Influence of the surface misorientation on the properties of N-polar AlGaN/GaN and InGaN/GaN heterostructures

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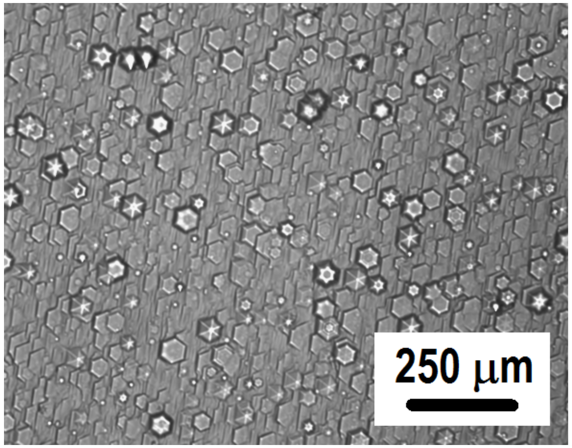
- **Introduction**
- **Experimental details**
- **InGaN/GaN MQWs**
- **AlGaN/GaN MQWs**
- **AlGaN/GaN 2DEG structures**
- **Summary**

Introduction

N-polar GaN: opposite direction of piezoelectric fields
+ different surface properties
...for tunnel junctions, transistors, sensors, solar cells...

- N-polar (Al,In,Ga)N often rough due to formation of hexagonal hillocks

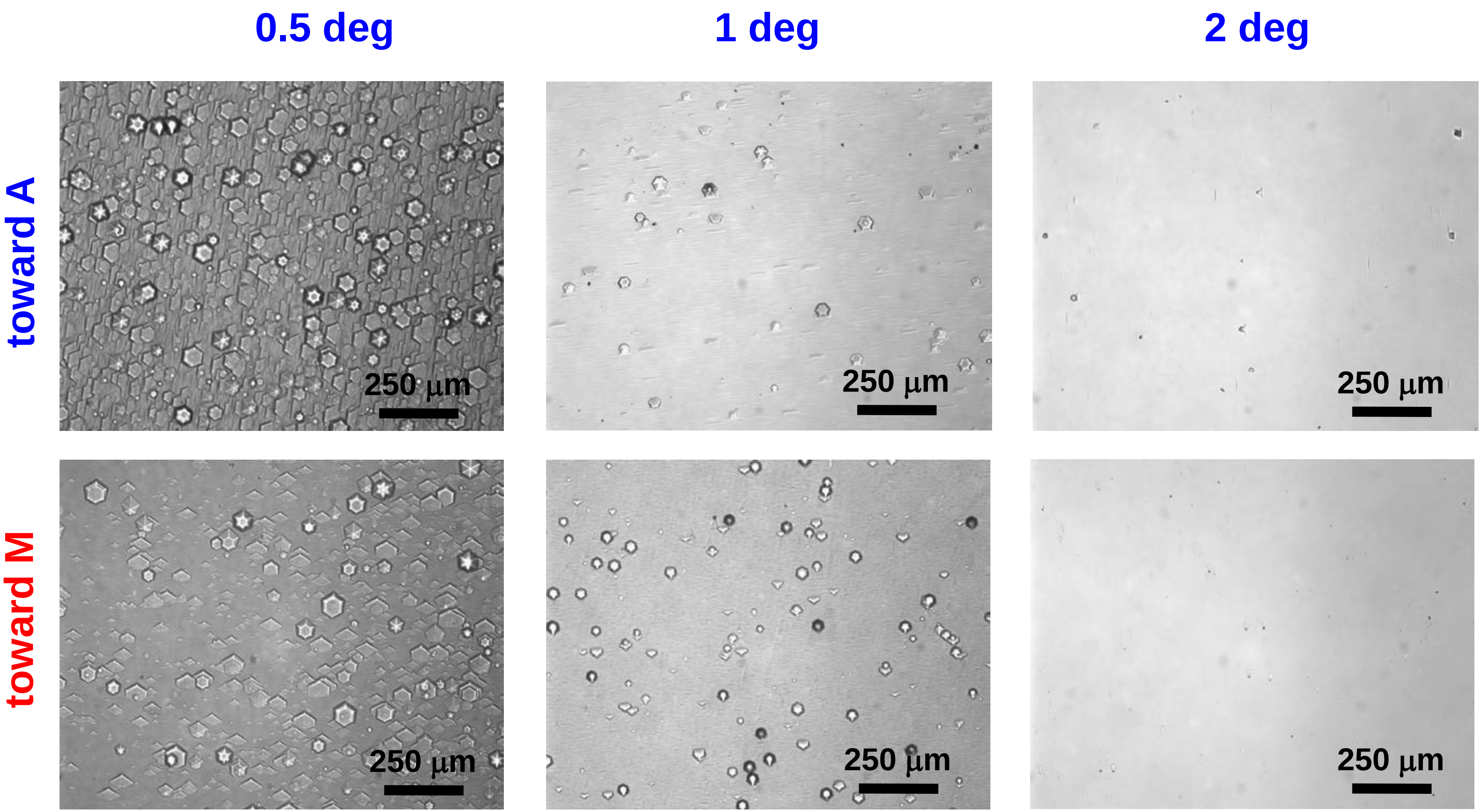
observed for hetero- and homoepitaxial growth of GaN
(associated with inversion domains)



- poor surface morphology prevented application for devices
- recently: high quality N-polar (Al,Ga)N by MBE on C-polar SiC
- few reports of smooth N-polar GaN by MOCVD

Smooth GaN through MOCVD on misoriented substrates

0.8 μm GaN on nitridized c-plane sapphire substrates with different misorientation angles and directions



- no hillocks on GaN films on substrates with misorientation angle of 4 deg

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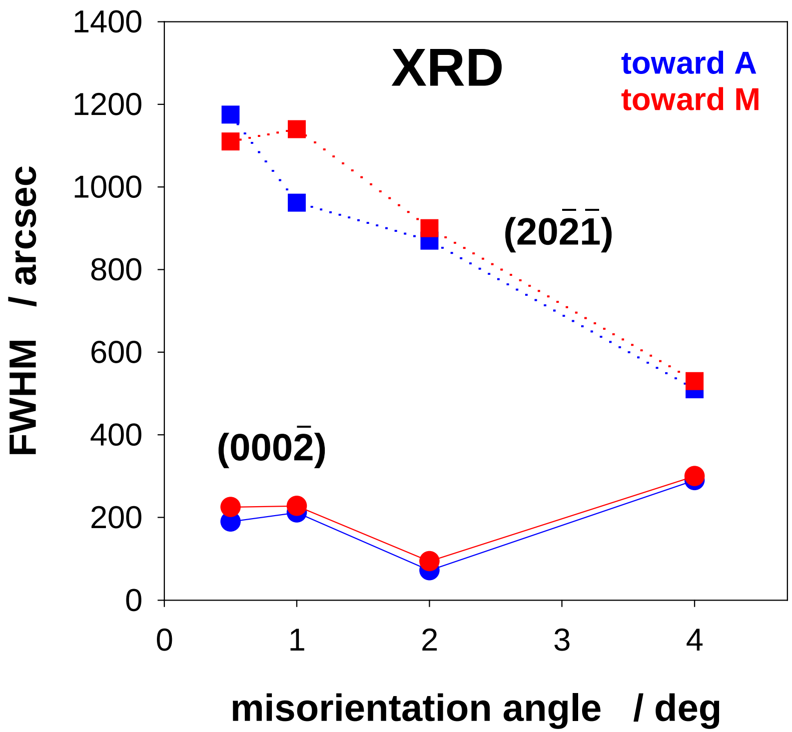
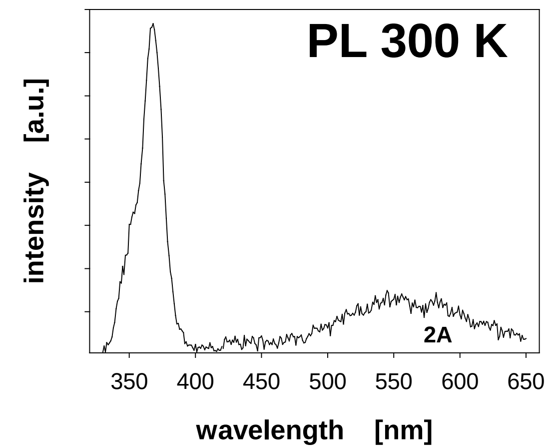
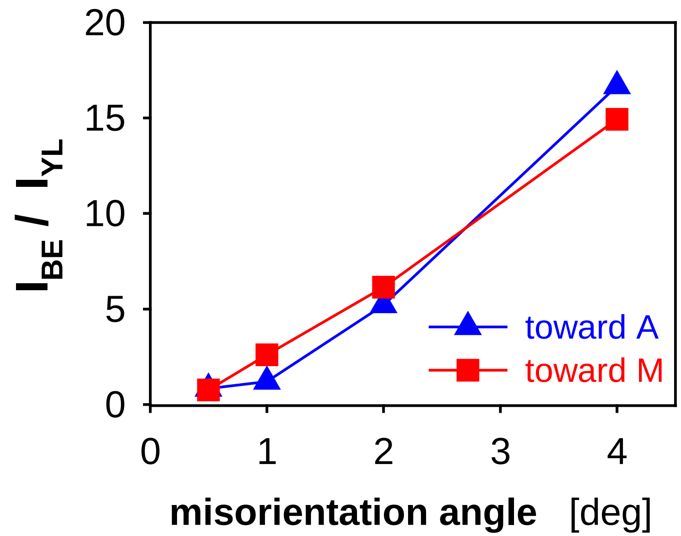
GaN: XRD and photoluminescence measurements



$d_{GaN} \sim 1\mu m$





- quality of GaN layers strongly improves with increasing misorientation angle
- N-GaN 4ºoff ~ Ga-GaN

- GaN:Si Hall data (4A samples):
  $n = 9 \times 10^{16}\ cm^{-3}$, $\mu = 650\ cm^2/Vs$
  $n = 1 \times 10^{18}\ cm^{-3}$, $\mu = 370\ cm^2/Vs$

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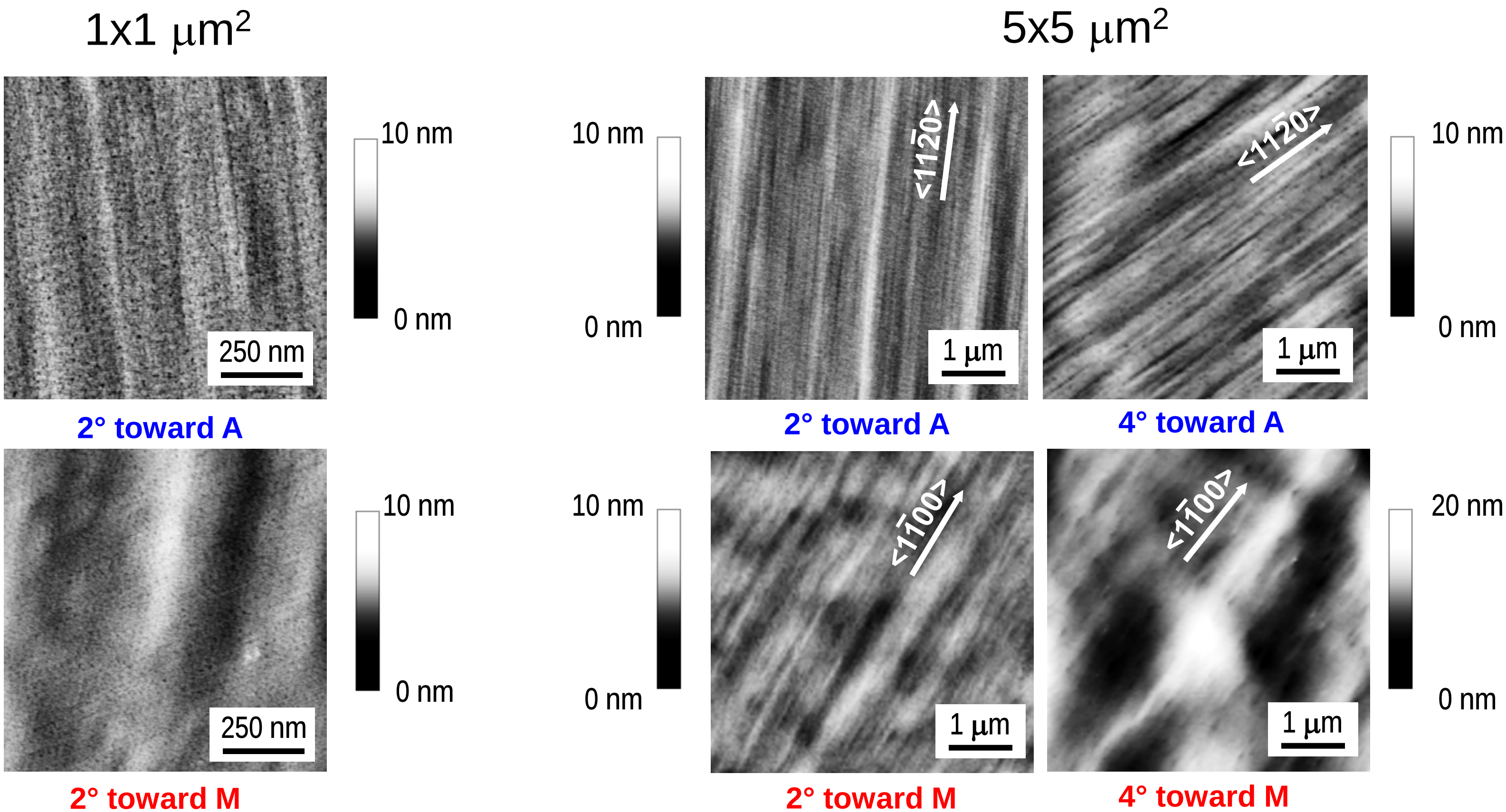
Atomic Force Microscopy



- Rms ~ 0.5 nm or lower for misorientation angle of 2°
- 4° toward A: Rms = 0.6 nm , 4° toward M: Rms = 1.8 nm (5x5 μm^2)
- misorientation toward A resulted in smoother films for higher angles

→ ***choose misorientation toward A for alloy study***

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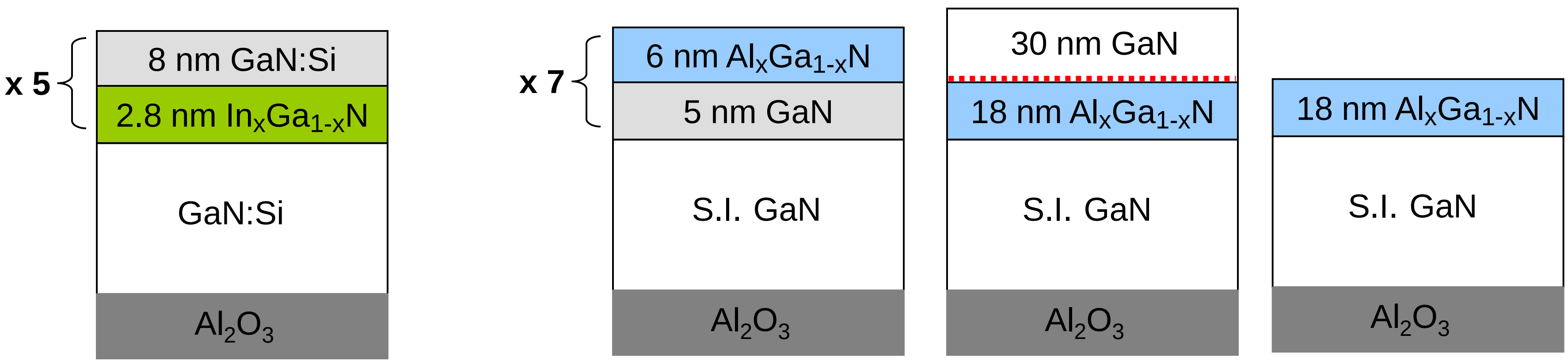
Sample structure

InGaN/GaN — MQW

AlGaN/GaN — MQW, HEMT, "interface"



InGaN/GaN MQW	AlGaN/GaN MQW	HEMT	"interface"
AFM XRD PL	AFM XRD PL	AFM XRD Hall CV TLM	AFM

- **samples simultaneously grown on Al_2O_3 misoriented 2º, 3º, 4º, and 5º toward A**

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Growth conditions

	N - face	Ga - face
Sapphire bake:	H_2, T = 1220 °, p = 76 Torr	H_2, T = 1180 °, p = 760 Torr
Nitridation:	2 slm NH_3, T = 1100 °, t = 120 s	
GaN NL:	N_2, **T = 1050** °, p = 76 Torr TMGa = 8 sccm, NH_3 = 2 slm, t = 180 s	N_2, T = 625 °, p = 760 Torr TMGa = 60 sccm, NH_3 = 4 slm, t = 120 s
GaN main layer:	H_2, **T = 1200** °, p = 100 Torr TMGa = 66 sccm, NH_3 = **1 slm**	H_2, T = 1170 °, p = 600 Torr TMGa = 66 sccm, NH_3 = 4 slm
InGaN MQW:	N_2, T = 880 - 920°, p = 500 Torr TMGa = 3 sccm, TMIn = 80 - 500 sccm, NH_3 = 5 slm **+ 1 slm H_2 during GaN barrier growth**	*→ increase surface mobility*
AlGaN :	N_2, T = 1145°, p = 100 Torr TMGa = 6 sccm, TMAl = 4 - 12 sccm, NH_3 = 1 slm	

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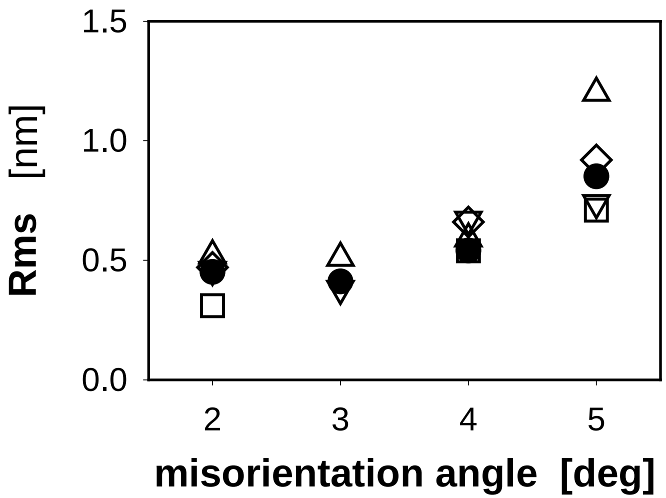
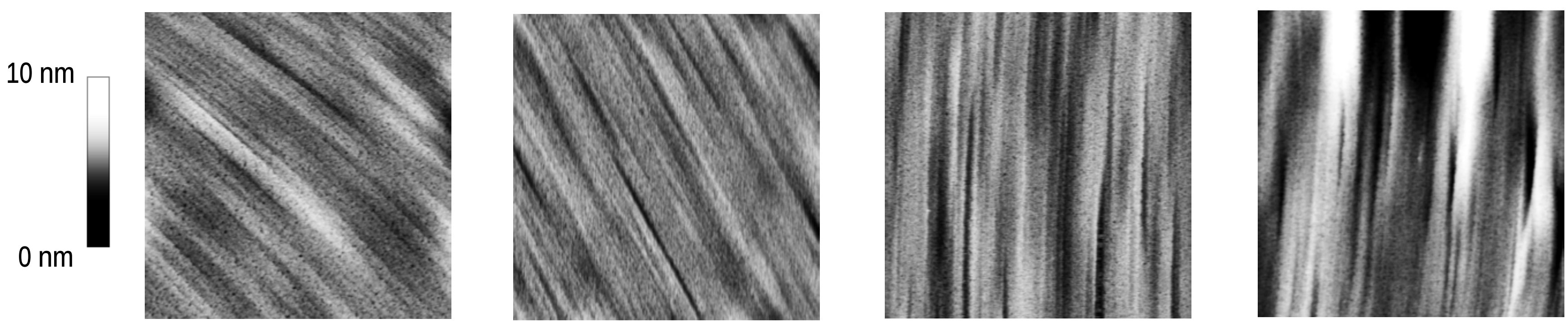
Atomic Force Microscopy



Rms of 2 μm x 2 μm AFM images:

(●) 1.5 μm GaN
followed by
(◊) InGaN/GaN MQW, TMIn = 3 μmol/min
(□) InGaN/GaN MQW, TMIn = 8 μmol/min
(Δ) 30 nm $Al_{0.2}Ga_{0.8}N$, and
(∇) 26 nm $Al_{0.32}Ga_{0.68}N$

1.5 μm GaN **2A** **3A** **4A** **5A**



all 2 x 2 μm

→ surface undulations through step bunching at higher misorientation angles

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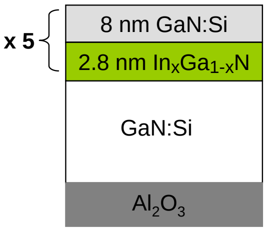
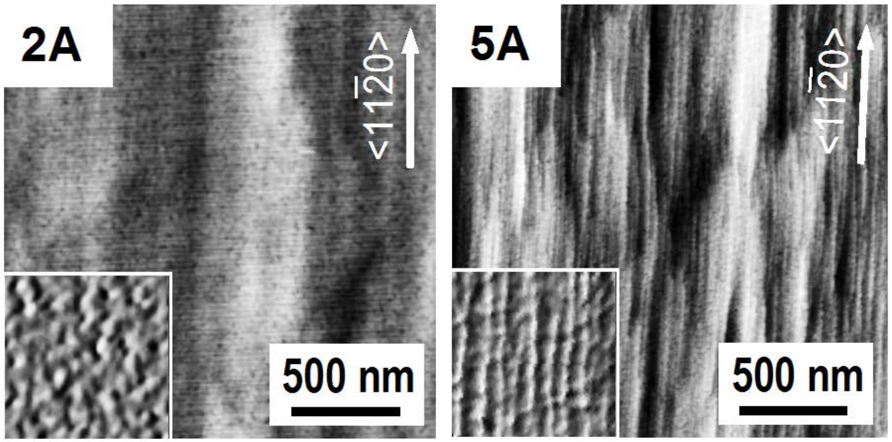
Atomic Force Microscopy

InGaN/GaN MQW

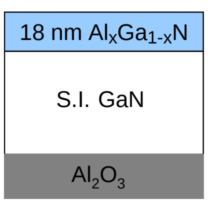


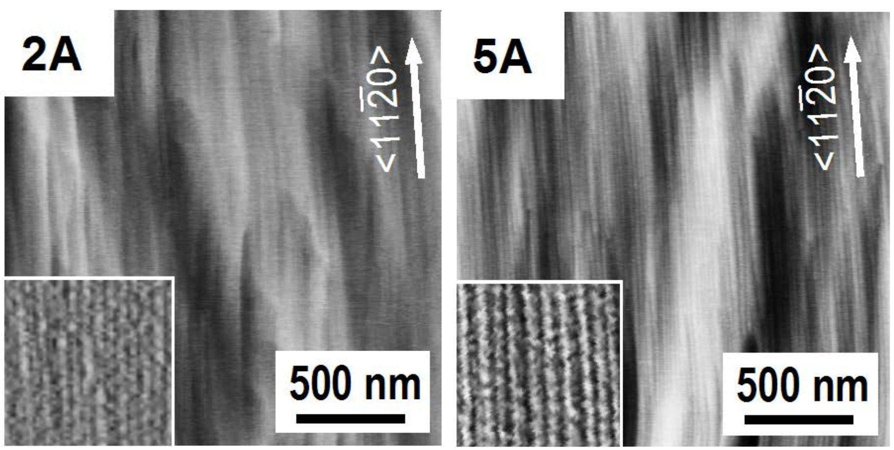


- no distinct steps visible on 2º and 3º samples
- 5º: step height 3-4 unit cells

Ga-polar films: step height 1/2 unit cell = 0.26 nm
terrace width:
2º - 7 nm
5º - 3 nm
too small for AFM

AlGaN/GaN





grayscale = 10 nm
Inserts: 4 fold enlargements in amplitude mode

- steps visible on all samples
- 2º: step height ~1 unit cell
- 5º: step height 3-4 unit cells

no V-defects !

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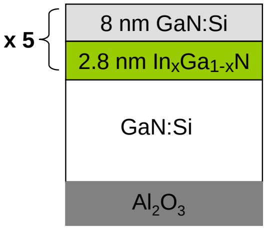
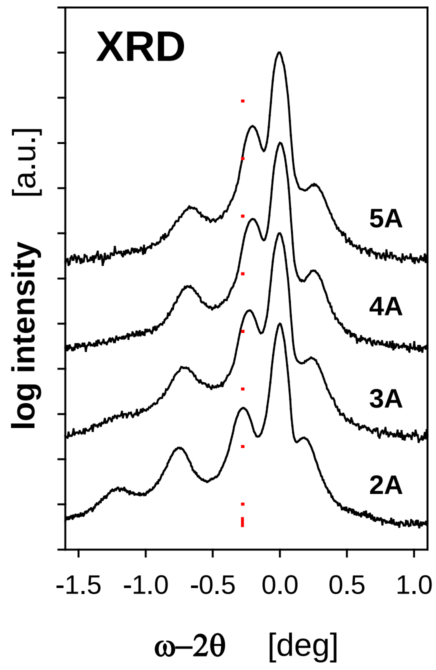
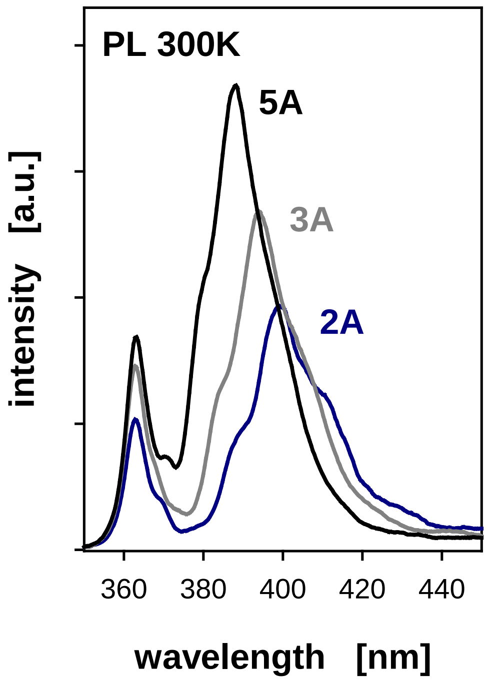
InGaN/GaN MQWs XRD, PL







- In incorporation decreases with increasing misorientation angle *as seen for Ga-polar InGaN*
- higher order XRD SL peaks vanish with increasing angle
- MQW related luminescence increases in intensity and shifts towards shorter wavelength

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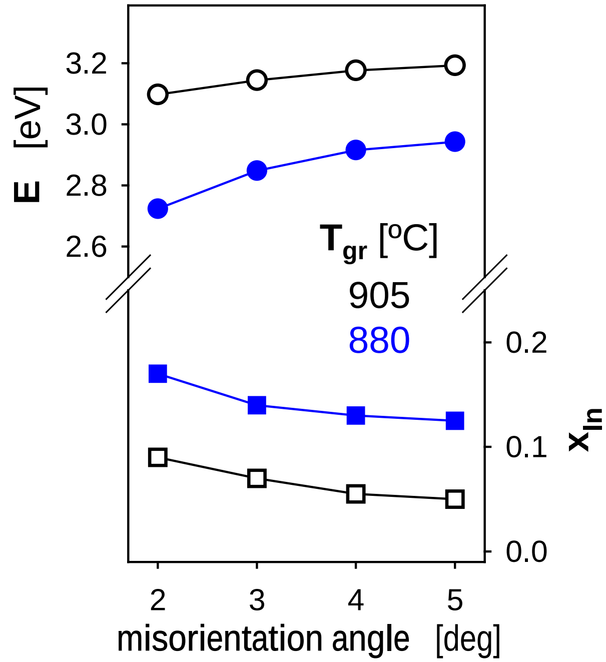
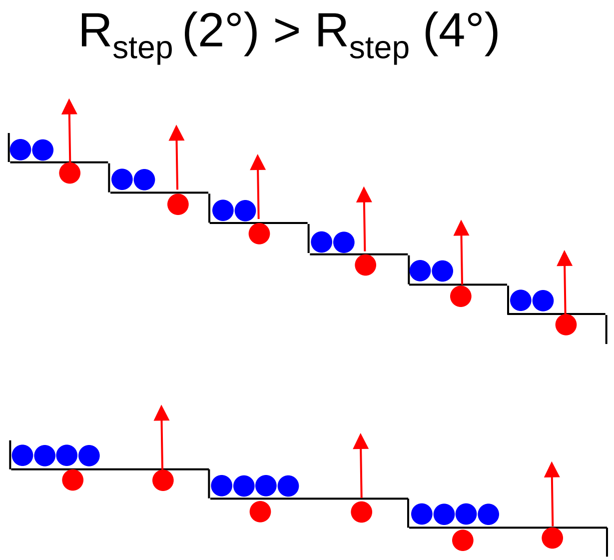
InGaN/GaN MQWs XRD, PL





- decrease in x_{In} with increasing angle observed under all growth conditions explored in this study
- possibly caused by increased In evaporation due to slower step propagation at higher misorientation angles

  and/or facet formation

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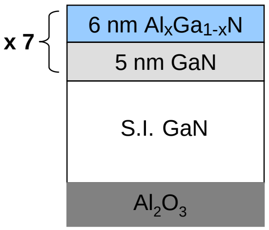
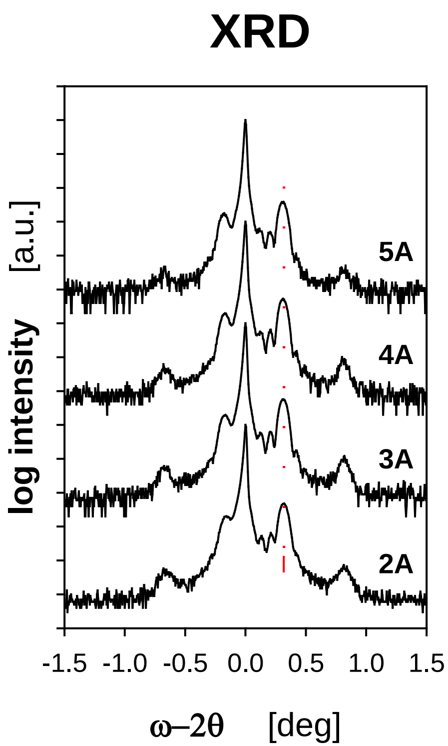
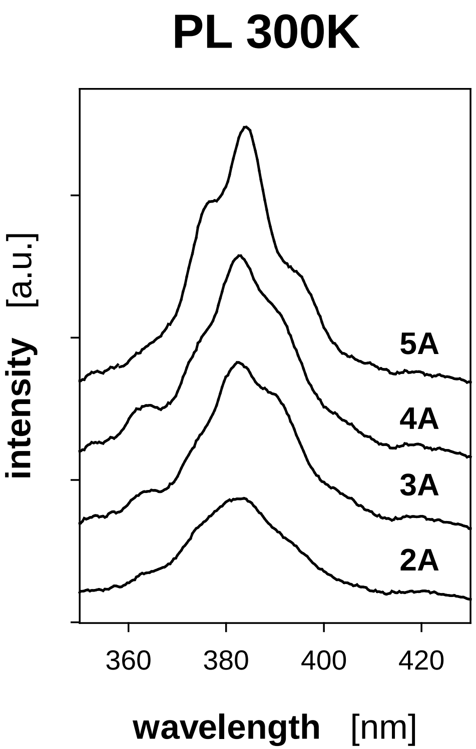
AlGaN/GaN MQWs XRD, PL







- Al composition, λ = constant
- XRD SL peaks less intense only at 5º
- MQW PL increases with increasing angle

- *Al forms strong bonds*

  E (Al-N) = 2.9 eV
  E (In-N) = 1.9 eV

- *treading dislocation density decreases with increasing misorientation angle*

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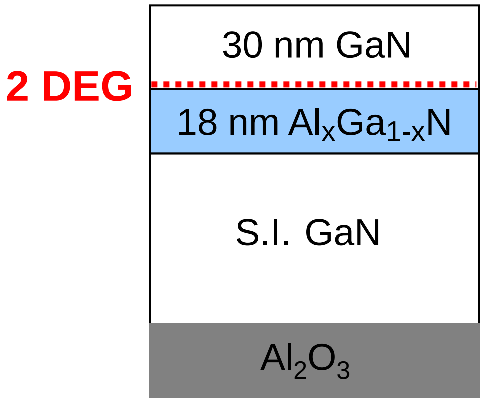
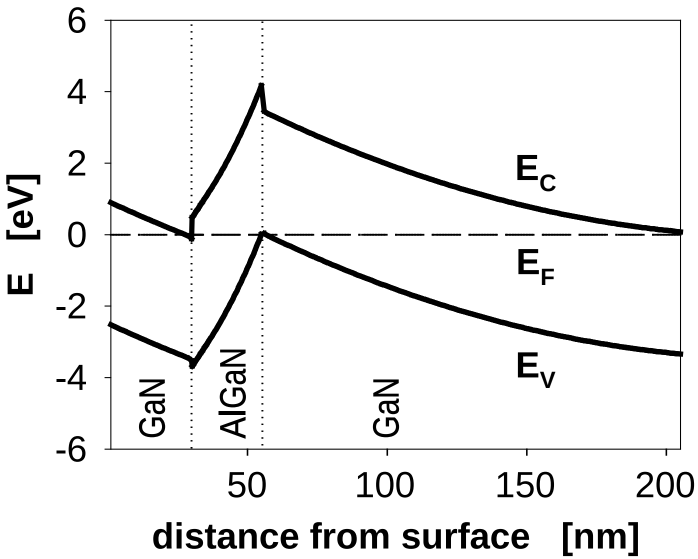
AlGaN/GaN 2DEG samples





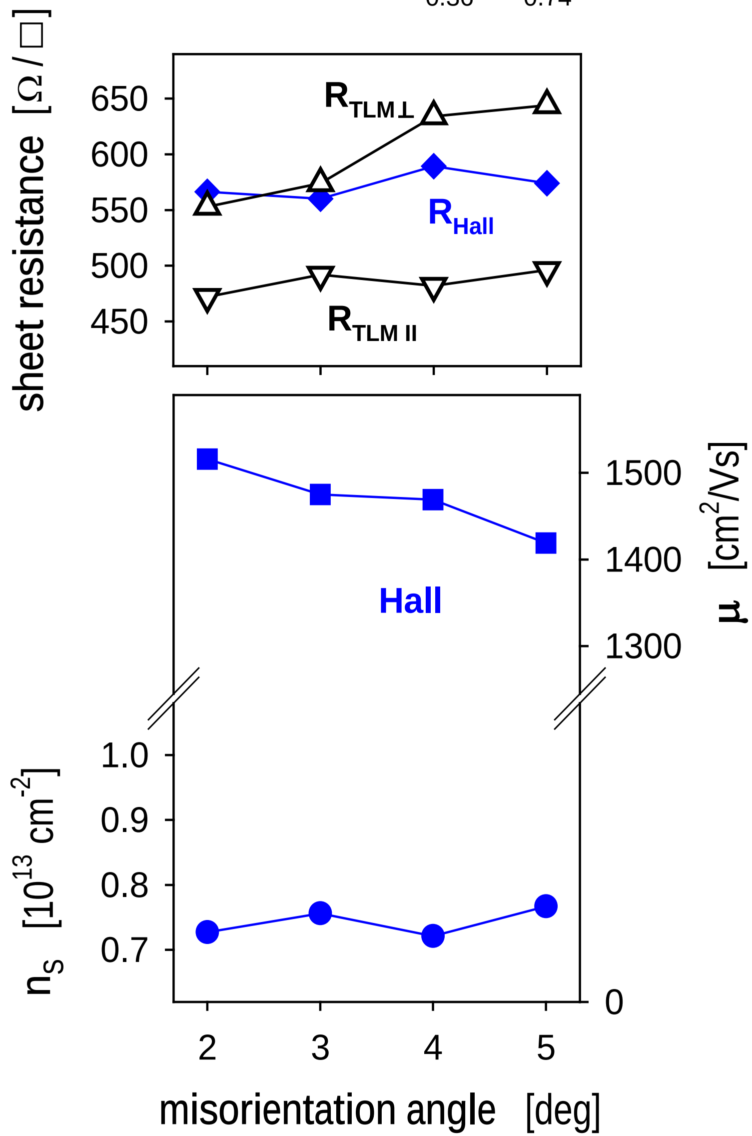
- S.I. GaN through Fe-doping similar to Ga-polar GaN

S. Heikman, S. Keller, S.P. DenBaars, and U.K. Mishra, Appl. Phys. Lett. 81, 439 (2002)

S. Keller, C.S. Suh, Z. Chen, R. Chu, S. Rajan, N.A. Fichtenbaum, M. Furukawa, S.P. DenBaars, J.S. Speck, and U.K. Mishra, J. Appl. Phys. 103, 033708 (2008)

AlGaN/GaN 2DEG samples electrical properties

30 nm GaN/ 18 nm $Al_{0.36}Ga_{0.74}N$/ S.I. GaN



Hall measurements:

n_s ~ constant - x_{Al} = constant
μ decreases with increasing angle
μ ~ *1/Rms, more severe step-bunching*

CV: $n_{CV} = n_{Hall}$

TLM measurements:
Investigate patterns parallel and perpendicular to steps/undulations

$\mathbf{R_{TLM\,II} << R_{TLM\perp}}$

$R_{TLM\,II} \neq f(\text{angle})$
$R_{TLM\perp}$ increases with increasing angle

Calculate μ_{II} from $\mathbf{R_{TLMII}}$ and n_s

$\mathbf{\mu_{II} = 1800\ cm^2/Vs}$

= comparable to Ga-polar structures

→ orient devices parallel to steps

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Summary

- smooth N-polar (Al,Ga,In)N heterostructures by MOCVD on vicinal substrates

- with increasing misorientation angle:
  - structural and optical properties improved
  - surface roughness increased due to step-bunching

InGaN/GaN

- x_{In} decreased
- intensity of higher order MQW SL peaks decreased

→ *roughness + compositional effects*

AlGaN/GaN

- x_{Al}= constant
- intensity of higher order MQW SL peaks reduced only at 5º
- 2DEG: $R_{\perp}$ decreased

- high mobility AlGaN/GaN 2DEG structures through alignment parallel to steps/undulations – $R_{II} \neq f(\text{angle})$, μ_{II} = 1800 cm^2/Vs

→ *for device applications*

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