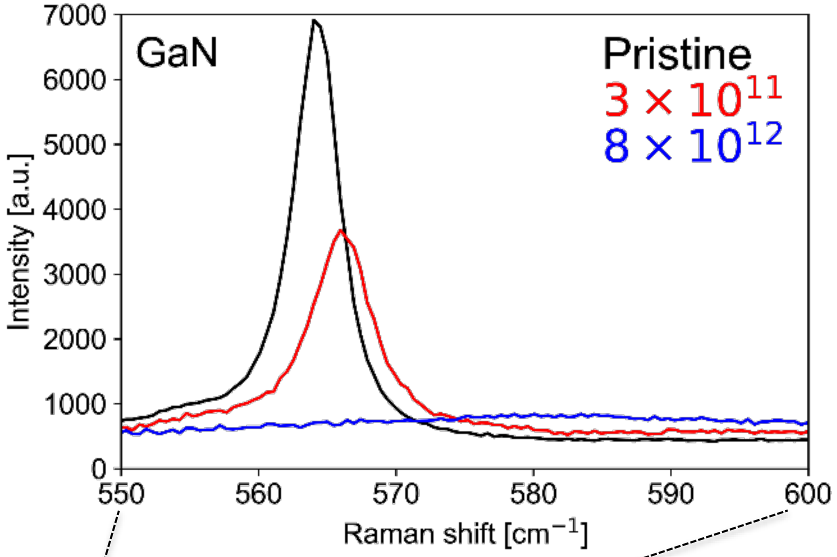
1 µm AlN
1 µm AlN
SiC

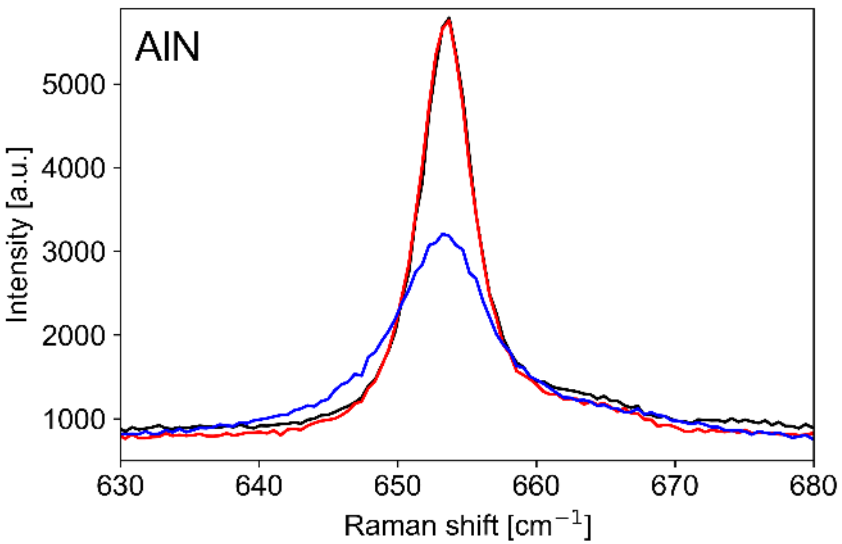
⇨ GaN sensitive to energetic heavy ions, large effect at 3×10^{11} cm^{-2} and loss of crystallinity at 8×10^{12} cm^{-2}

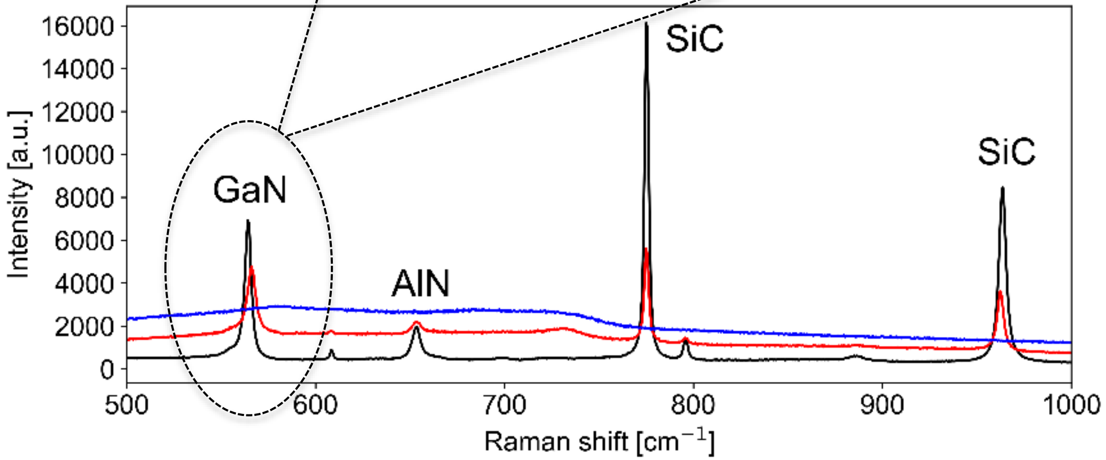
⇨ Addition of Al greatly increases radiation resistance with no detectable structural defects in AlN at 3×10^{11} cm^{-2}

The University of Tennessee Knoxville, Department of Nuclear Engineering

Raman Spectroscopy: Irradiated AlGaN Series





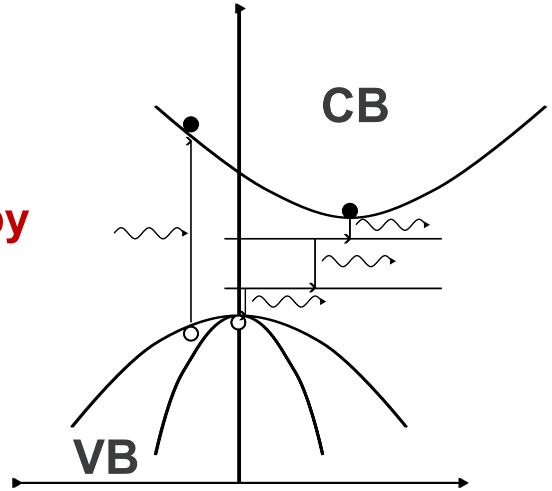


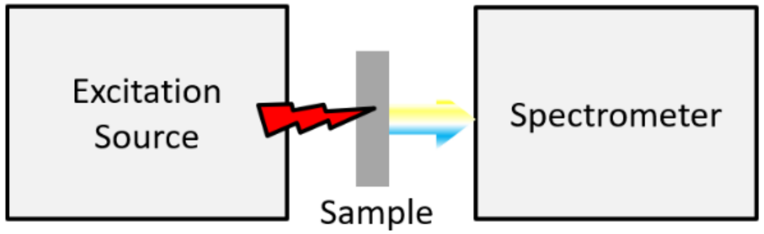
- ⇨ Changes in Raman spectra of both end-members
- ⇨ AlN significantly more resistant than GaN
- ⇨ Bandgap closure in GaN at maximum fluence

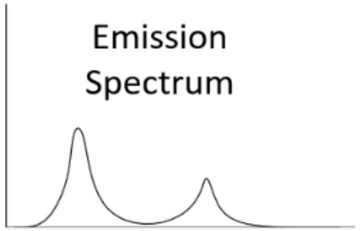
The University of Tennessee Knoxville
Department of Nuclear Engineering

Luminescence Spectroscopy for Characterization of Radiation Defects

Excitation by photons





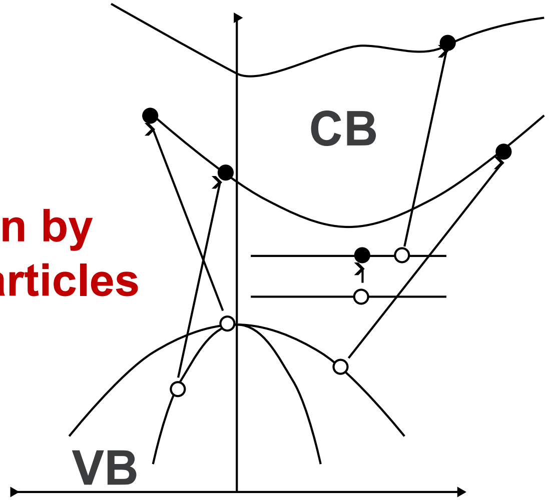


Photoluminescence (PL)

\+ easy access and straightforward

Courtesy: Prof. Joseph Graham

Excitation by charged particles



Cathodoluminescence (CL)

stimulated by electrons

\+ easy access

\+ spatially resolved imaging

\+ broader excitation spectrum

Ionoluminescence (IL)

stimulated by ions

\+ *in situ* information

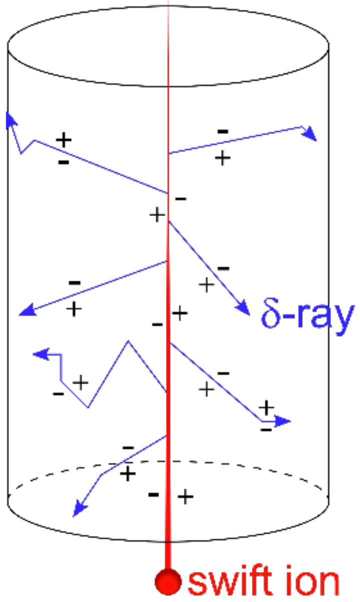
\+ cryogenic temperatures (30 K)

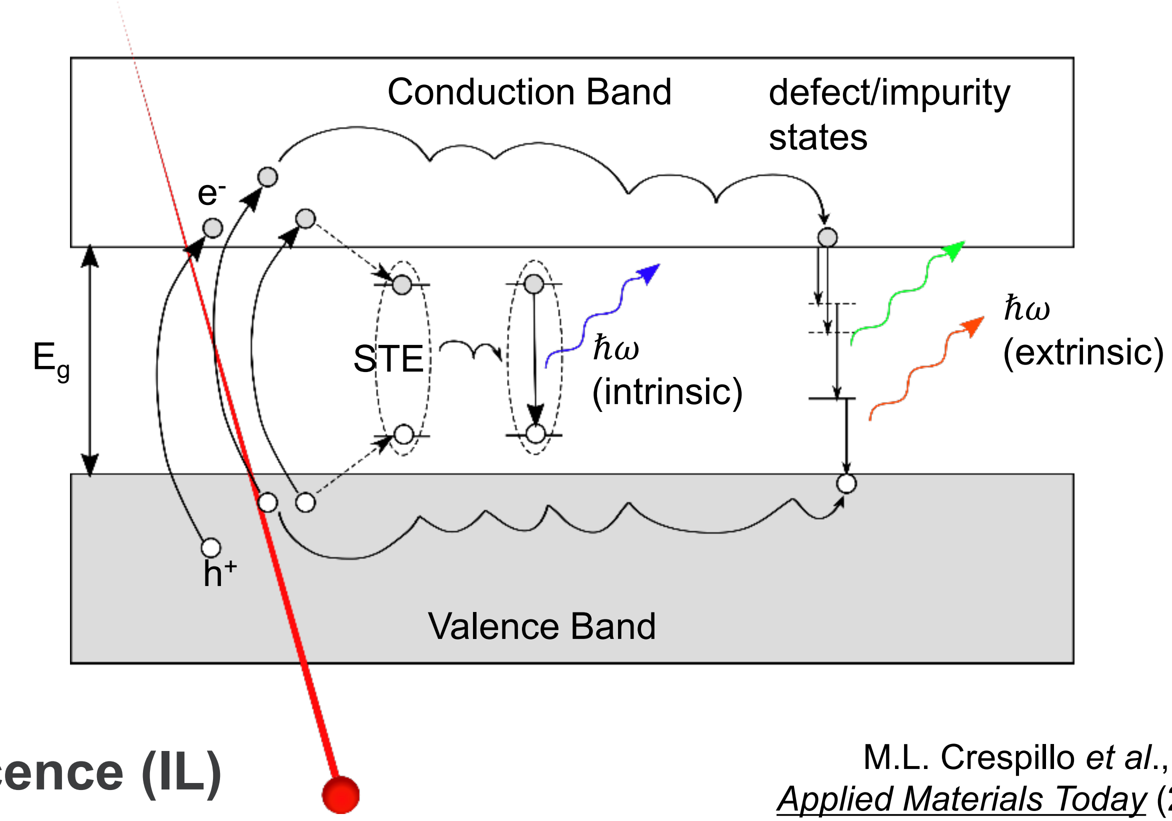
\+ very broad excitation spectrum

\+ large penetration depth

\+ time resolved (for pulsed beam)

Cryo-Ionoluminescence at the Tennessee Ion Beam Materials Laboratory

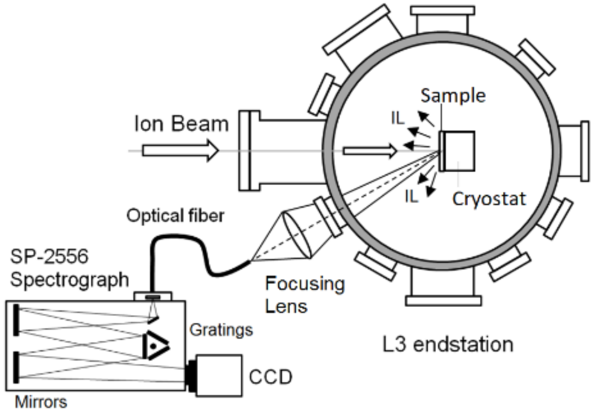




Ionoluminescence (IL)

M.L. Crespillo *et al.*, Applied Materials Today (2018)

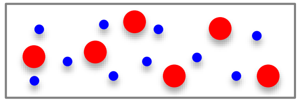
- ⇨ Ion beam optical technique down to 30 K
- ⇨ Broad electronic excitations coupled with *in situ* damage kinetics
- ⇨ Simultaneous access to all emission bands including deep levels
- ⇨ Electronic defects and their interplay can be analyzed in real-time



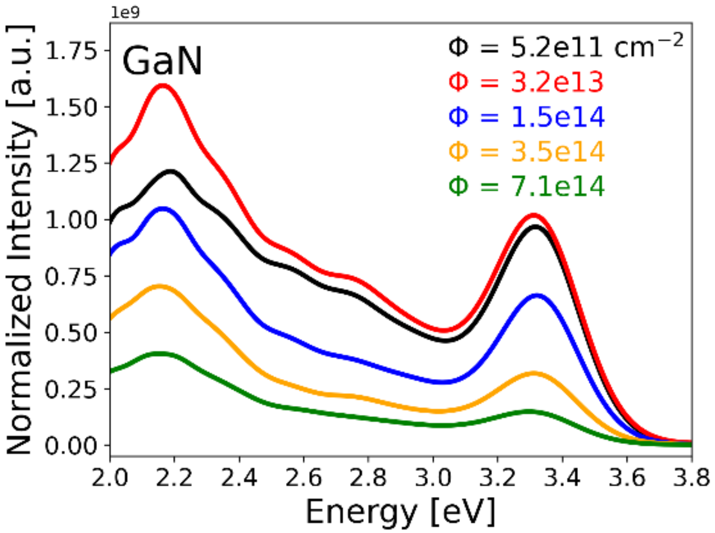
Cryo-IL experimental setup @ TIBML

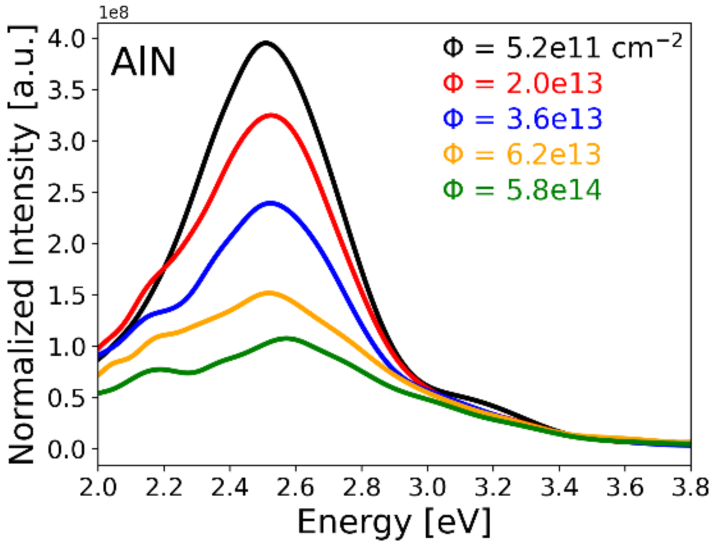
Ionoluminescence: Pristine and Irradiated AlN – GaN

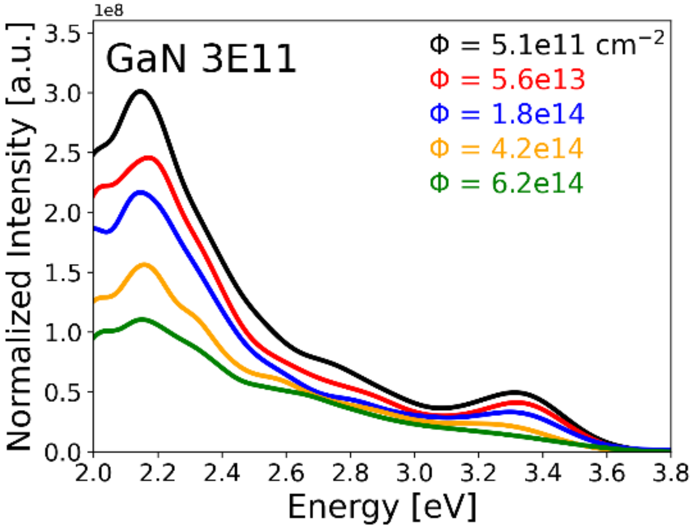
3.5 MeV He ions (analysis)

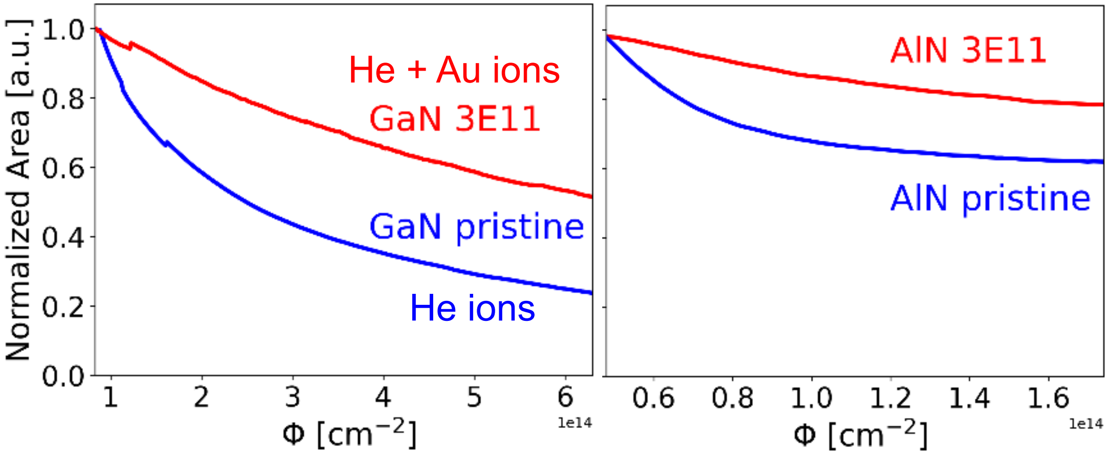


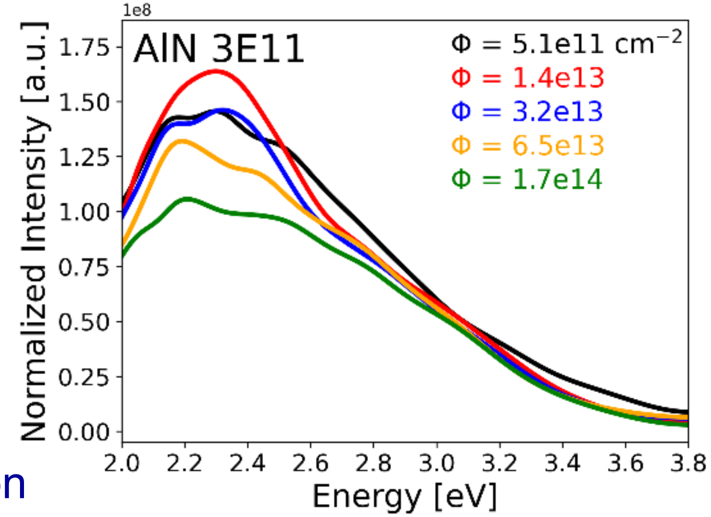
946 MeV Au ions (irradiation)







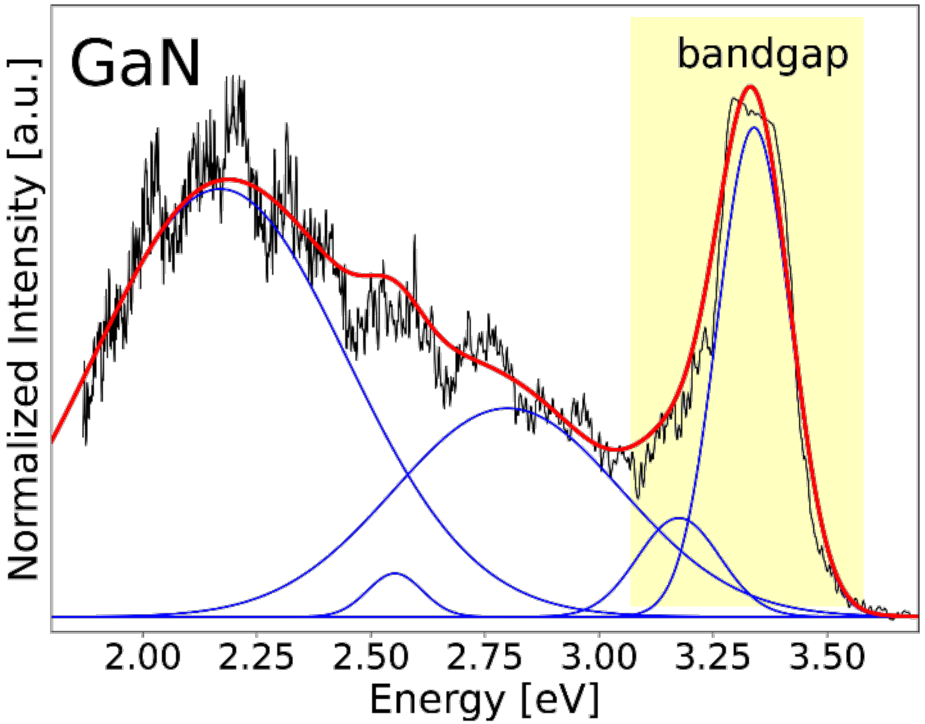




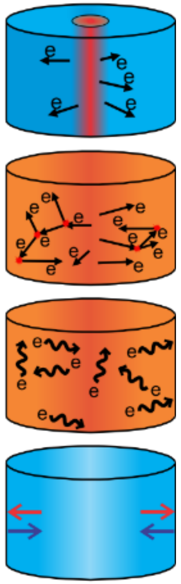
⇨ Defect formation in both materials under He irradiation

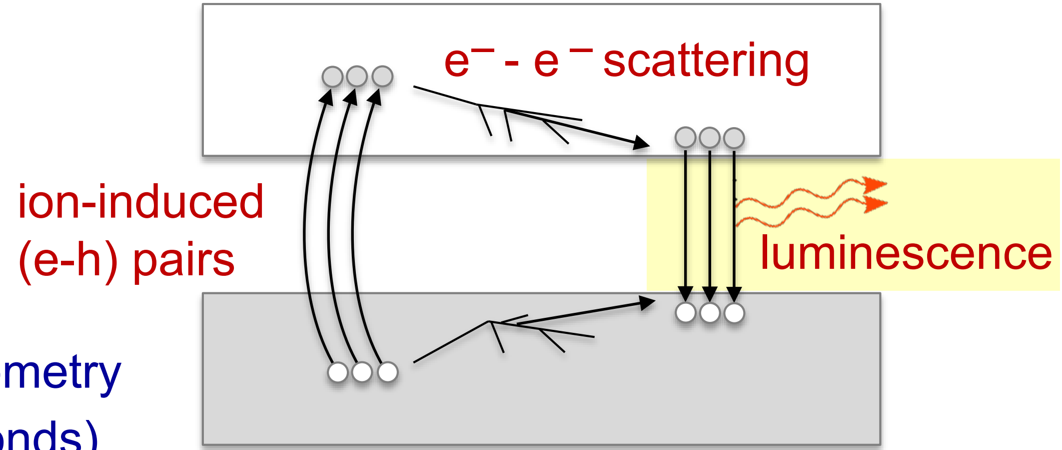
⇨ Much higher defect concentration in GaN after Au irradiation

Defect and Bandgap Emission, Electron-Hole Pairs, and Ionoluminescence



2.2 eV	C_N acceptor (Carbon substitutional on N site)
2.5 eV	Possible DX center from Al below (lattice distortion at or near the donor site)
2.8 eV	Nitrogen vacancy complex
3.2 eV	Possible electronic defect acceptor center
3.4 eV	GaN bandgap emission

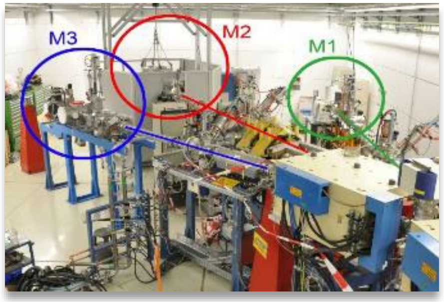


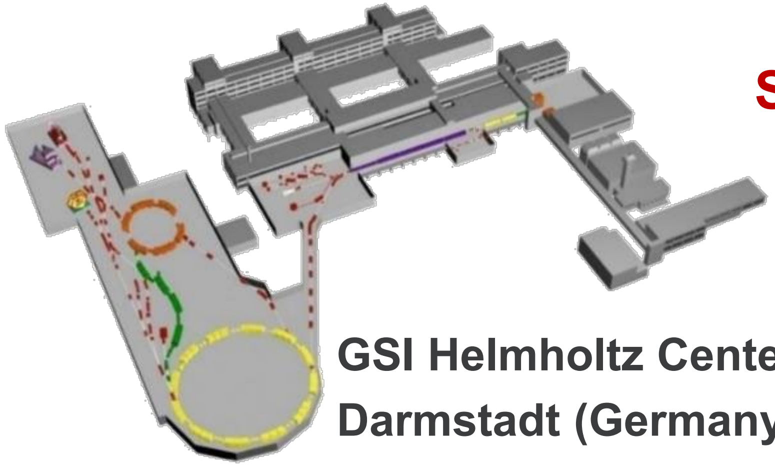


- ⇨ Several defect bands detectable with ionoluminescence
- ⇨ Pronounced bandgap emission: electron-hole recombination
- ⇨ Low-fluence measurement will give # of (e-h) pairs per ion
- ⇨ Calibration with scintillator materials: detector efficiency and geometry
- ⇨ Pulsed ion beam IL measurement will give kinetics (~ nano-seconds) and carrier lifetime

Beamtimes Accomplished in Spring 2024 at GSI

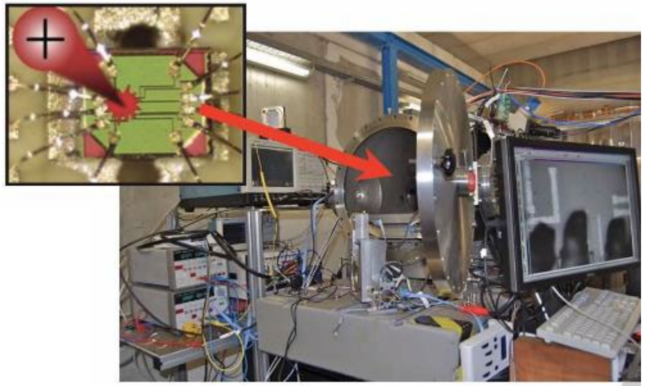
Broadbeam Experiments





GSI Helmholtz Center
Darmstadt (Germany)

Single Ion Beam Experiments



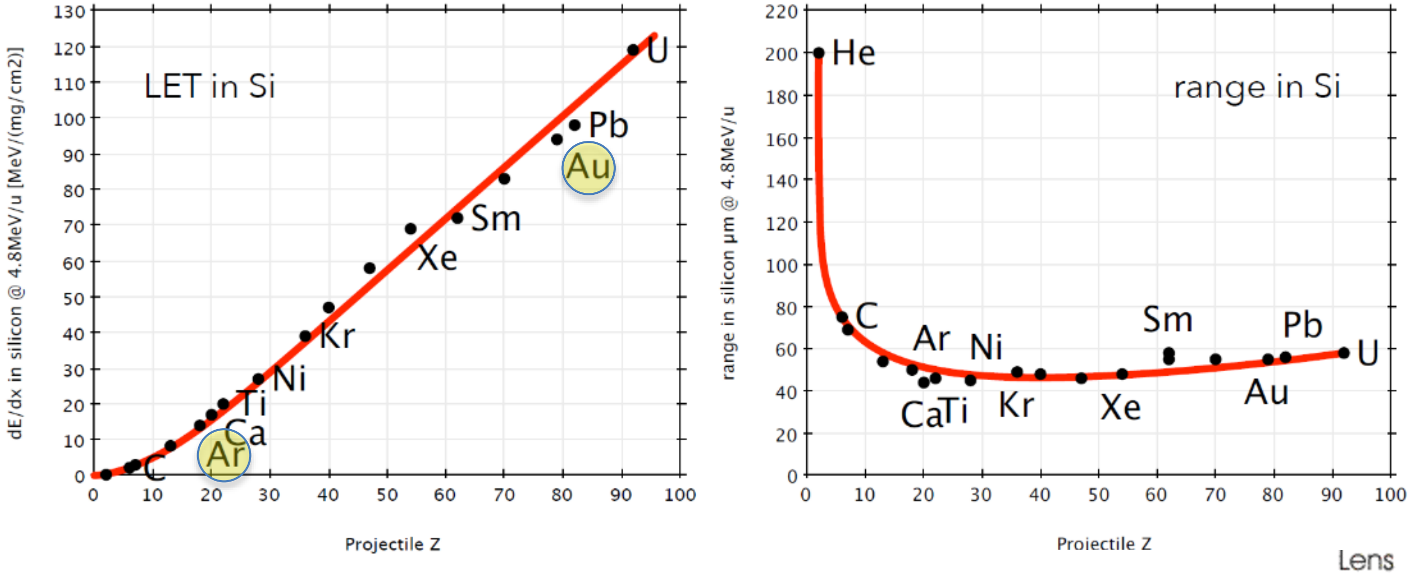
March 2024 (950 MeV ^{197}Au – 72.4 MeV/(mg/cm^2)
April 2024 (192 MeV ^{40}Ar – 10.8 MeV/(mg/cm^2)

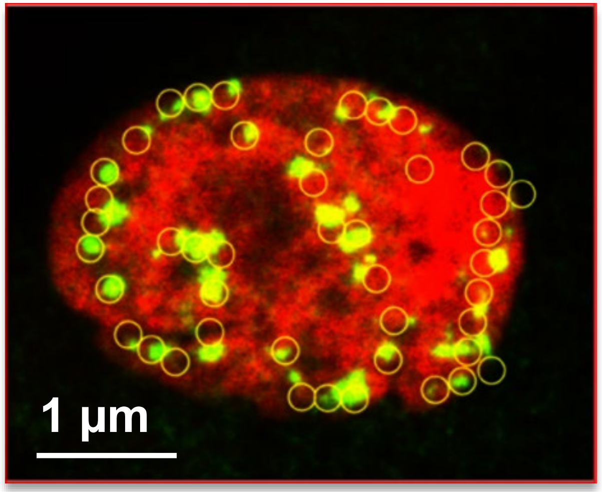
- ⇨ AlGaN sample series (AFRL)
- ⇨ AlN, GaN, and Ga_2O_3 based device irradiations (Rongming Chu's team and Aaron Arehart's team)
- ⇨ Capacitance measurements before/after irradiation
- ⇨ Fluence series on AlN, GaN, and SiC powder samples

- ⇨ Single-events testing
- ⇨ Established ion-beam scanning routines and correlation to data acquisition
- ⇨ Tested various devices for several groups:
  - Adam Neal (Ga_2O_3-based transistors)
  - Rongming Chu (GaN-based JFET/ PN diodes)
  - Aaron Arehart (GaN-based diodes)

Swift-Heavy Ion Irradiation: GSI Ion Microprobe and SEE Testing

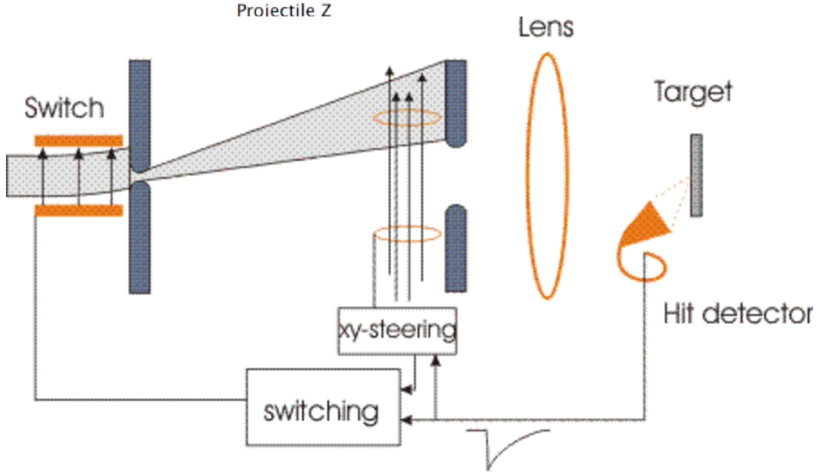
LETs and ranges in Silicon at standard 4.8MeV/u*





Ion Microprobe

- ⇨ targeted single ion irradiations
- ⇨ 500 nm spatial resolution
- ⇨ large scan area



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DEPARTMENT OF NUCLEAR ENGINEERING

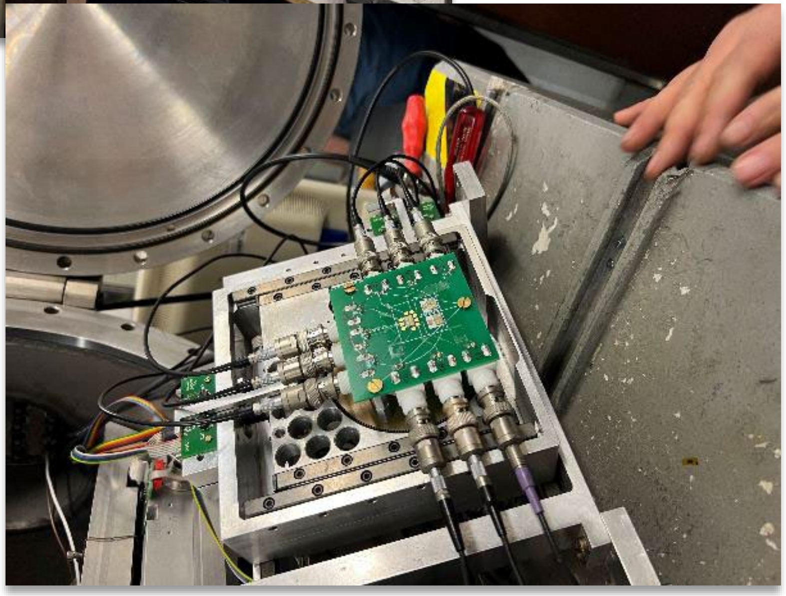
Swift-Heavy Ion Irradiation: GSI Ion Microprobe and SEE Testing

Instrument scientist Dr. Voss with two students

Support Equipment

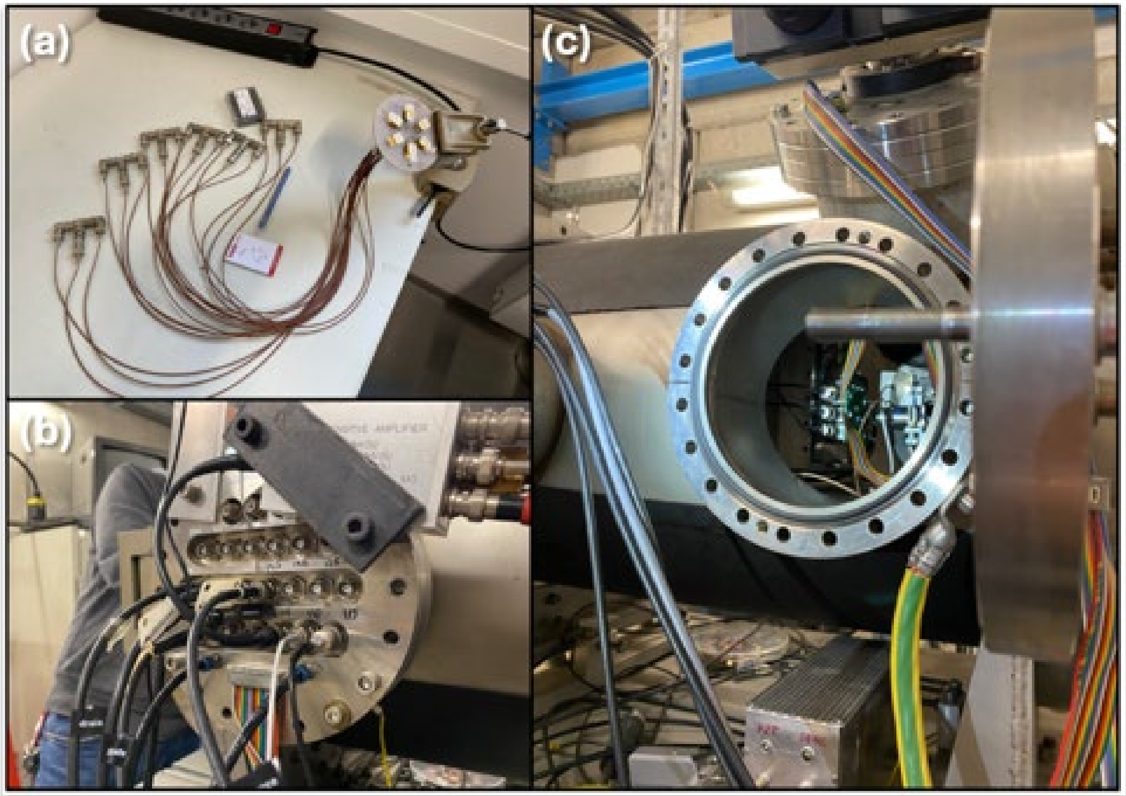
- Electronics performance
- Voltcraft Laboratory Power Supply (VSP1410)
- Keithley Series 6400 Picoammeter (6485)
- Keithley Series 2400 Source Measure Unit (2400)

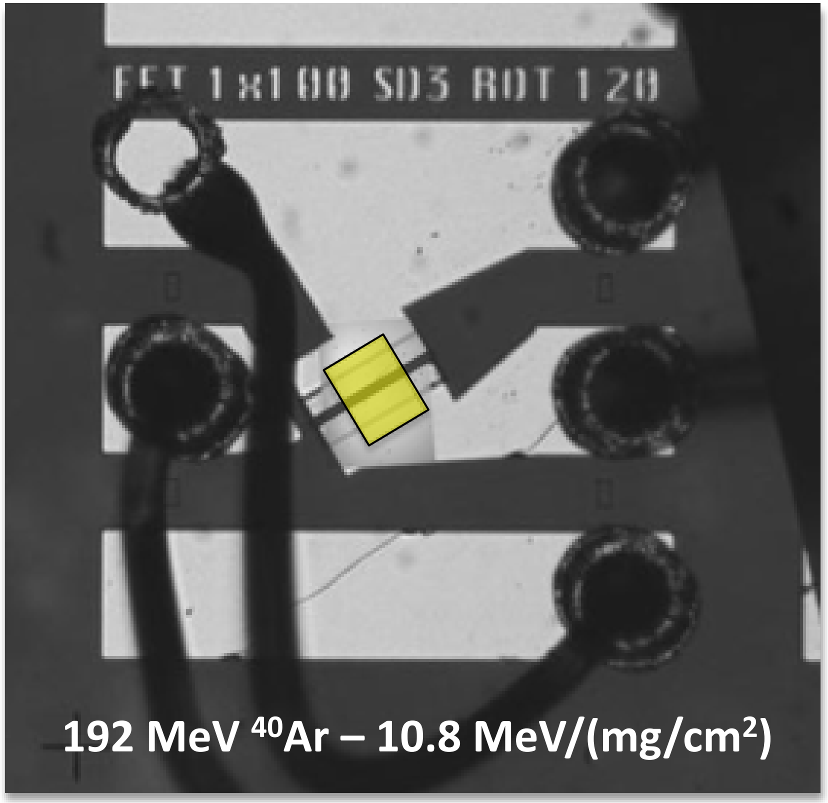
Device board on cylindrical holder connected with BNC to support equipment



Computer-aided measurement and control

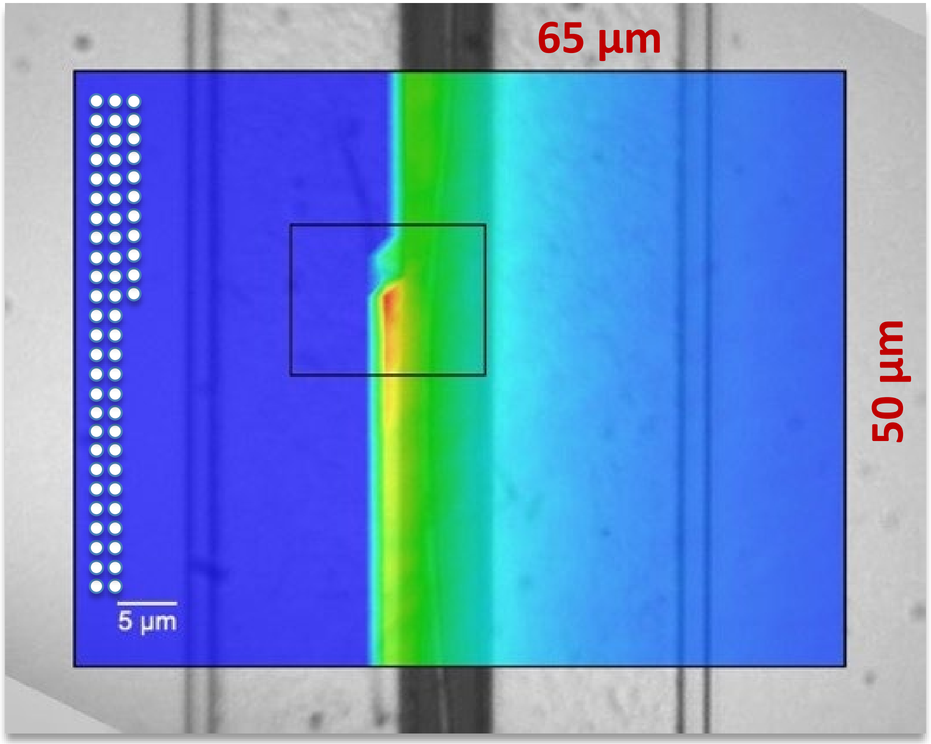
Swift-Heavy Ion Irradiation: GSI Ion Microprobe and SEE Testing





- ⇨ AFRL, Ga_2O_3 transistor SEE testing (Adam Neal *et al.*): -8 V gate-to-source and +100 V drain-to-source
- ⇨ C++ script to control: (*i*) irradiation area, (*ii*) irradiation timing, (*iii*) bias conditions, and (*iv*) current measurements
- ⇨ Initial scan area: 65 μm x 50 μm with single ion impacts into 3 μm^2 region with 2 sec delay (5 current measurements) (final scan area: 16 μm x 13 μm with single ion impacts into 0.1 μm^2)

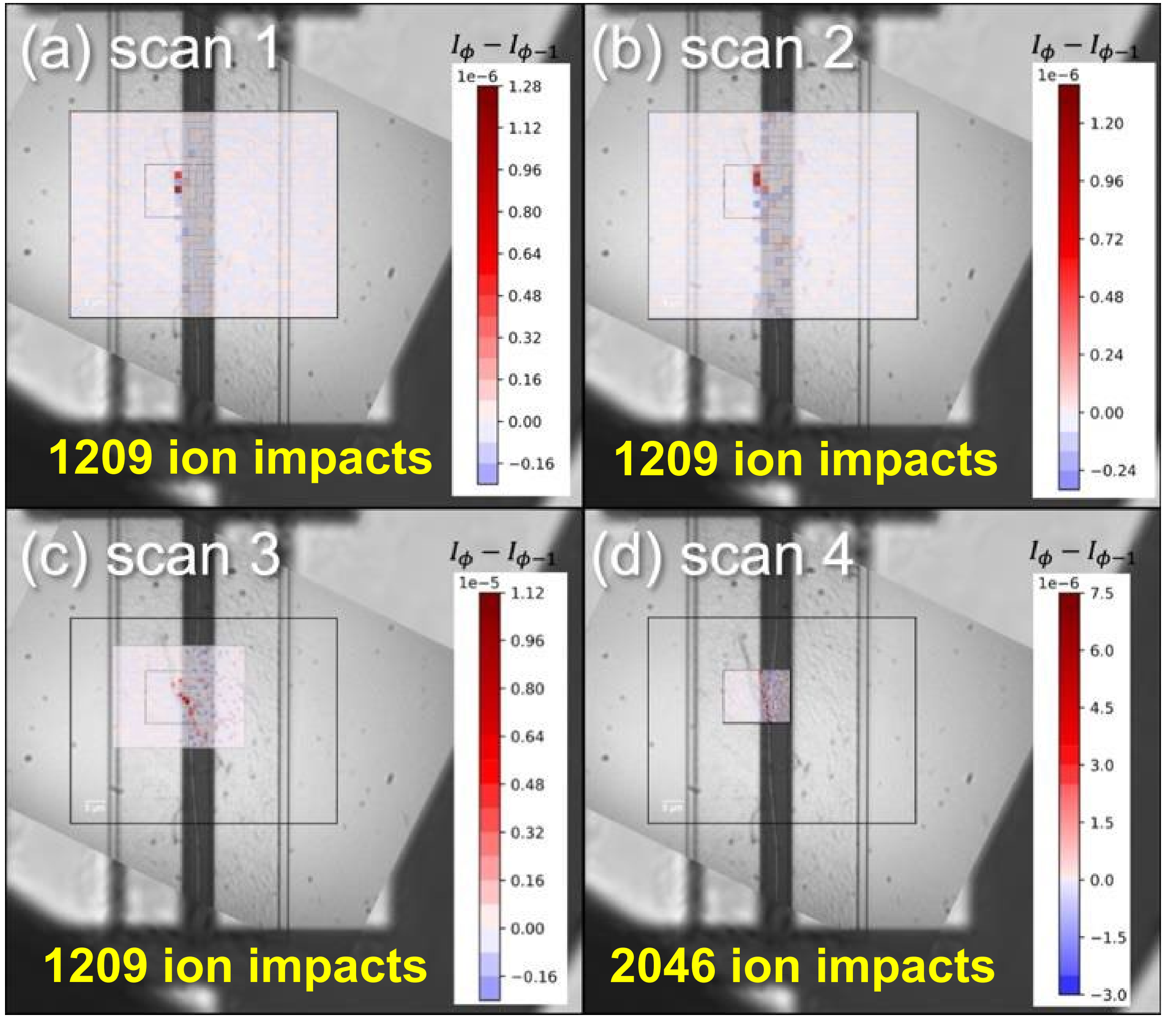
Swift-Heavy Ion Irradiation: GSI Ion Microprobe and SEE Testing



1209 ion impacts into area of 65 µm × 50 µm

- ⇨ Drain current transient event detected
- ⇨ Smaller scan areas to localize device region
- ⇨ Detailed information see presentation of Adam Neal

Scan #1: 65 µm × 50 µm **Scan #2:** 65 µm × 50 µm

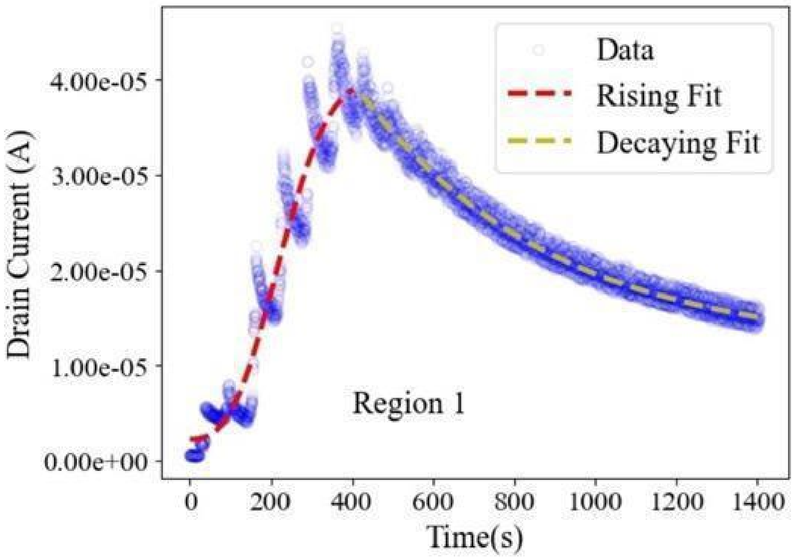


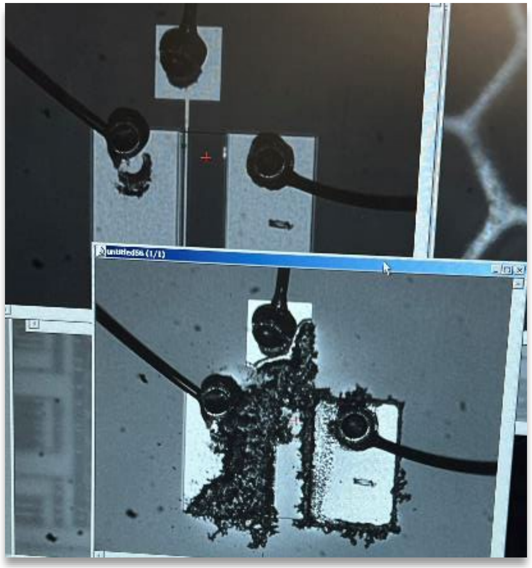
Scan #3: 33 µm × 25 µm **Scan #4:** 16 µm × 13 µm

Swift-Heavy Ion Irradiation: GSI Ion Microprobe and SEE Testing

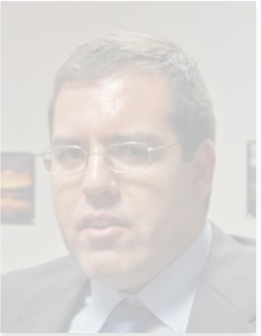
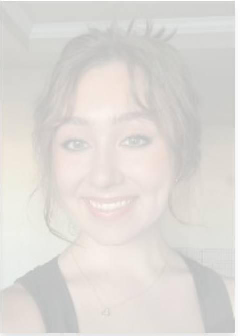
Lessons Learned from first SEE Testing Campaign

- ⇨ Microbeam experiments completed for several groups
- ⇨ Transient single-ion event successfully detected
- ⇨ Infrastructure at GSI suitable for Air Force needs
  (*e.g.*, spatially resolved SEE testing with bias voltage)
- ⇨ Irradiation and measurement plan essential
  (*e.g.*, what will be measured and equipment is needed?)
- ⇨ Device performance must be well characterized prior to irradiation
- ⇨ Functionality tests before and after transfer to GSI
- ⇨ Limited beamtime has to be efficiently utilized
- ⇨ Anticipated beamtime March 2025 (1-2 days)
- ⇨ Beamtime request for 2026-2027 underway





Acknowledgement and Research Team


Eric O'Quinn

(Researc

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Rongming Chu, Xing Wang, Mia Jin, and Reeja Jayan (MURI)
Aaron Arehart (COE)

TICKLE COLLEGE OF ENGINEERING
THE UNIVERSITY OF TENNESSEE, KNOXVILLE

MISSOURI S&T

Joseph Graham (Missouri S&T)

AFRL THE AIR FORCE RESEARCH LABORATORY

Alexander Chaney (AFRL)
Thaddeus Asel (AFRL)
Adam Neal *et al*. (AFRL)