Mechanisms of cavity formation in GaN devices induced by swift heavy ion irradiation

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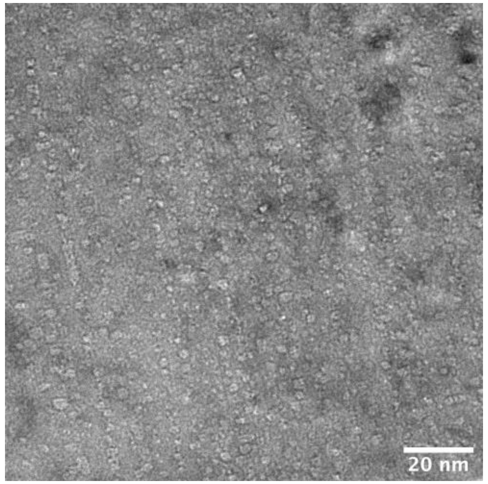
2024 AFRL Radiation Damage of Electronics Review
AFOSR MURI: REDESIGN

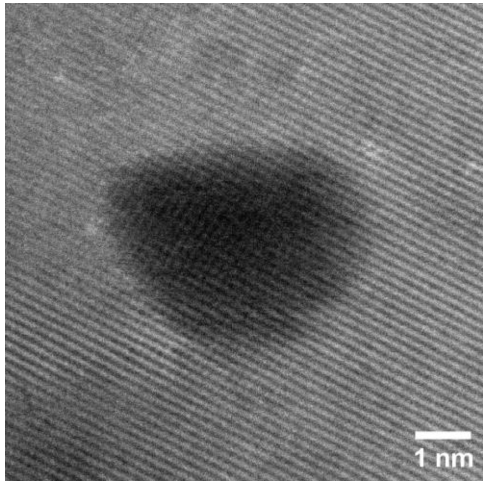
Background

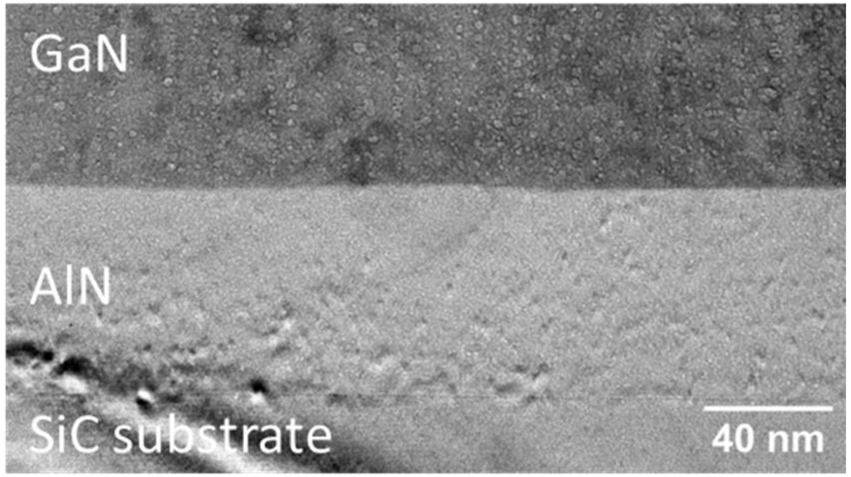
- **Swift Heavy Ions**: **Z>6, Ion Energy>MeV/amu**
- **Lower fluence than lighter ions but substantial damage**
- **950 MeV Au ions irradiation with fluence ~ 10^{12} cm^{-2} in GaN**
  - ***Dense nano-sized cavities formed in GaN***
  - ***Cavities formed along the Au ion trajectory, indicating the effect of single ion on cavity formation***
  - ***Much smaller cavities in AlN than GaN***

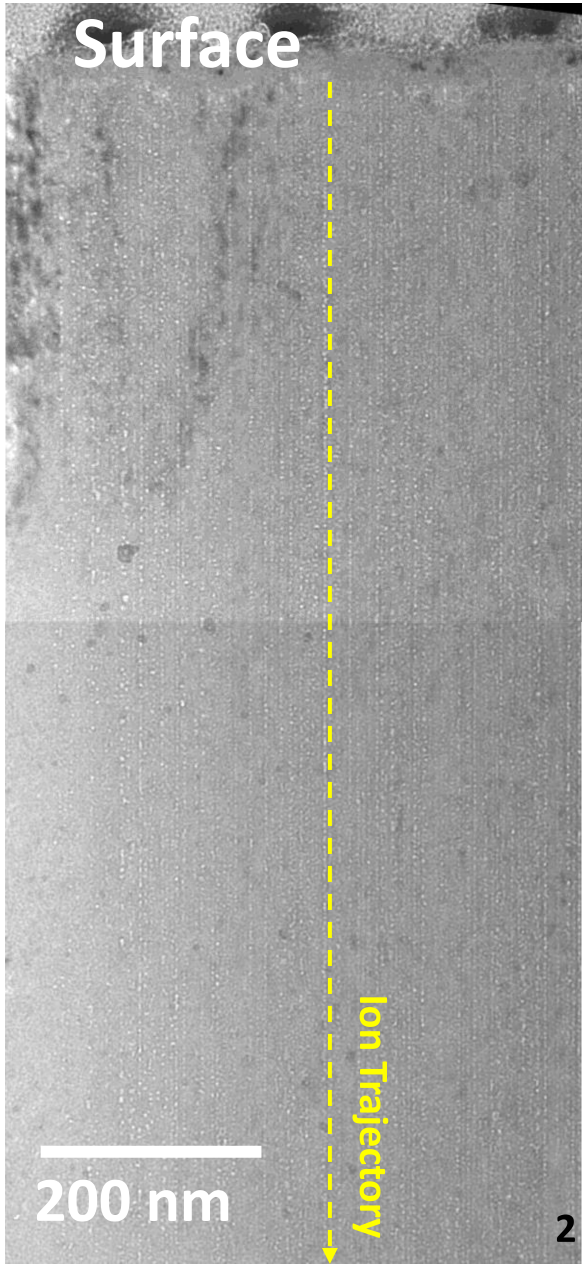
Under-focused TEM



STEM-HAADF

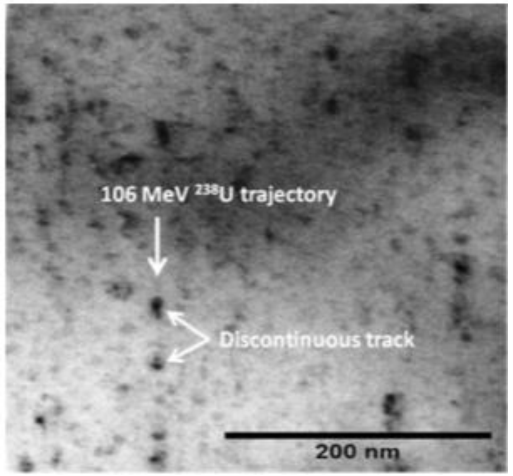




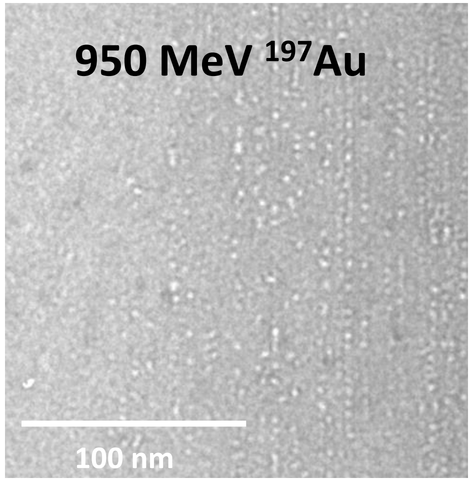


Mechanisms for cavity formation remains unclear

- Why cavities only formed at high LET (> 40 keV/nm)?
- Cavity: voids or N_2 gas bubbles?
- What is the impact of Al in Al_xGaN on cavity formation?

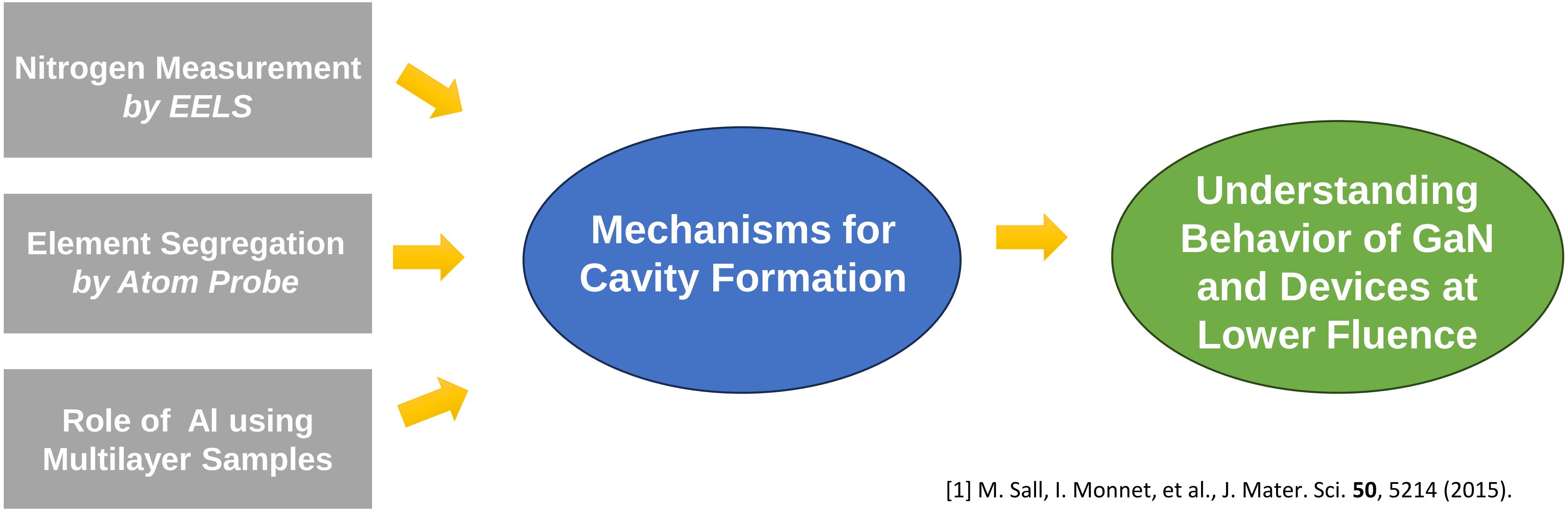


LET = 24 keV/nm [1,2]



LET = 46 keV/nm

Microscopy Characterization

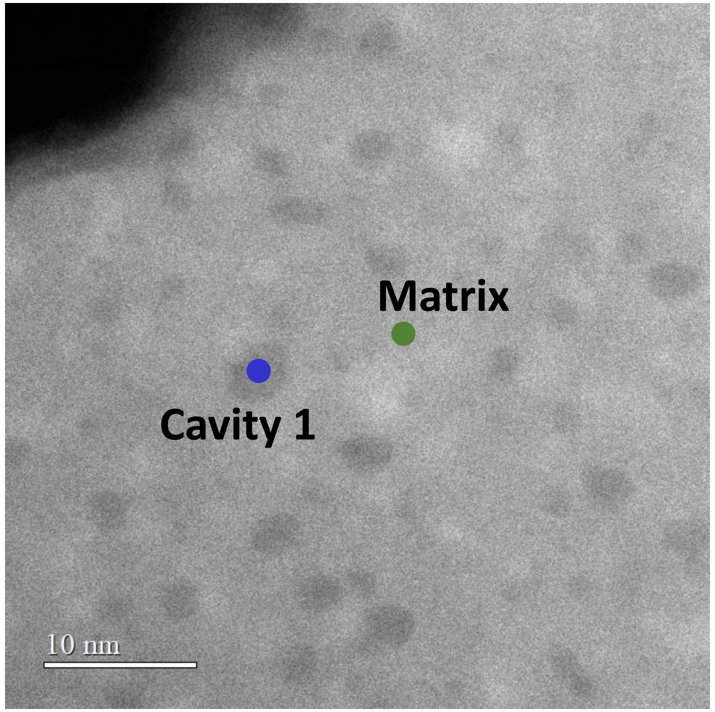


[1] M. Sall, I. Monnet, et al., J. Mater. Sci. **50**, 5214 (2015).
[2] M. C. Sequeira, et al., Small **18**, (2022).

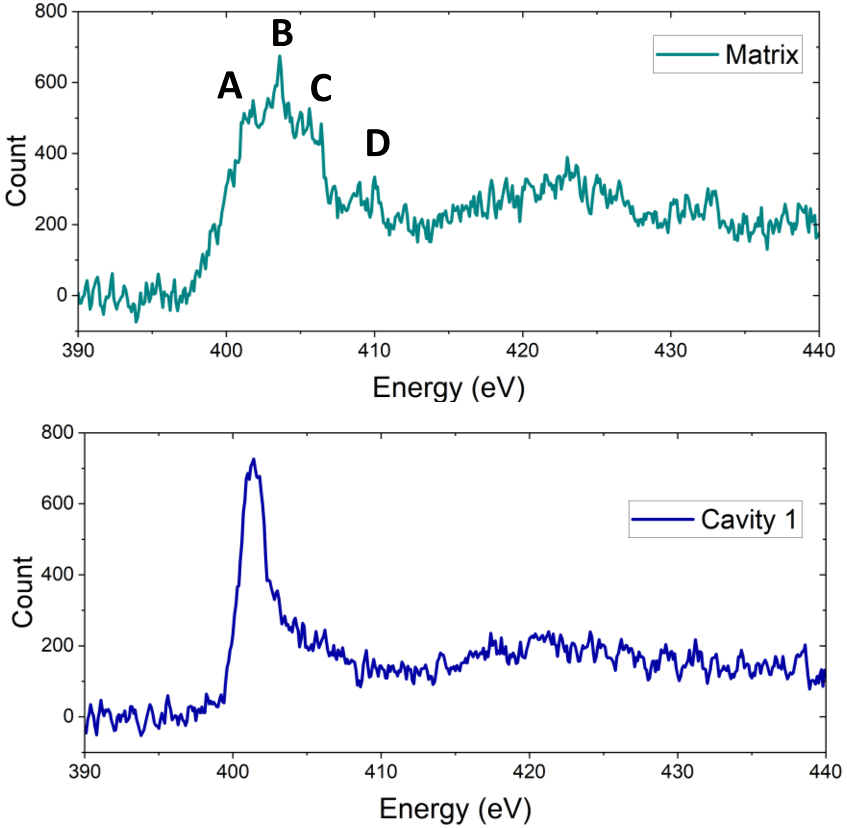
Nitrogen Measurement using Electron Energy Loss Spectroscopy (EELS)

Why EELS?

- More sensitive for lighter elements, like N, C, O, than EDS
- Fine features near core-loss peaks can reveal bonding environment, as it is related to density of states of unoccupied electronic orbitals
- Measurement of relative element concentration with careful data processing



[1] I. Arslan, A. Bleloch, E.A. Stach, S. Ogut, N.D. Browning,, Philosophical Magazine 86 (2006).



A peak: hybridization between all electrons
B peak: hybridization of Ga s and N p in x-y plane
C peak: hybridization of p states
D peak: hybridization of Ga p and N px, py

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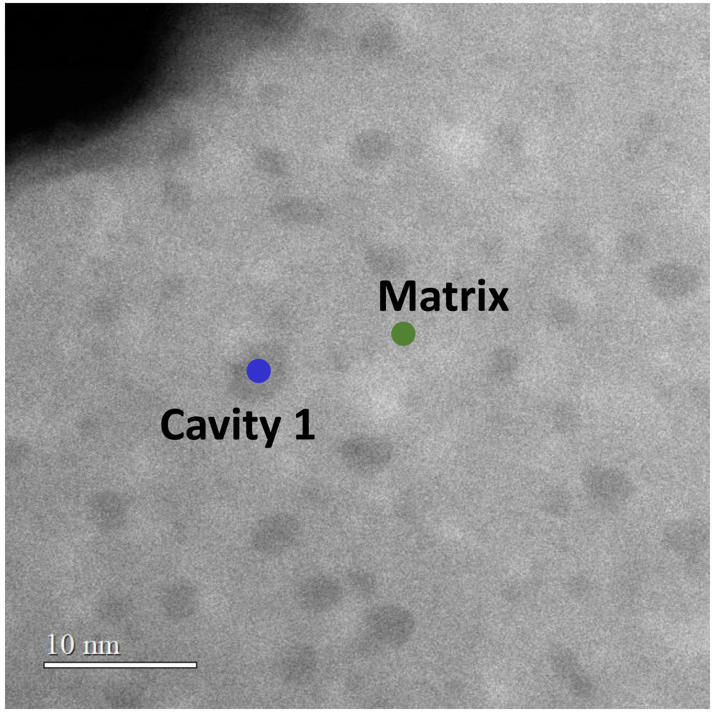

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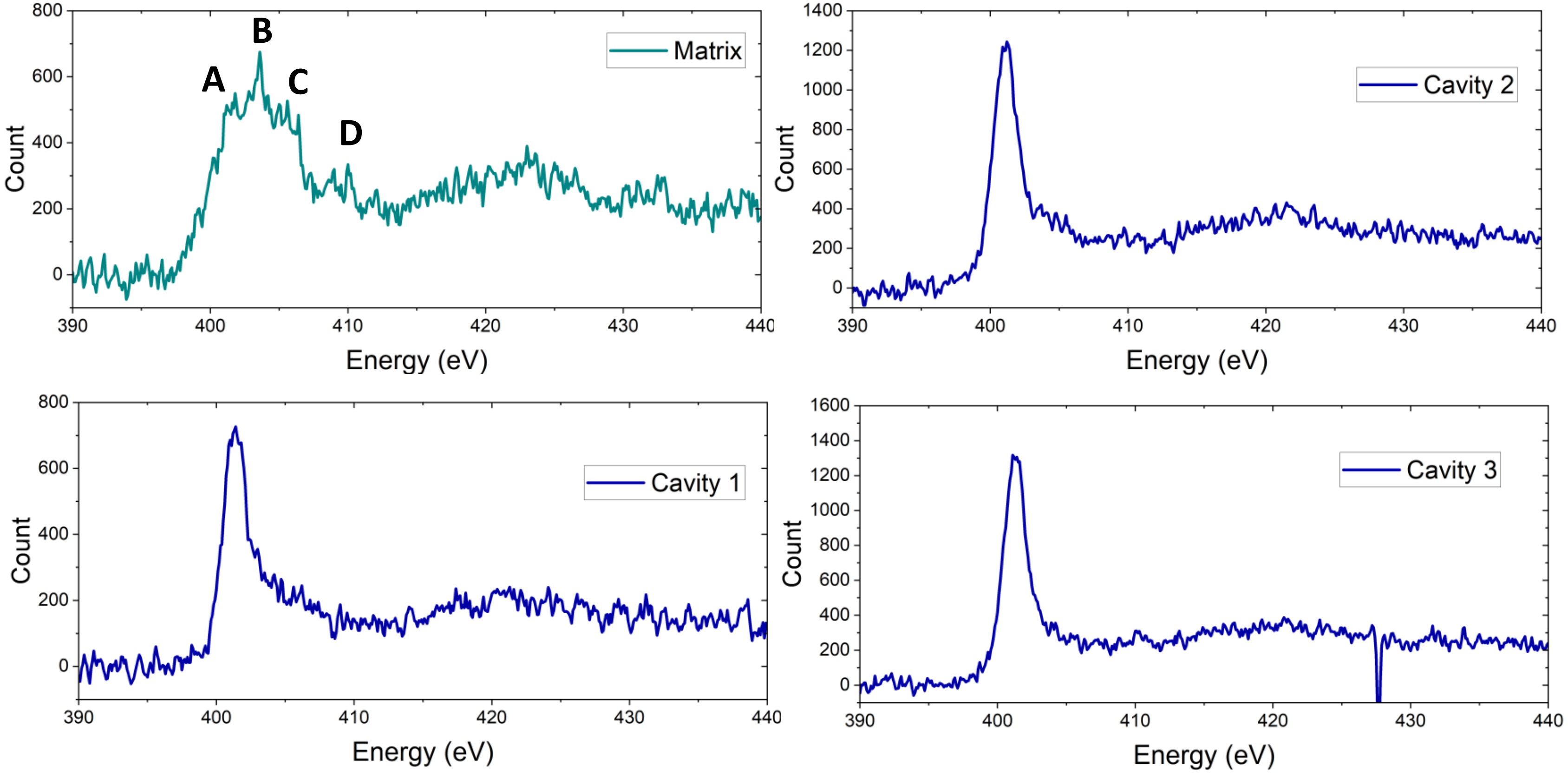
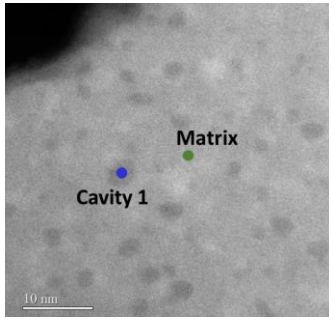
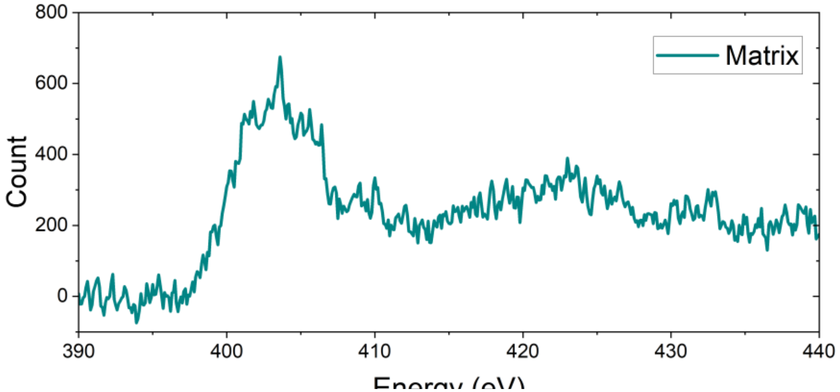
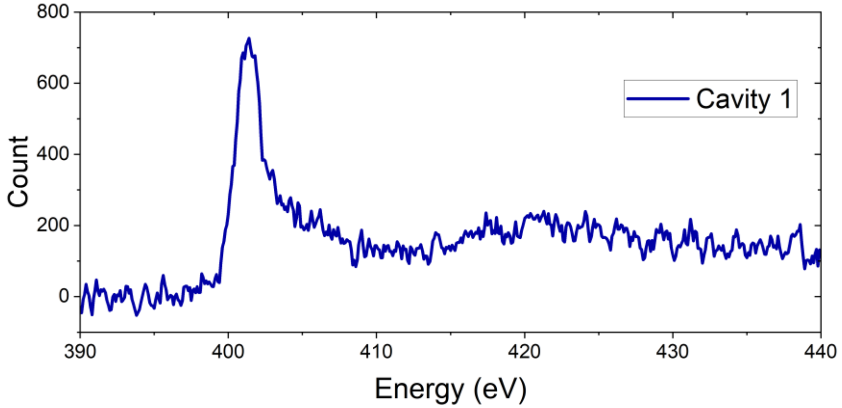


Nitrogen Measurement using Electron Energy Loss Spectroscopy (EELS)

- **GaN irradiated by 950 MeV Au**



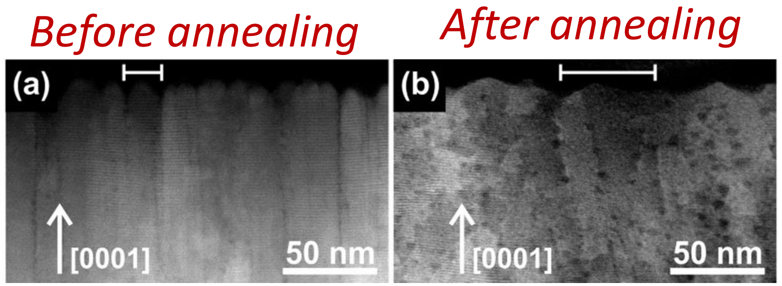


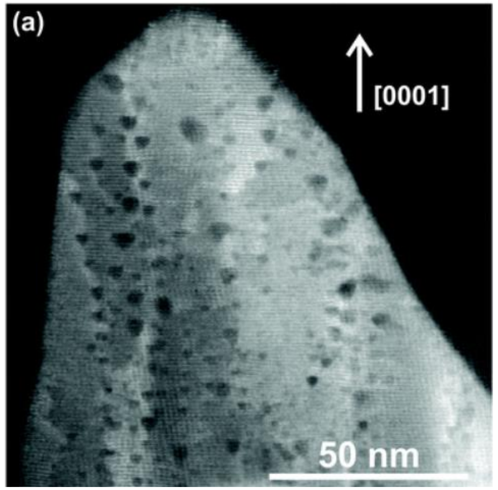


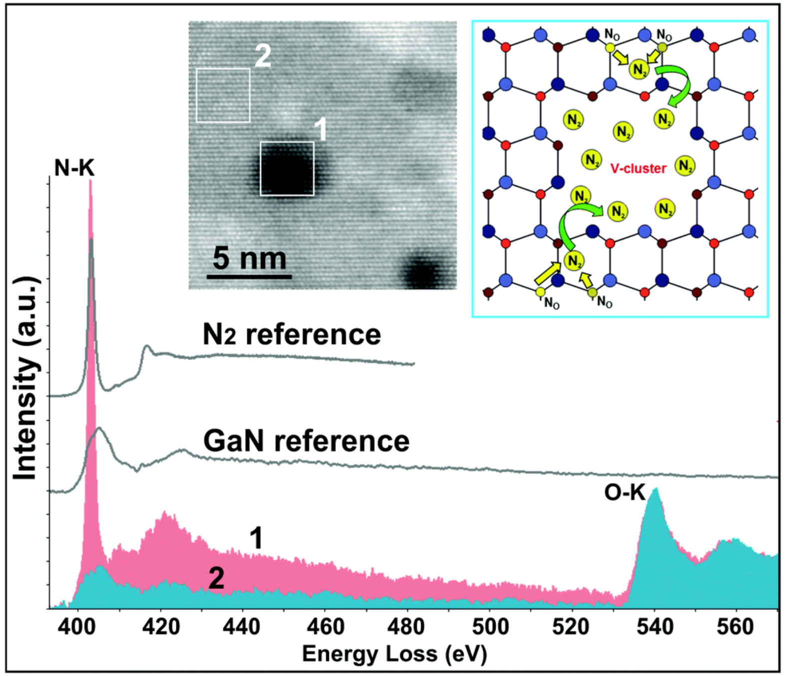
- **Annealing of $(ZnO)_{1-x}(GaN)_x$ thin film**

C. Bazioti, V.S. Olsen, A.Y. Kuznetsov, L. Vines, Ø. Prytz, Phy. Chem. Chem. Phy. 22 (2020), 3779.

- Magnetron sputtering to form thin film
- Annealing under N_2 environment at 800C for 1hr



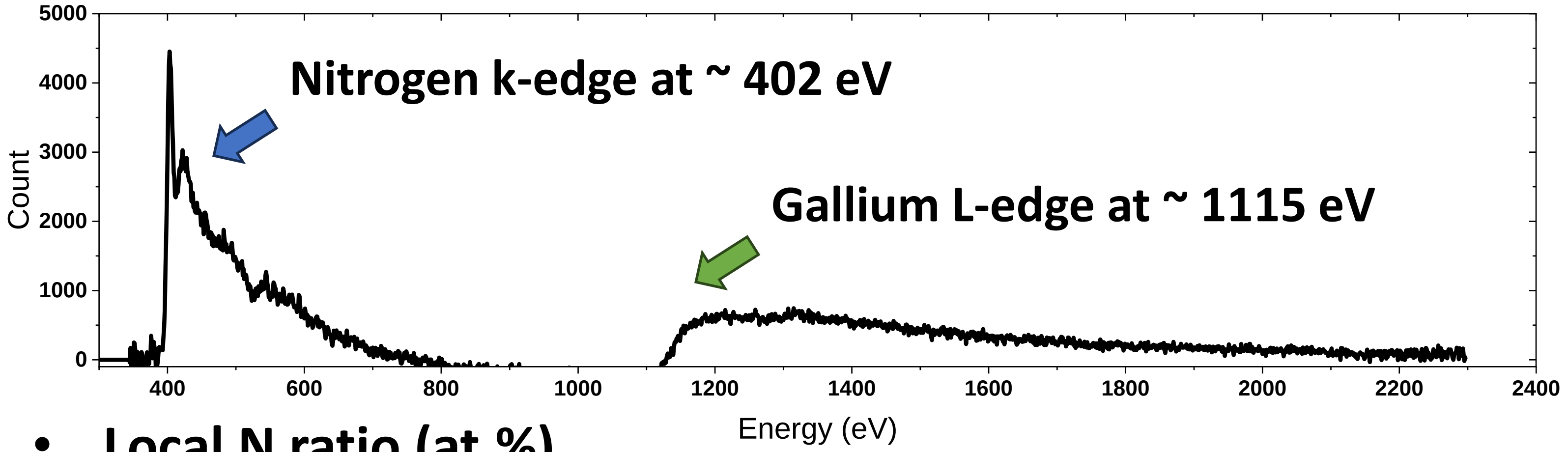




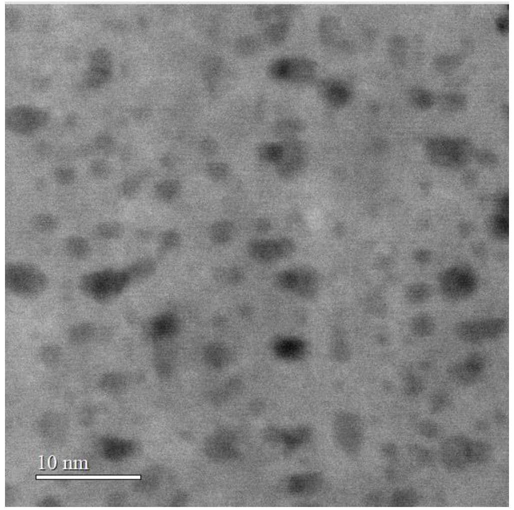
- Cavities formed near grain boundaries

Nitrogen Measurement using Electron Energy Loss Spectroscopy (EELS)

- **Wider EELS for measuring local N to Ga ratio**



$$\frac{N\ conc.}{Ga\ conc.} = \frac{N\ peak\ counts \times \sigma_{Ga}}{Ga\ peak\ counts \times \sigma_N}$$



- **Local N ratio (at.%)**

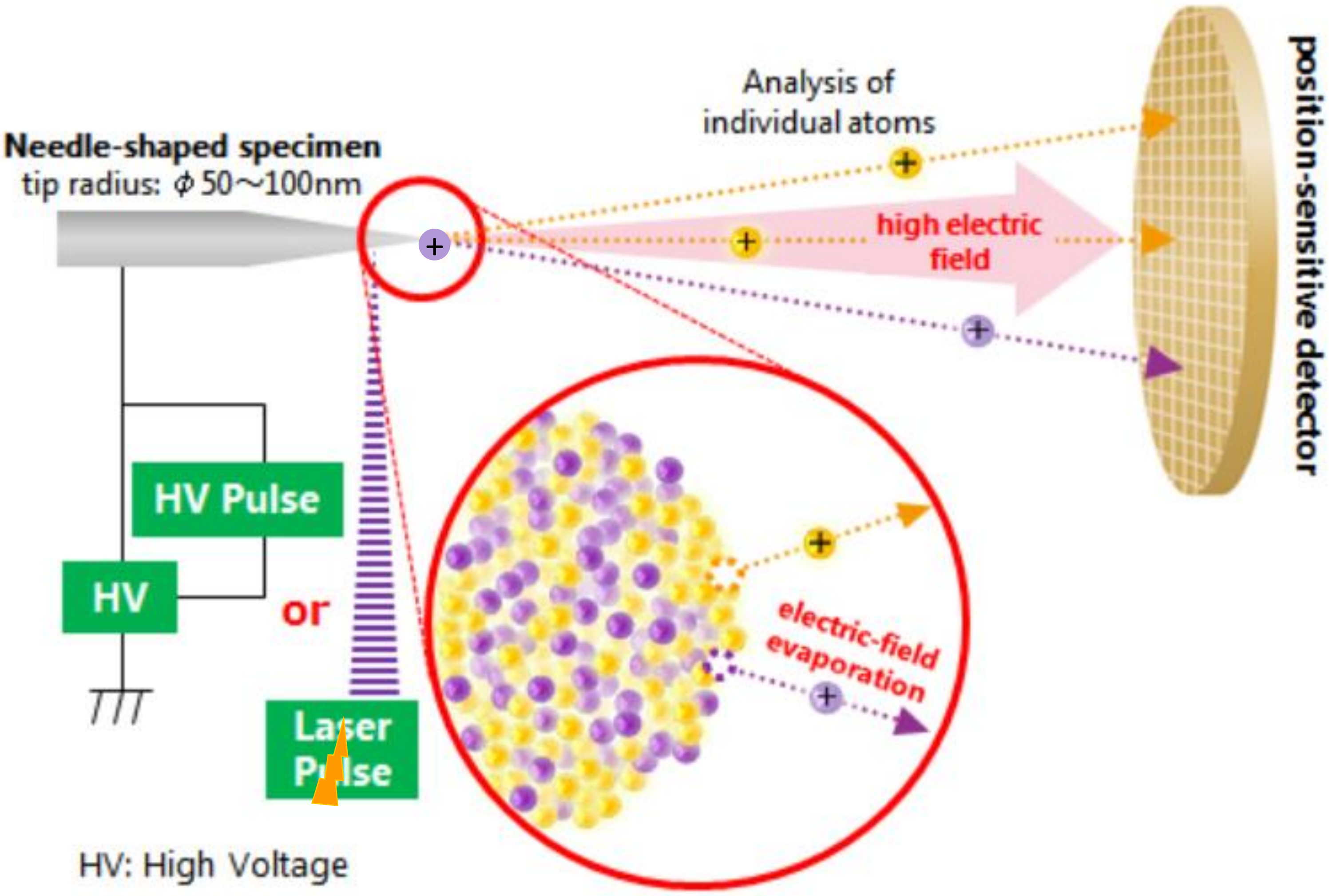
Measure.	1	2	3	4	5	6	Ave.
Cavities	37.1	43.5	37.5	39	36.2	36.5	38.3±2.5
Matrix	31.8	31.7	33.3	32	30.9	32	32.0±0.7

- **Potential EELS signals of N_2 were detected inside the cavities**
- **Cavities are slightly more enriched in nitrogen than matrix**
- **Potential Issues & Limitation**
  - *Beam damage from 300 keV electron used in STEM → will use 80 kV STEM*
  - *Effects of sample thickness on EELS background → will prepare thinner samples for EELS*
  - *Nanosized cavities are buried inside the TEM foil → averaging effect*

3D Segregation near Cavities – Atom Probe Tomography (APT) Characterization

- **APT: identify materials' composition atom-by-atom**
- **High sensitivity for most elements and isotopes (<10 ppm)**
- **3D reconstruction of atom positions and element type → no averaging effect**
- **APT sample temperature:**

30-50 K (< N_2 melting point 63.15K)



The basic principle of APT

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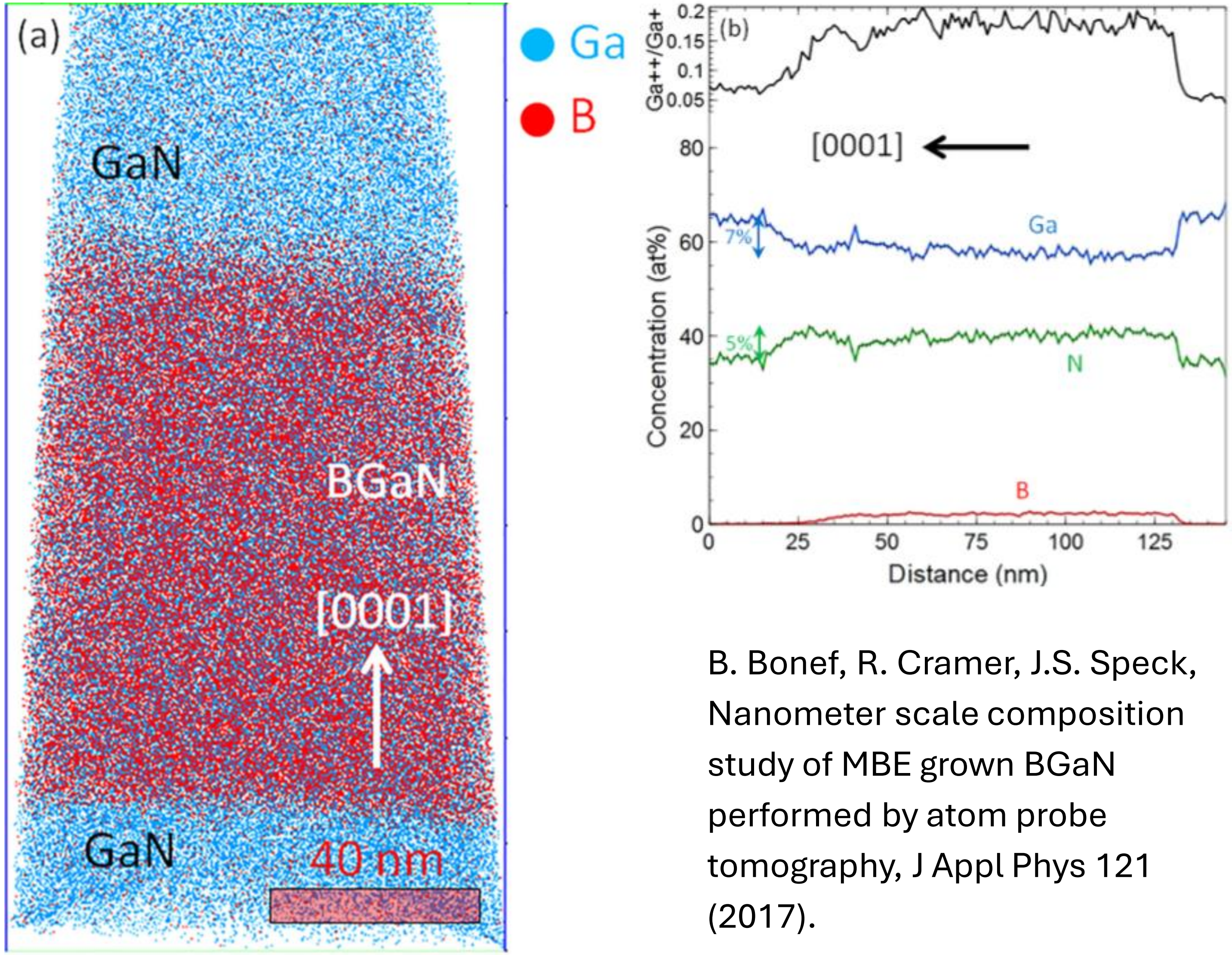


B. Bonef, R. Cramer, J.S. Speck, Nanometer scale composition study of MBE grown BGaN performed by atom probe tomography, J Appl Phys 121 (2017).

3D Segregation near Cavities – Atom Probe Tomography (APT) characterization

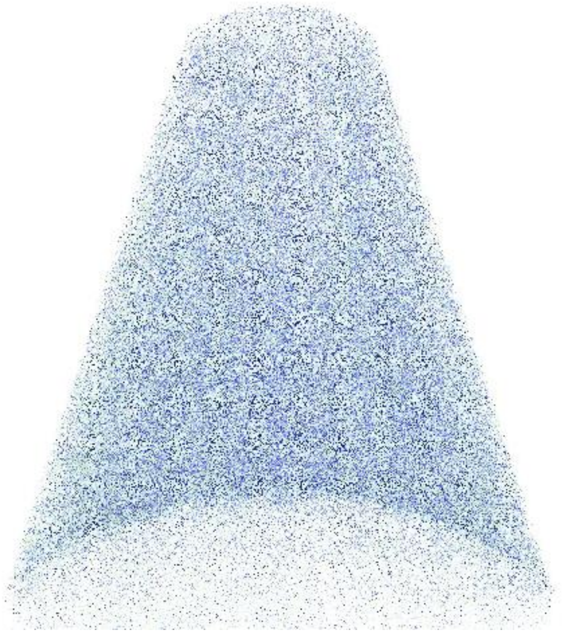
20 nm

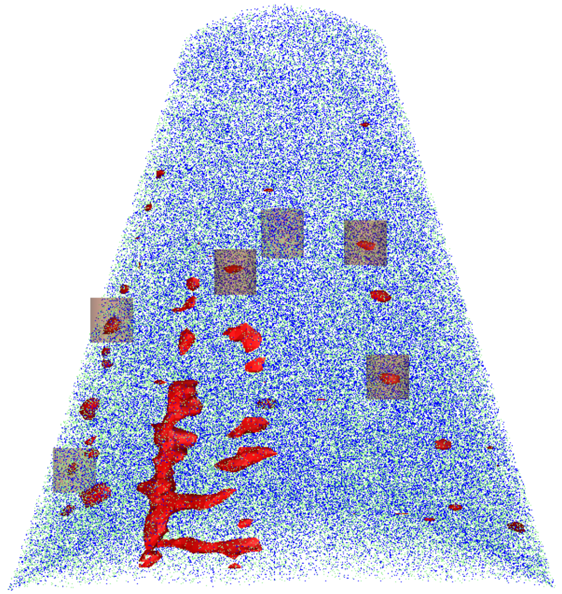
Ga

N

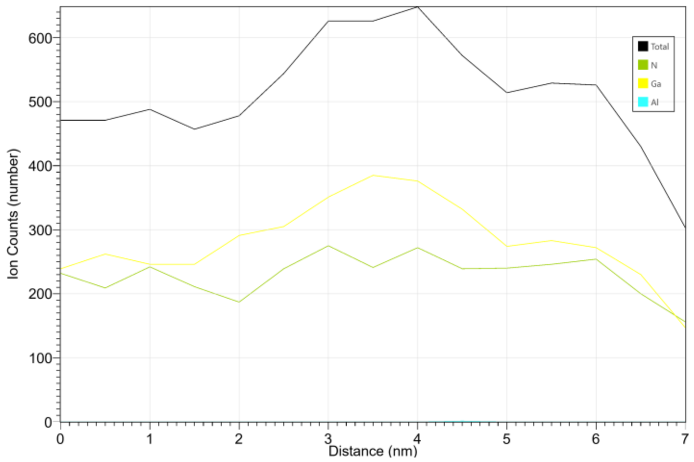
950 MeV Au

8 x 10^{12} cm^{-2}





- **No nitrogen-rich region could be detected**
- **Potential reasons: (1) N_2 may quickly evaporate under laser pulse even at 30 K; (2) Low N_2 concentration inside cavities**
- **If GaN dissociates, Ga-rich rims should form around cavities**
- **Multiple local regions showing slight Ga enrichment**
- **More APT with better controlled parameters (tip temperature, laser energy, etc.) will be conducted**

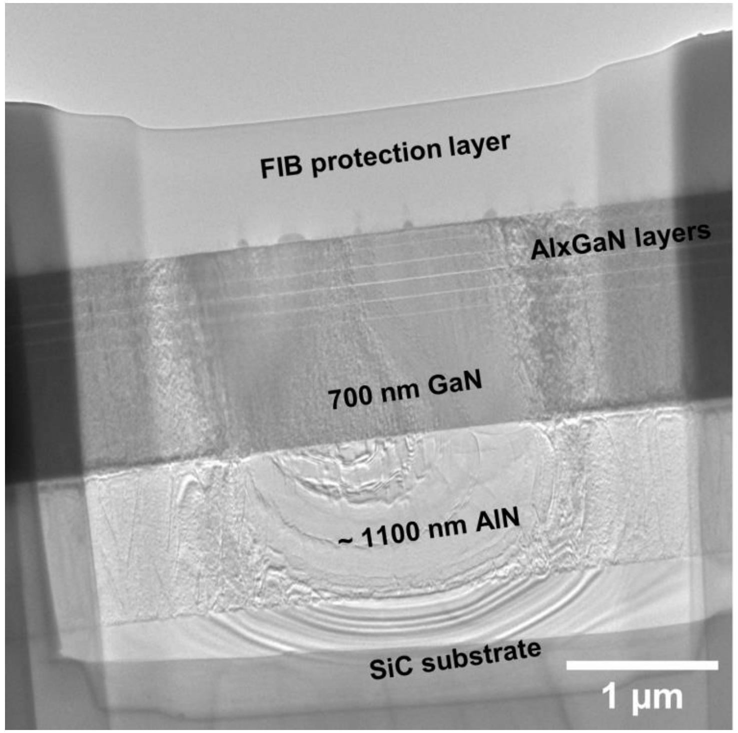


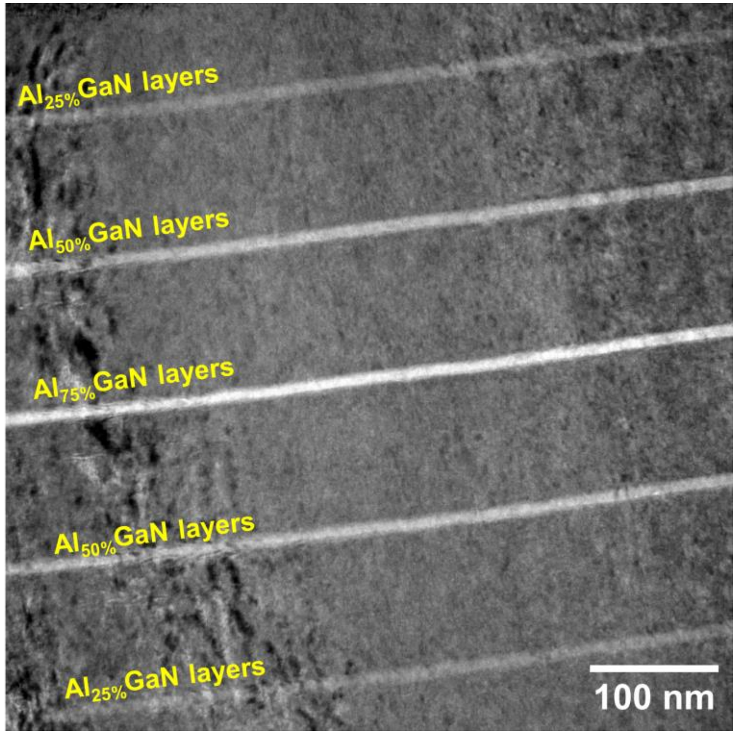
Total Cavities	Ga-rich	N-rich
15	14	1

Impact of Al concentration on cavity formation

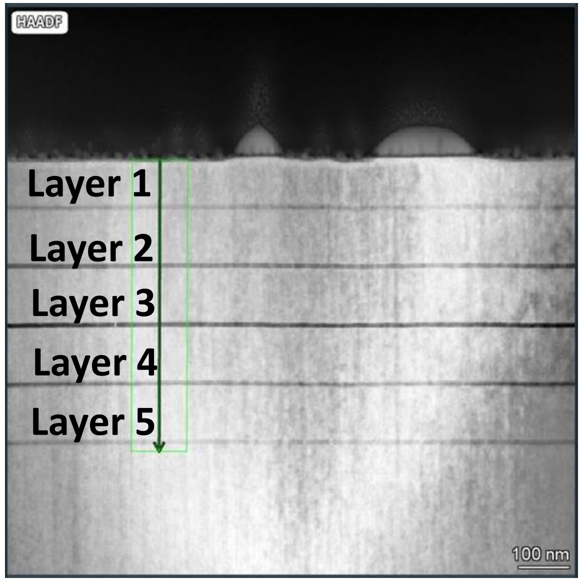
- **Multilayered sample fabricated by AFRL and irradiated by Prof. Maik Lang at UTK**
- **950 MeV Au ion; two different fluences; room temperature**

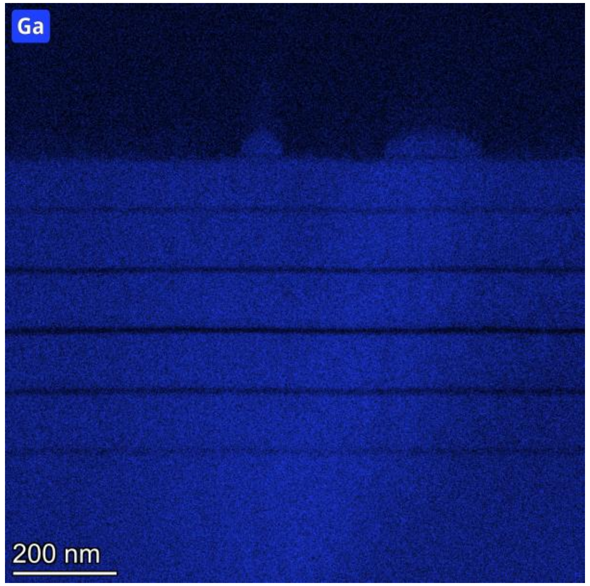
Sample	Pristine	Low-fluence	High-fluence
Fluence ($ions/cm^2$)	0	3e11	8e12

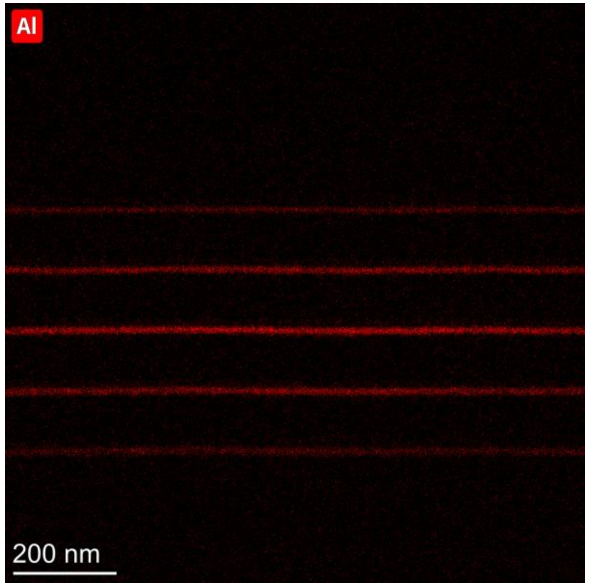


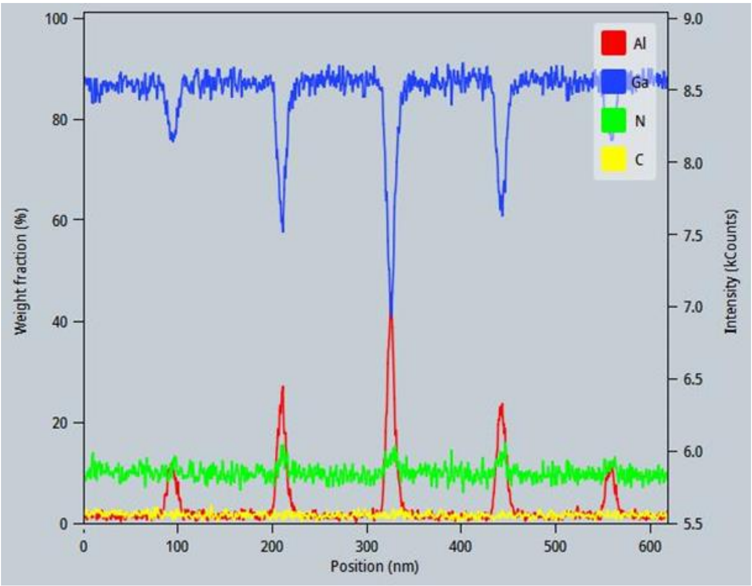


Impact of Al concentration on cavity formation





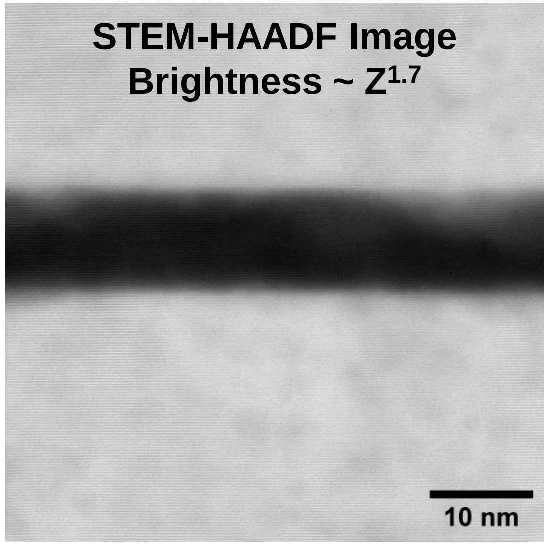




- **Al concentration: Layer 3 > Layer 2 or 4 > Layer 1 or 5**
- **More accurate composition measurement using RBS (from Prof. Maik Lang)**

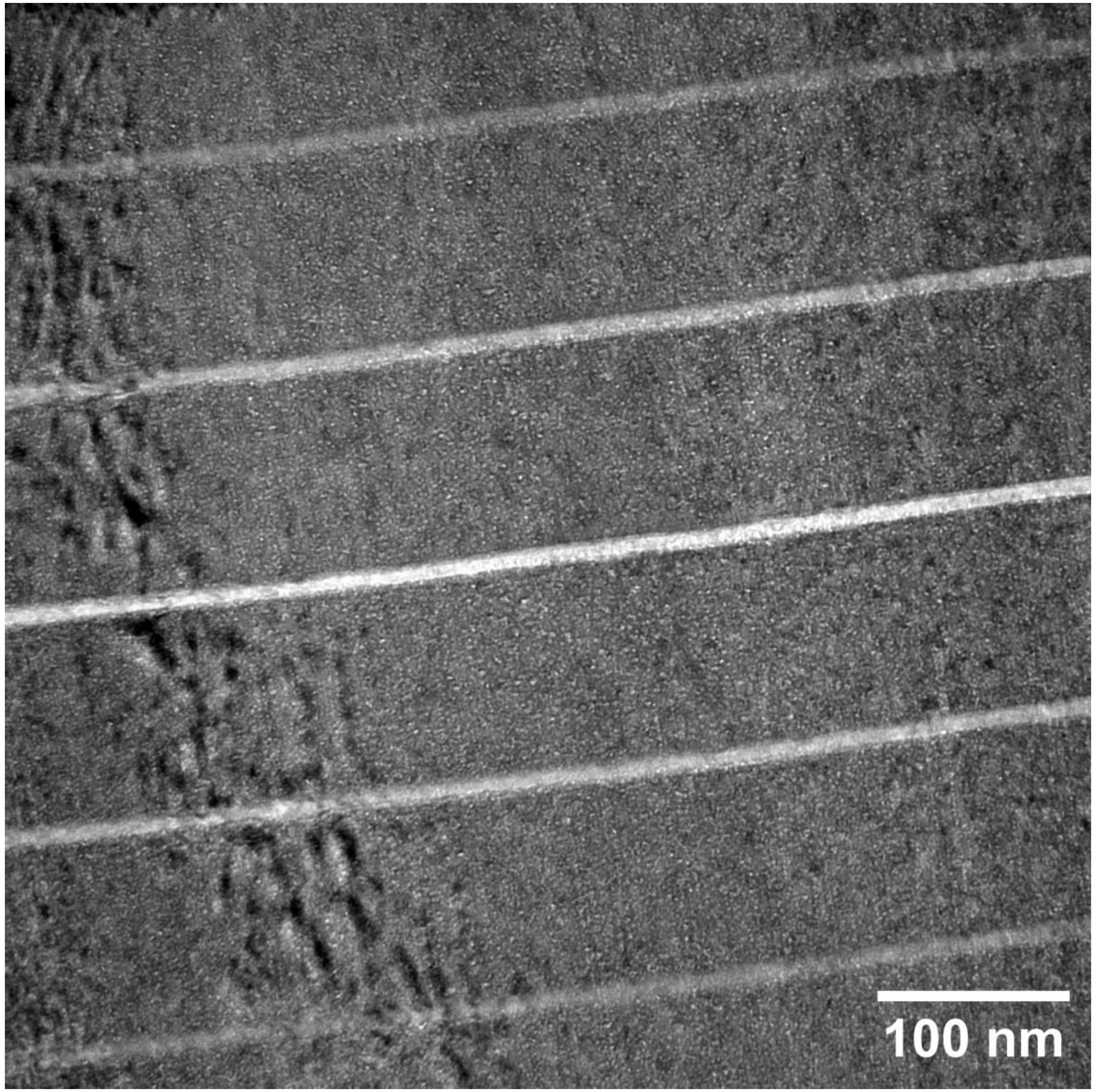
Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
17% Al	26.5%	37.5%	25.5%	26.5%

- **Element intermixing occurs between layers, likely due to fabrication & irradiation**



Impact of Al concentration on cavity formation

Under-focused TEM images

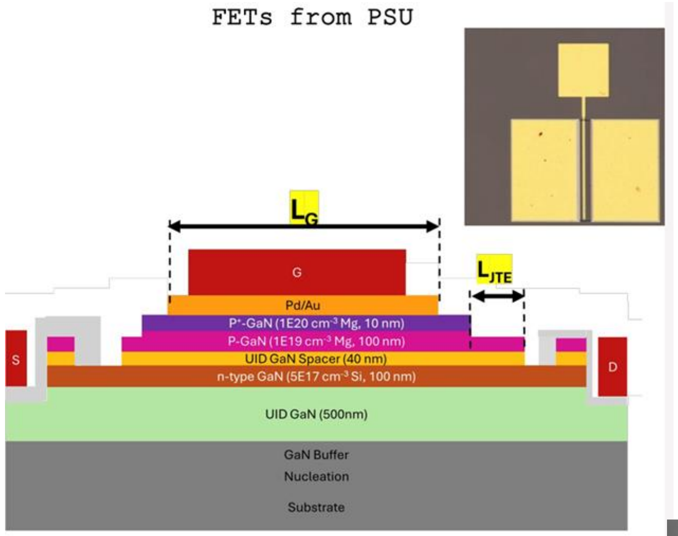


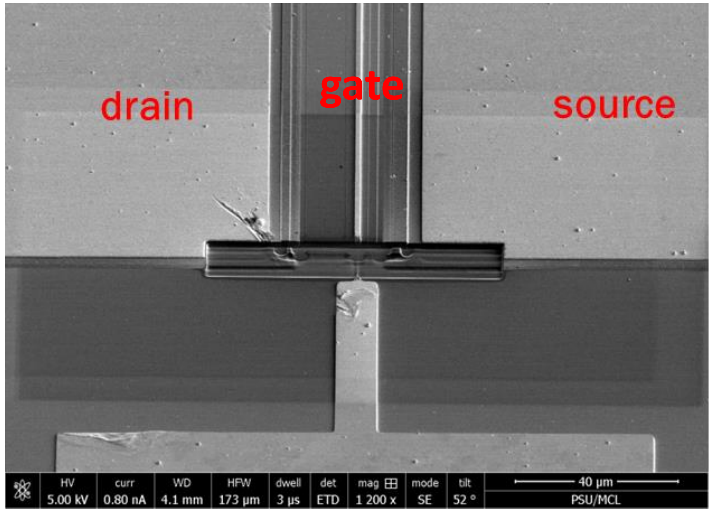
- **Cavity formation is reduced as Al concentration increases**
- **Results consistent with MD simulations**
- **Element intermixing at interfaces may cause cavity formation near Layer 3**
- **Analysis of similar samples with thick layers in collaboration with Prof. Reeja Jayan from CMU**

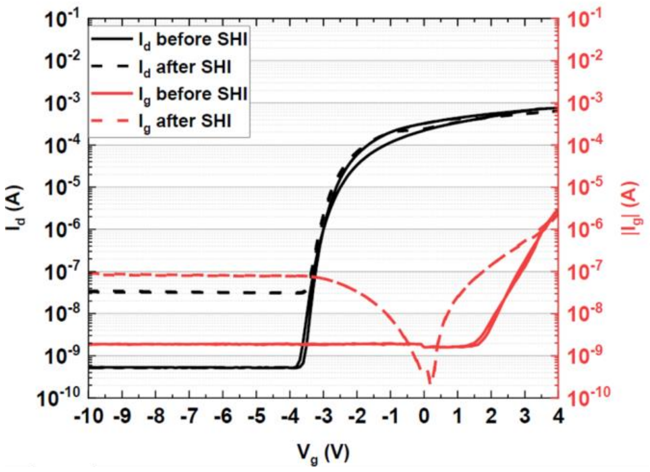
	Ave. cavity diameter (nm)	Cavity density ($1/nm^2$)
Layer 1	1.3	0.075
Layer 2	1.7	0.044
Layer 3	1.4	0.024

Impact of Cavities on GaN Properties and Device Performance

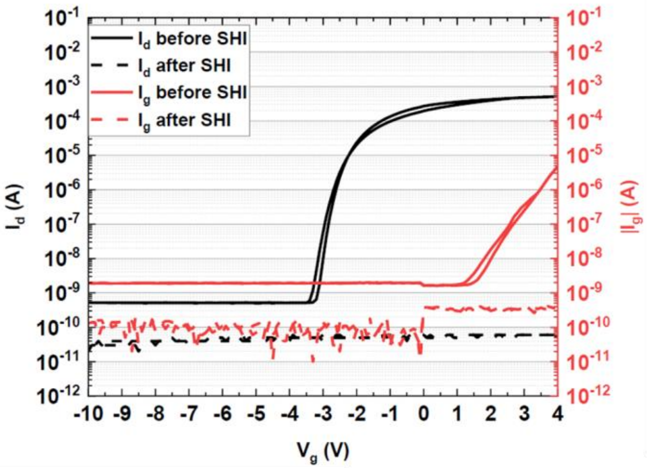
- **950 MeV Au ion**
- **Room temperature irradiation**
- **Two difference fluences:** *1×10^7 ions/cm^2 and 5×10^{11} ions/cm^2*





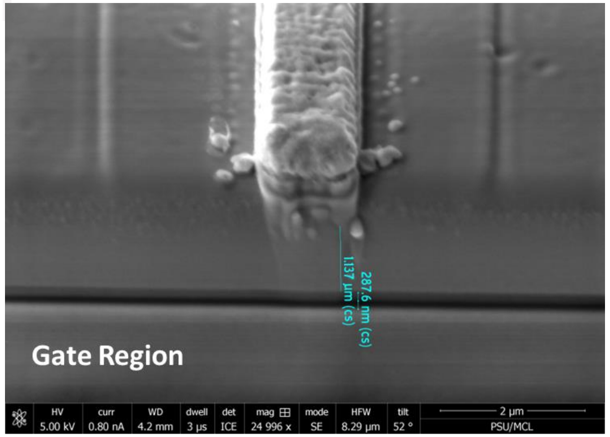


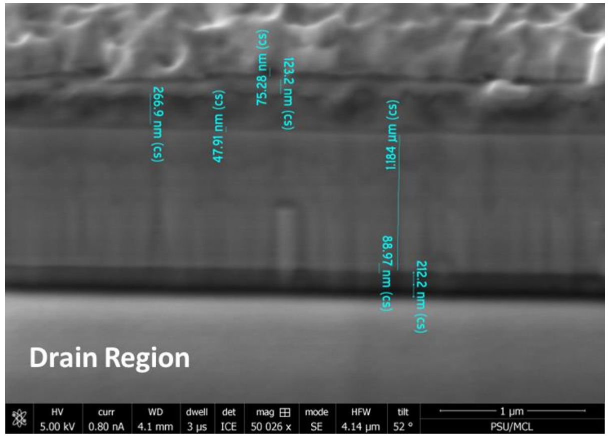
1×10^7 ions/cm^2



5×10^{11} ions/cm^2

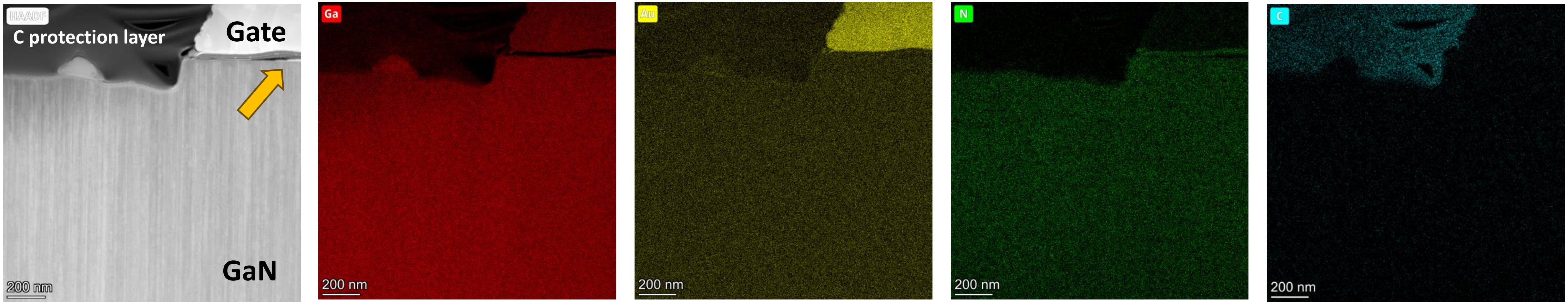
Device testing results from Prof. Chu's group

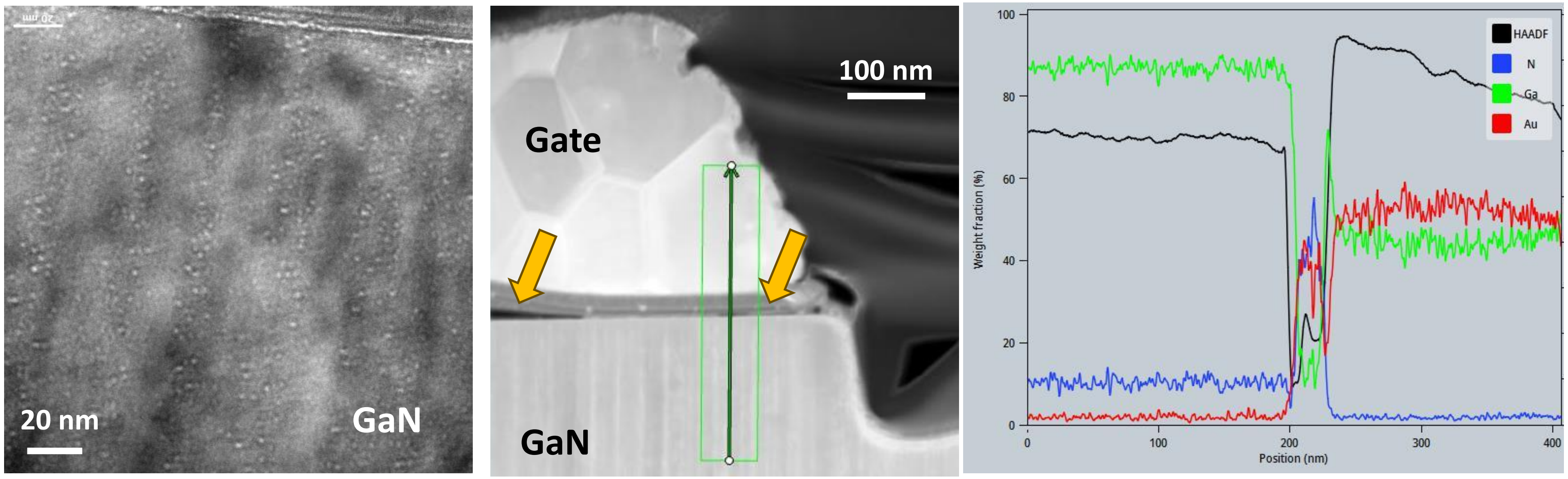




- **Despite high ion fluence and device failure, no delamination can be found using FIB-SEM**

Impact of Cavities on GaN Properties and Device Performance – TEM analysis





- **Dense nano-sized cavities in GaN**
- **Gaps between gate and GaN**
- **A layer of different composition between GaN and gold gate**

Conclusions

- Potential EELS signals of N_2 were detected inside the cavities; Cavities are slightly more enriched in nitrogen than matrix → Potential GaN dissociation under SHI irradiation
- APT did not observe nitrogen-rich regions
- As aluminum concentration increases in Al_xGaN, the cavity density decreases, which is consistent with MD simulation

Future Work

- Analysis of low-fluence samples (1E10-1E11 ions/cm^2) to identify single track effect, *in collaboration with Dr. Maik Lang and AFRL*
- Role of N2 and Al concentration in cavity formation, *in collaboration with Dr. Mia Jin at Penn State*
- Impact of swift heavy ion on devoices, in collaboration with Dr. Rongming Chu
- Local strain near surfaces and interfaces, in collaboration with Dr. Reeja Jayan

Thank you!

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