Sep. 25, 2008

Molecular Beam Epitaxy and p-type doping of InN

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Collaborators/Appreciation

InN Properties
P-type doping
P-type eviden.

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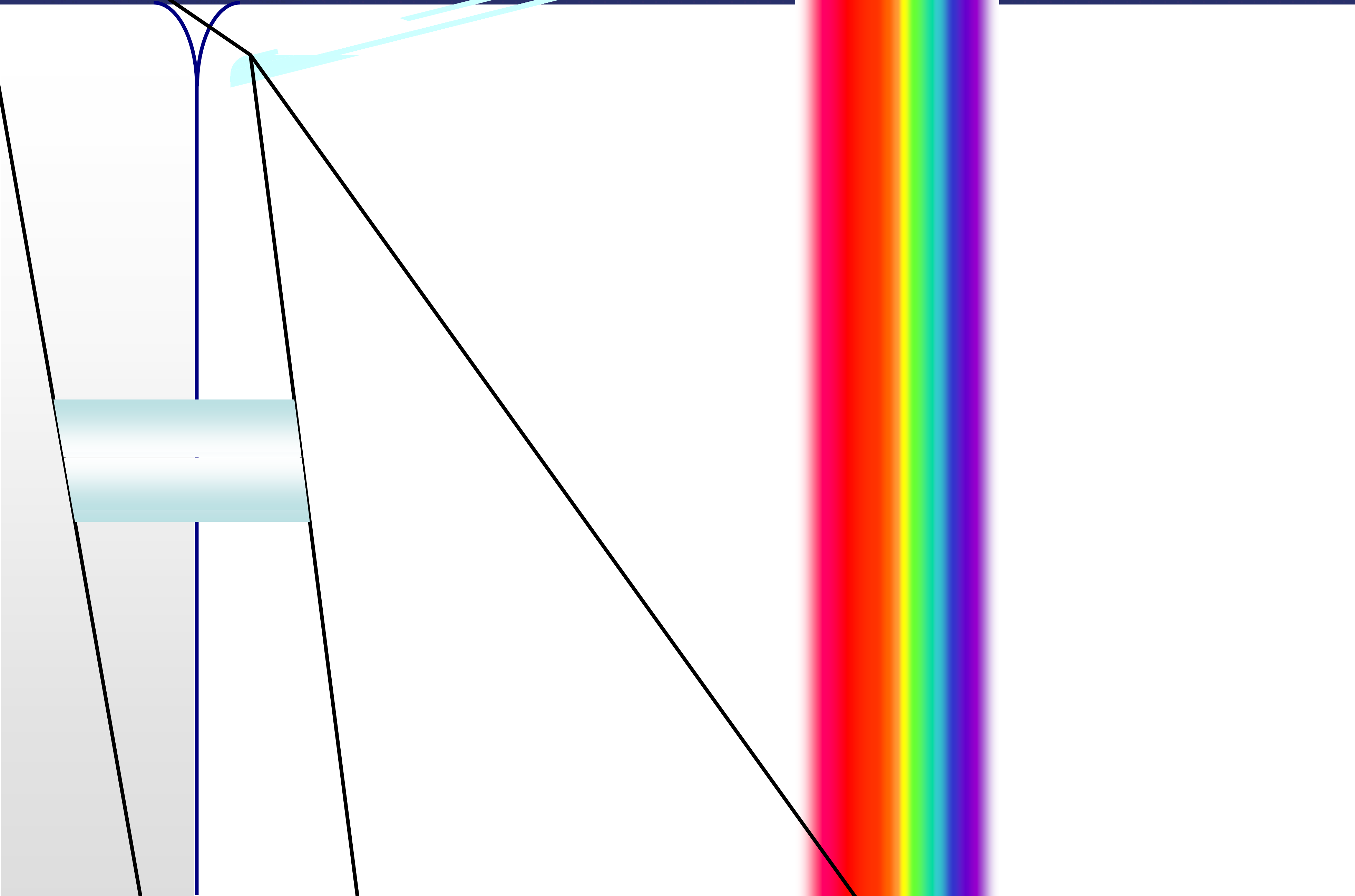
Outline

- Introduction
- Molecular Beam Epitaxy
- InN Epitaxy: Polarity effect and atomically flat surface
- Quality Improvement for InN epilayers
- Properties of InN epilayers
- P-type doping of InN
- Polarity Inversion InN:Mg
- Evidence of p-type
- InN based alloys and nanostructures
- Summary

Introduction



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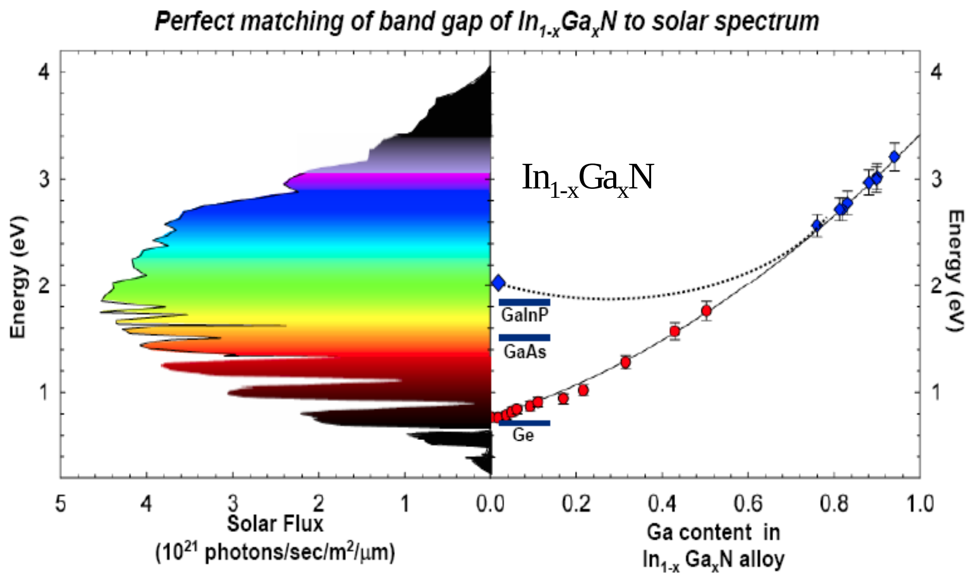
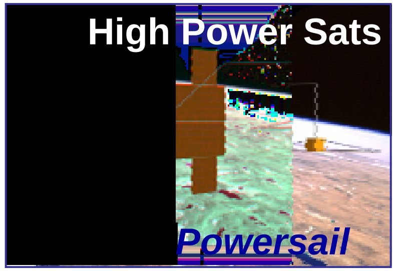
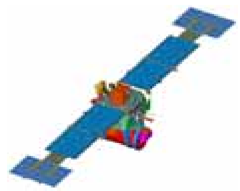
High Efficiency Solar Cell

Radiation-hard material-very suitable for using in space



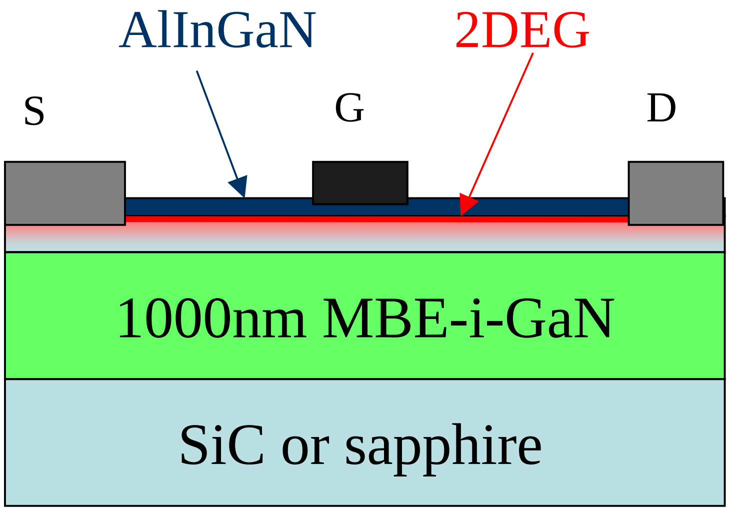


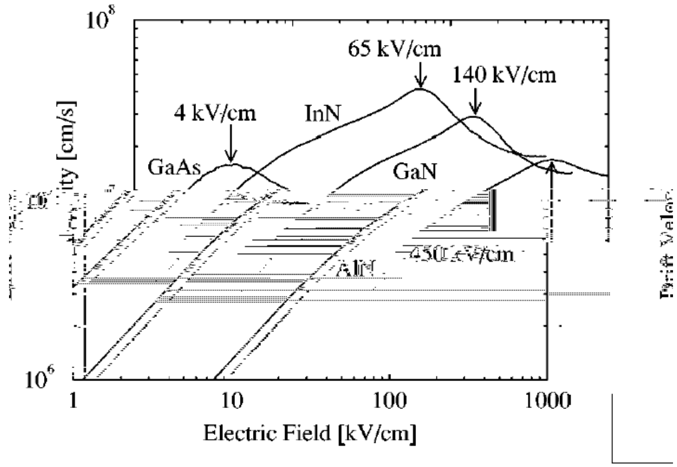


Theoretical Conversion Efficiency of InGaN Tandem Cell as a Function of Number of Junctions under AM 1.5.

High Electron Mobility Transistor HEMT

AlInN/InN InGaN/InN HEMT





B.Foutz et.al, JAP, 85 (1999) 7727

Topics/Keypoints in InN research

- High Quality InN epilayers

  Low defect density, atomically flat surface, low residual carrier concentration

- Origin of high residual electron concentration

  InN-degenerate semiconductor

- P-type doping for InN

  Necessary for fabricating light emitting device

- InN based alloys

  High In content InGaN, InAlN

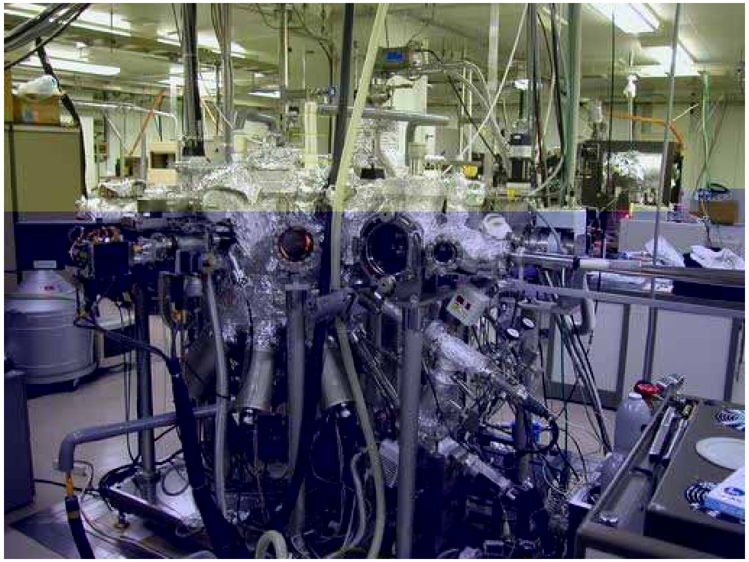
- InN based quantum structures, nanostructures

  InN well based quantum wells, InN quantum dots, nanowires

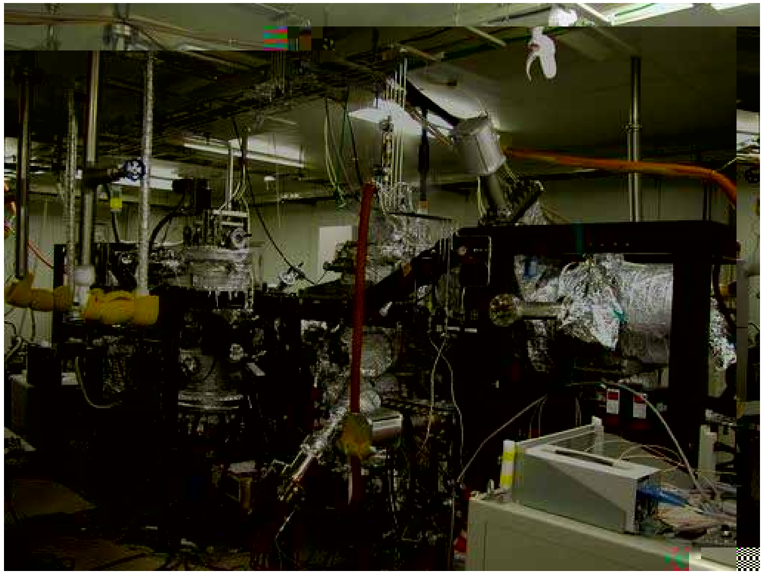
- Parameters/Physics for InN

  Several Parameters for InN are not clear yet.

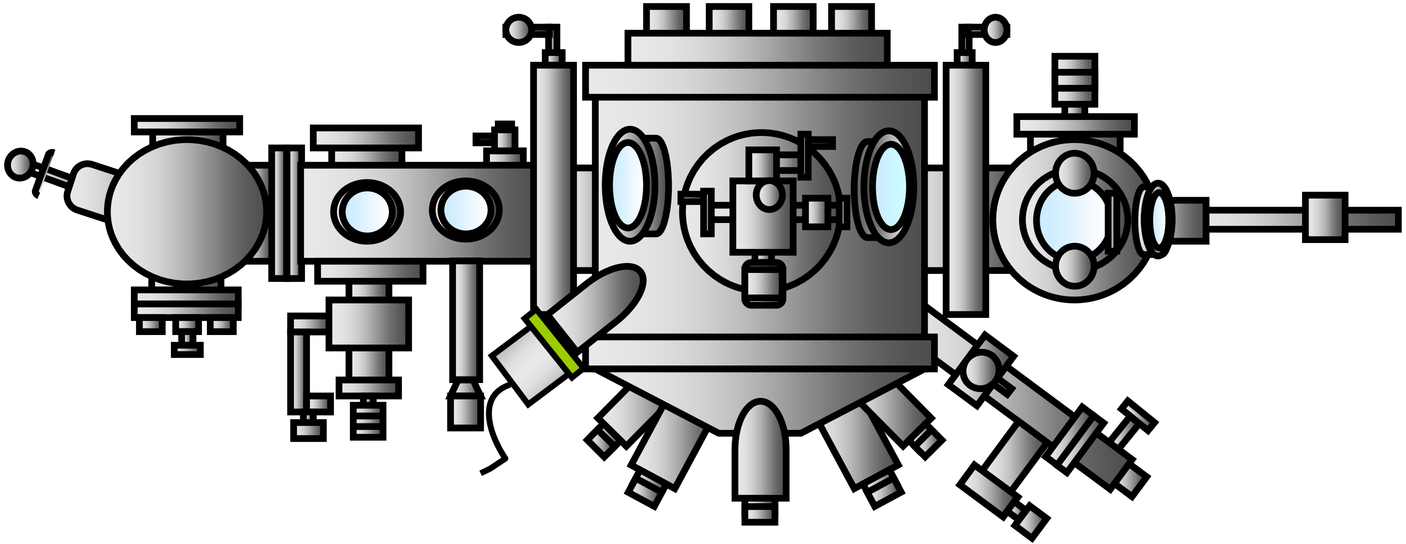
Molecular Beam Epitaxy



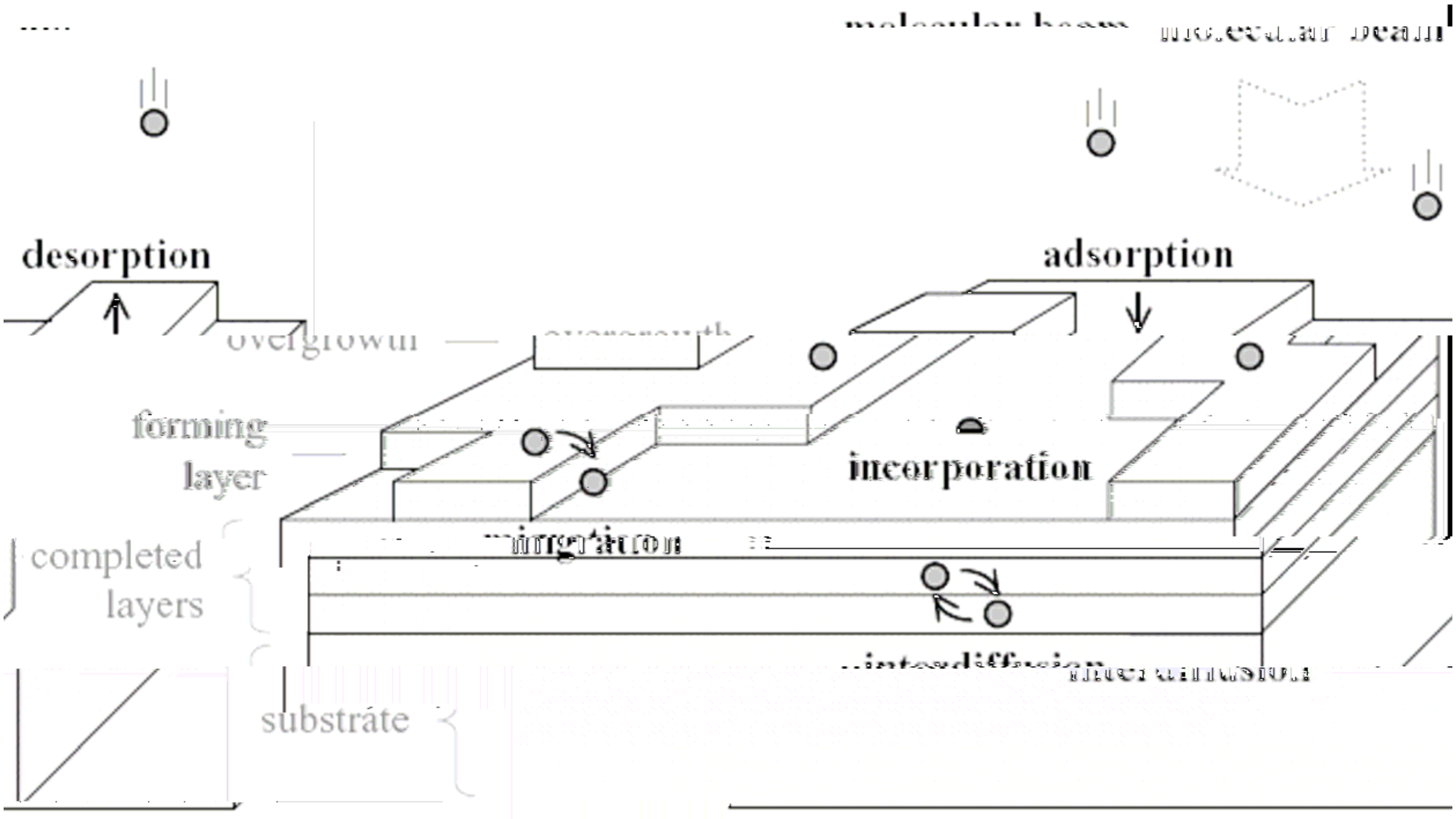
Eiko MBE



ULVAC MBE twin chamber



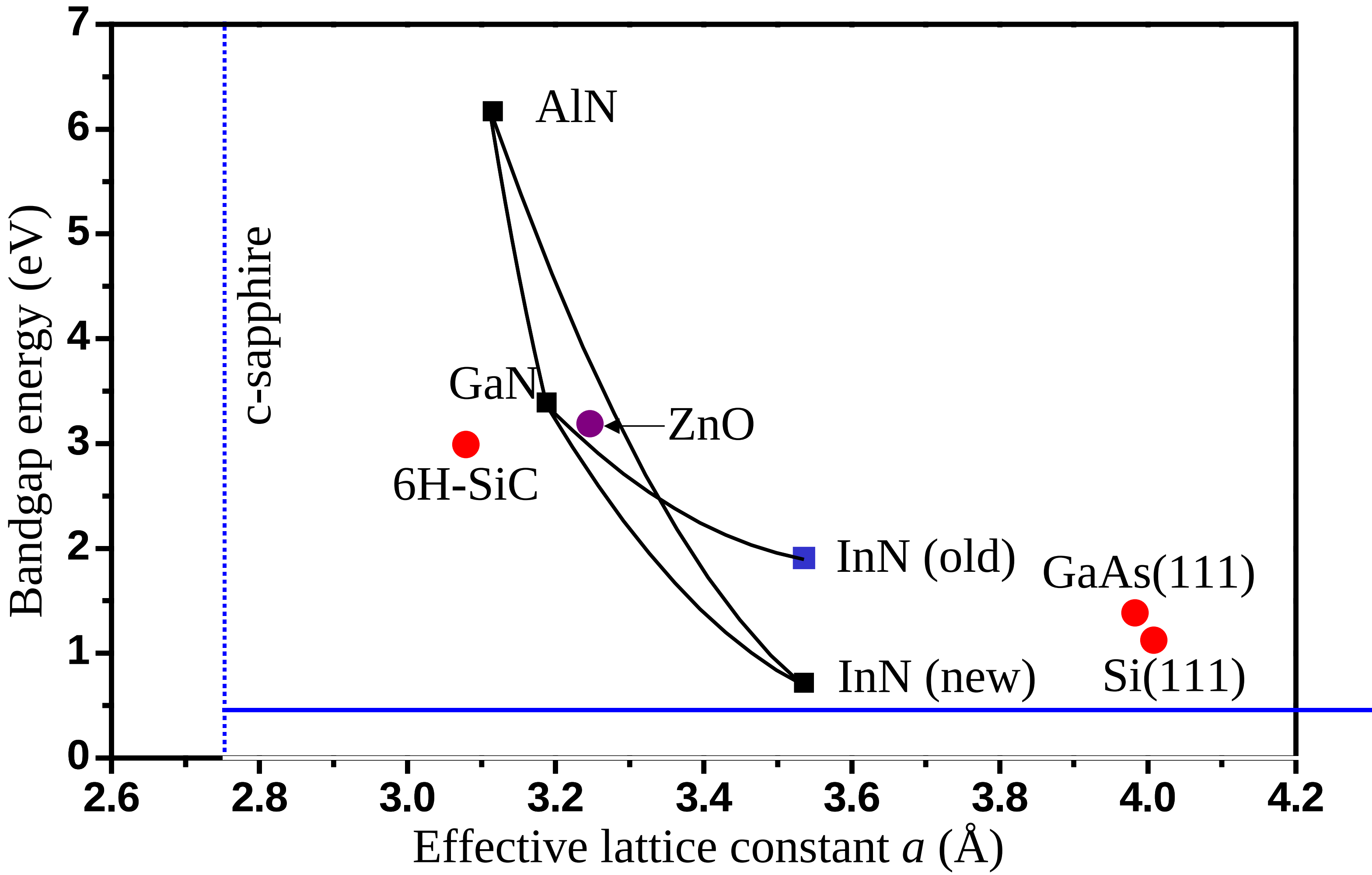
Epitaxy Mechanism



It is important to improve migration ability of surface atoms

Difficulty in InN Epitaxy

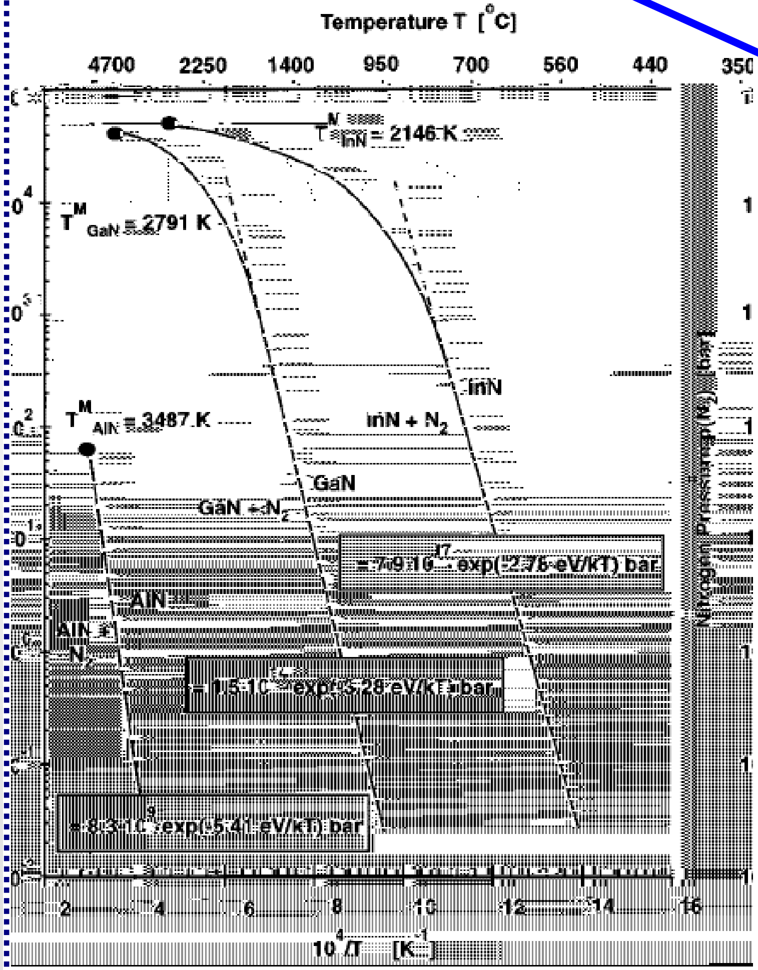
Large lattice mismatch leads to high defect density and poor quality



Difficulty in InN Epitaxy

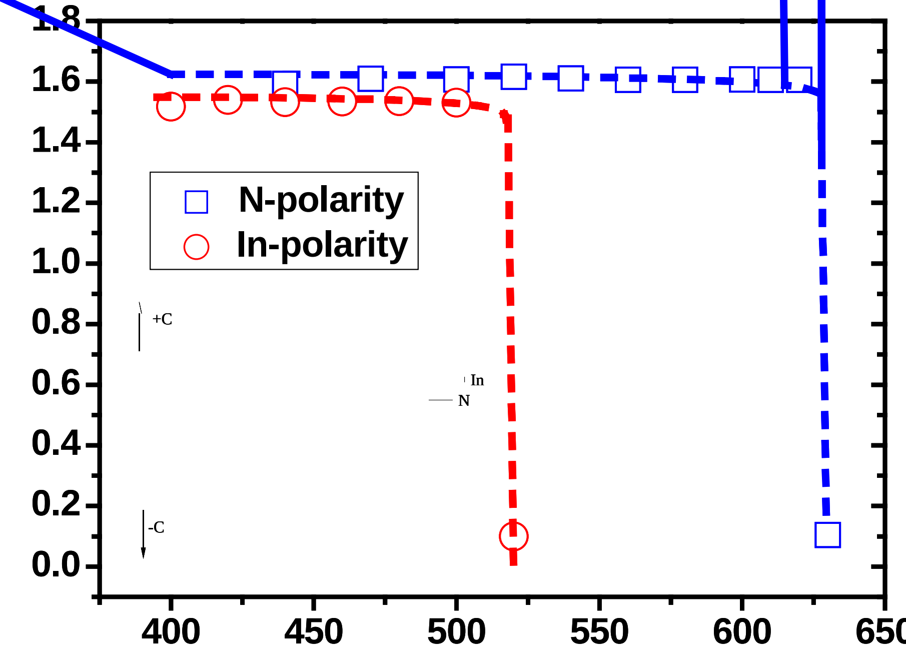
high equilibrium N vapor pressure over InN film

Low maximum growth temperatures much smaller than GaN and AlN



O. Ambacher, et al, J. Vac. Sci. Technol. B 14 (1996) 3532

Low Epitaxy Temperature



InN

InN 620 C

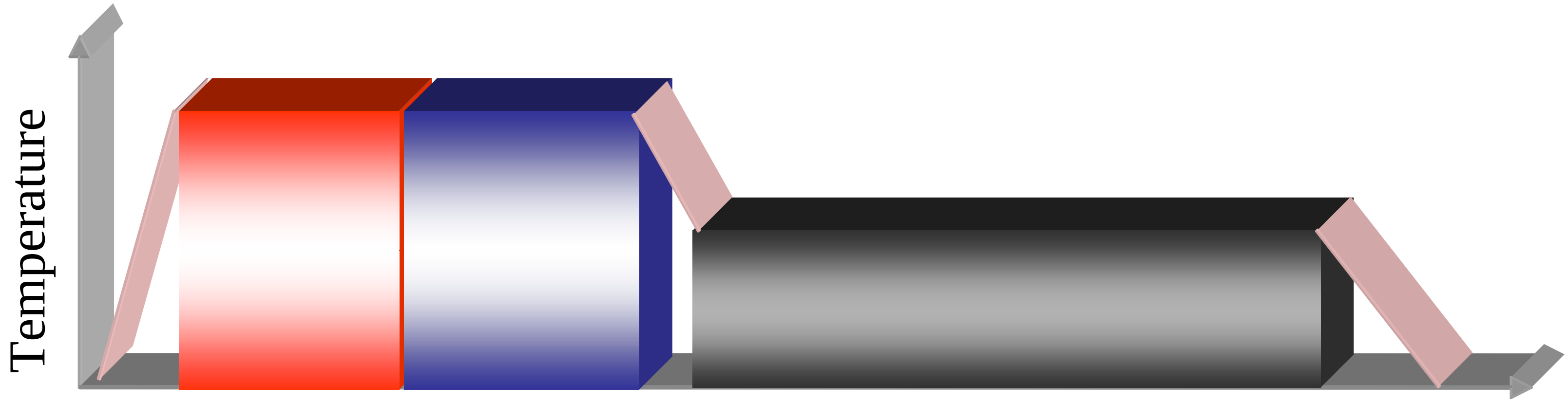
Problem for MOCVD: Low epitaxial temperature of InN

		MOCVD	MBE
	In	(TMIn)	In
	N	- -	Plasma
		520ºC/620ºC	520ºC/620ºC
		/N	
	n_e (cm^{-3})	10^{18}	10^{17}
	(RT) cm^2/Vs	>1000	>2000

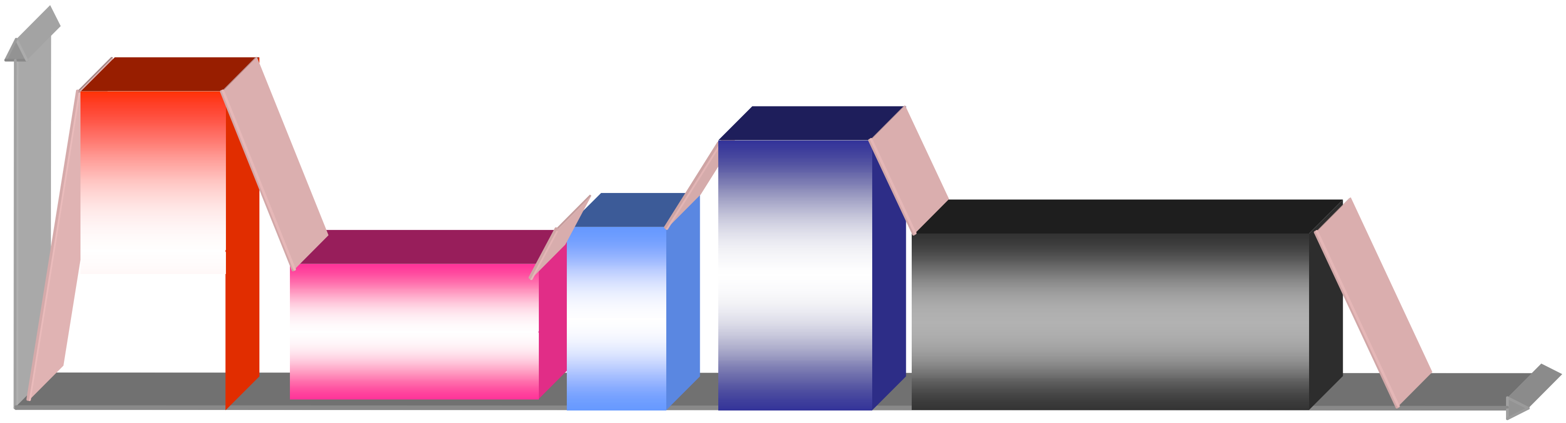
MBE shows advantage than MOVPE

Typical Growth Procedure

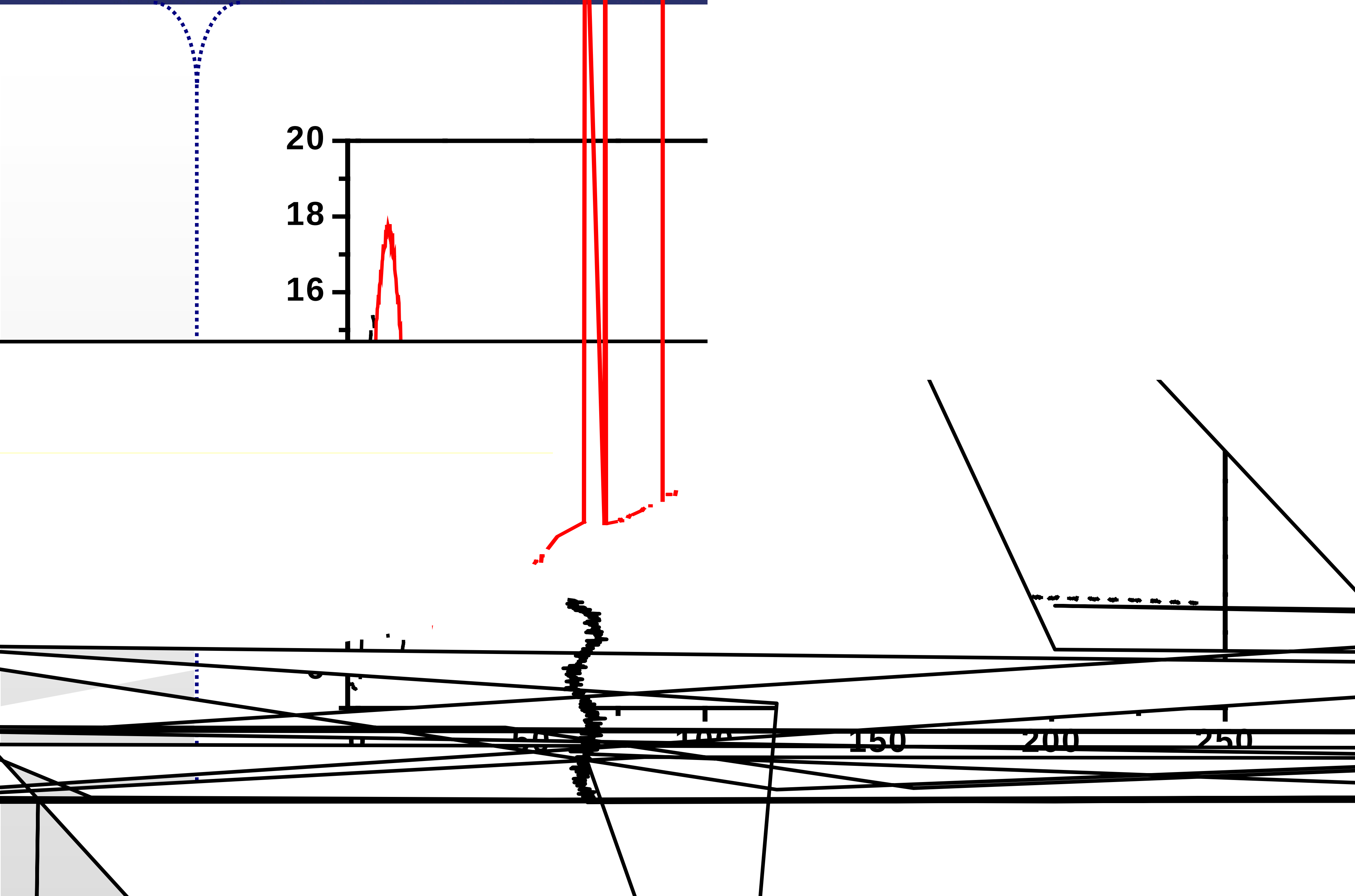
In-polar InN grown on Ga-polar GaN



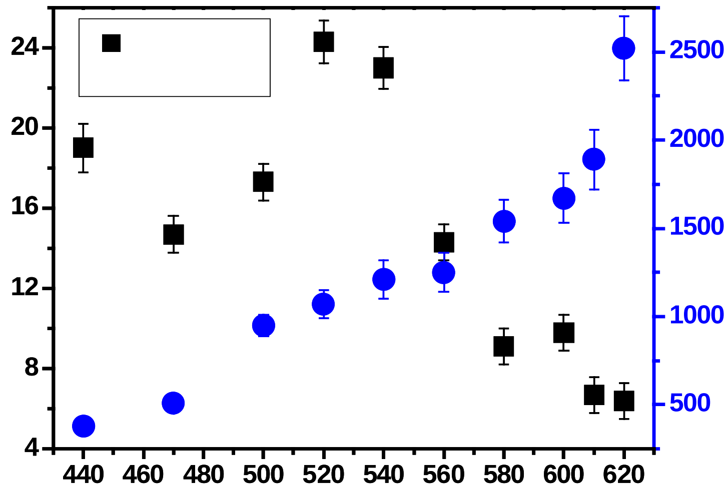
N-polar InN grown on N-polar GaN



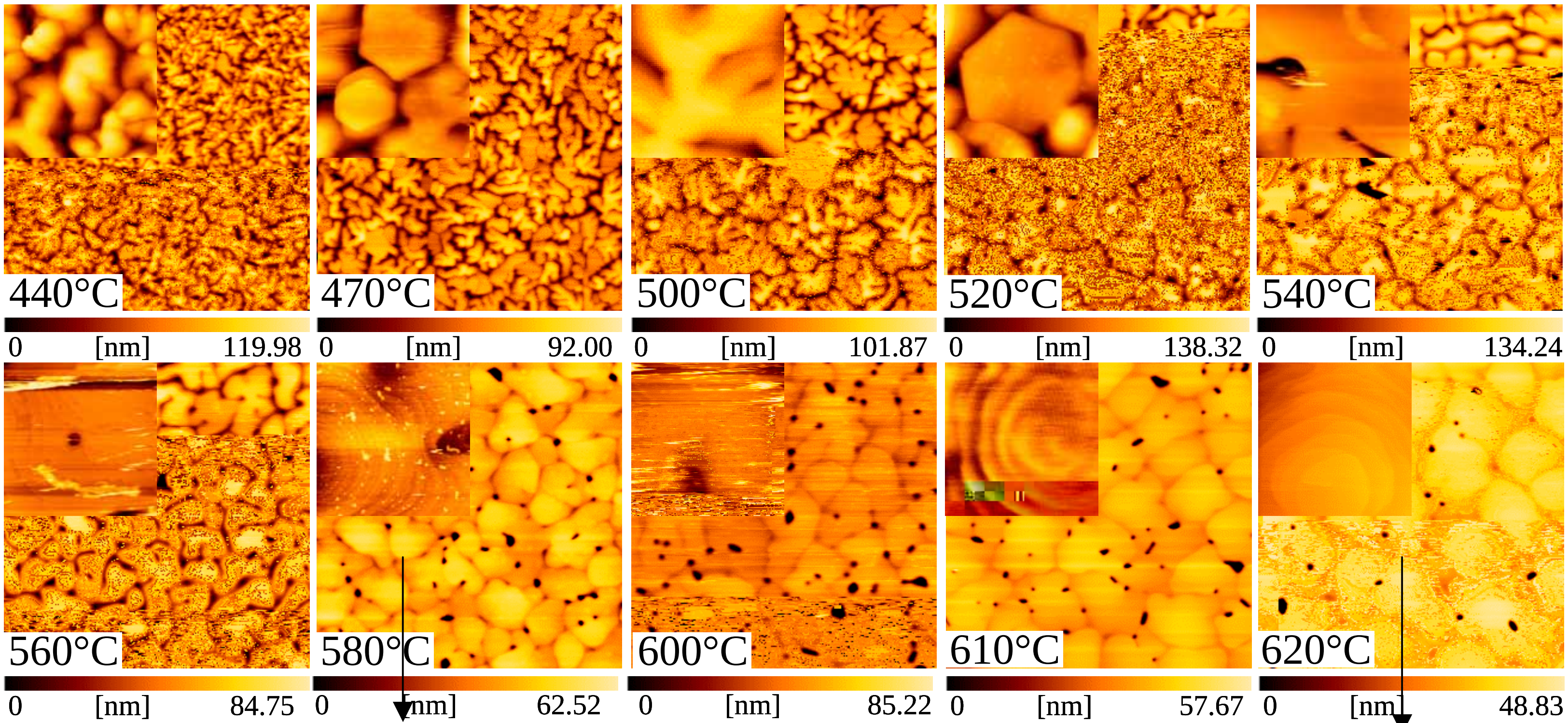
Epitaxy

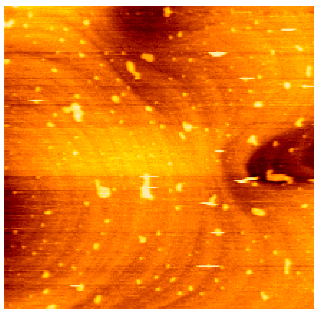


Effect of Growth Temperature

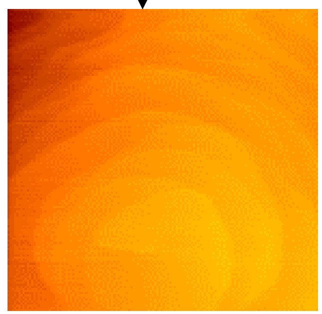


Typical Morphologies of N-polar InN

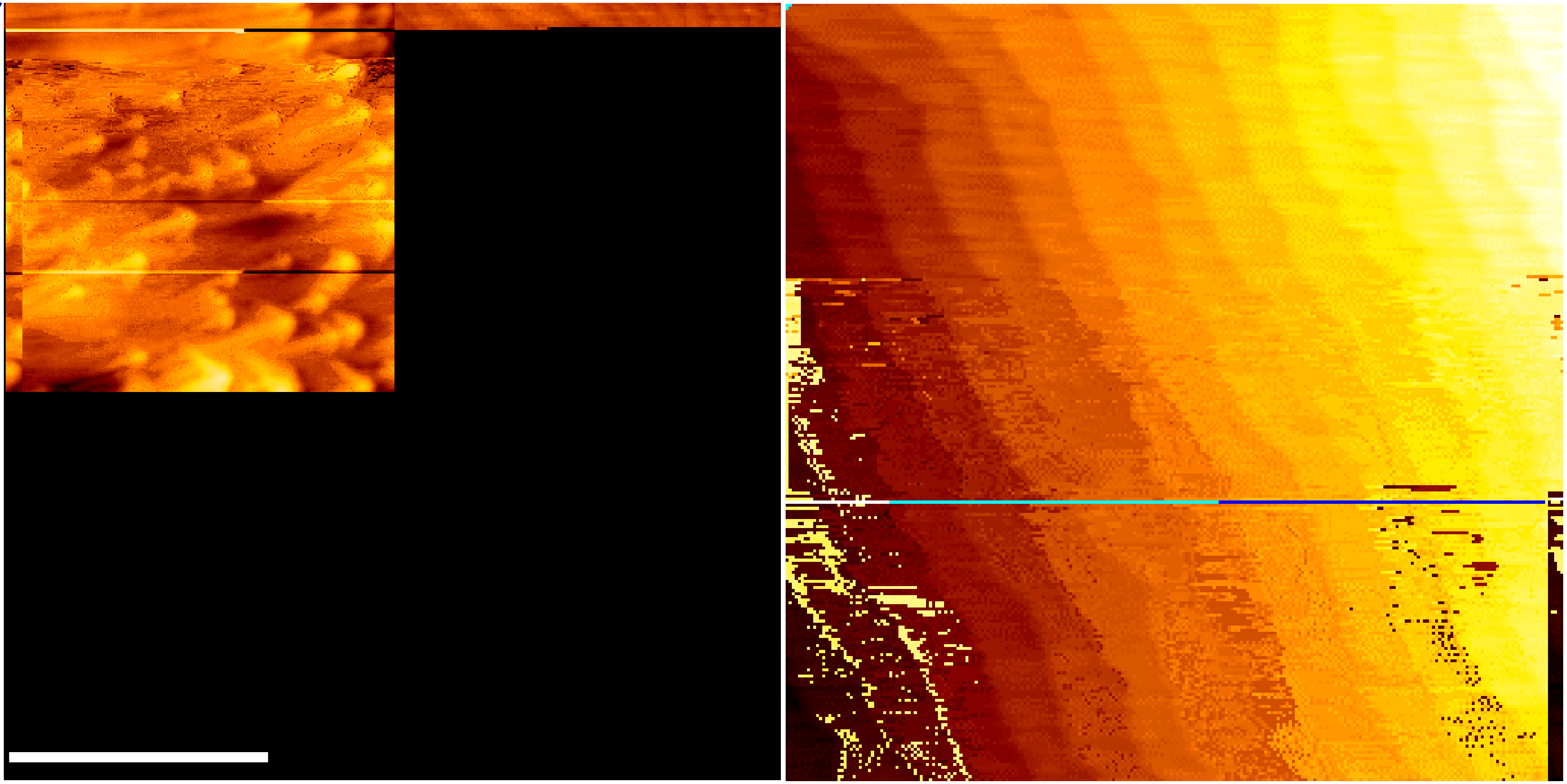




Enhanced migration of In adatoms with increasing growth temperature



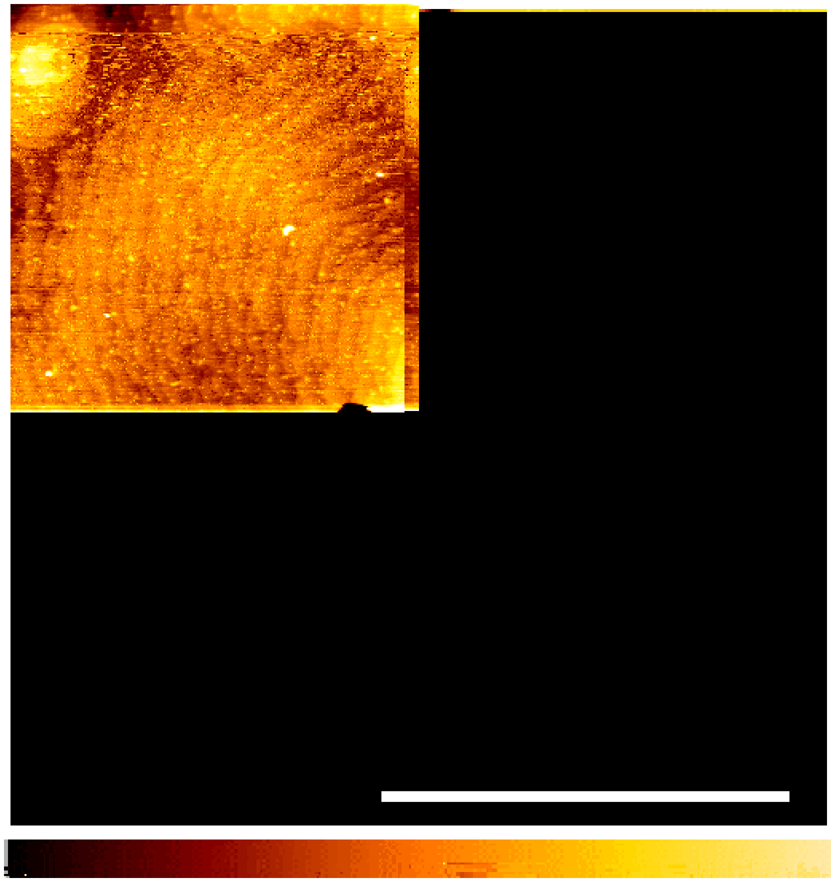
Atomically Flat Surface



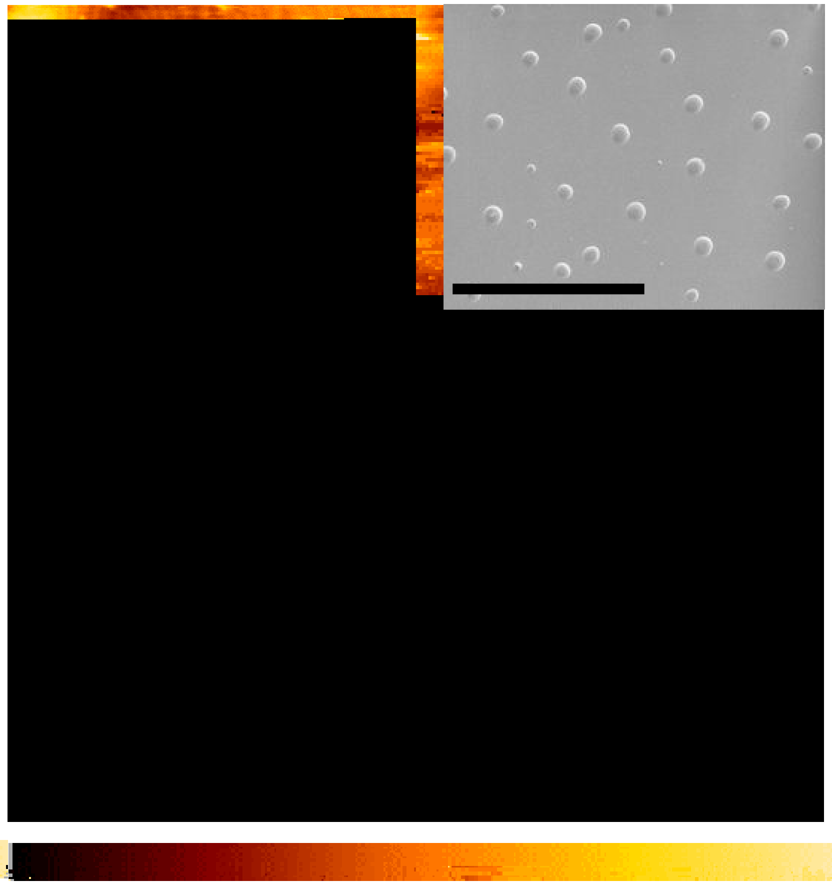
0.00 [nm] 4.03

Surface roughness is less than 1 nm in 10 m × 10 m area

How to get atomically flat surface



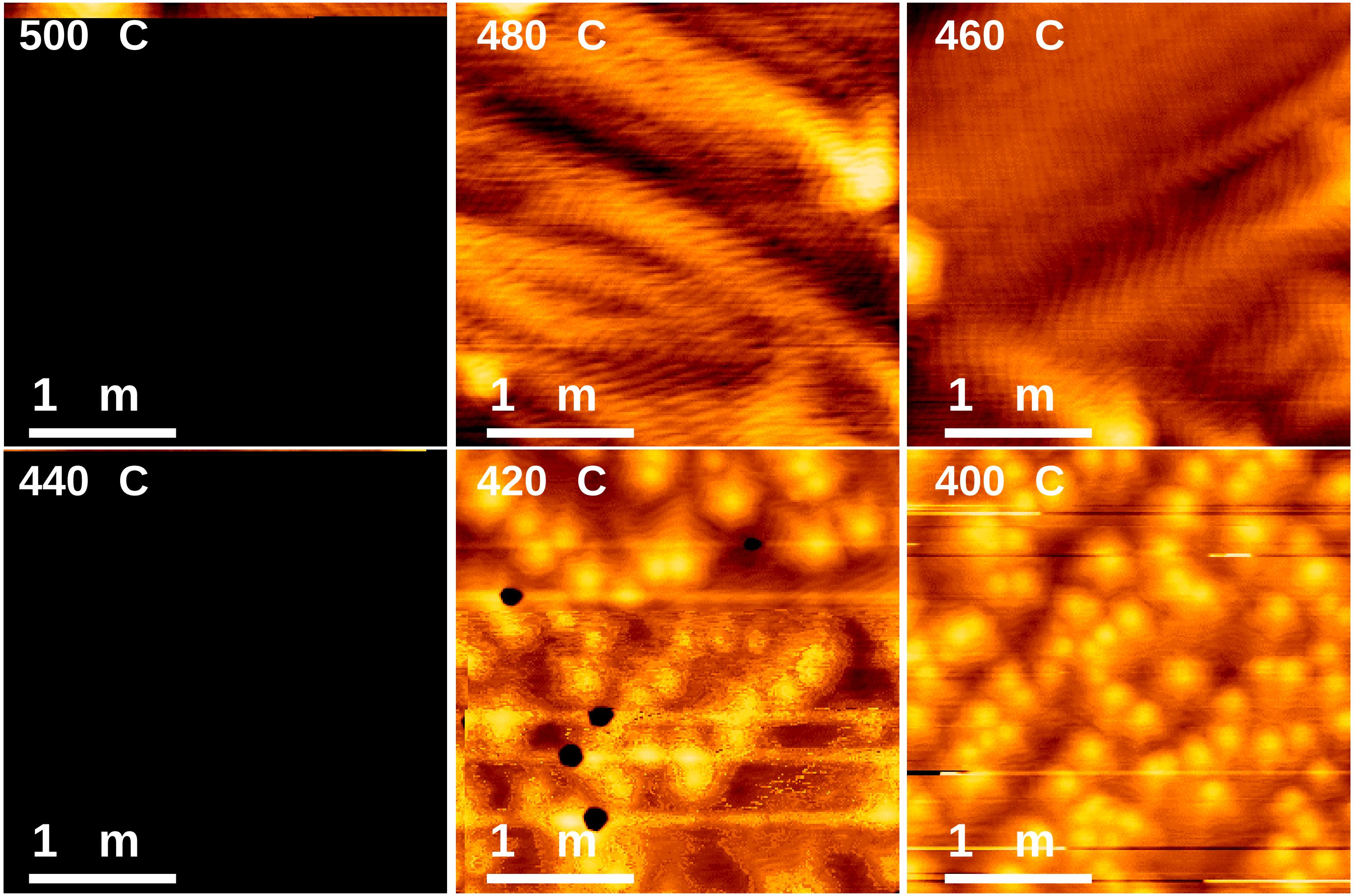
In/N=0.97



In/N=1.05

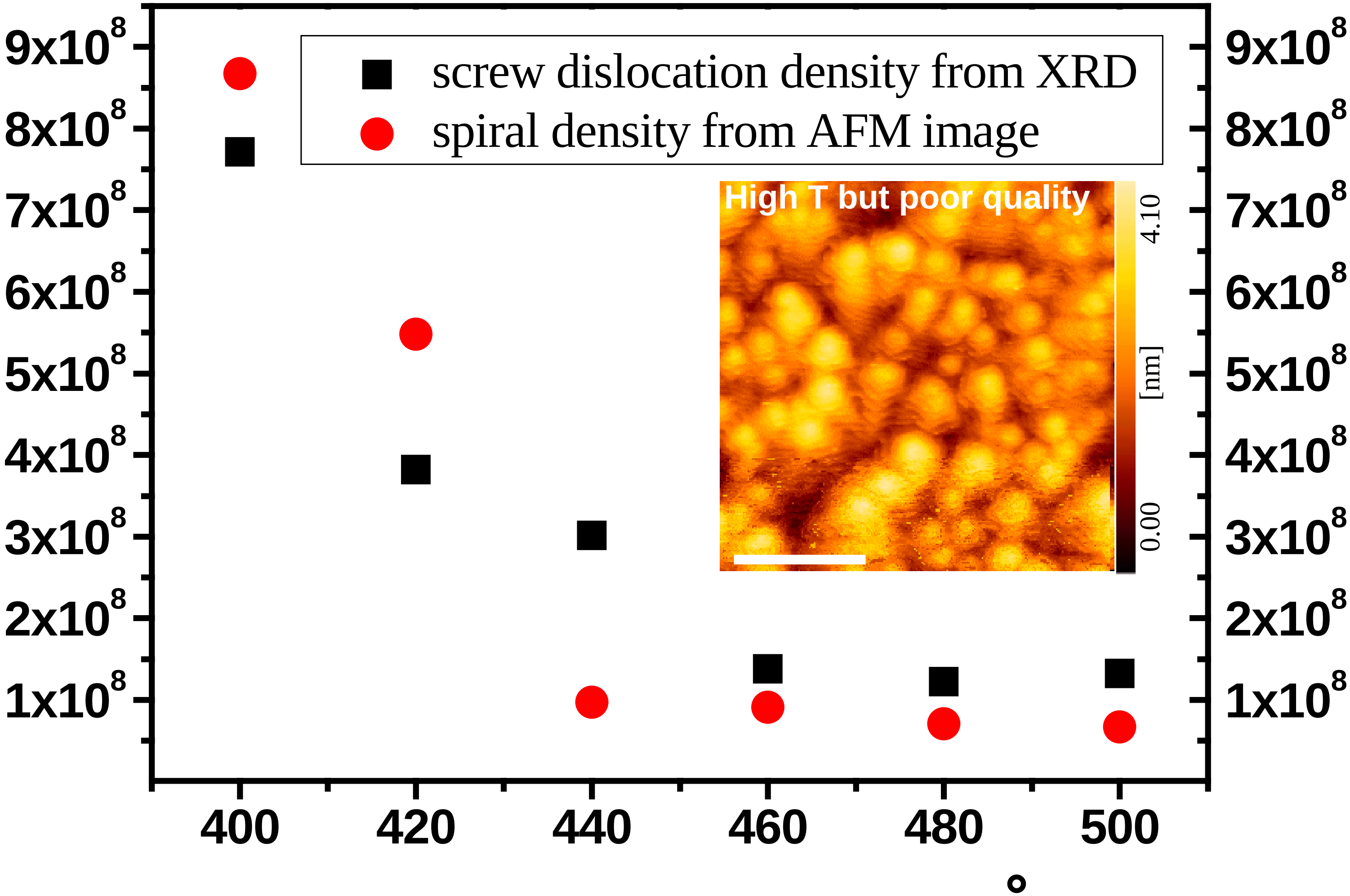
Slight In-rich condition is preferred

How to get atomically flat surface



High growth temperature is preferred

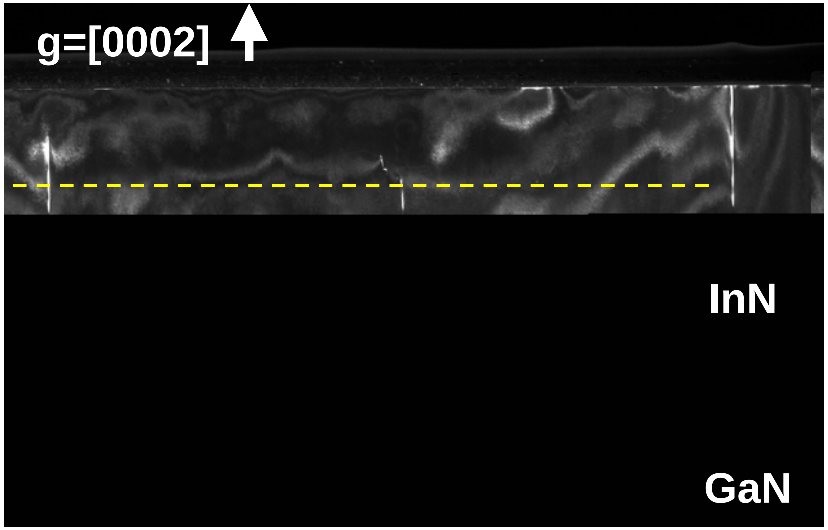
How to get atomically flat surface



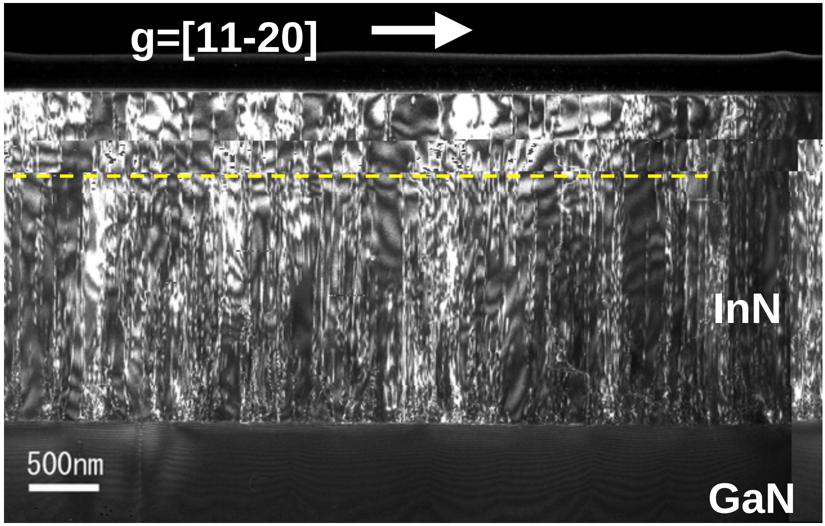
Low screw-type threading dislocation density

Crystalline Quality

Scew-type TD



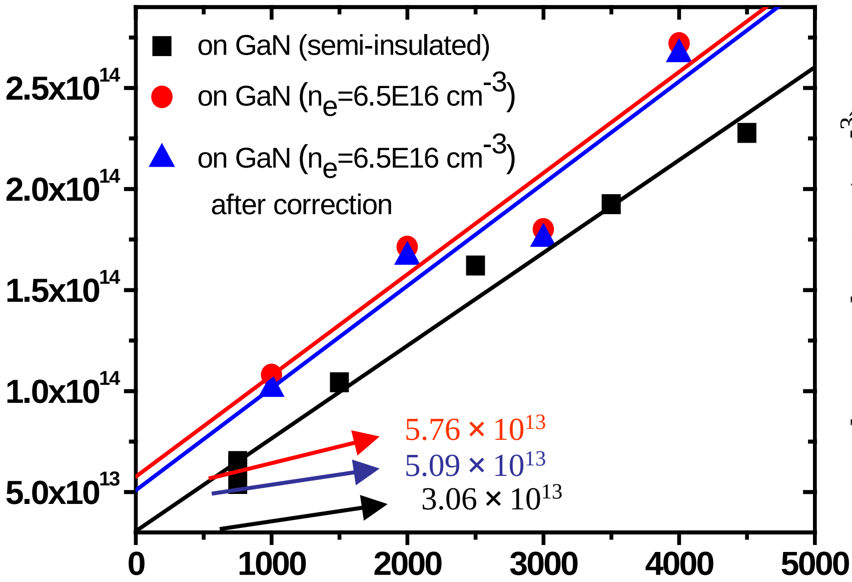
Edge-type TD



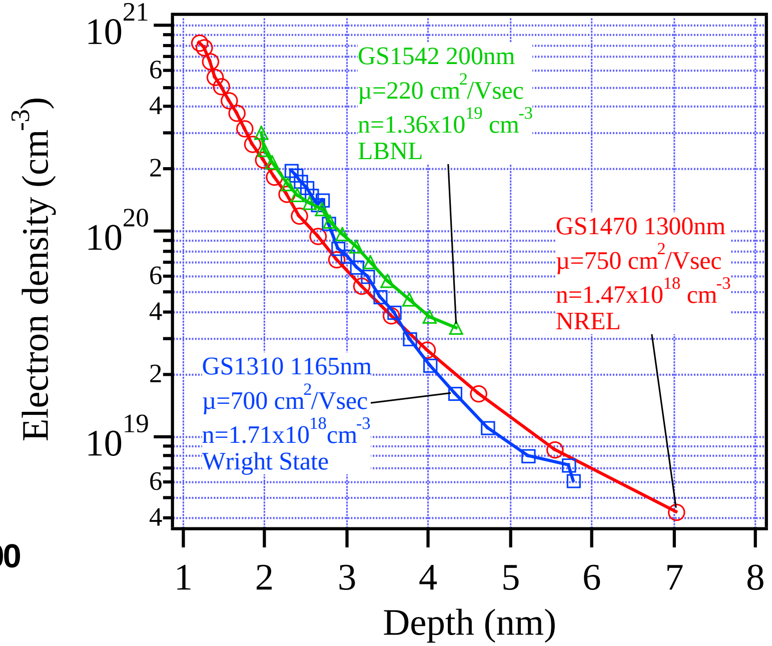
	XRD		TEM	
TDs (cm^{-2})	Screw-	Edge-type	Screw-	Edge-
On GaN template	1.3 10^8	2.1 10^{10}	2.8 10^8	1.2 10^{10}

Crystalline quality was not good, in particular ETD density was still high

Surface Electron Accumulation

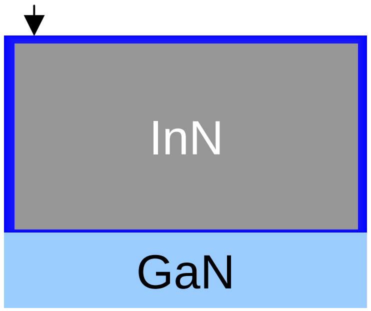


Sheet electron density at zero film thickness attributed to surface charge accumulation



High density surface electron was observed from ECV measurement.

Surface/interface electron accumulation

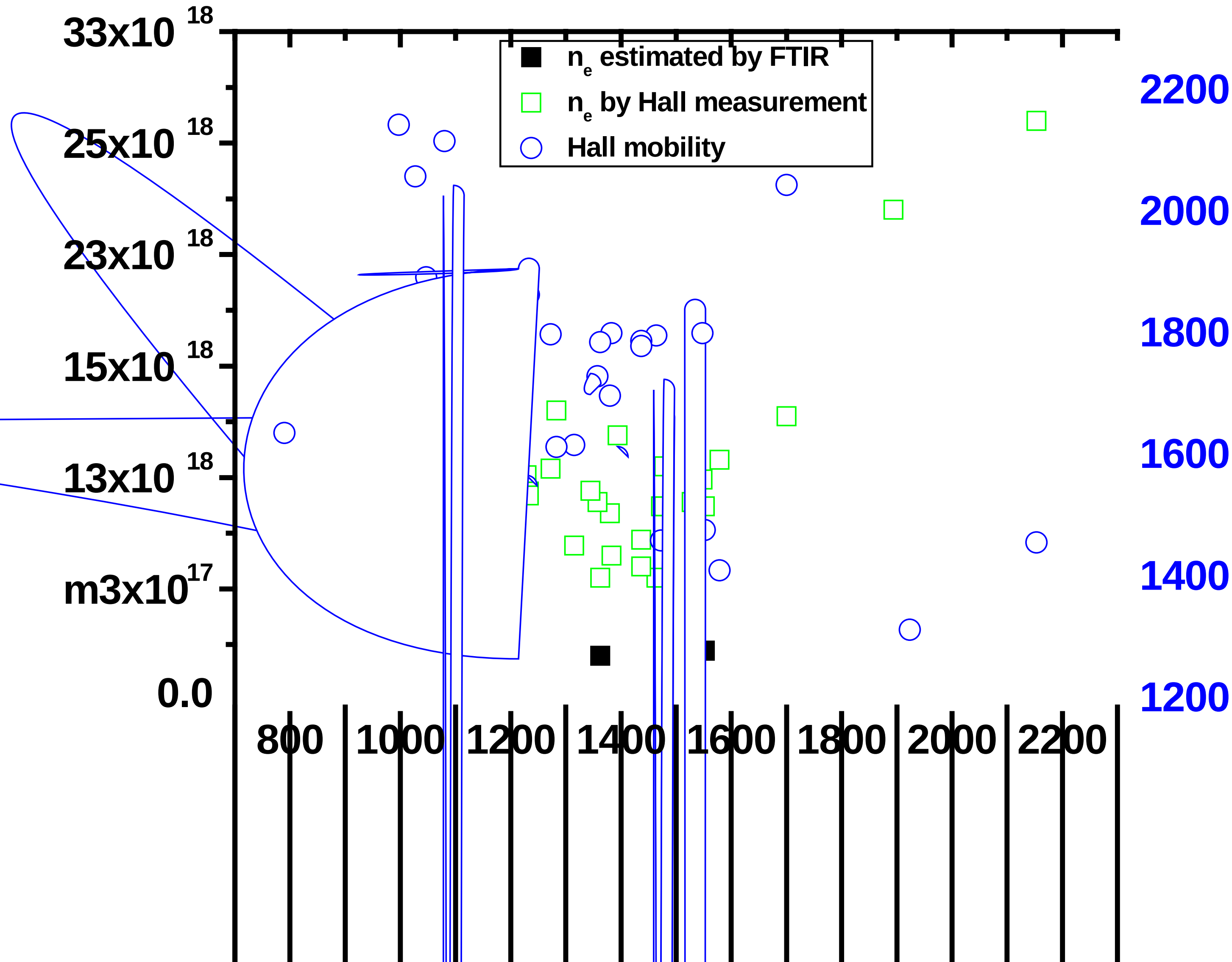


All metals form Ohmic contact on InN, also indicates surface accumulation, similar to InAs

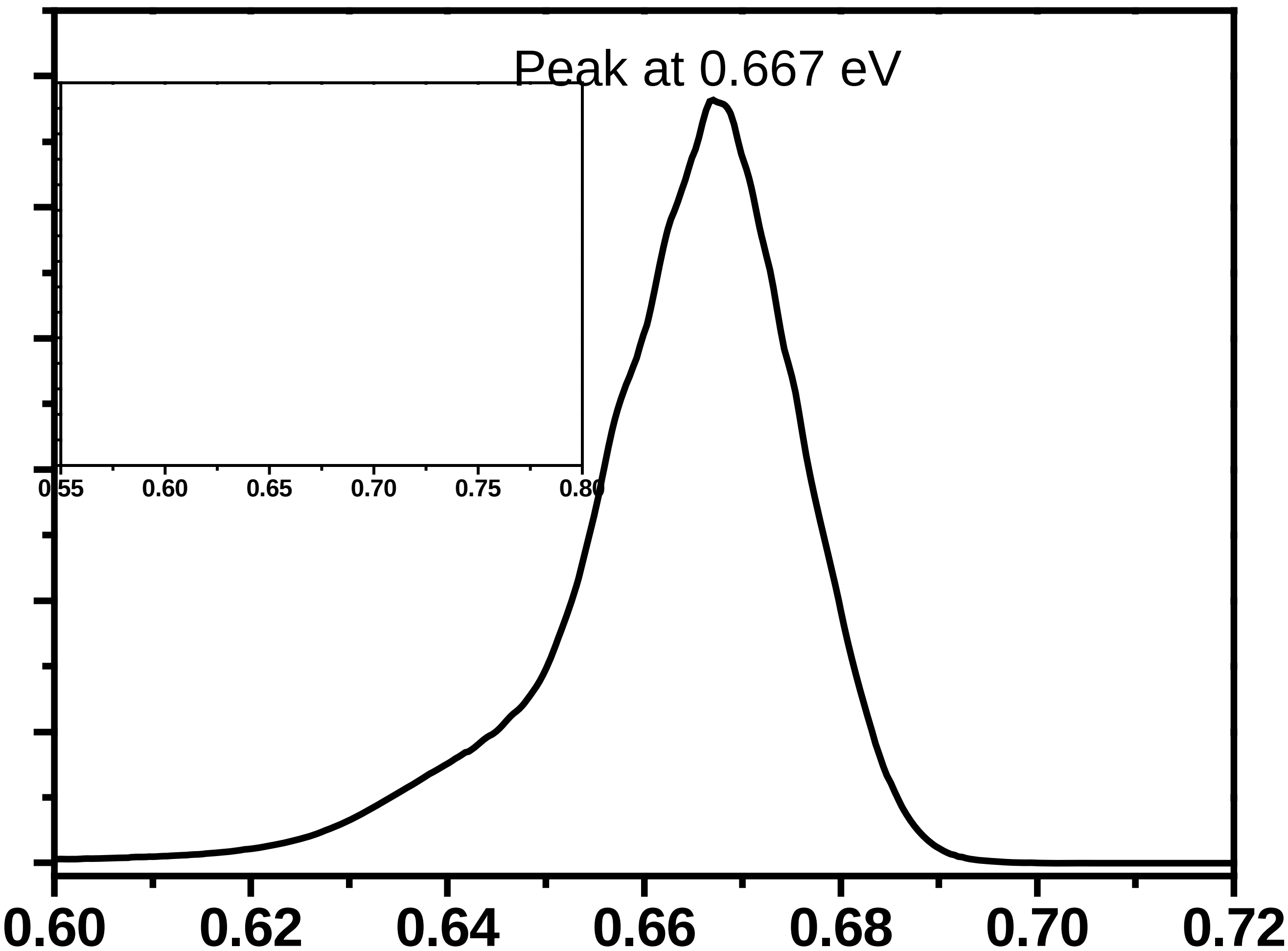
Hai Lu, W. J. Schaff, L. F. Eastman, and C. E. Stutz, Appl. Phys. Lett. , 1736 (2003)

W. J. Schaff, Hai Lu, L. F. Eastman, W. Walukiewicz, K. M. Yu, S. Keller, S. Kurtz, B. Keyes, L. Gevilas, Oct 2004 ECS meeting

Threading dislocation effect on n_e

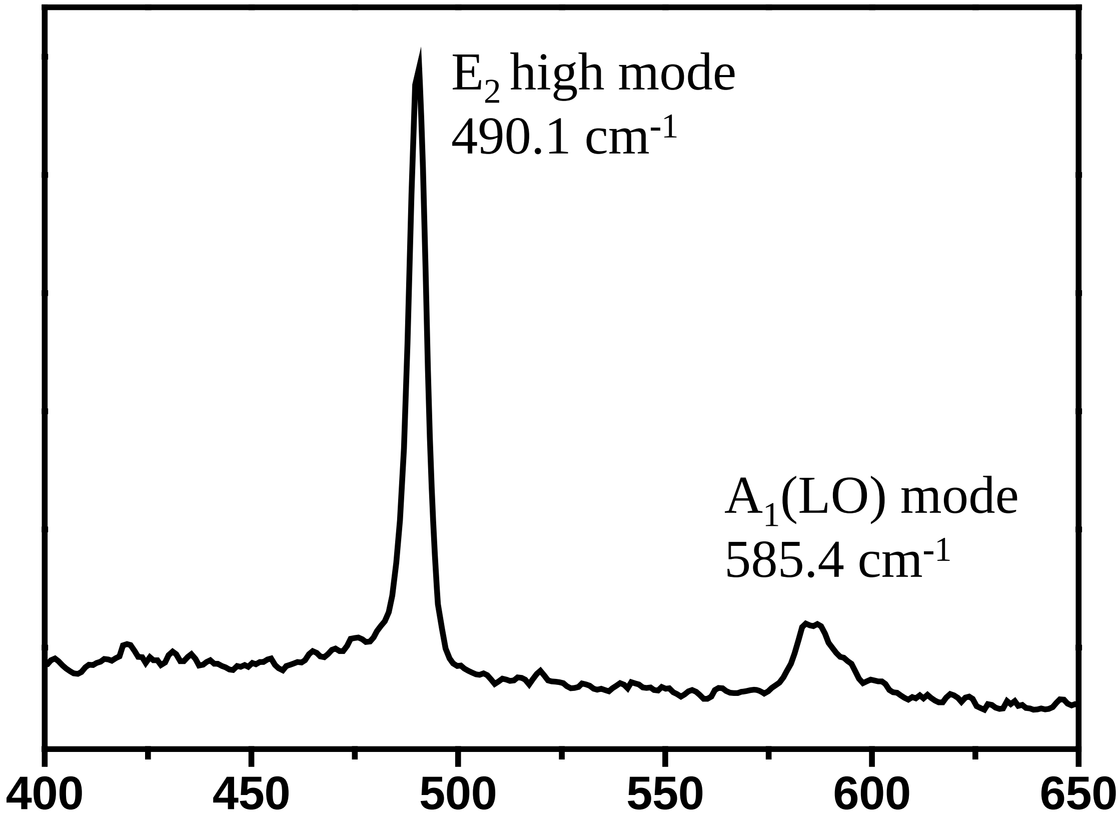


PL Results



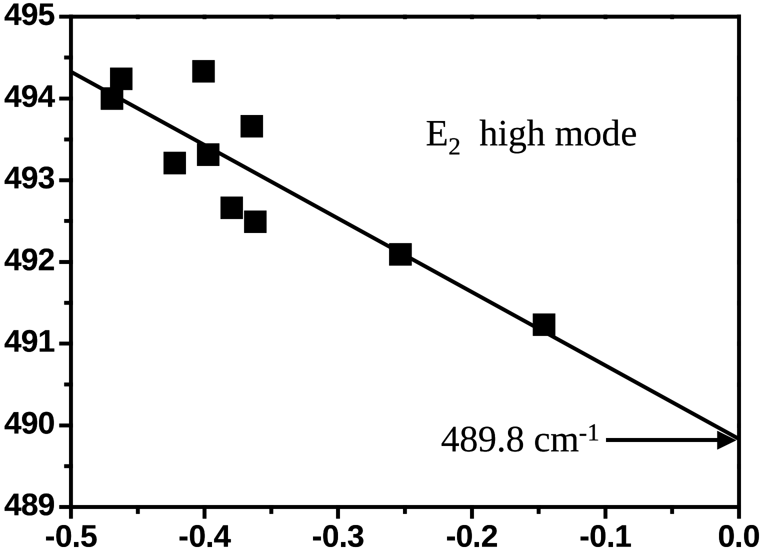
Peak at 0.667 eV
0.55
0.60
0.65
0.70
0.75
0.80
0.60
0.62
0.64
0.66
0.68
0.70
0.72

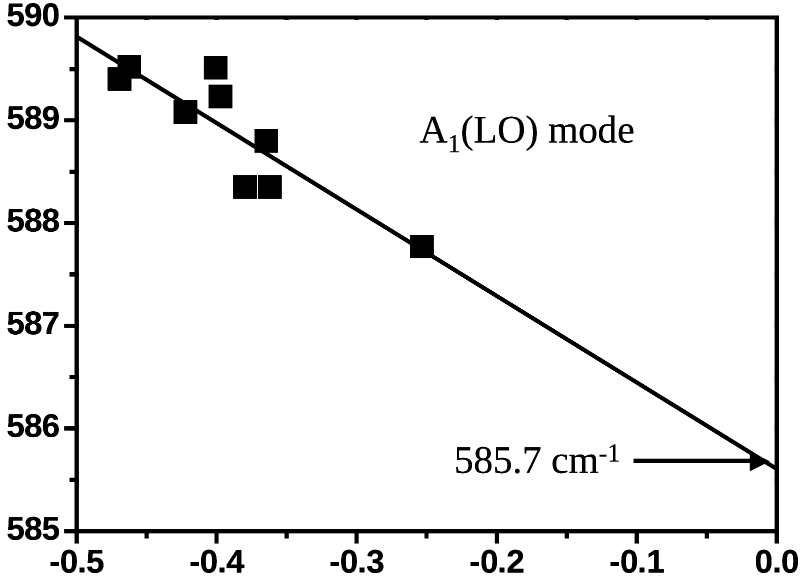
InN Parameters: Raman Scattering

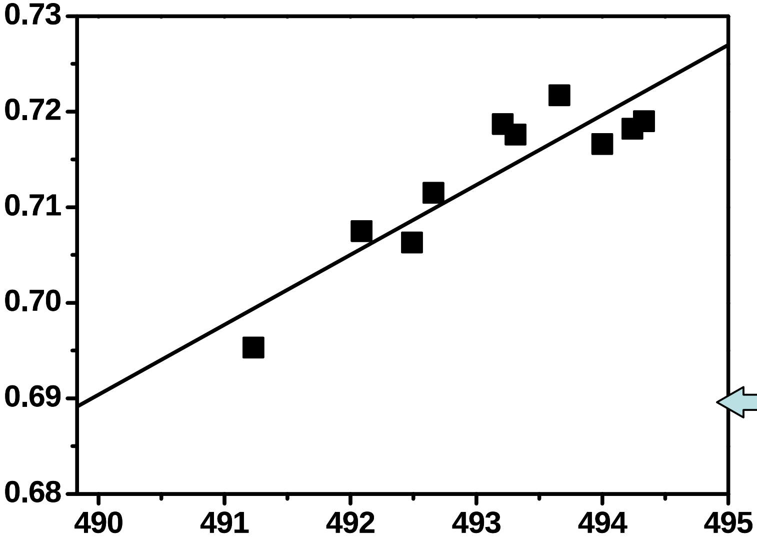


X Wang, S Che, Y Ishitani, A Yoshikawa, *Appl. Phys. Lett. 89 (2006) 261643.*

InN Parameters: Raman Scattering







Raman E2

8.99 ± 1.7 cm^{-1}/Gpa

Raman A1(LO) 8.4 ± 1.7 cm^{-1}/GPa

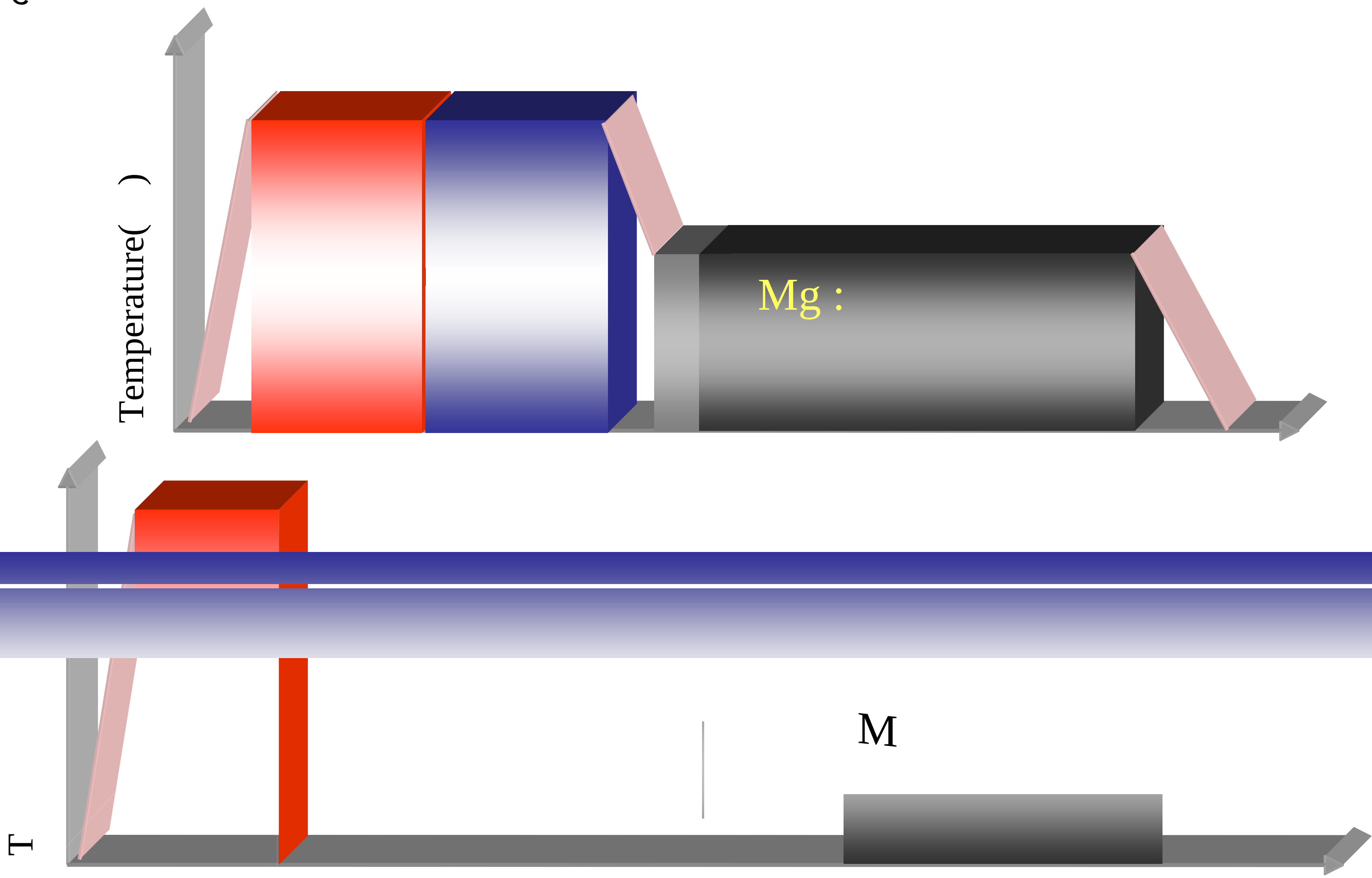
E/ $= 7.3 \pm 1.2$ meV/cm^{-1}

P-type doping of InN

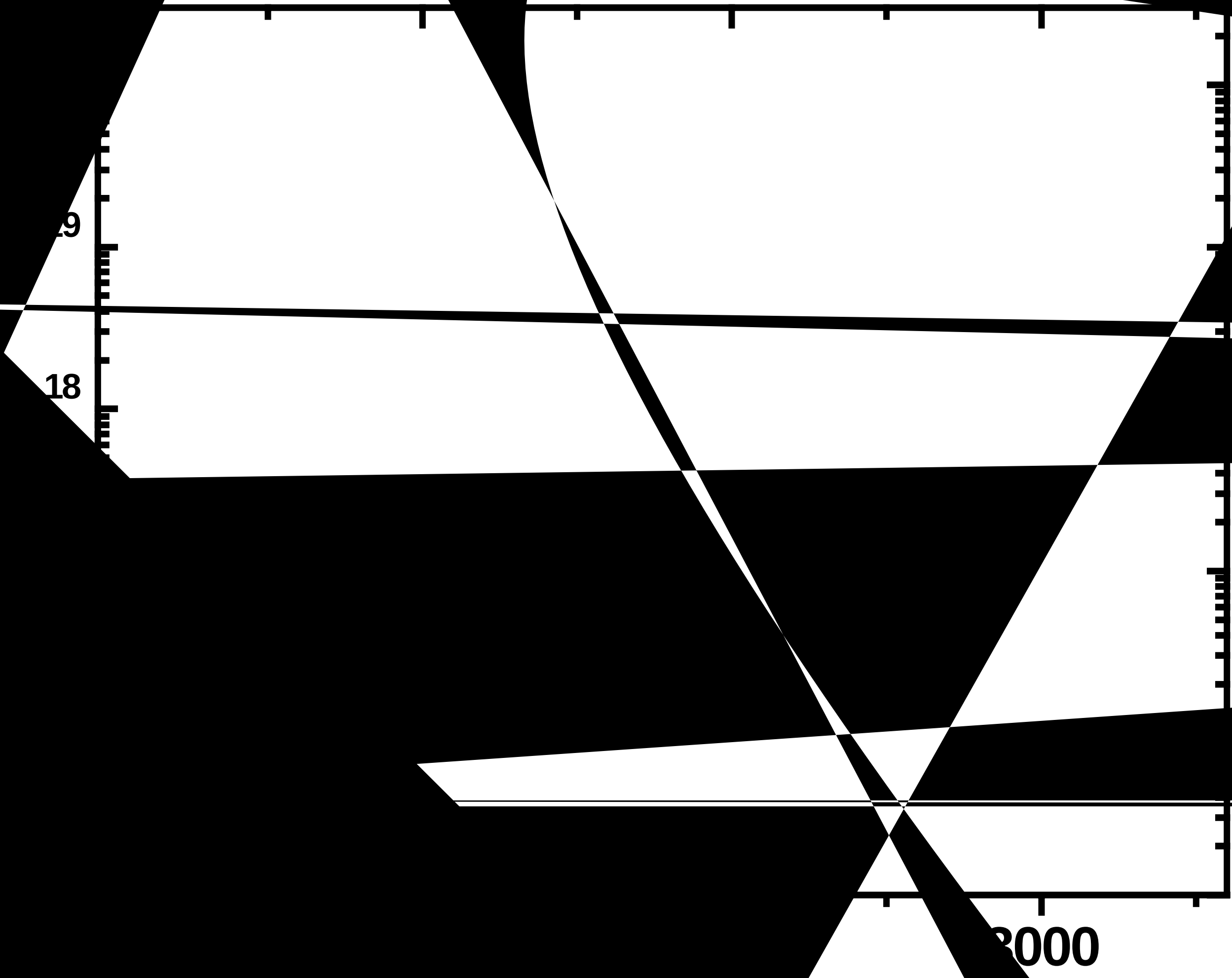
G

O u M t l i n e

l

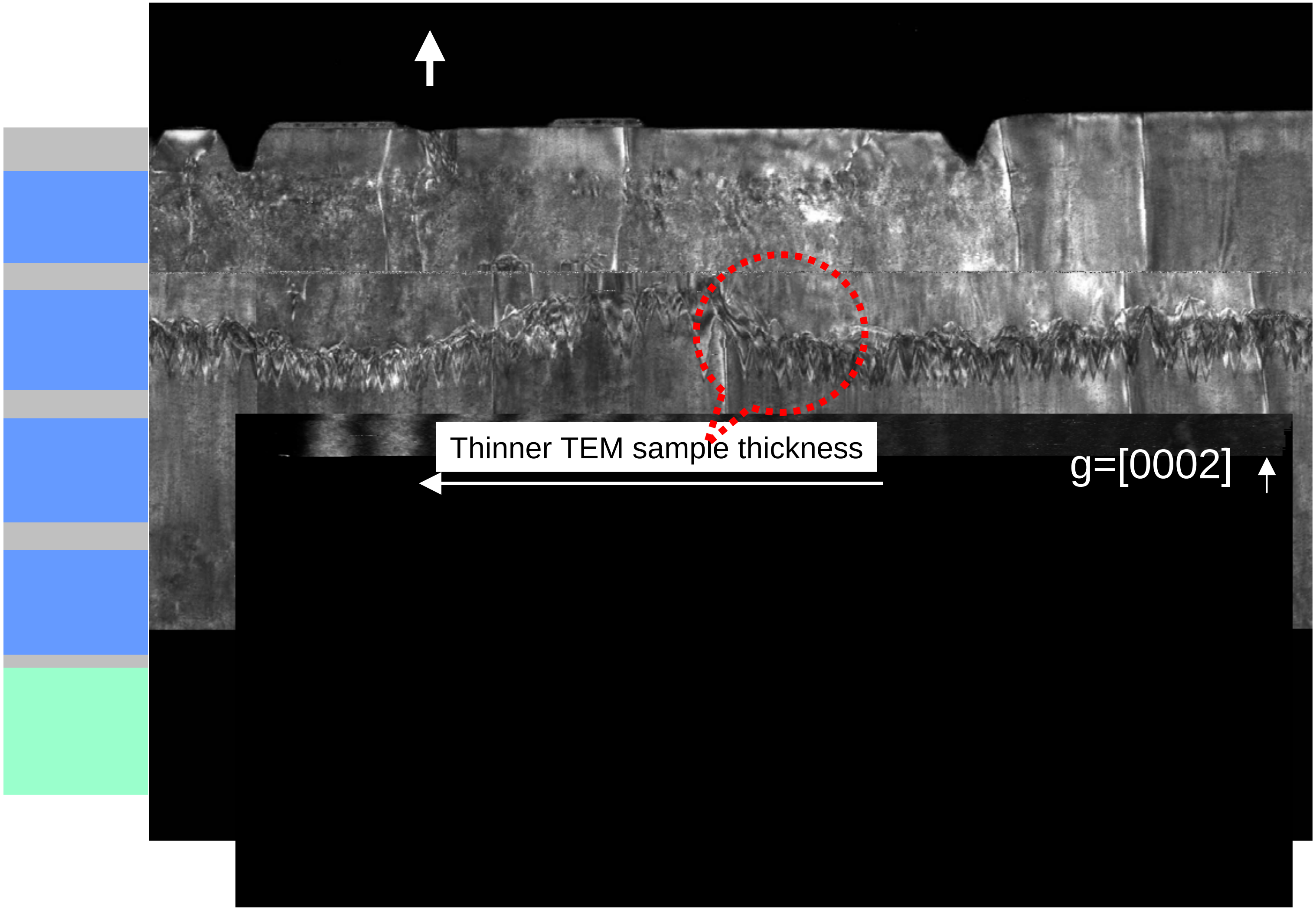


[redacted] concentration in InN:Mg



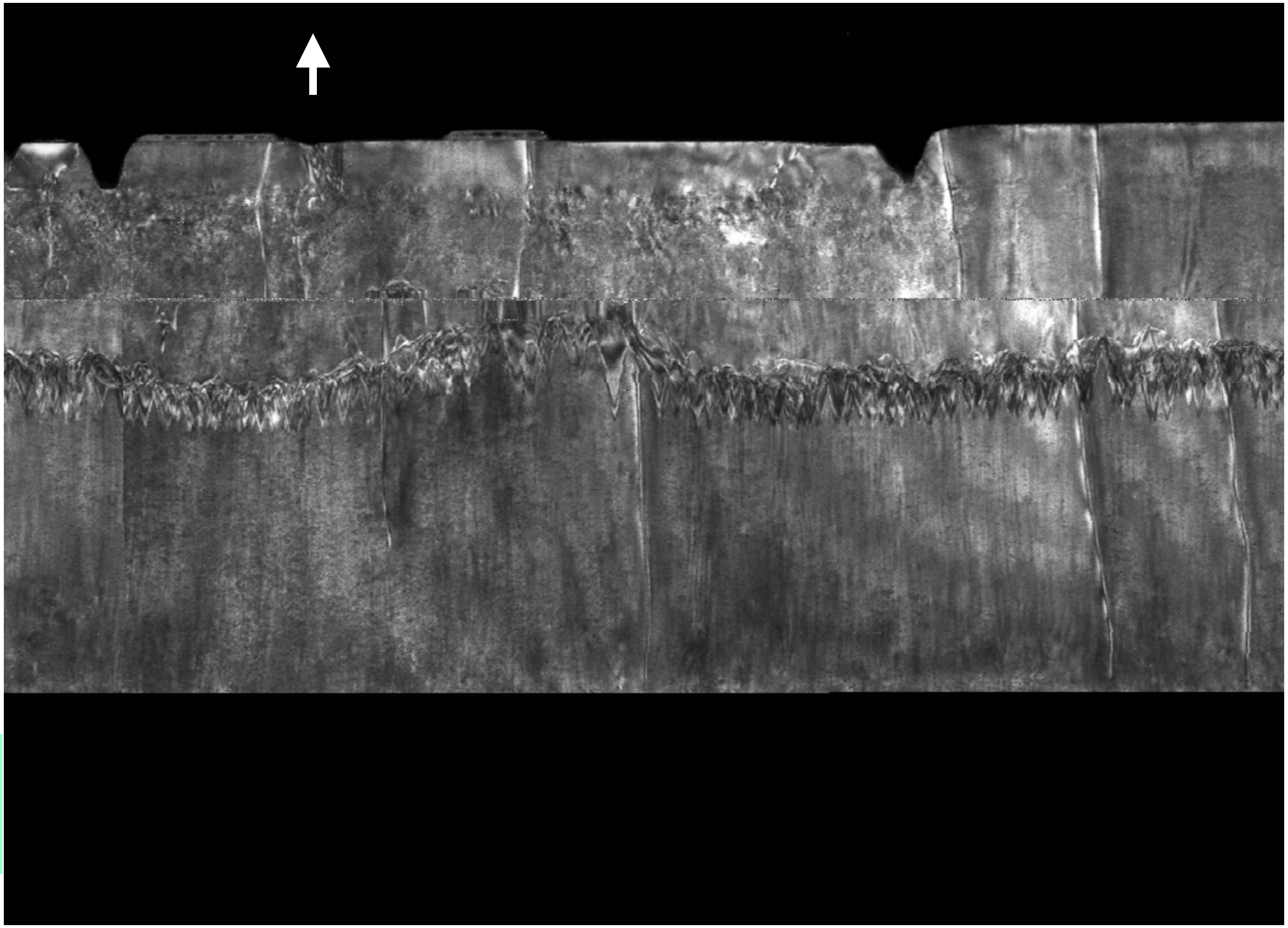
[redacted] st constant and [redacted] boundary at the
[redacted] ion changes expo[redacted]ally with T_{Mg},.
[redacted] most unit.

Domain structure in InN:Mg

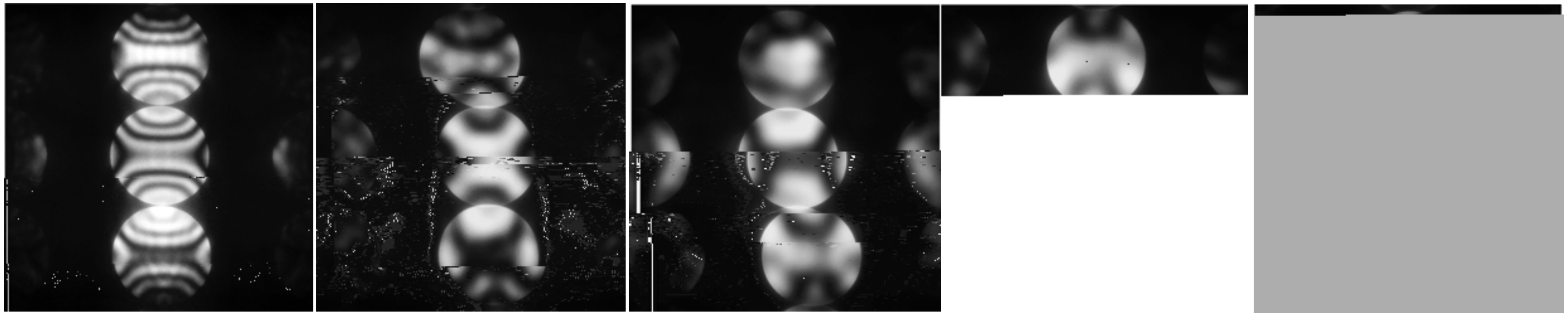


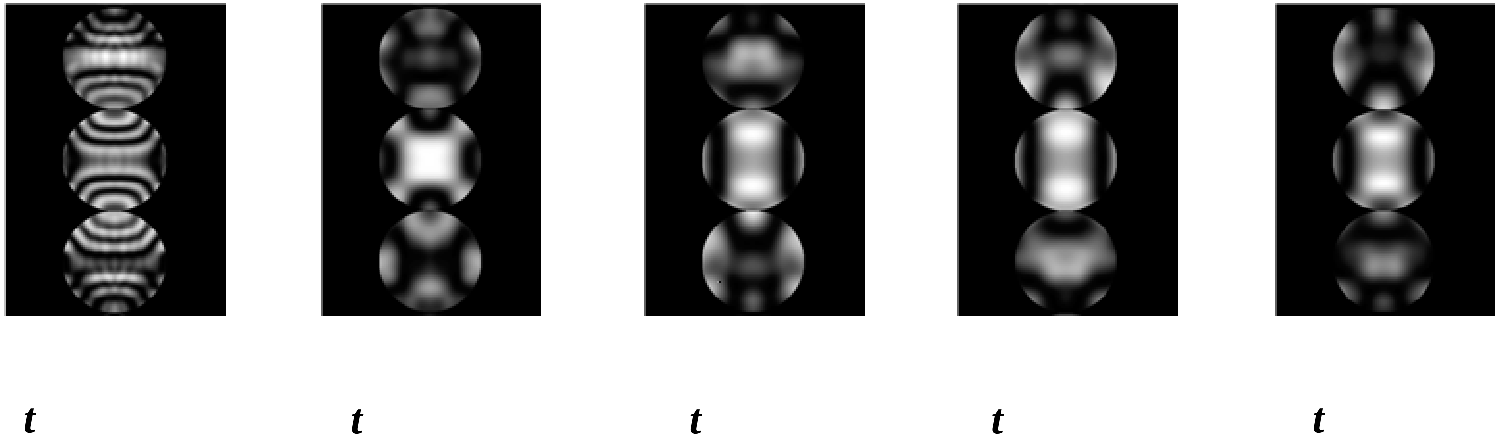
A layer with domain structure is observed at 3rd Mg:InN layer with Mg concentration of $2.9\ \ 10^{19}$ cm^{-3}. Are these domains inversion domains?

Polarity Investighed4nE



CBED Results in TEM Measurement

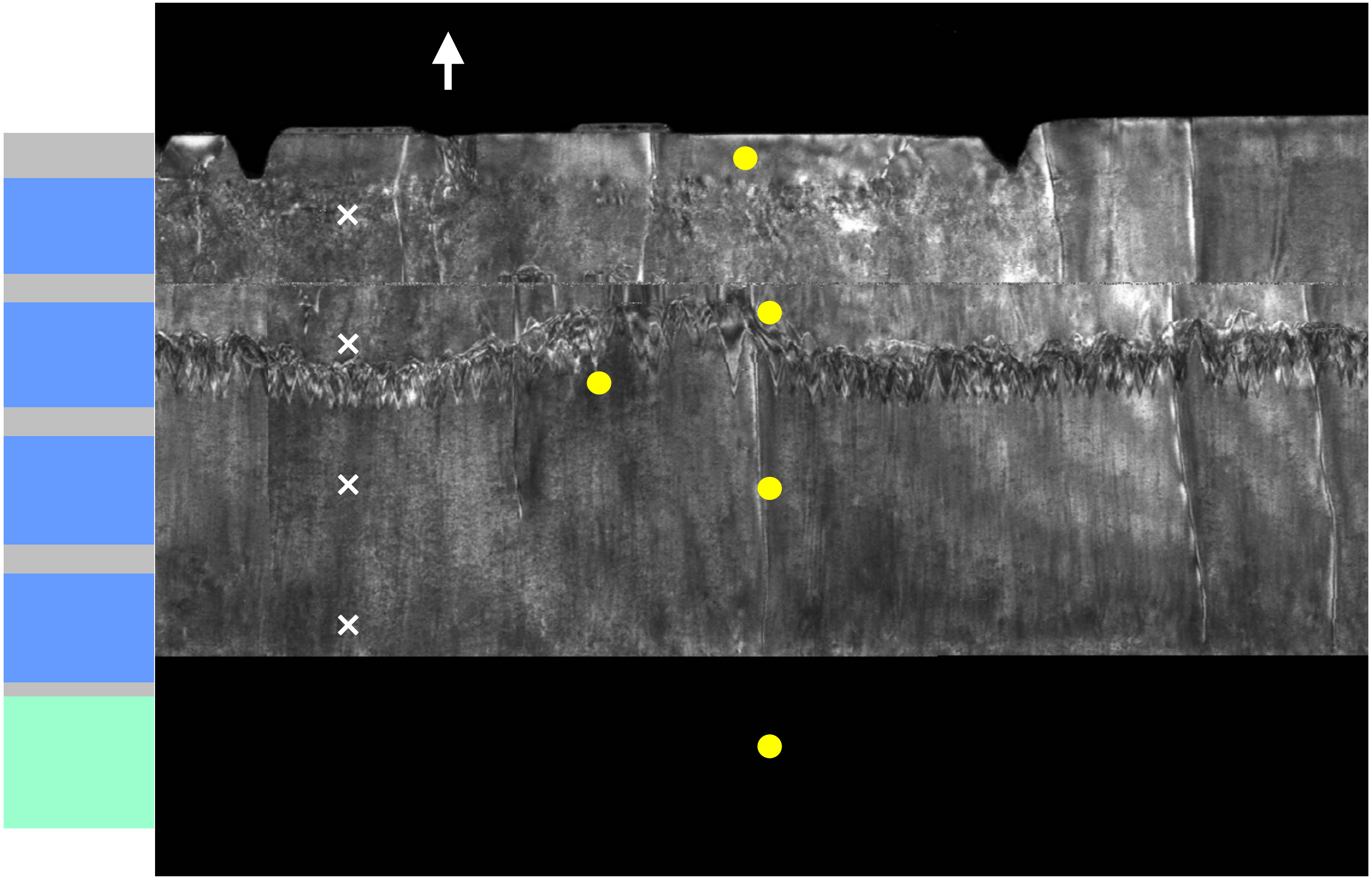




Simulation

Polarity was determined by comparison between measured CBED patterns and simulated patterns

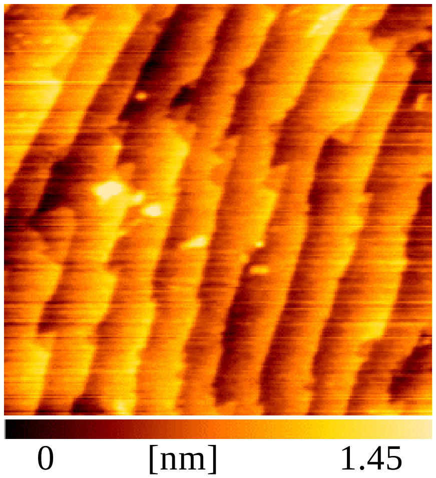
Polarity Inversion in InN:Mg

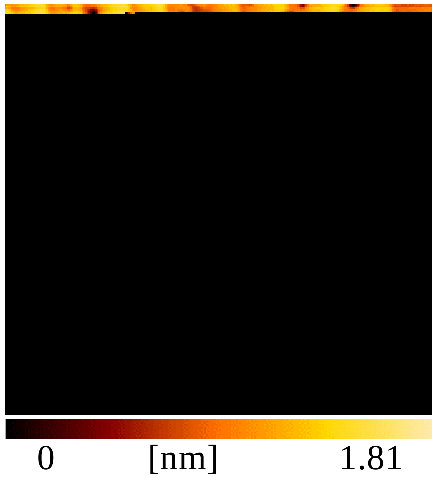


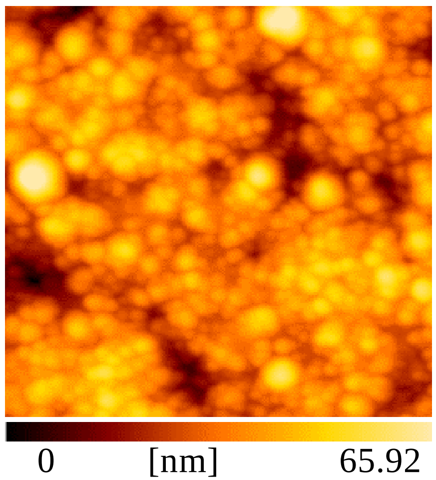
Polarity was inverted from In-polarity to N-polarity, confirming domains are inversion domains.

X Wang, S Che, Y Ishitani, A Yoshikawa, *Appl. Phys. Lett. 91 (2007) 081902*

Polarity Investigation by Chemical Etching

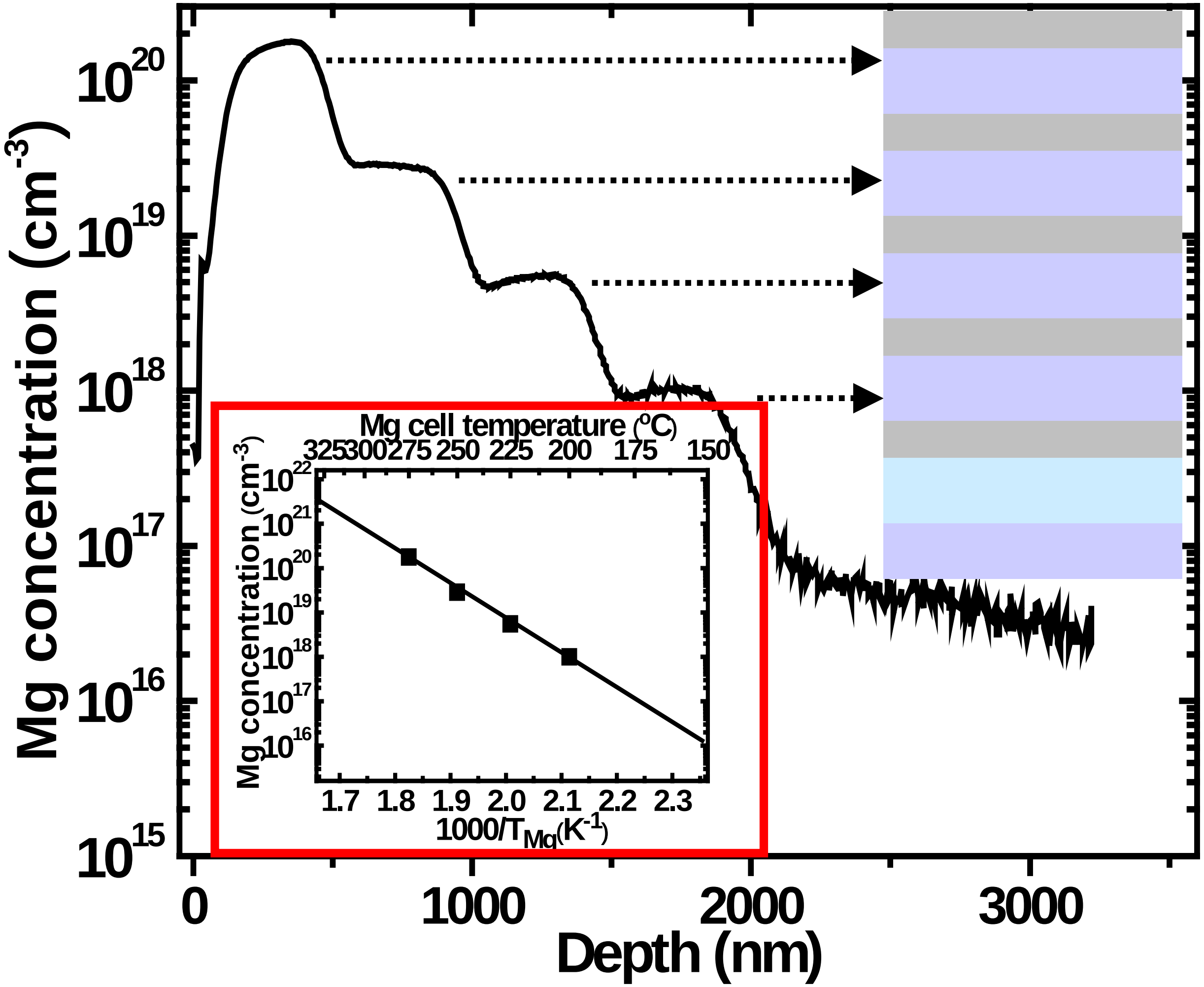






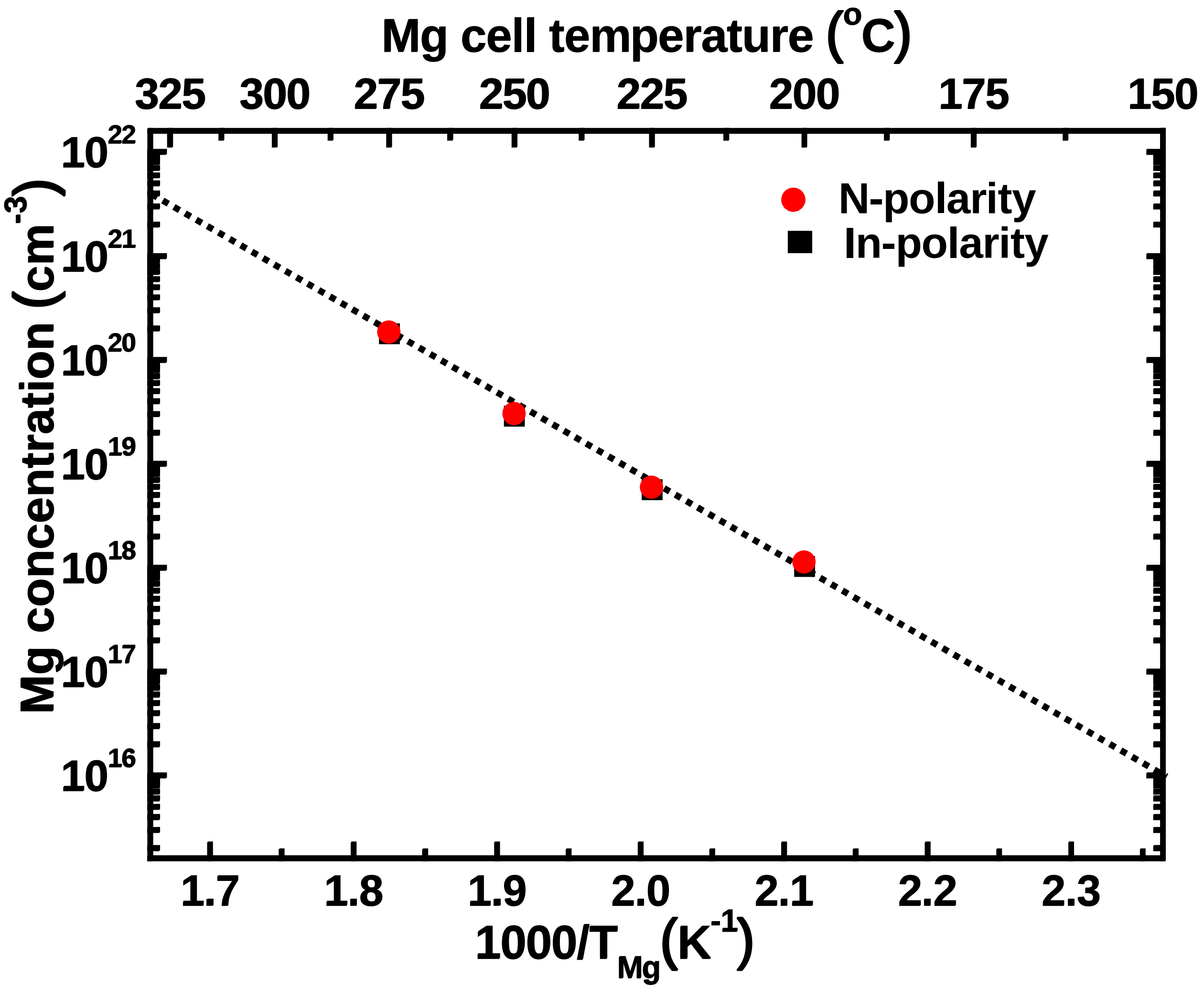
In-polarity InN was difficult to be etched, and step-flow feature was kept after etching. N-polarity InN was easily etched, surface became rougher and small island-like structure was observed on surface.

Mg concentration in InN:Mg



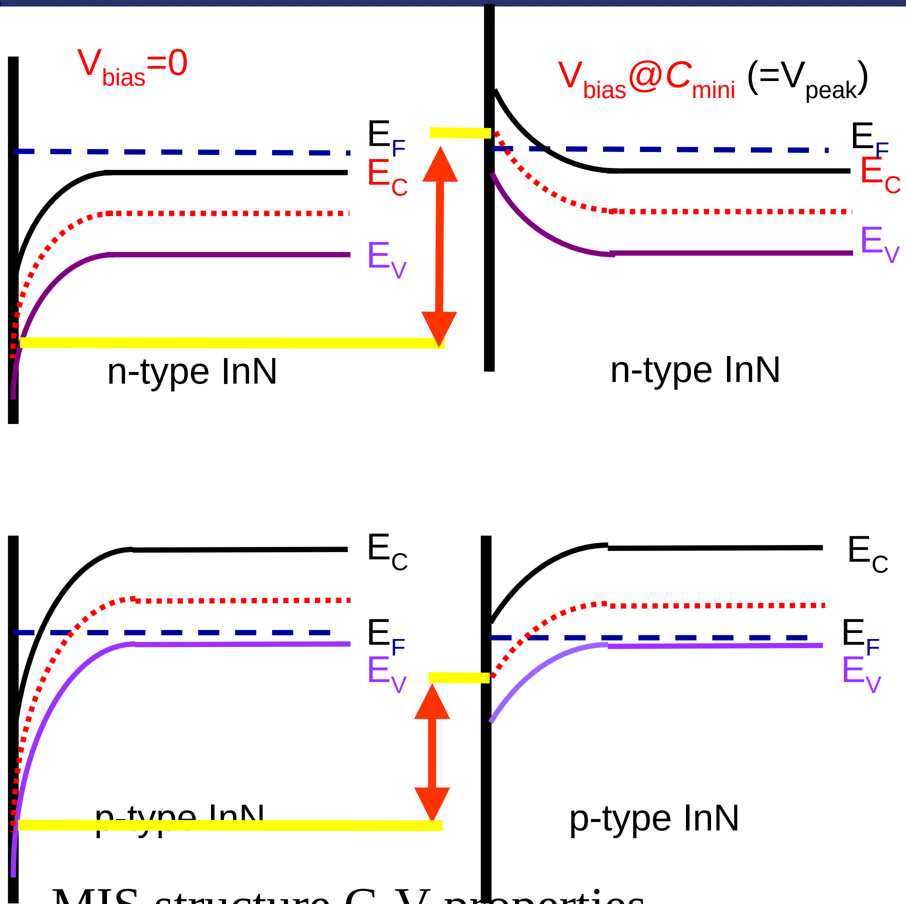
Return to Mg concentration at different Mg cell tempeature.

[Mg] Comparison between In and N polarities



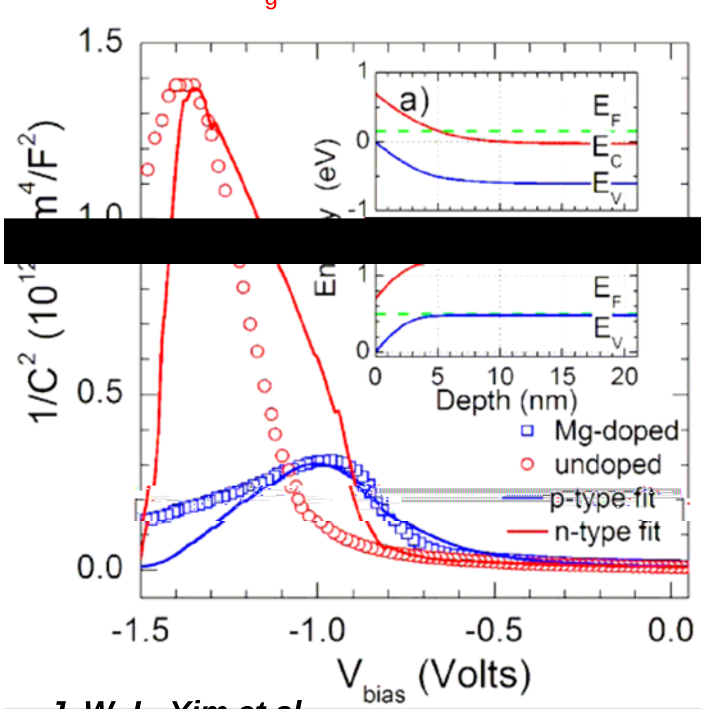
[Mg] shows almost the same value at the same supplied Mg beam flux, independent of polarity, probably due to the low growth temperature.

P-type Mg:InN-ECV measurement



MIS structure C-V properties

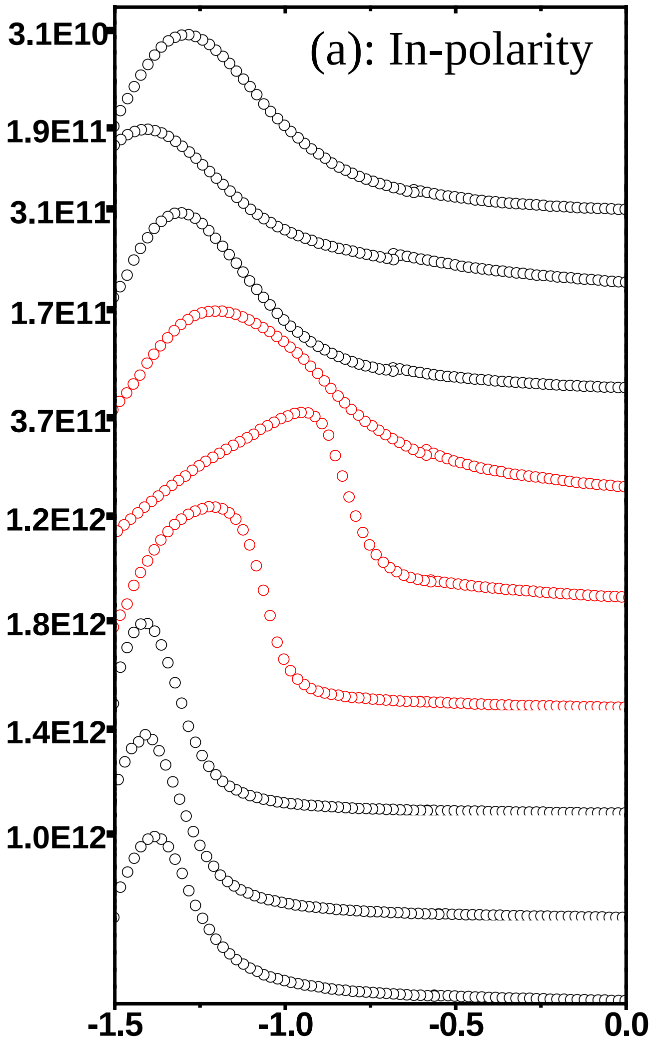
N_a=2.3E19 cm-3
m_h =1.65 m_0
E_g=0.7 eV

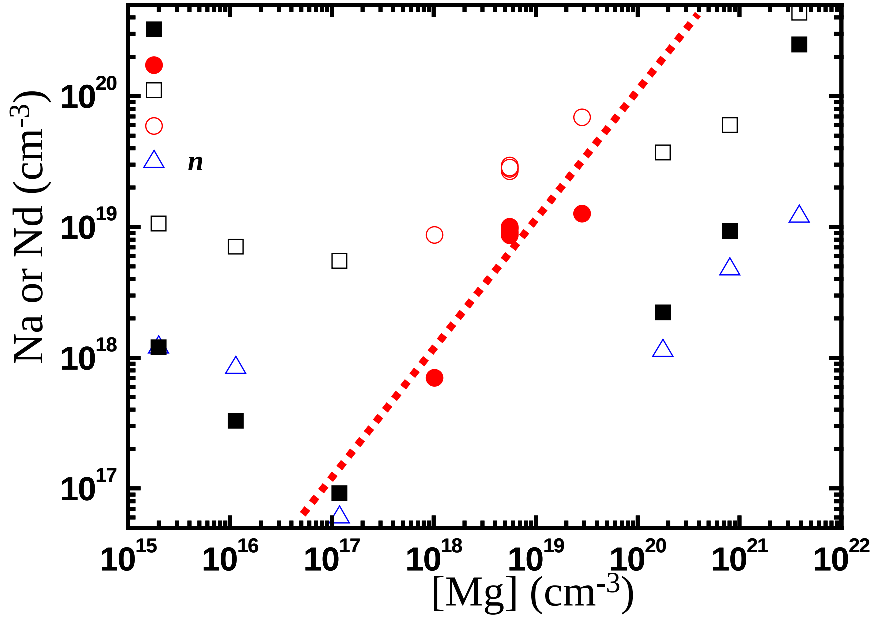


J. W. L. Yim et al., Phys. Rev. B 76, 041303 (2007)

C^{-2}-*V*bias spectra can be simply understood as follows: 1) under thermal equilibrium, i.e., under zero *V*bias, the surface Fermi levels for both p-type and n-type InN samples are pinned at about 0.9 eV high above the conduction band bottom. 2) the surface Fermi level or surface potential can be modified by the applied voltage and the surface Fermi level position inside the forbidden band corresponding to the C^{-2} peak is different in magnitude of 0.35 to 0.45 eV between p-type and n-type InN samples, and then 3) *V*bias values when detect-ing C^{-2} peaks are different for p-type and n-type conduction InN.

P-type conduction - ECV measurement In-polarity





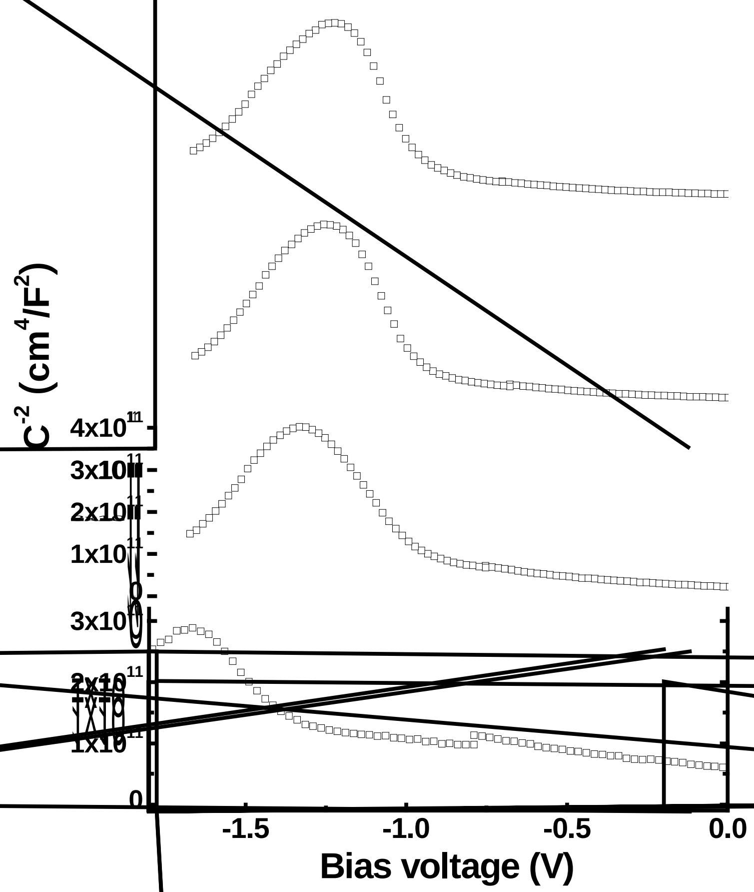
Sample	$n_{e\text{-Hall}}$ (cm^{-3})	$N_{d\text{-ECV}}$ (cm^{-3})	$C_{min\text{-cal.}}$ (nF/cm^2)	$C_{min\text{-exp.}}$ (nF/cm^2)	$C_{.}$ (nF/cm^2)
E861	5.08E17	6.9E18	254	834	580
E868	5.17E17	8.9E18	256	938	682
E863	5.08E17	6.6E18	254	816	562
E671	6.01E17	1.2E19	274	1067	793
E920	9.08E17	7.8E18	330	885	555

m_h =0.42 m_0 E_g=0.63 eV $_r$=9.3 $_0$

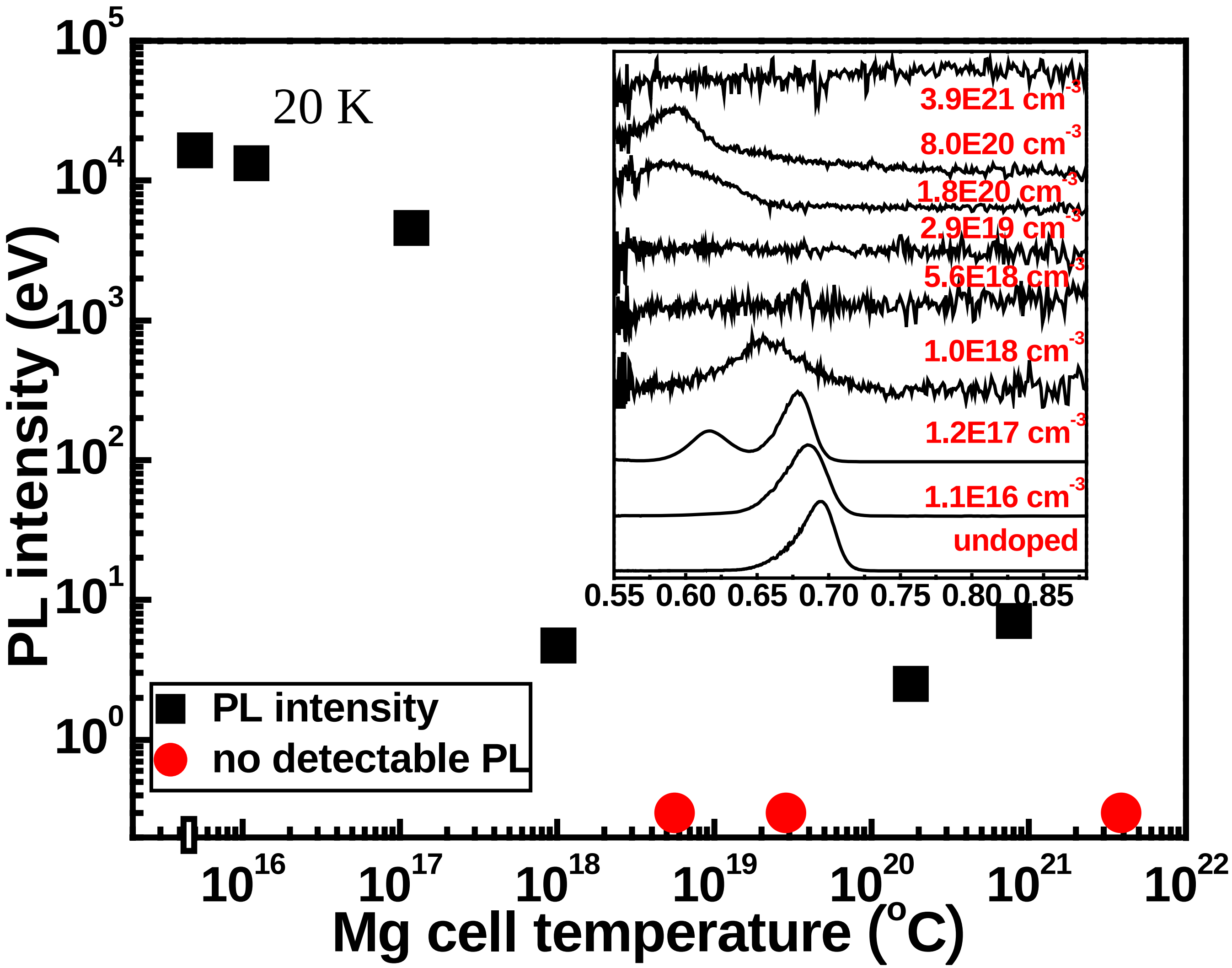
In-polarity regime

X Wang, S Che, Y Ishitani, A Yoshikawa, *Appl. Phys. Lett. 91 (2007) 242111*

Mobility of hole in p-type InN

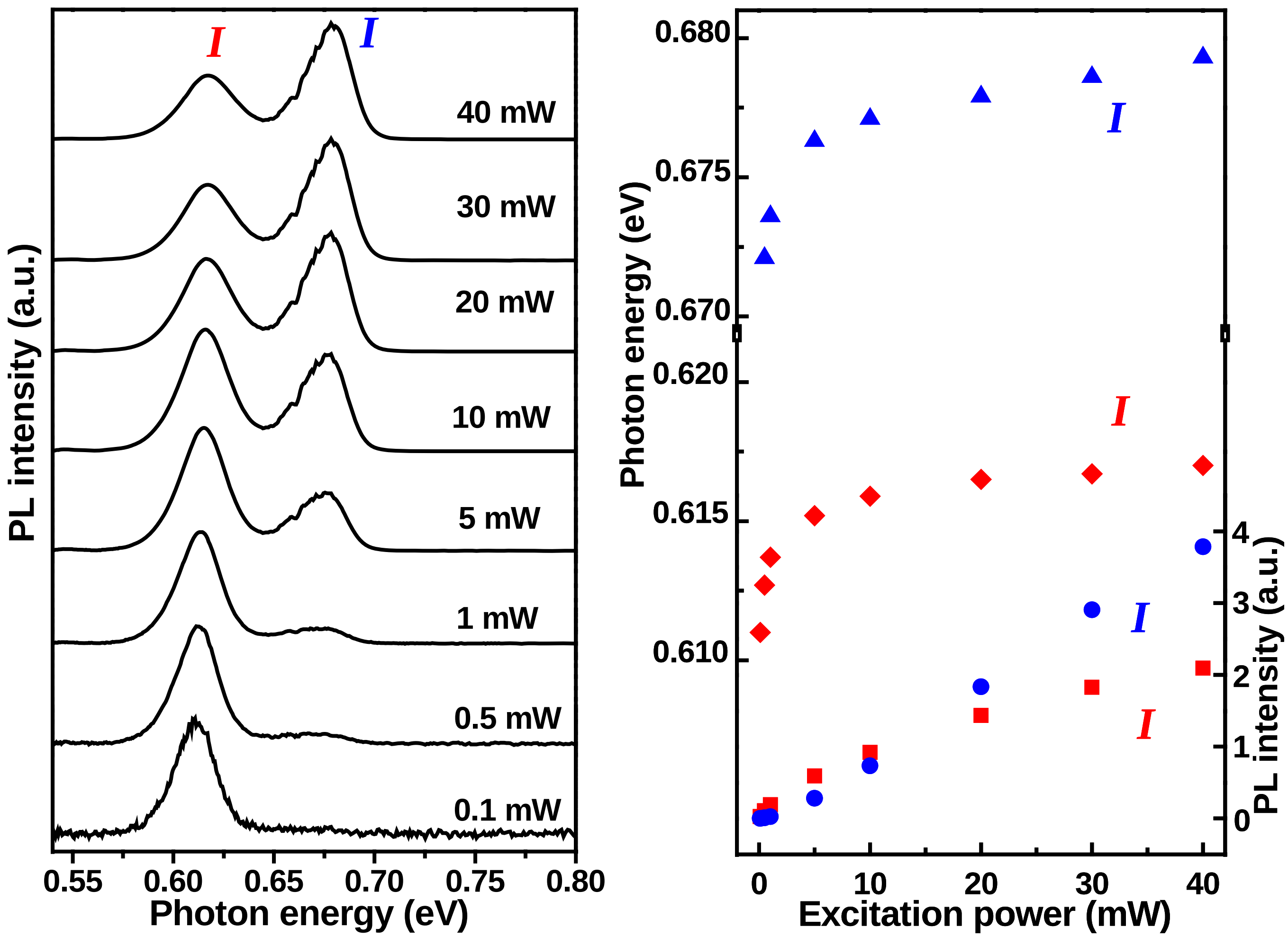


Photoluminescence study of Mg-doped InN



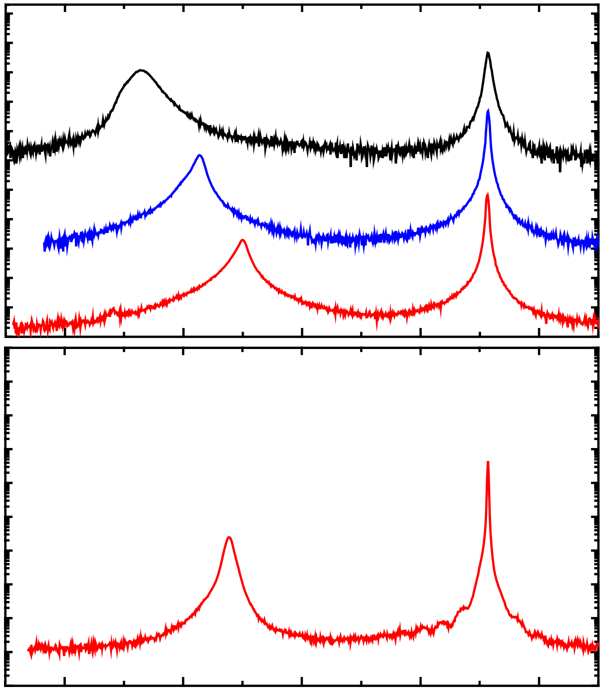
PL intensity was greatly reduced with Mg doping.

Activation Energy

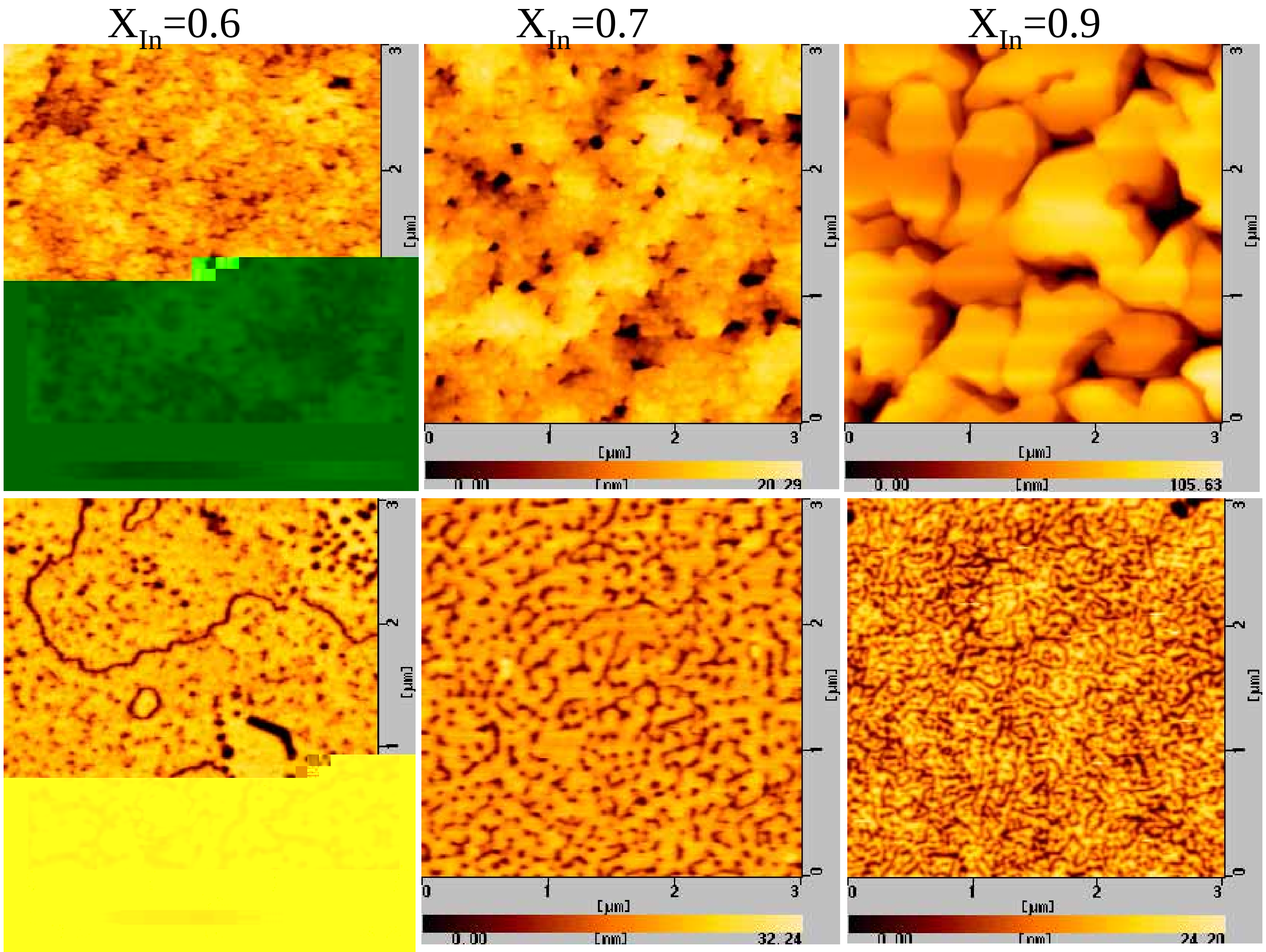


A Mg-related acceptor level of about 61 meV above the valence band

InN-based Alloys-InGaN



InN-based Alloys-InGaN



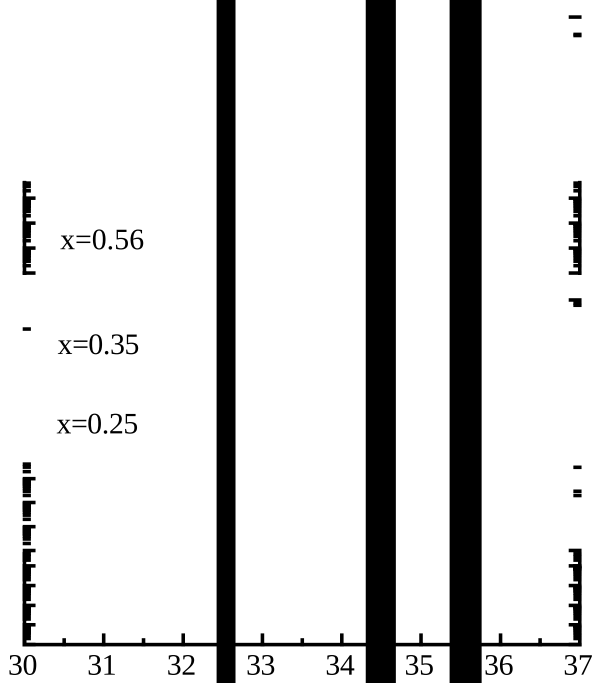
Surface morphologies of InGaN in both polarities

InN-based Alloys-InGaN

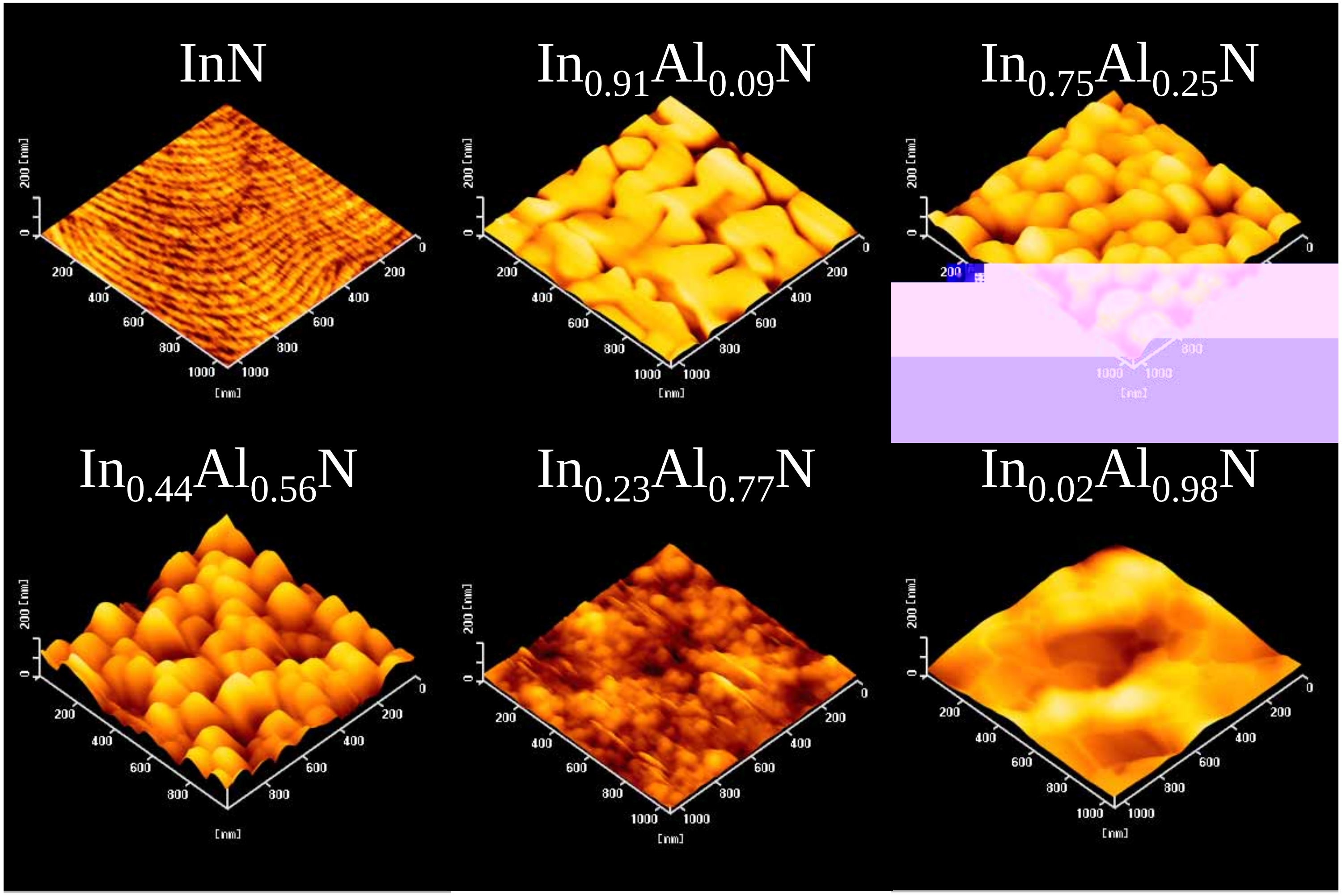
A shutter control method was used to improve quality of InGaN. XRD results showed that the quality was improved as expected.

31 32 33 34 35

N-based A s-InAlN

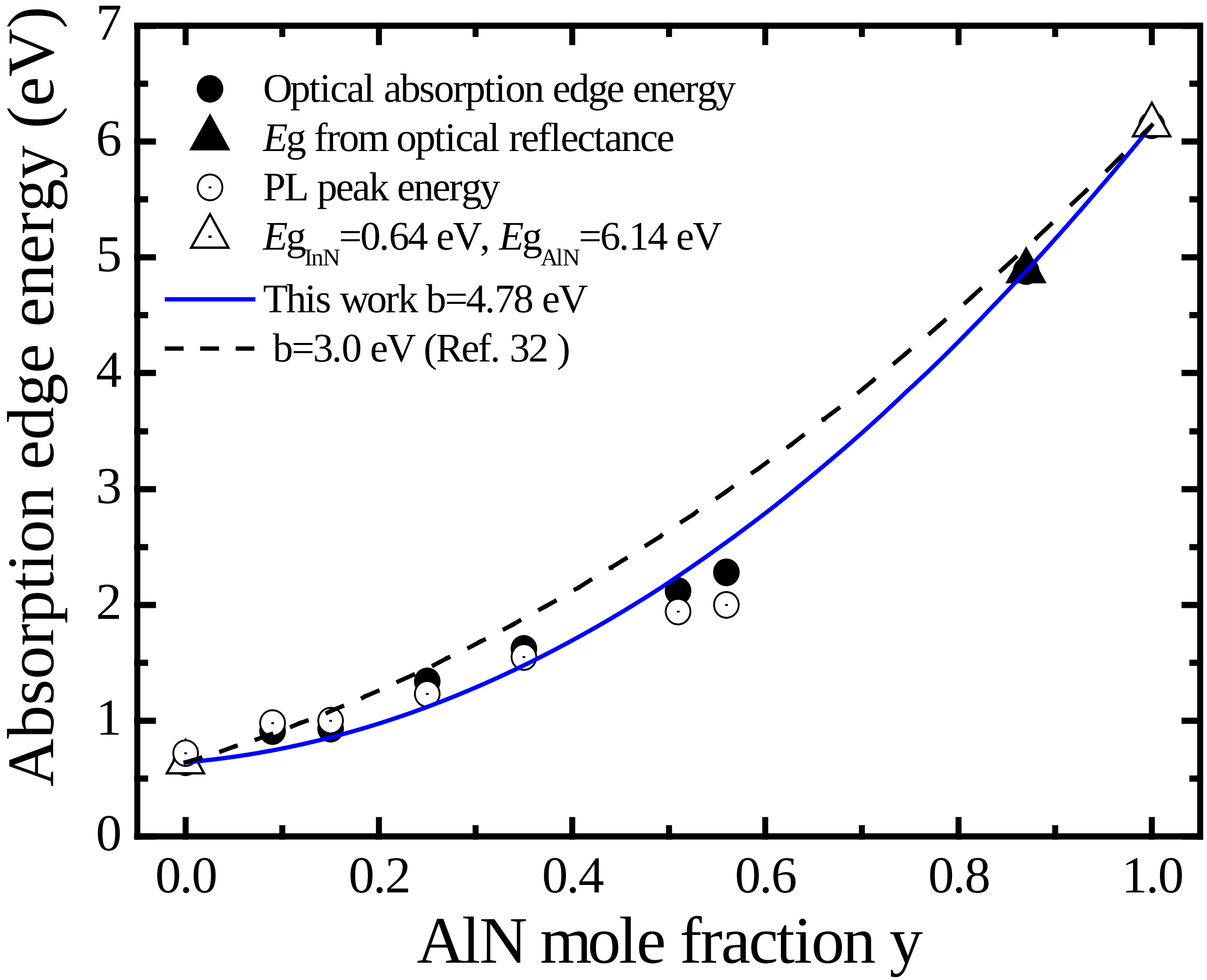


InN-based Alloys-InAlN



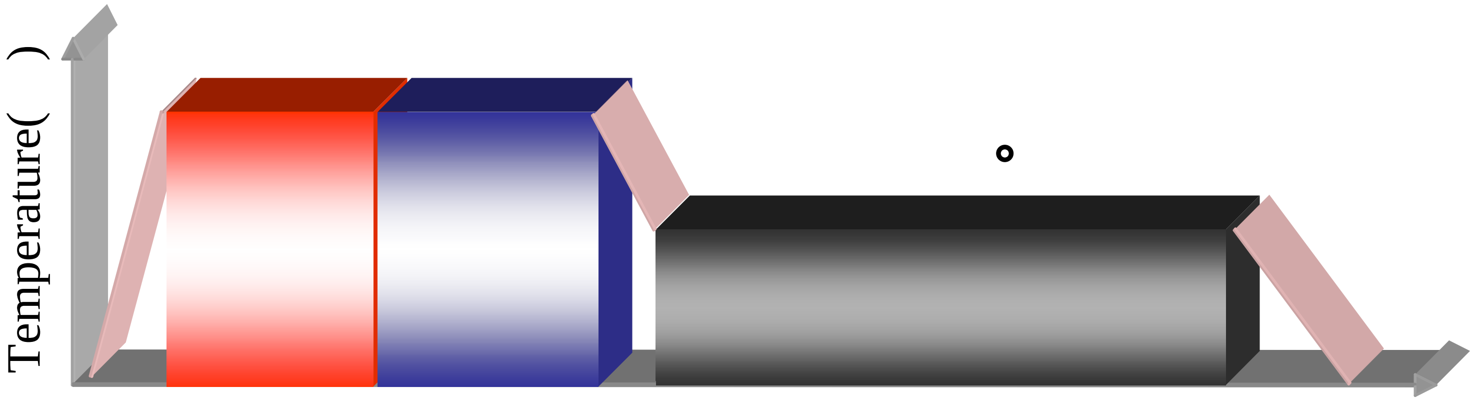
Surface morphology of InAlN, grain structure was observed .

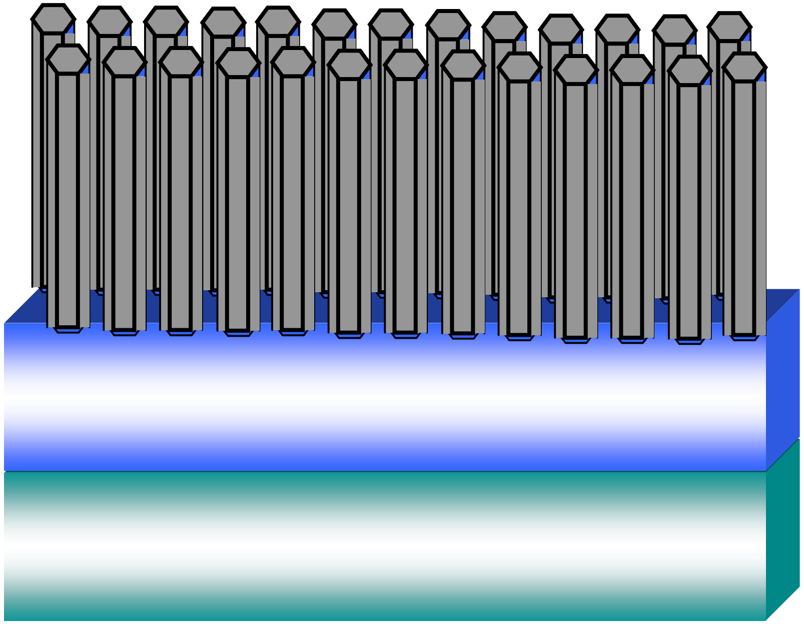
InN-based Alloys-InAlN



A bowing parameter b=4.78±0.30 eV was observed for InAlN

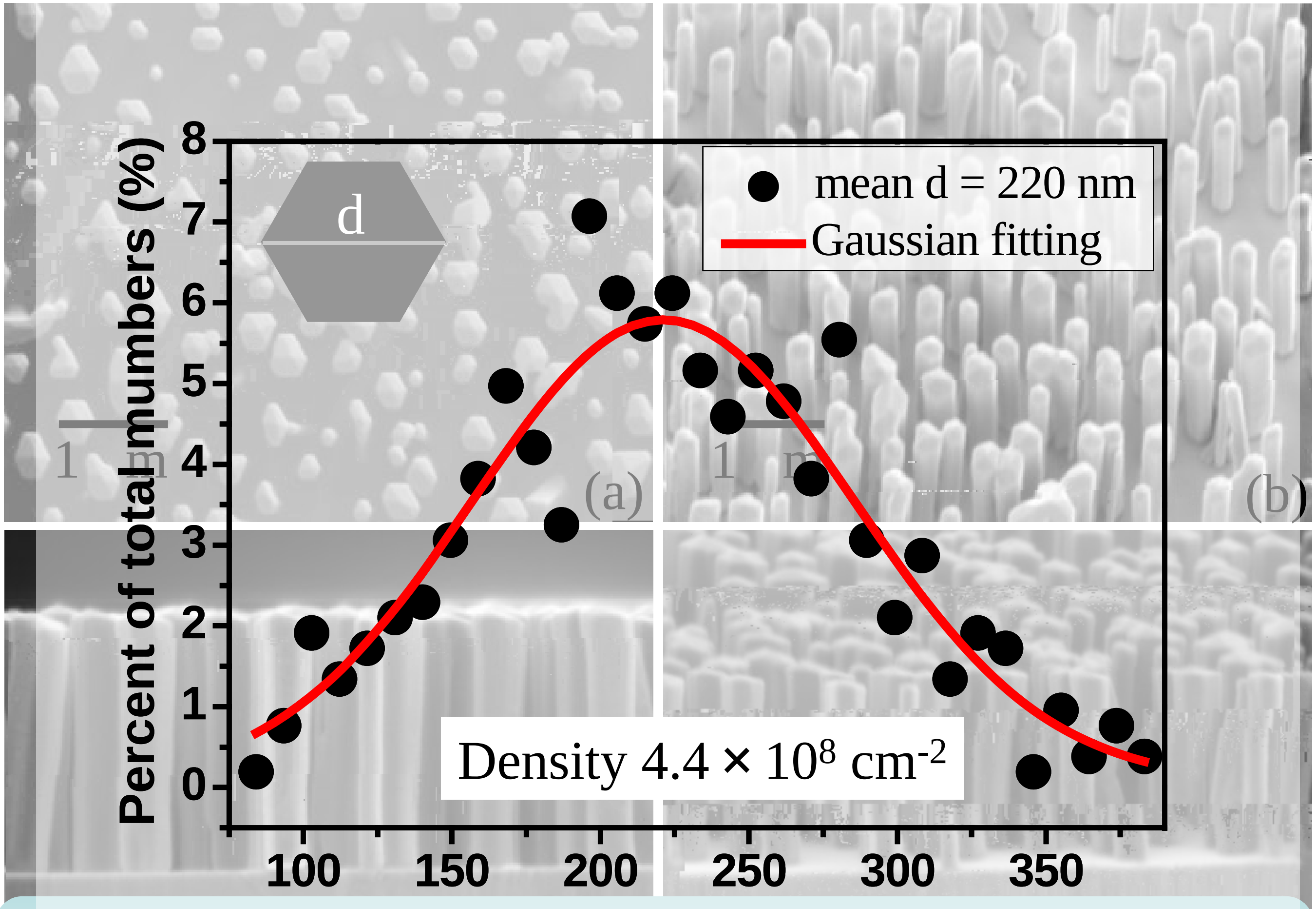
InN nanocolumns-growth process





InN NCs-typical morphology

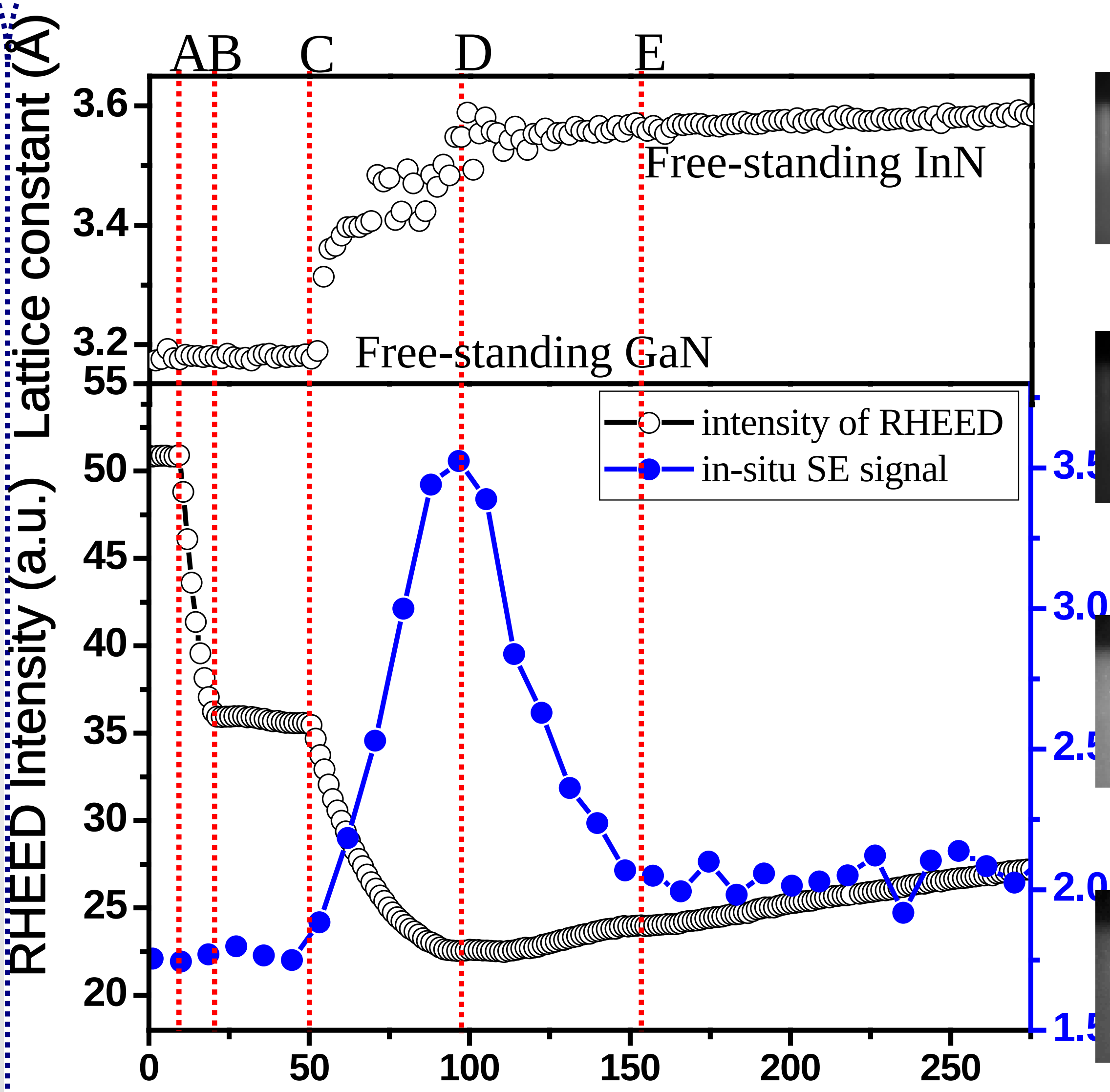
Outline
Introduction
MBE
InN epitaxy
Flat surface
Quality Up
InN Properties
P-type doping
Polarity Invers
P-type eviden.
InN Alloys
Nanostructure
Summary
Supplement

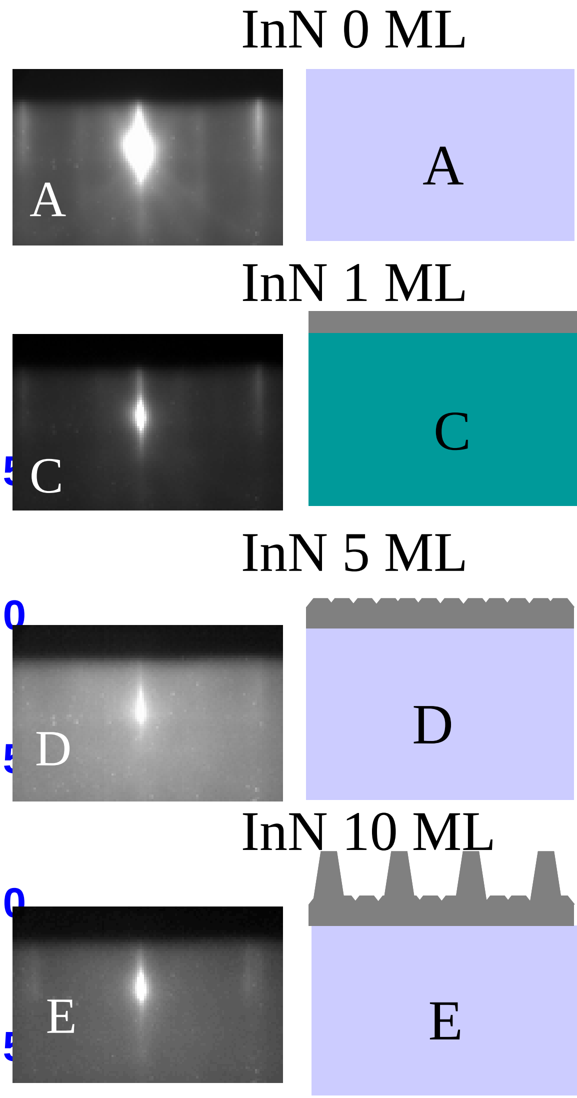


Growth rate 2.5-3 times to InN film, hexagonal shape, uniform height of 1.2 um, smooth side walls

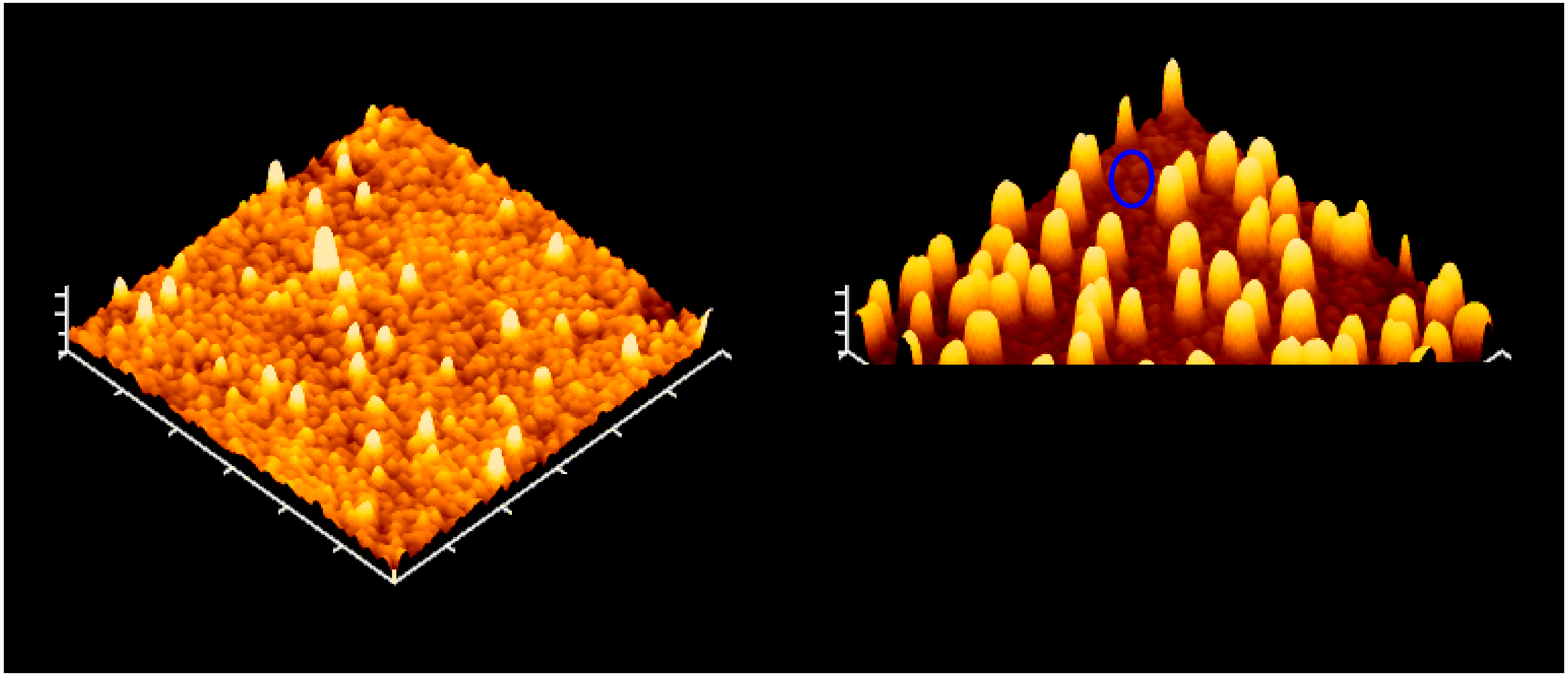
X Wang, S Che, Y Ishitani, A Yoshikawa, *J. Cryst. Growth 301 (2007) 496*

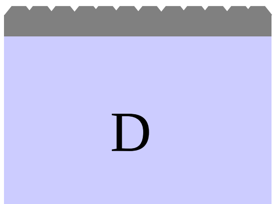
InN NCs-Nucleation Mechanism



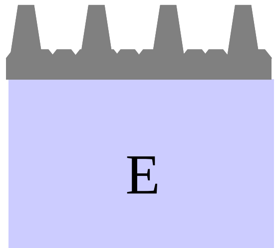


InN NCs-Nucleation Mechanism





5 ML, QDs



10 ML, embryonic, columns

InN NCs growth was initiated from InN QDs growth in S-K mode

Summary

- Atomically flat InN in step-flow-growth mode was obtained. The surface was quite smooth with rms roughness of less than 1 nm (the best one 0.3 nm) in 10 m 10 m area .
- InN films were dominated by edge-type TDs while the density of screw-type TDs NCs were about two orders lower. InN film with edge-type TDs density in low 10^9 cm^{-3} was obtained.
- Electron accumulation layer exist in the surface of InN or interface between InN/GaN with sheet electron concentration of about 3-5 10^{13} cm^{-2}. InN film with ne=2 10^{17} cm^{-2} and mobility of about 2150 cm^2/Vs at RT was obtained.
- SIMS results showed that Mg concentration was linearly proportional to Mg-beam flux, indicating Mg-sticking coefficient is almost unity.
- Polarity inversion was found when [Mg] is over 10^{19} cm-3.
- Buried p-type InN was confirmed by ECV measurment in Mg:InN films at [Mg] of 1-30 × 10^{18} cm^{-3}. An acceptor activation energy of about 61 meV for Mg acceptor was obtained. Mobility of holes in p-type InN was estimated to be about 17 to 36 cm

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