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Growth of $B_xAl_{1-x}N$ Alloys by Metalorganic Vapor Phase Epitaxy – Towards a Lattice-Matched Ultra-Wide Bandgap Semiconductor

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ULTRAWIDE BANDGAP
POWER ELECTRONICS

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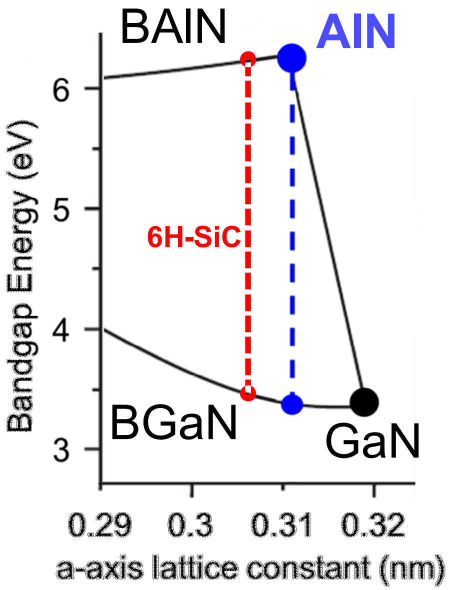
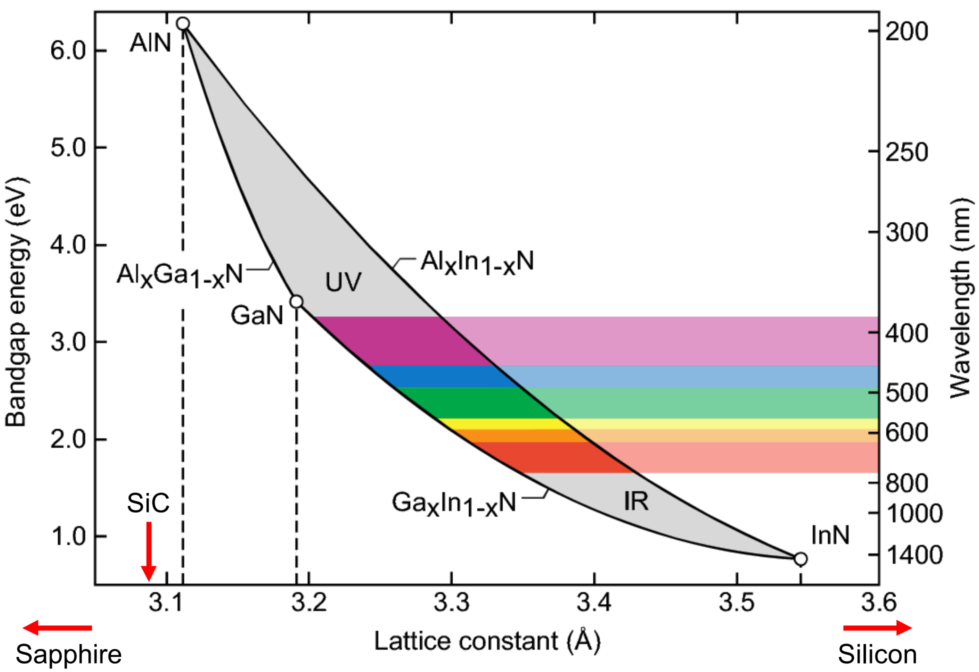
Outline

- **Background**
  - Dislocation generation
  - Opportunities for lattice-matched epitaxy
- **Preliminary BAlN growth study**
  - Low-temperature growth
  - Pulsed/modulated growth
  - H_2 ambient
- **Structural & electrical characterization**
  - TEM microstructure
  - CV characteristics



III-Nitride Challenges

Substrate choice and trade-offs

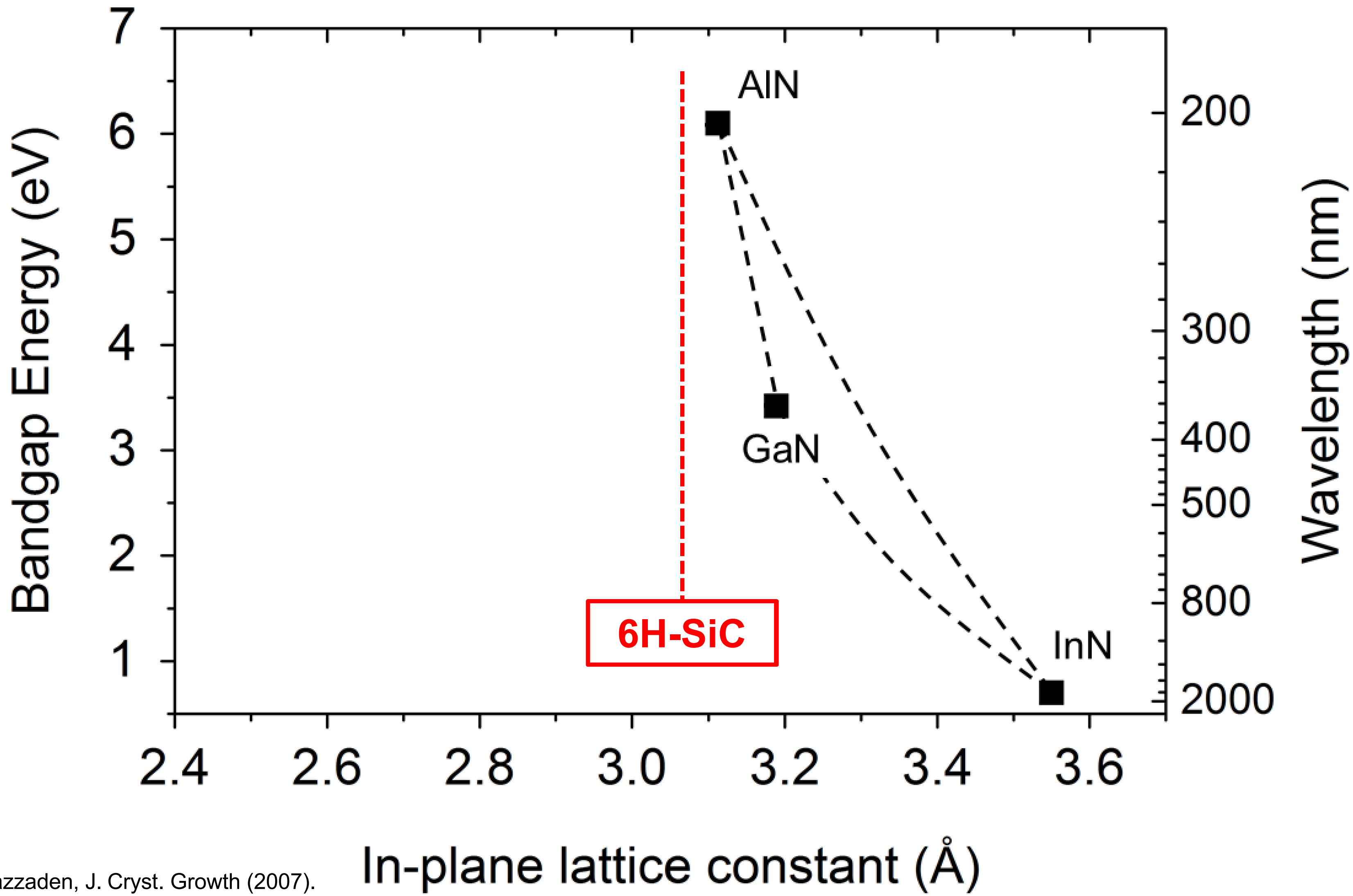


M. F. Schubert, Ph.D. Thesis, Rensselaer Polytechnic Institute (2009).

Substrate	*Mismatch vs. GaN*	*Additional notes*
Sapphire	14%	**Cheap**, electrically and thermally insulating
SiC	3.4%	**Expensive**, electrically and thermally conductive
Si (111)	17%	Cheap, mature, **forms amorphous SiN layer**
Bulk AlN	2.4%	**Expensive**, maturing technology
Bulk GaN	0%	**Expensive**, maturing technology

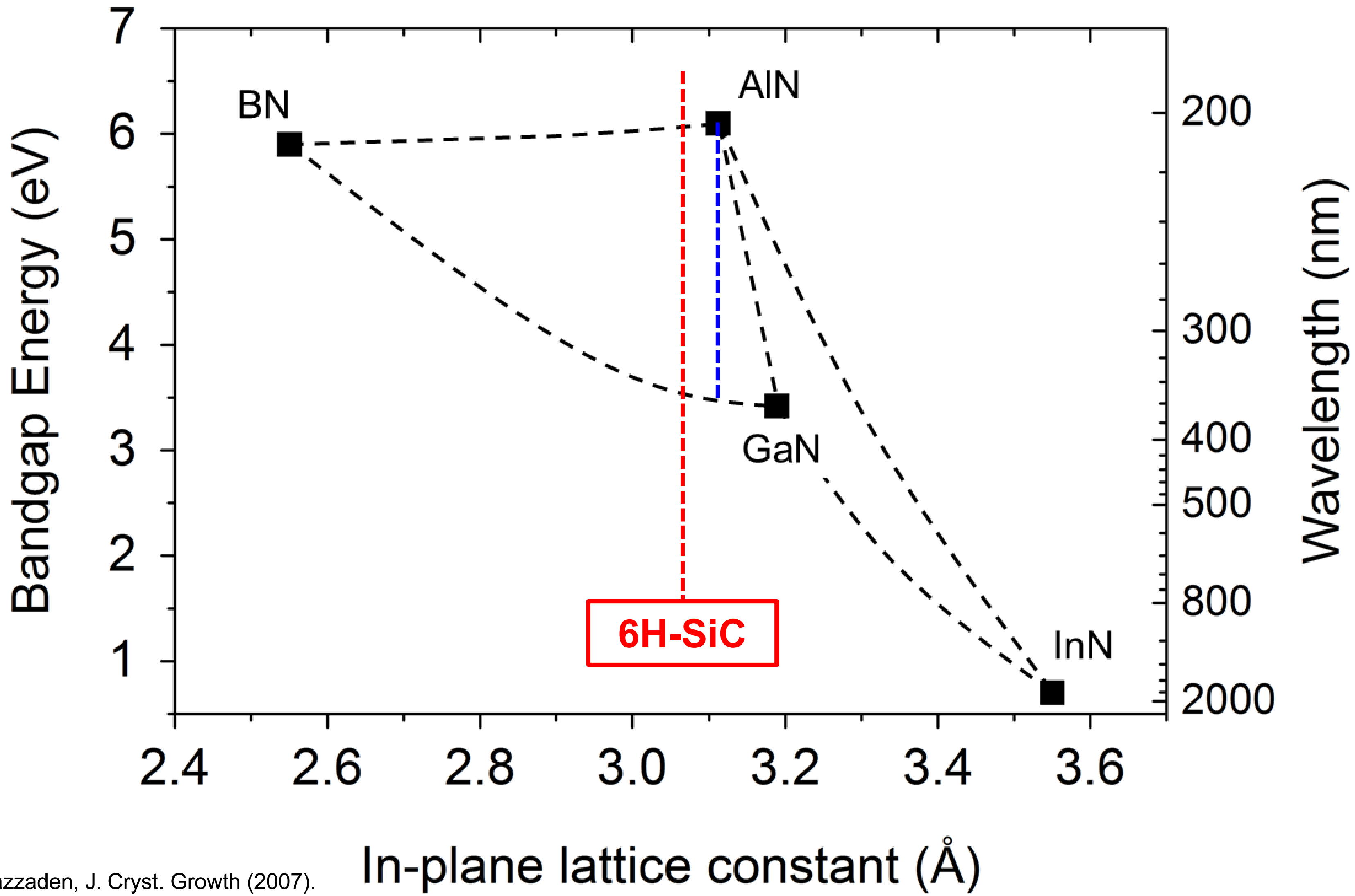
No native substrate for AlGaN alloy growth

InAlGaN materials system



after Ougazzaden, J. Cryst. Growth (2007).

Boron-containing nitride alloys



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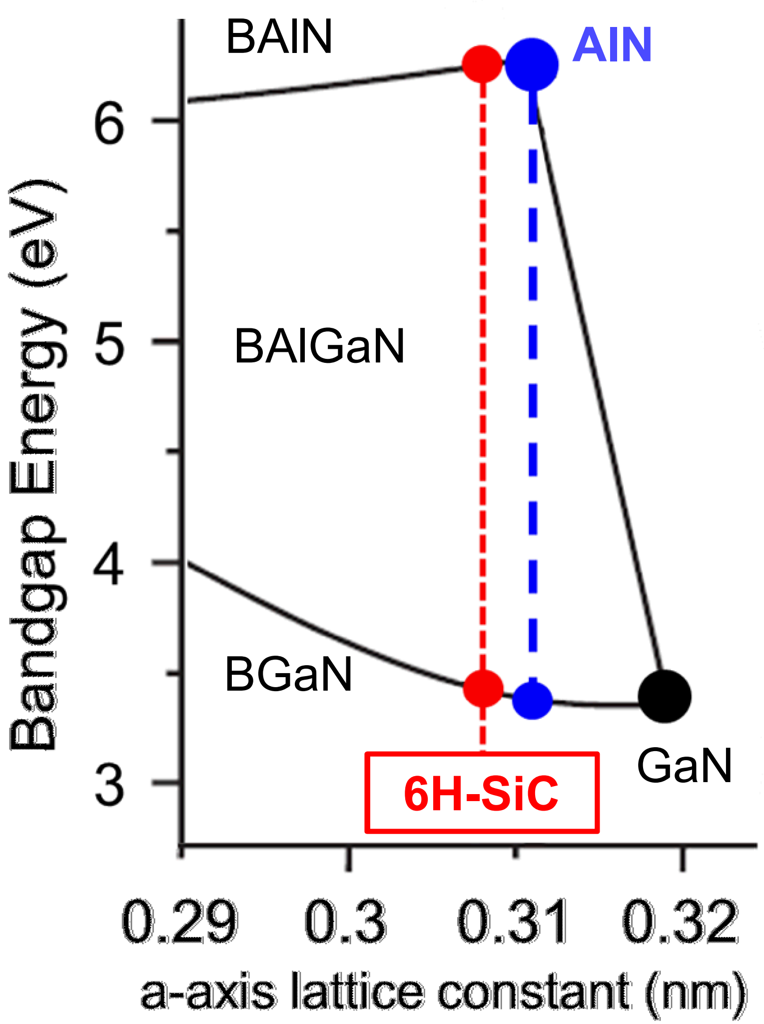
BGaN and BAlN

Expanded view:



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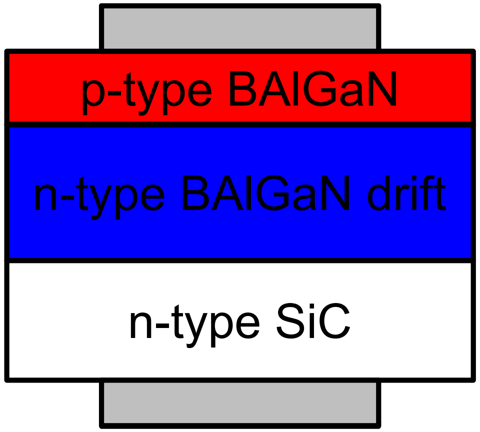
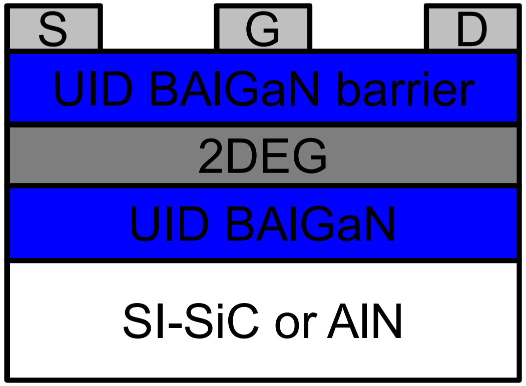
Lattice-matching opportunities:

$B_{0.12}Ga_{0.88}N$ on AlN
$B_{0.17}Ga_{0.83}N$ on 6H-SiC
$B_{0.05}Al_{0.95}N$ on 6H-SiC

Device prospects:



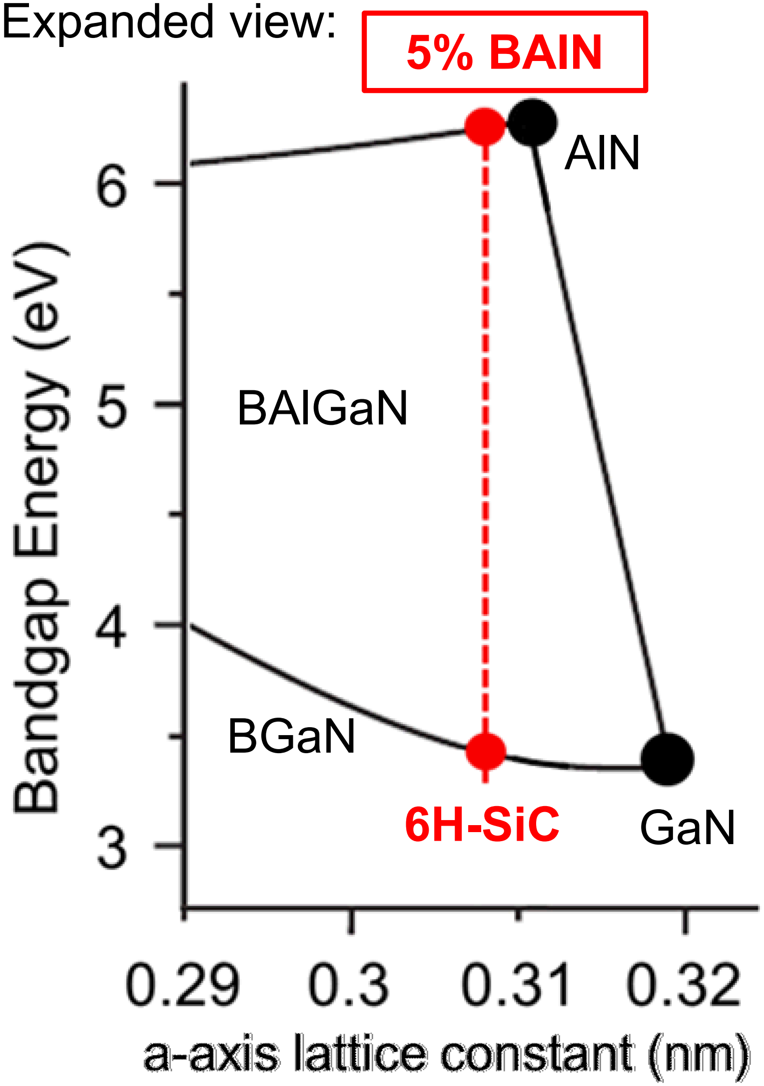
Two-terminal vertical device



Three-terminal lateral device

BGaN and BAlN

Expanded view:



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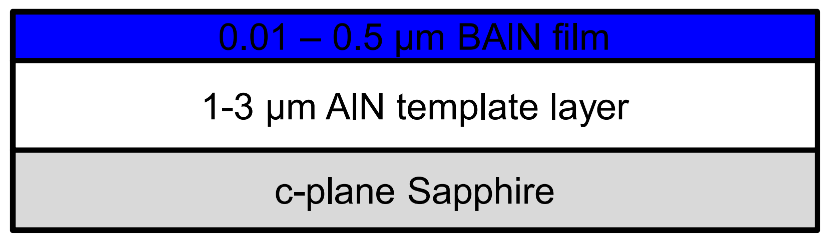
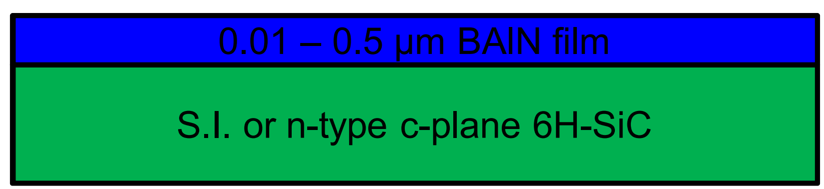
Growth structures:



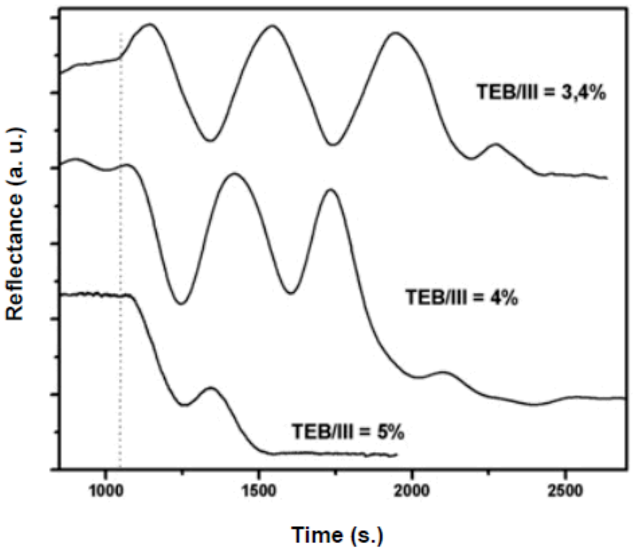


Challenges in BAlGaN Growth

Growth of BAlGaN alloys not yet extensively studied

- Few groups actively publishing on BAlGaN
- Typical B mole fractions **less than 5%**
- Simplistic calculations of B% in literature
- Rough surfaces, poor crystal quality

in situ reflectance



Potential obstacle with B miscibility in AlN/GaN

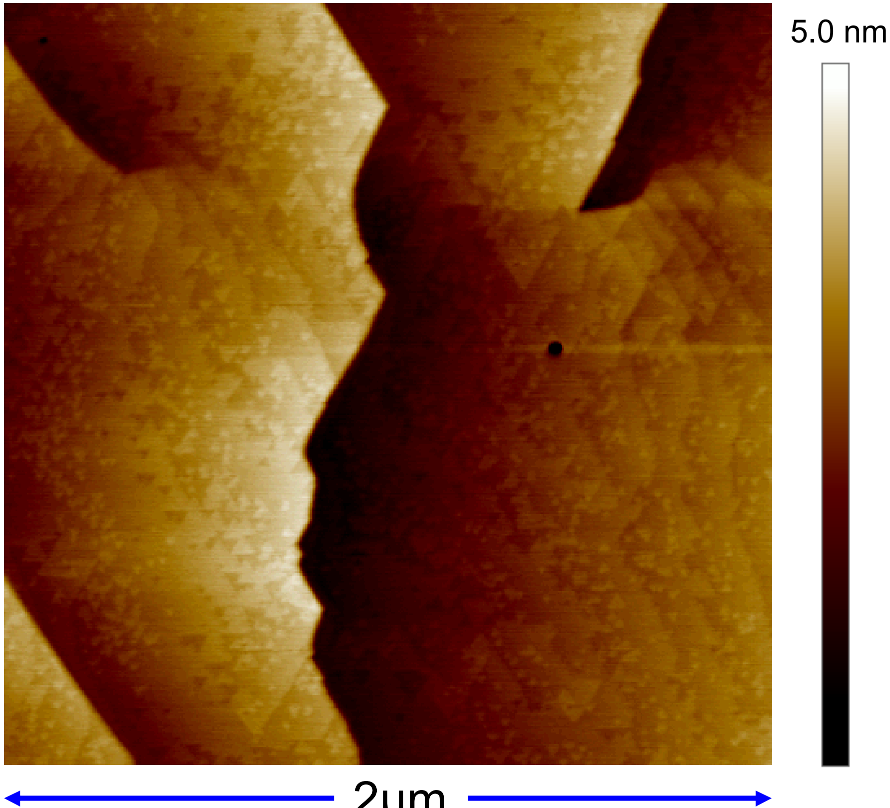
- Calculated miscibility gap beginning at ~5% B in GaN
- Phase mismatch – hexagonal (2D) BN vs. wurtzite AlN/GaN

V. Ravindran, Ph.D. Thesis, Georgia Institute of Technology (2013).

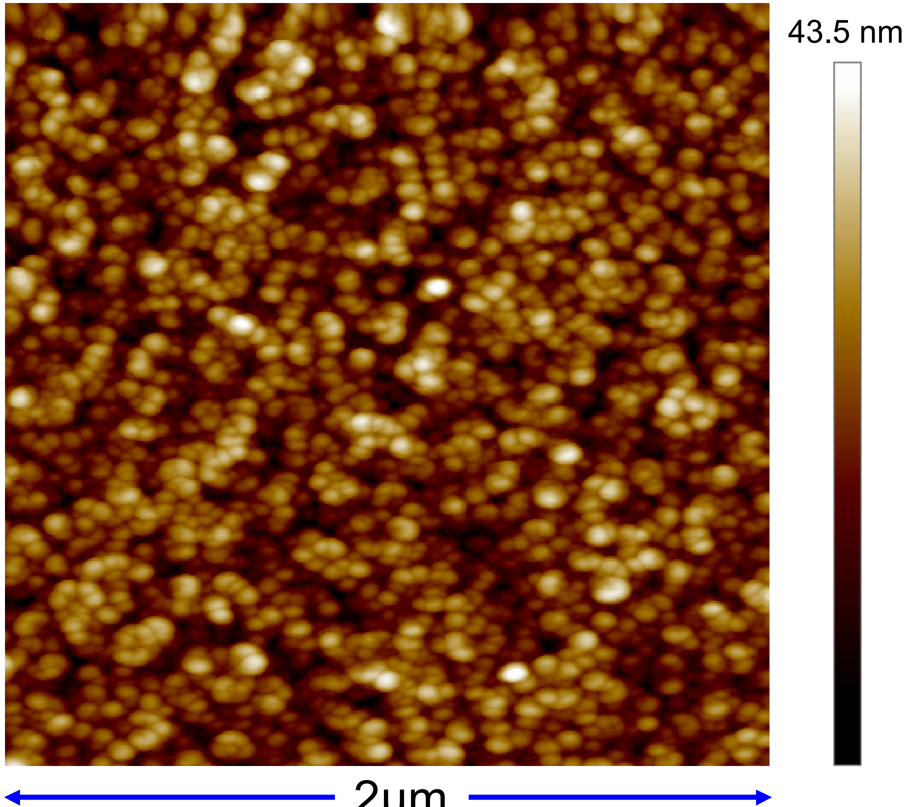
Initial BAlN Growth on AlN

- 1070°C, H_2+N_2 ambient, 75 Torr
- 10 µmol/min TMA, 0% or 5% TEB, 20 sccm NH_3

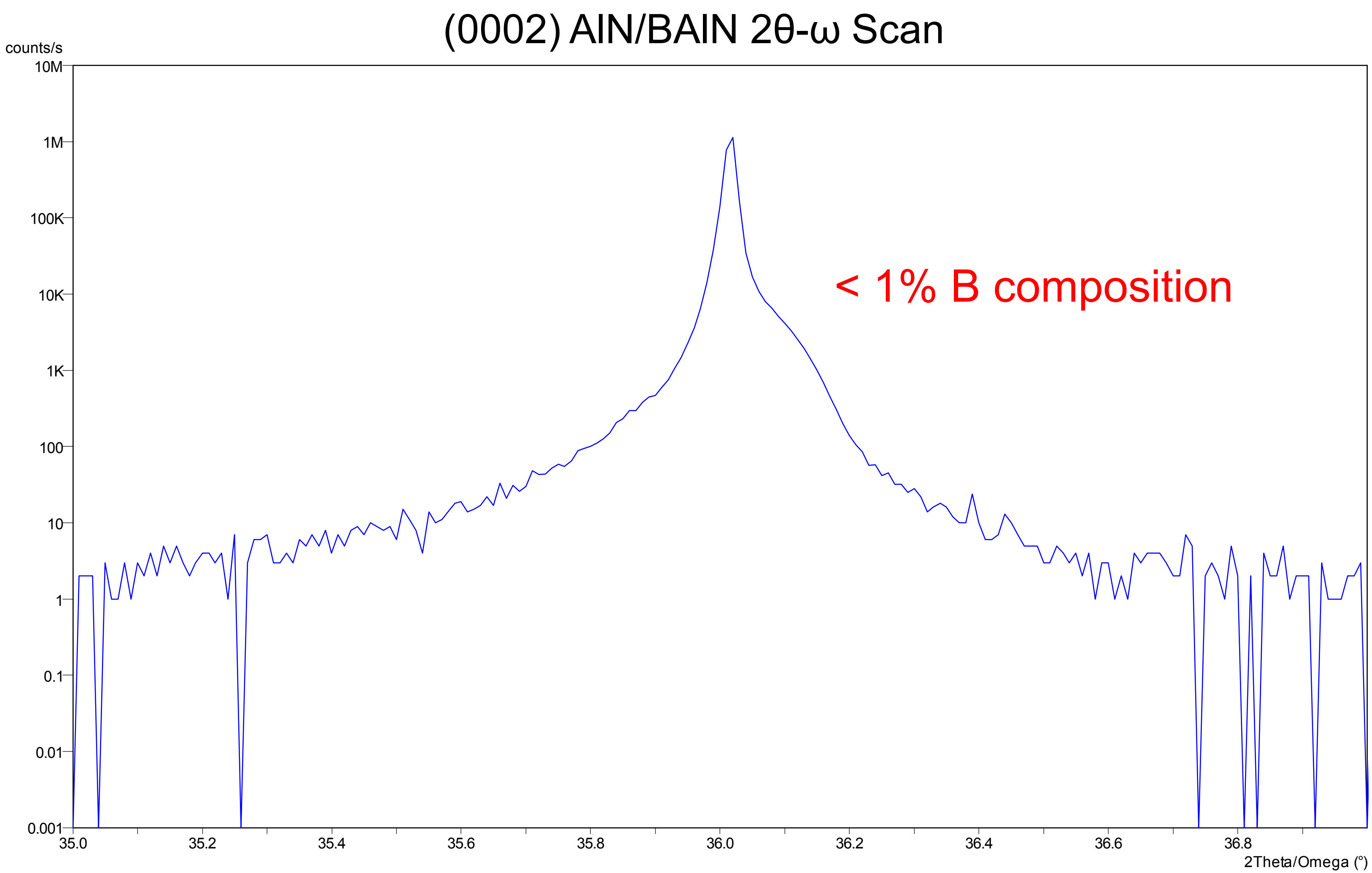
No TEB – 0.8 nm RMS



5% TEB – 6.5 nm RMS

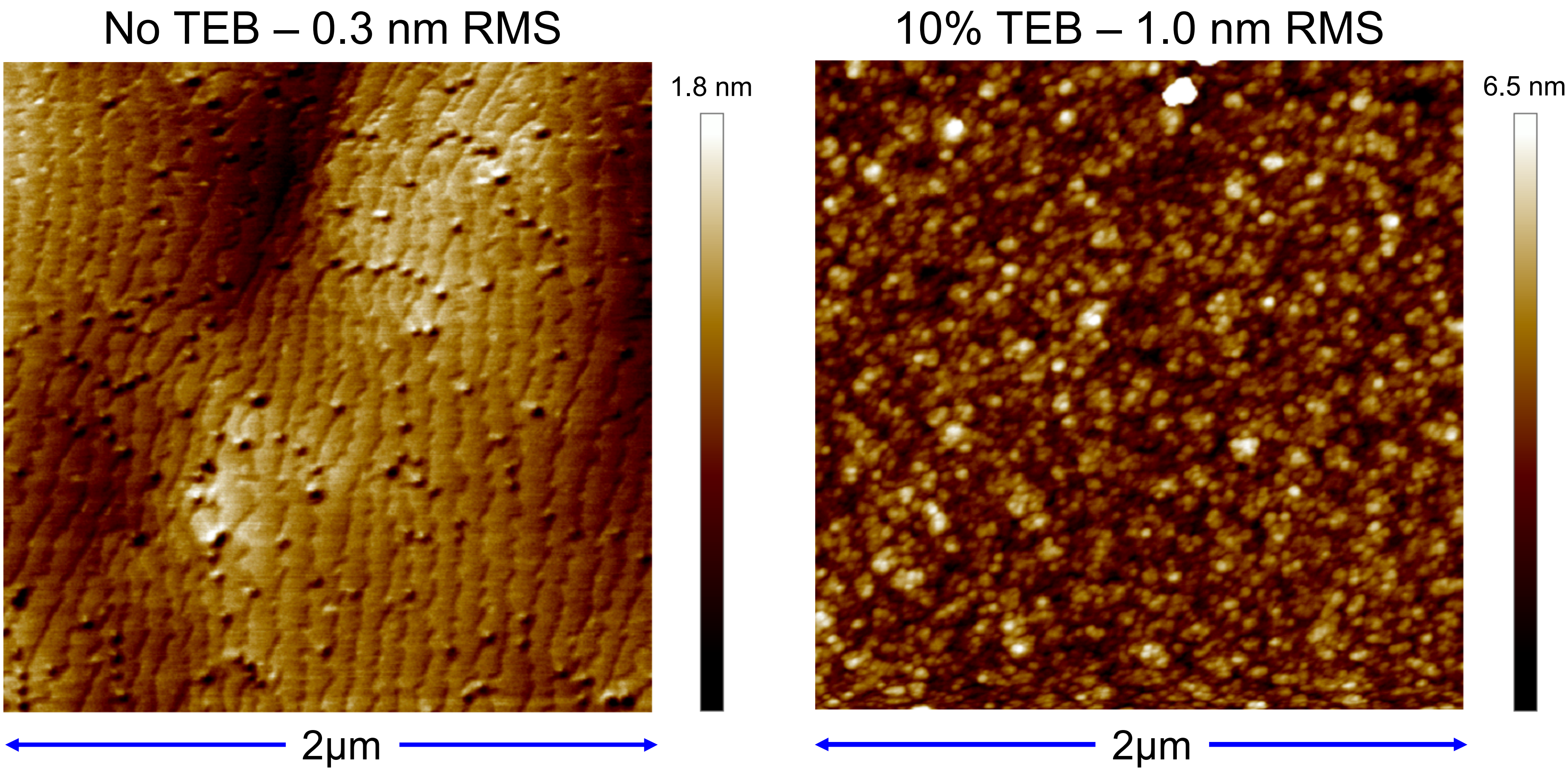


Initial BAlN on AlN

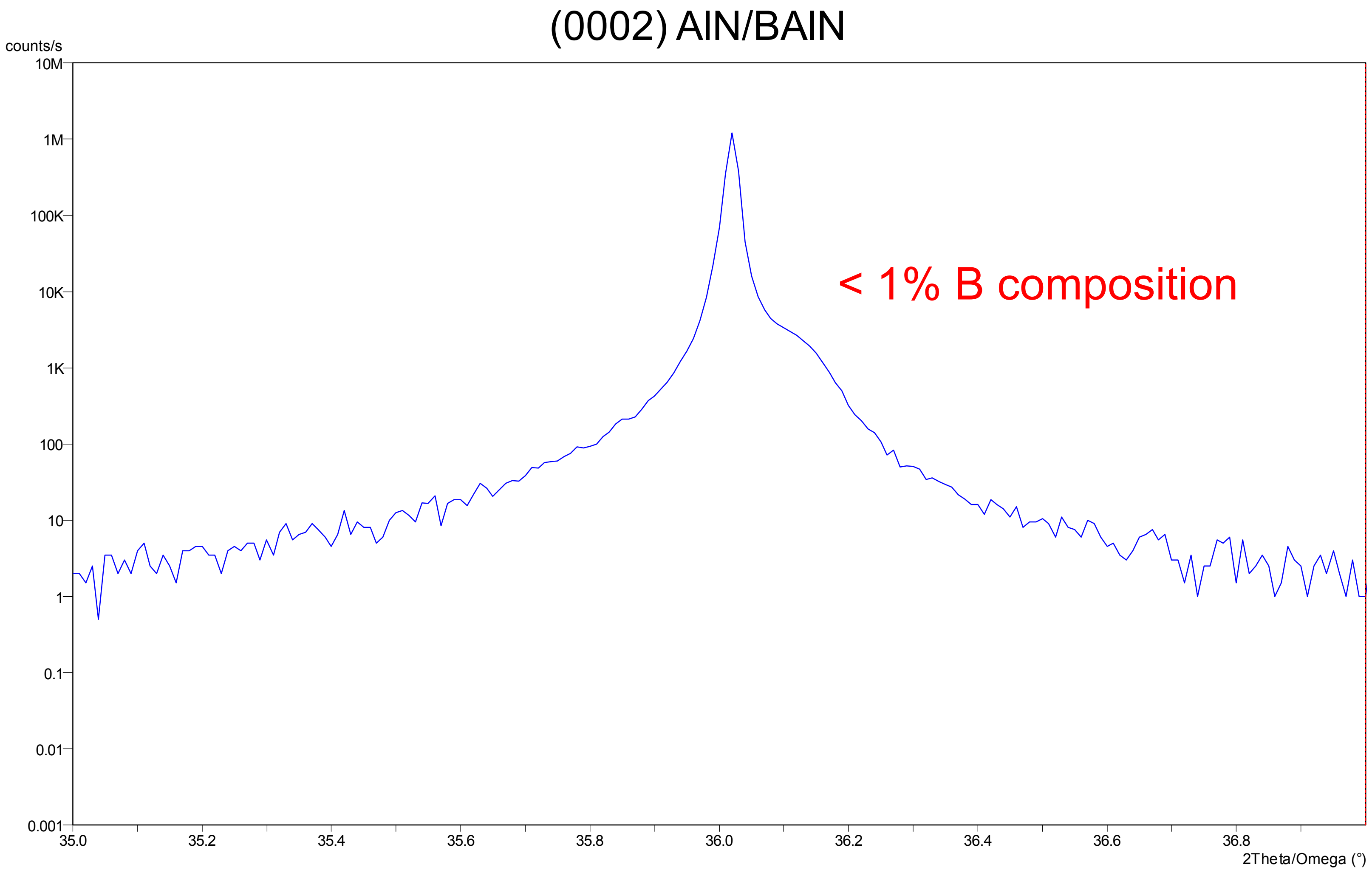


Pulsed BAlN on AlN

- Pulse sequence: 3s MO / 3s NH_3
- 1070°C, 20 Torr, H_2 ambient
- 10 µmol/min TMA, 10% TEB, 15 sccm NH_3



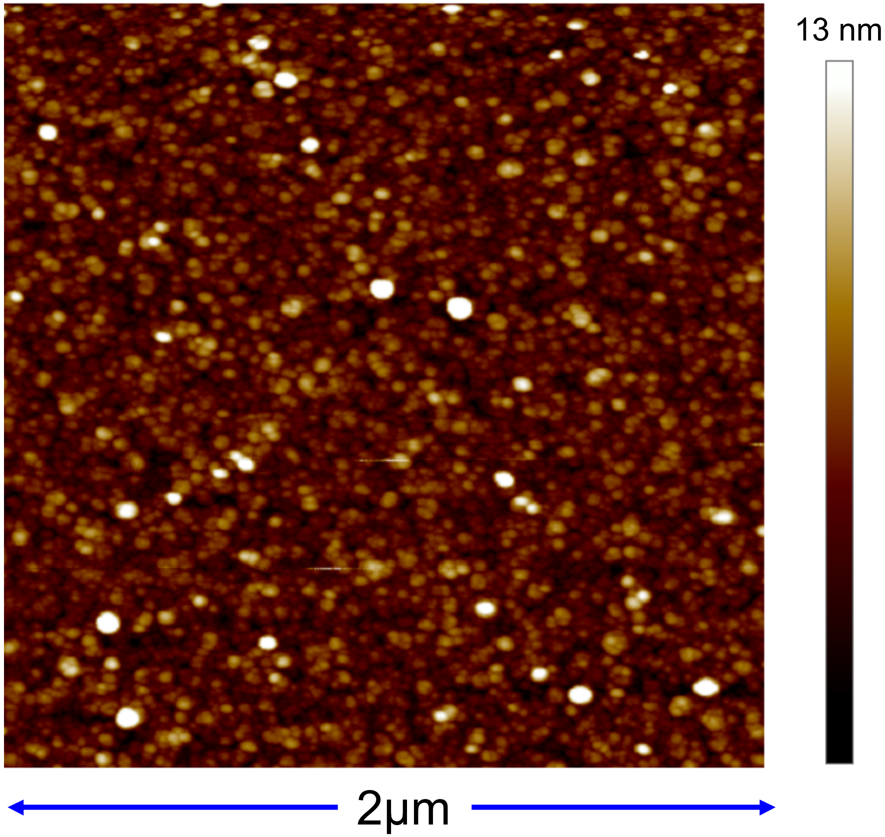
Pulsed BAlN on AlN



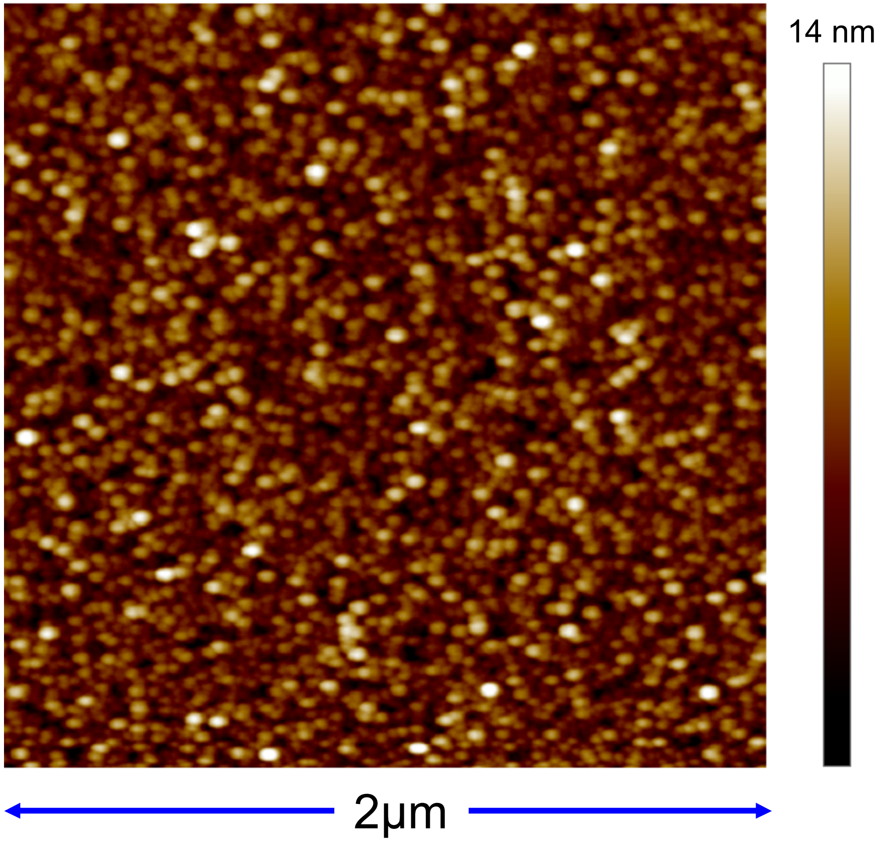
Low-temperature pulsed BAlN: AlN vs. SiC Substrate

- 980°C, H_2 ambient, 10% TEB, pulsed 3s MO / 3s NH_3

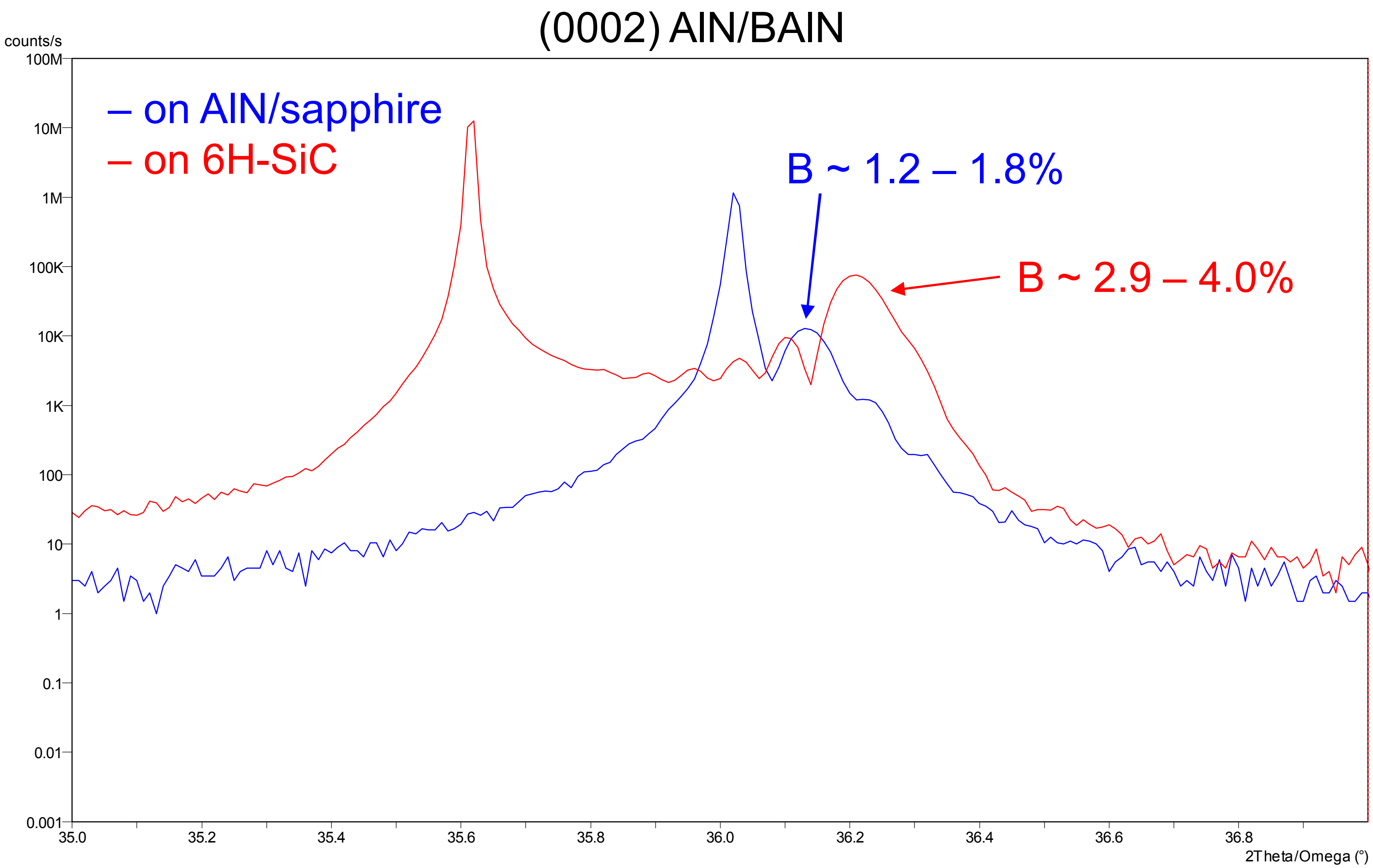
On AlN – 1.8 nm RMS



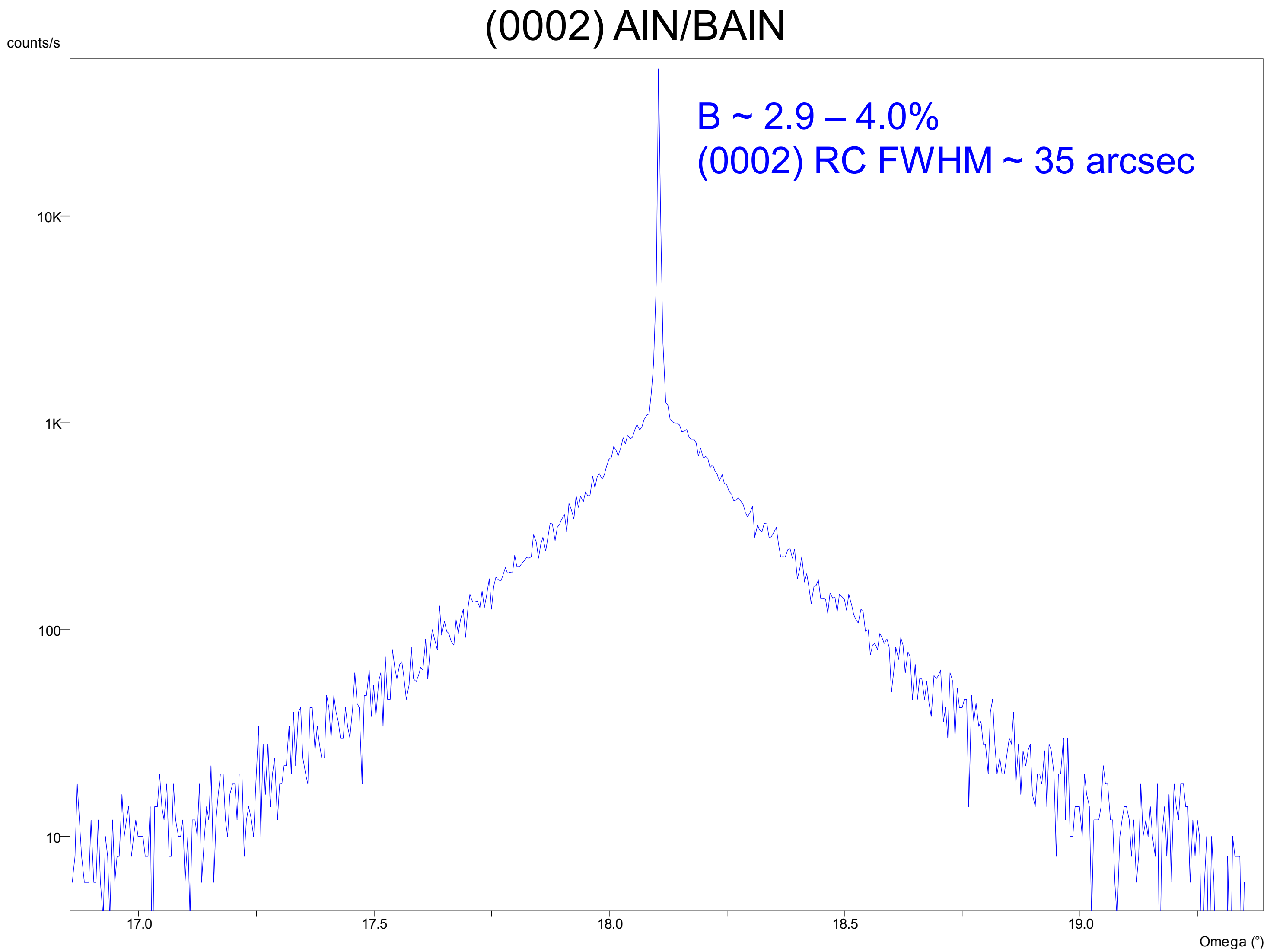
On 6H-SiC – 2.0 nm RMS



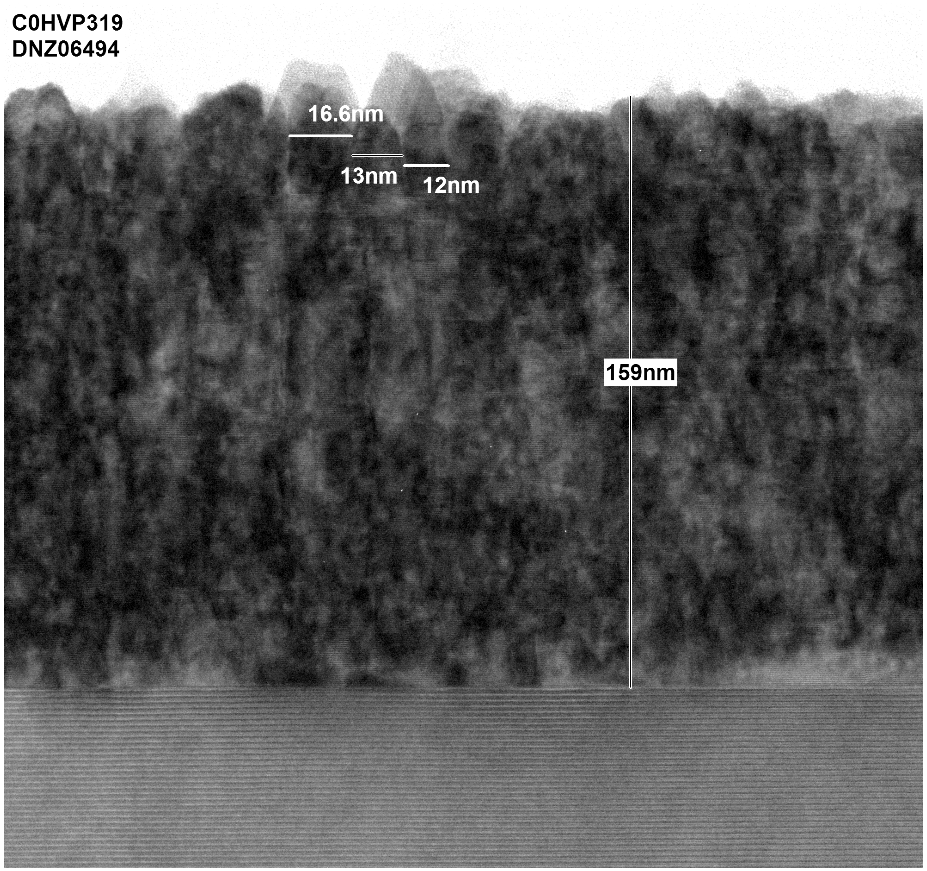
Low-temperature pulsed BAlN: AlN vs. SiC Substrate



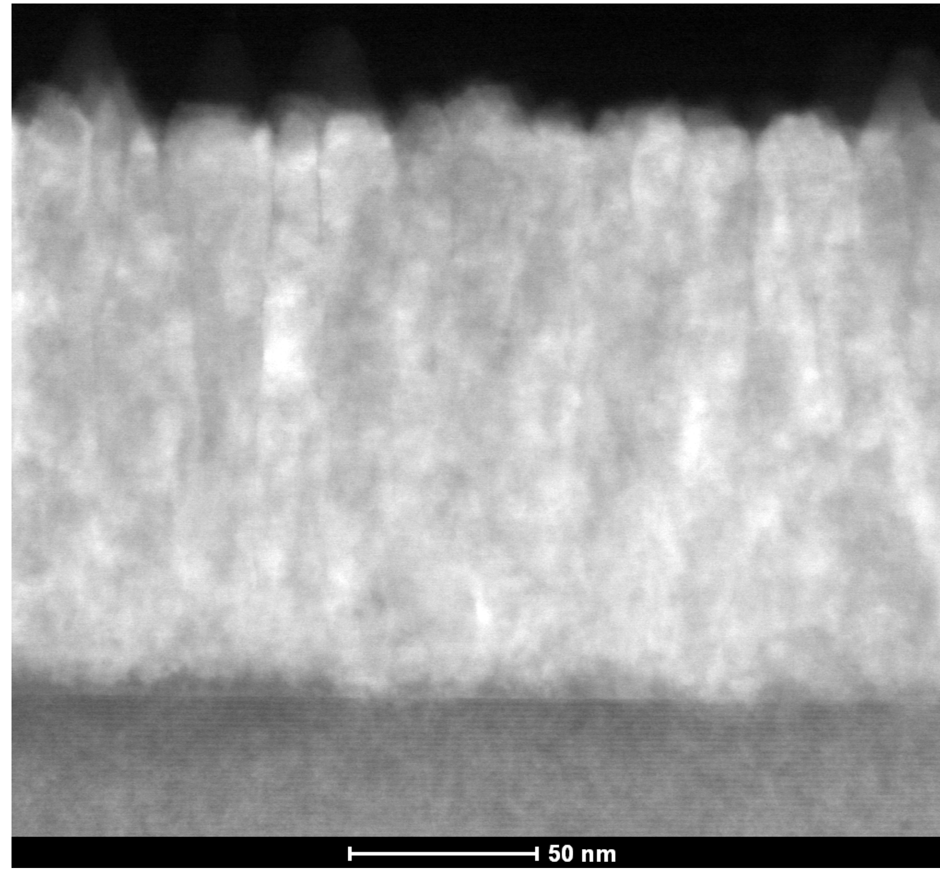
LT Pulsed BAlN on SiC



BAlN/SiC TEM Microstructure

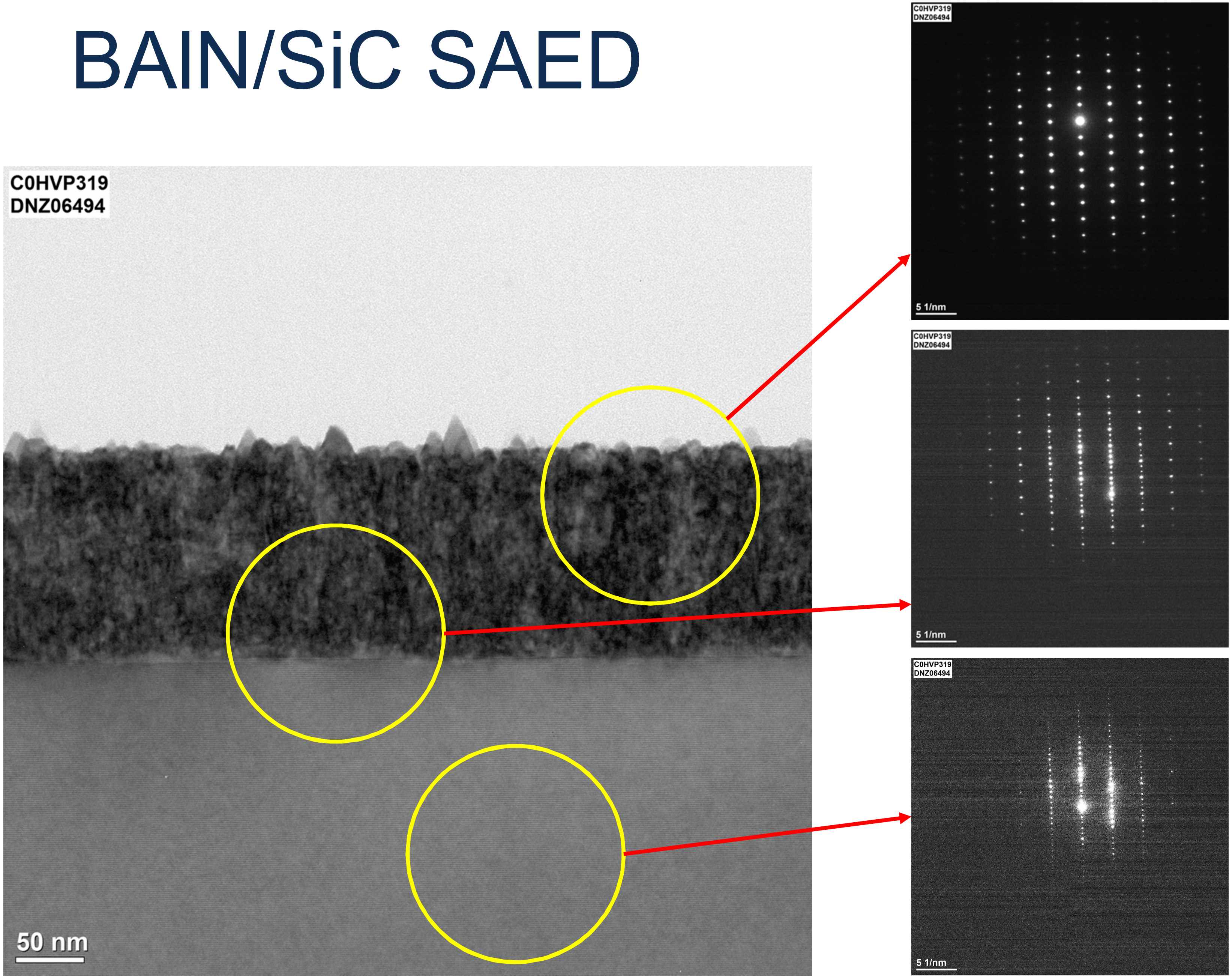


Dark Field TEM

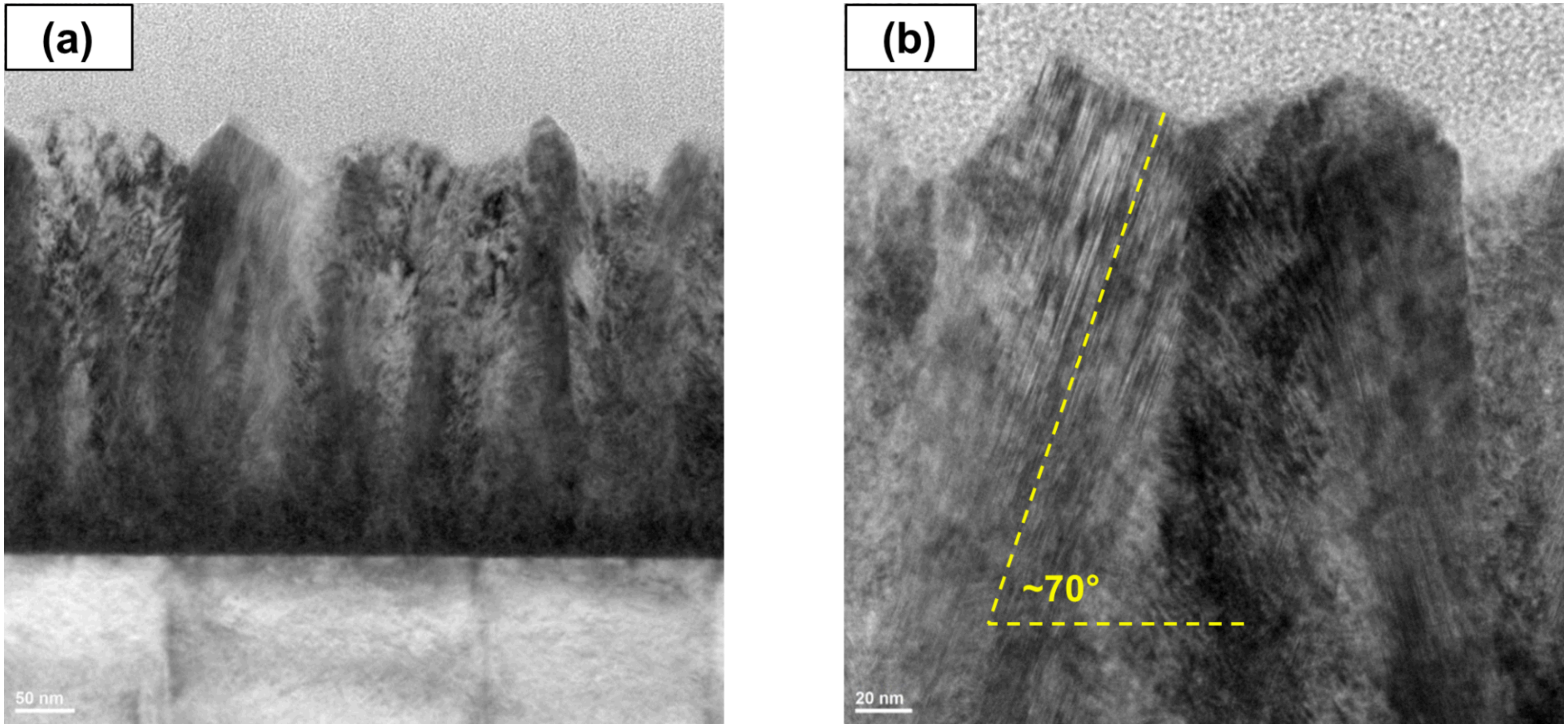


HAADF STEM

BAlN/SiC SAED



Prior Work on BGaN – Cubic Phase

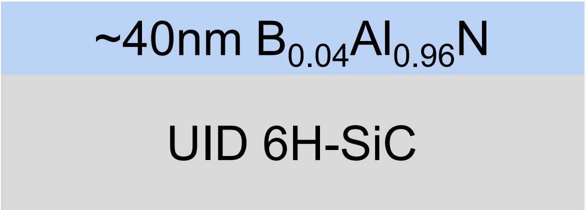


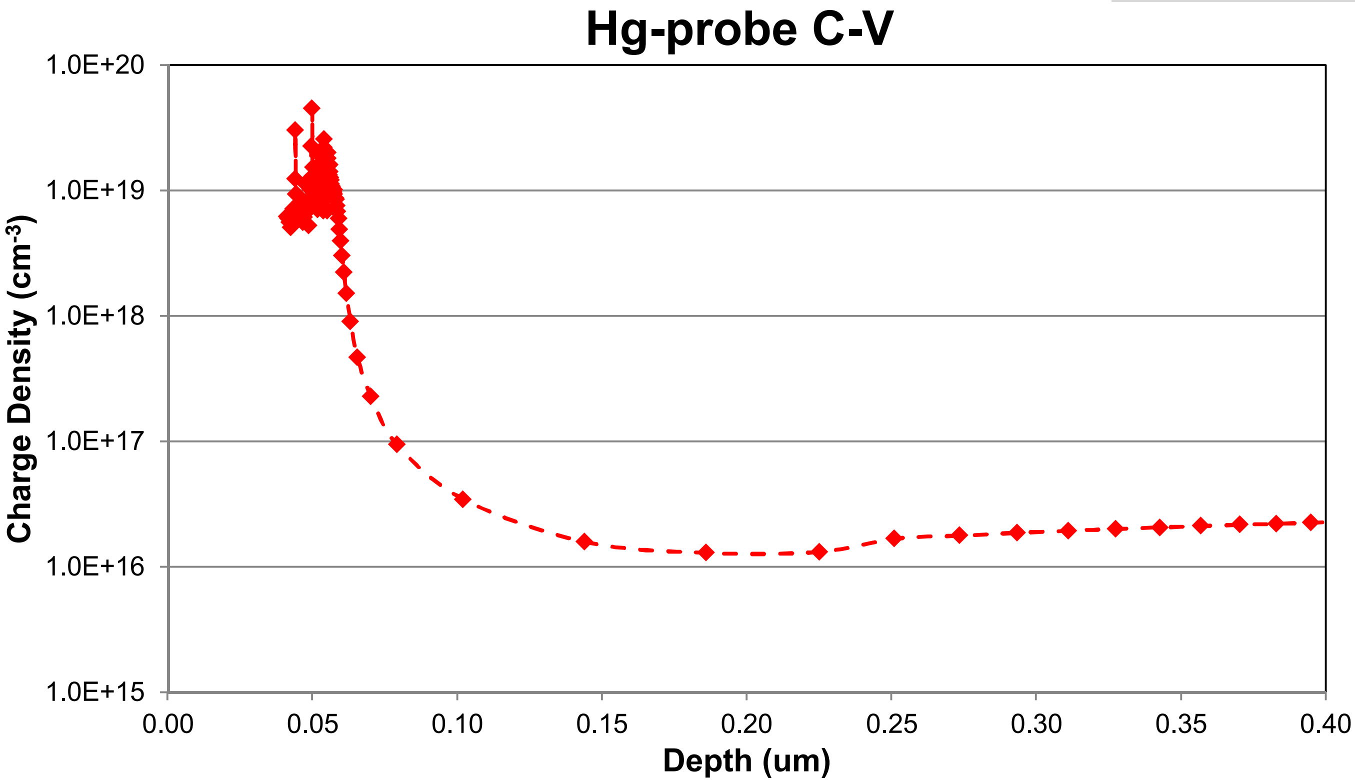
- Stacking faults tilted by ~70° relative to substrate
- <110> {111} slip system in zinc-blende crystal
  - → Basal plane stacking faults on equivalent (1 1 1) planes
  - → 70.5° angle between (1 1 1) and (1 -1 1) planes

Gunning *et al.,* J. Crystal Growth **464** (2016) 190-196.

Potential Device Prospects

- ~40nm BAlN grown directly on undoped 6H-SiC wafer
- ρ_{sp_AlN} ~ .081 C/m^2 -- $\rho_{sp\_wz\text{-}BN}$ ~ ???
- $\rho_{sp\_6H\text{-}SiC}$ ~ .009 C/m^2
- σ_{sh} ~ 4x10^{13} cm^{-2}





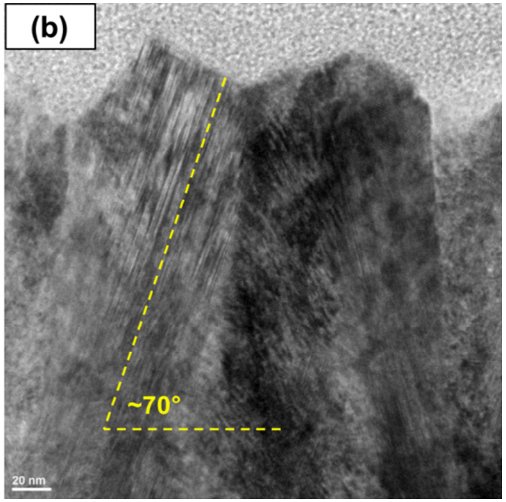
Summary

Initial BAlN investigation

- AlN-like conditions → very rough surfaces, poor boron incorporation
- Low temp, low pressure, H2 ambient, **pulsed growth** → ~4.5% boron, specular surfaces
- Higher B incorporation on SiC substrate vs. AlN

BAlN structural characterization

- Fine-grained surface morphology
- Extremely columnar microstructure
- No evidence for cubic phase (vs. BGaN)



Possible SiC/BAlN heterostructure device

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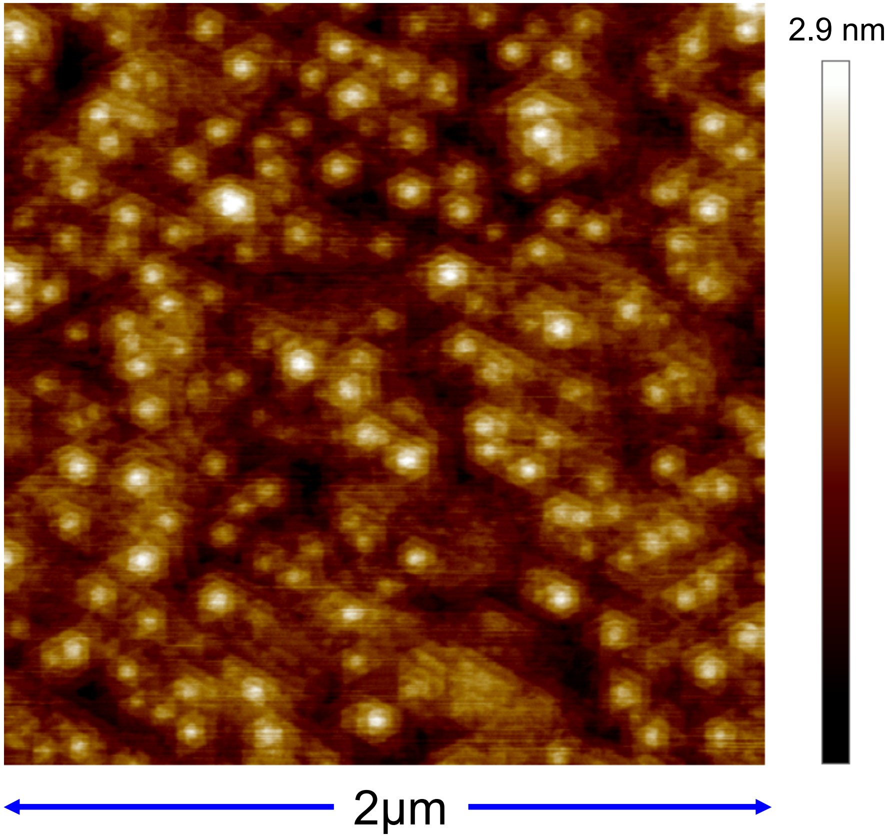
Pulsed AlN vs. BAlN on SiC

- 980°C, H_2 ambient, pulsed 3s MO / 3s NH_3

Without TEB – 0.4 nm RMS



With TEB – 2.0 nm RMS