Geographic location of St. Petersburg

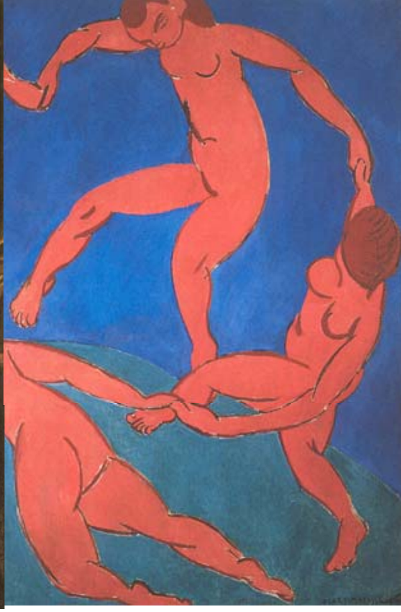
St. Petersburg

the capital of Russia since 1703 till 1918


Mariinskii theater
Pushkin
Hermitage
Pavlovsk
Russian Museum
Peterhof
Palaces and Squares of St. Petersburg

Parks and Palaces of St. Petersburg Suburbs





Treasures of Art in our Museums



White Nights season

Ioffe Institute of RAS

1918 — Physical-Technical Department of the State Institute of X-Rays and Radiology was founded by Profs. M. I. Nemenov and A. F. Ioffe

Nobel Prize Winners which works in the Ioffe Institute :
N. N. Semenov, L. D. Landau, P. L. Kapitsa,
I. E. Tamm, **Zh. I. Alferov**

Soviet Nuclear Programme Leaders :
I. V. Kurchatov, A. P. Aleksandrov,
Ya. B. Zel'dovich

Total staff - 2000
researchers – 1100

Several hundred of former Ioffe researchers are spread around the globe

Ioffe Institute of RAS

Division of Plasma Physics, Atomic Physics and Astrophysics

Division of Solid State Electronics

Division of Solid State Physics

Division of Physics of Dielectric and Semiconductors

Centre of Nanoheterostructure Physics

Ioffe Institute of RAS

Abraham Ioffe 1918

- Point defect theory (1926, Frenkel)
- Prediction and discovery of the excitons (Frenkel, 1932, Gross, 1951)
- Start of Russian Nuclear project (Kurchatov, 1940s)
- Prediction and first experimental confirmation of semiconductor properties of III-V compounds (InSb) (1950, Goryunova, Regel)
- Studies of excitonic properties of bulk II-VI materials (in 60th– 80th, Zakharchenya, Kapliansky, Permogorov et al.)
- Discovery of semiconductor heterostructures (since 1967, Alferov et al. – Nobel Prise, 2000)
- Theory of resonance tunneling in superlattices, idea of quantum cascade laser (1971, Kazarionov, Suris)
- Idea of spin injection, theory of spin polarization and first experiments on optical detection of spin polarization (1976 and later, Aronov, Pikus, Zakharchenya et al.)
- Dyakonov-Perel spin relaxation mechanism by (1978, Dyakonov, Perel)
- Discovery of semiconductor quantum dots – II-VI in glass (1982, Ekimov, Efros)
- Lowest threshold AlGaAs QW SCH laser diode (40 A/cm^2) with GRIN SL waveguide (Alferov, Ivanov, Ledentsov, Ustinov, Kop’ev, Meltser,1988)
- First AlGaAs laser diode with InAs QD (Alferov and co-workers,1994)
- Recent works on MBE technology and studies of II-VI wide gap nanostructures for optoelectronics and spintronics (Ivanov, Toropov, Shubina et al., 90-s)

Quantum-size Heterostructure Lab

MBE growth & processing	Total 24	Optical & Electrical Studies
8	Senior Researchers and Researchers	5
3	PhD students	2
3	undergraduate students	1
1	manager, technician	1

Group Activity Scope

Main goal: Molecular beam epitaxy and fundamental studies of semiconductor heterostructures (with quantum wells, quantum dots and superlattices) based on

- narrow gap III-V compounds - (Al,Ga,In)(As,Sb) - for mid-IR optoelectronics and HEMTs (**MBE setup Riber 32P, France**);
- wide gap II-VI compounds - (Zn,Cd,Mg)(S,Se,Te) and ZnO - for visible (blue-green) and UV spectral range optoelectronics, including lasers with electron beam and optical pumping, as well as spintronic studies of diluted magnetic semiconductor heterostructures (**double chamber III-V/II-VI MBE setup, Semiteq, Russia**);
- hybrid III-V/II-VI structures with a heterovalent interface in the active region for mid-IR applications, solar cells, and spintronics (**double chamber III-V/II-VI MBE setup, Semiteq, Russia**);
- III-nitrides - (Ga,In,Al)N - for optoelectronic applications in visible (green-red) and deep UV spectral ranges as well as fundamental studies of In-riched compounds and metal-semiconductor composite nanostructures (**PA MBE setup Riber Compact 21T, France**).

Projects

Russian Foundation for Basic Research (basic & applied research) – 12 (1 with PKU)
Presidium of RAS, Physical Sciences Department of RAS – 5
Russian Agency for Science and Innovations – 2
International contracts (OSRAM, Germany; ETRI, Korea; KACST, Saudi Arabia) - 3
Marie Curie training network on Spinoptronics (FP7) – 1
Russian Ministry on Industry and Trade, Ministry of Deffence - 2

Plasma-assisted molecular beam epitaxy of Al(Ga)N layers and quantum well structures on c-Al_2O_3 for mid-UV emitters and solar-blind photodiodes

S.V. Ivanov

Acknowledgments

V.N. Jmerik, D.V. Nechaev, T.A. Komissarova, E.A. Shevchenko, A.A. Toropov, A. A. Sitnikova, V.V. Ratnikov, M.A. Yagovkina

Ioffe Physical-Technical Institute of RAS, Polytekhnicheskaya 26, St. Petersburg 194021, Russia

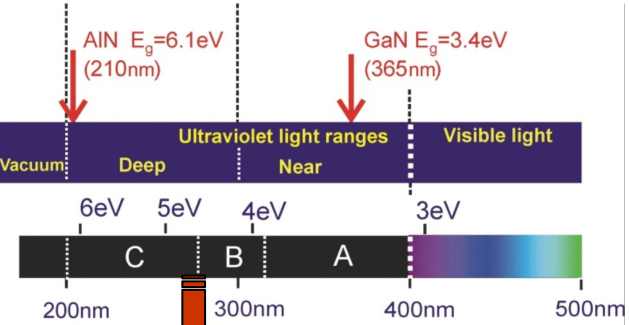
E.V. Lutsenko, N.V. Rzheutskii, G.P. Yablonskii

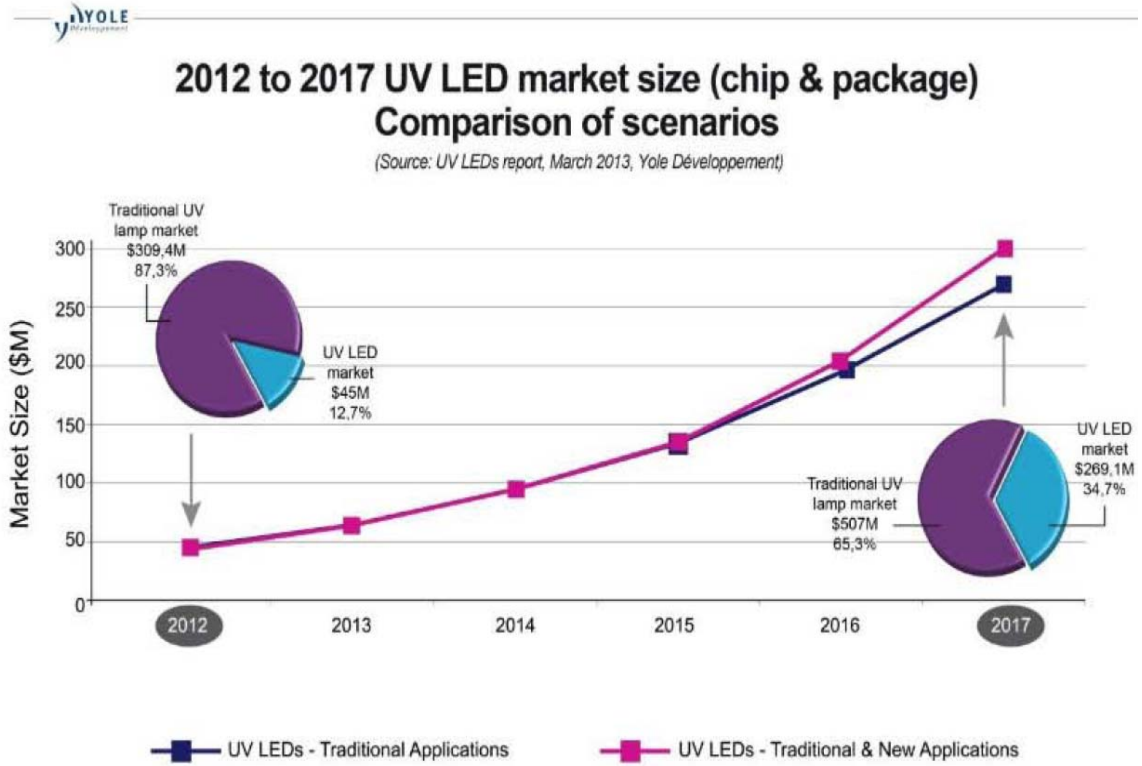
Stepanov Institute of Physics of NAS Belarus, Independence Ave. 68, Minsk 220072, Belarus

Outline

- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
- PA MBE growth and surface morphology control of III-Nitrides
  - Al-rich growth of thick AlN/c-Al_2O_3 buffer layers
  - Growth kinetics of AlGaN layers (2D-3D transition)
- Dislocation control and filtering in AlGaN/AlN/c-Al_2O_3 heterostructures
- Sub-monolayer Digital Alloying growth of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ QWs
- Strain engineering in AlGaN QW heterostructures to prevent TE/TM switching of photoluminescence polarization
- Low-threshold optically pumped QW laser structures in the 258-303 nm range
- LEDs and solar-blind p-i-n photodiodes
- Conclusions

Market and main applications of UV-optoelectronics



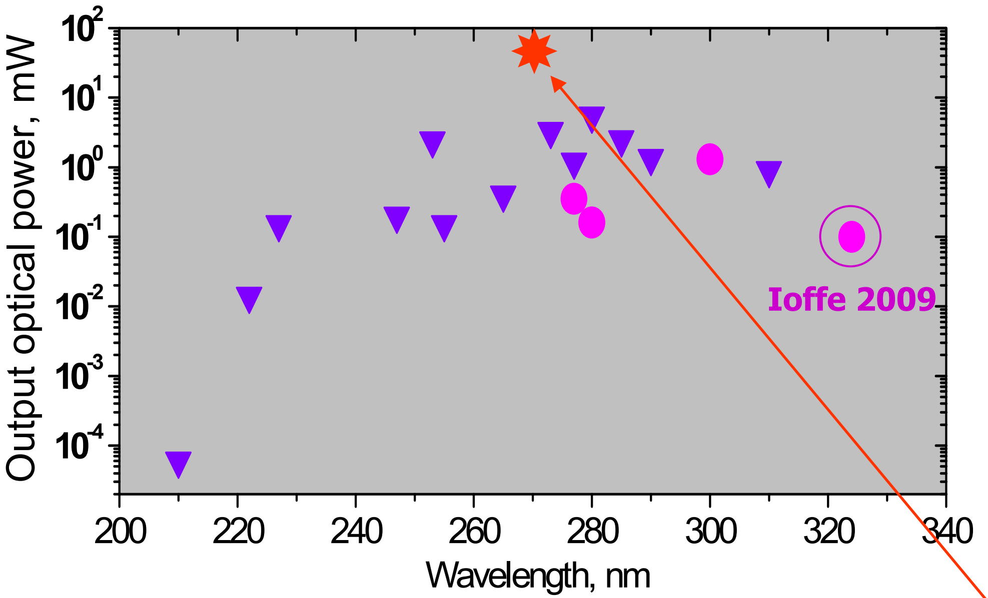


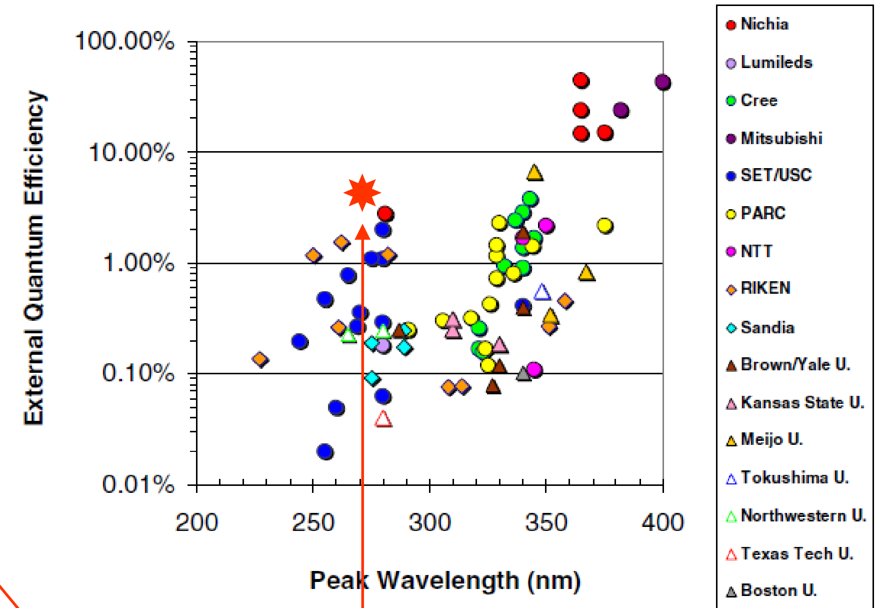
Main applications of UV-lasers

UV-spectroscopy *Biomedical applications* *Millitary & Security systems*

Peking University, May 15, 2014

State of art of UV-LEDs (2013)





M.Kneissl et al., Semicond. Sci.Technol. 26 (2011) 014036

MOCVD ▼

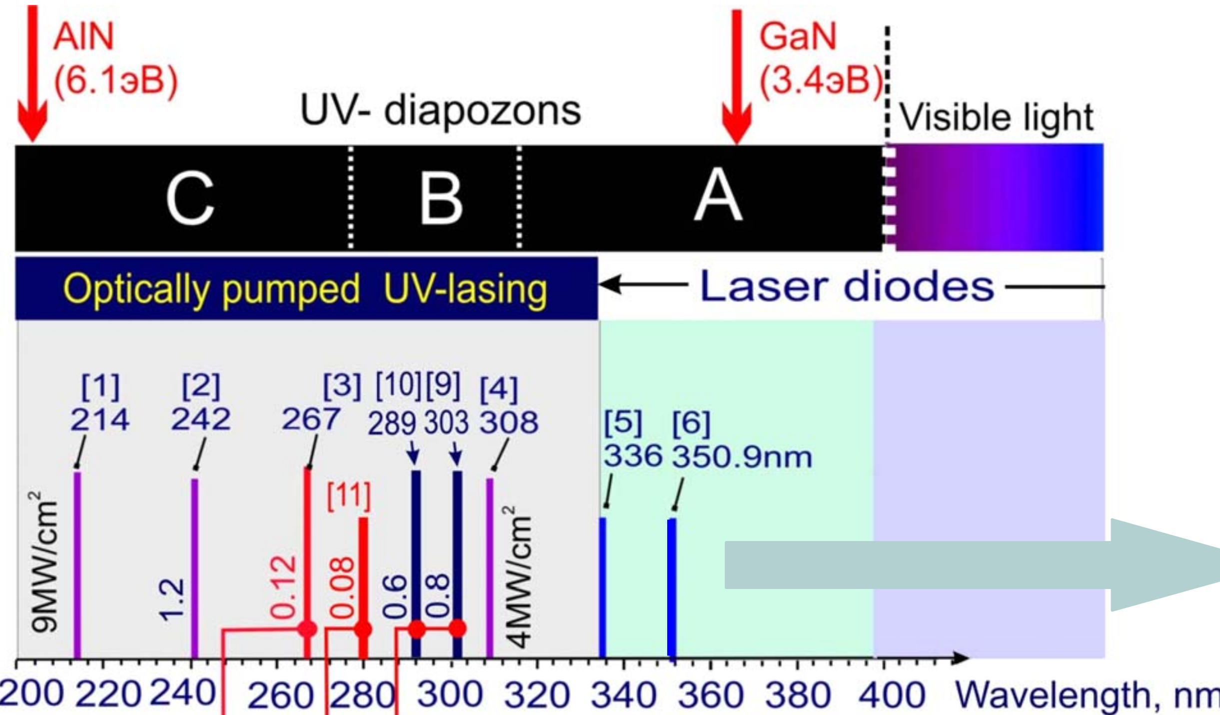
MBE ●

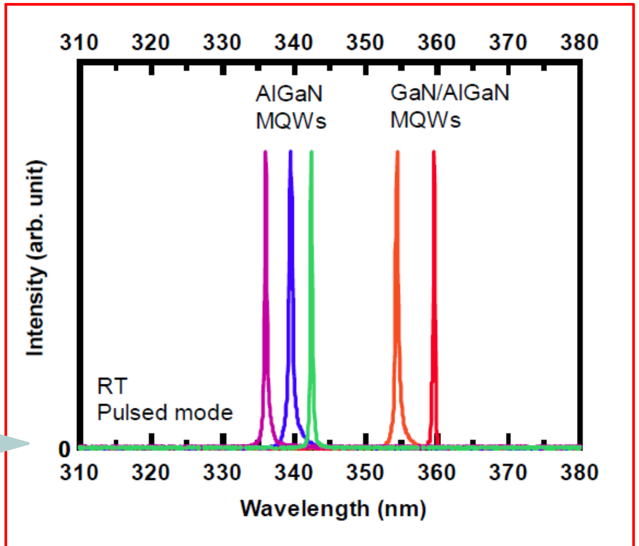
MOCVD		MBE
SET Sensor Electronic Technology, Inc. SEOUL	Crystal IC	BU BOSTON UNIVERSITY
USC Nitek UNIVERSITY OF SOUTH CAROLINA	NU NORTHWESTERN UNIVERSITY	TTU TEXAS TECH UNIVERSITY
Riken	NTT NTT	ARL
SNL Sandia National Laboratories	TU berlin	IOFFE, *Stepanov*

Crystal IS, Inc. & US ARL
Pseudomorphic single-chip UV LED
on bulk AlN substrate:
λ = 271nm, P_{out} = 60mW CW,
EQE = 4.9%, WPE = 2.5%

Grandusky et al., APEX 6, 032101 (2013)

State-of-the-art of UV-lasers (2013)





HAMAMATSU Global

AlGaN-based Laser Diodes (MOCVD):

[5] Yoshida et al., APL,93,241106 (2008).

Optically pumped lasing (PA MBE):

[9] Jmerik et al. APL **96**, 141112 (2010)

[10] —//—//— PSS A, **210**, 439 (2013)

Optically pumped lasing (MOCVD):

[1] Shatalov et al., JJAP, **45**, L1286(2006).

[2] Takano et al., APL, **84**, 3567 (2004).

[3] Wunderer et al., APE, **4**, 092101, (2011).

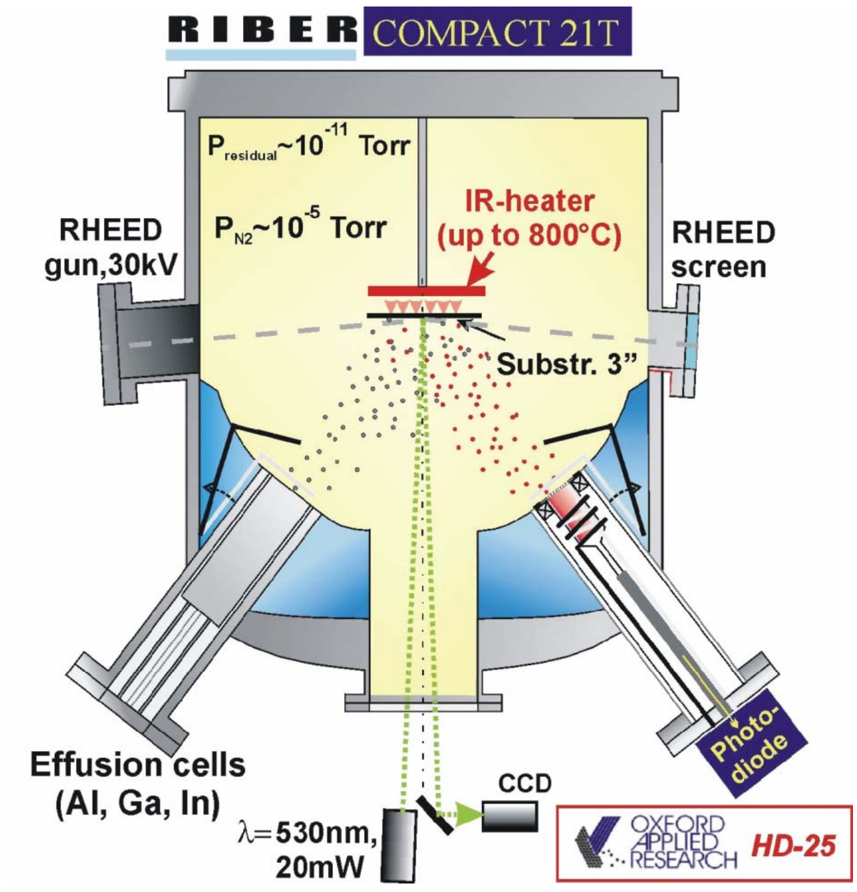
[4] Kneisslet al., JAP,**101**, 123103 (2007).

[11] Xie et.al., APL 102, 171102 (2013).
HexaTech, Inc., North.Carolina State Univ., Army Res.Lab.
OP Lasing at 280.8 nm and with P_{th}=84kW/cm^2 on bulk AlN substrate

Outline

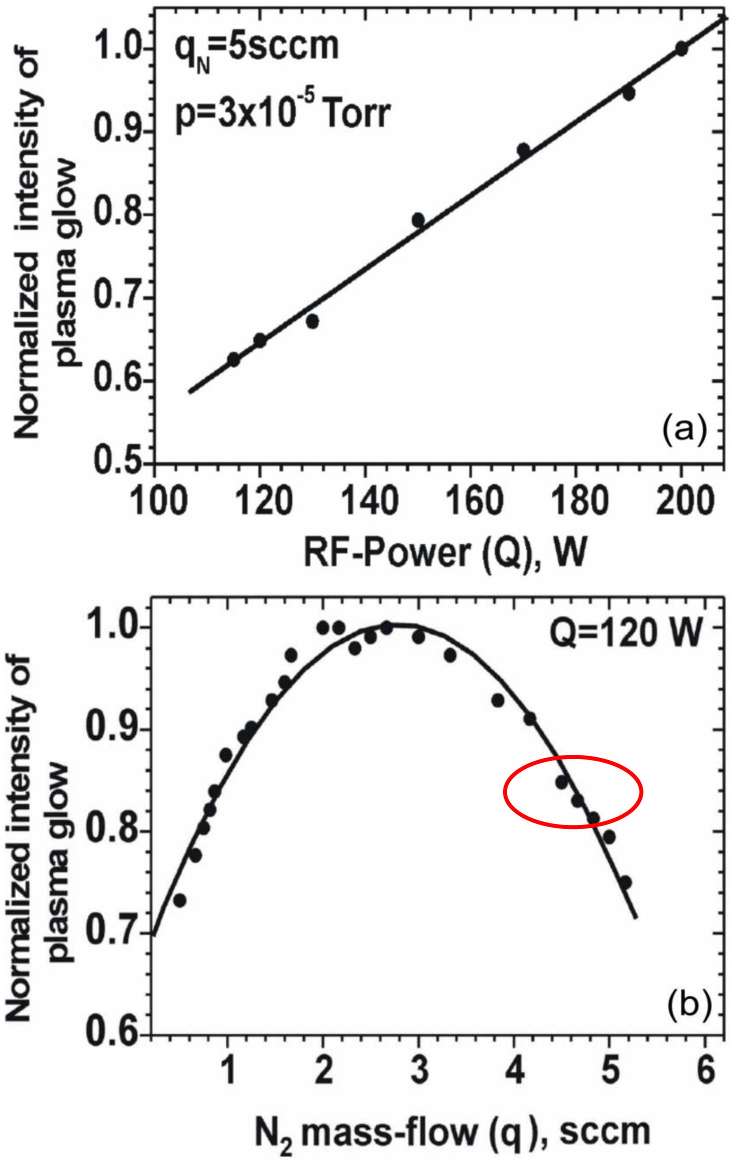
- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
- PA MBE growth and surface morphology control of III-Nitrides
  - Al-rich growth of thick AlN/c-Al_2O_3 buffer layers
  - Growth kinetics of AlGaN layers (2D-3D transition)
- Dislocation control and filtering in AlGaN/AlN/c-Al_2O_3 heterostructures
- Sub-monolayer Digital Alloying growth of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ QWs
- Strain engineering in AlGaN QW heterostructures to prevent TE/TM switching of photoluminescence polarization
- Low-threshold optically pumped QW laser structures in the 258-303 nm range
- LEDs and solar-blind p-i-n photodiodes
- Conclusions

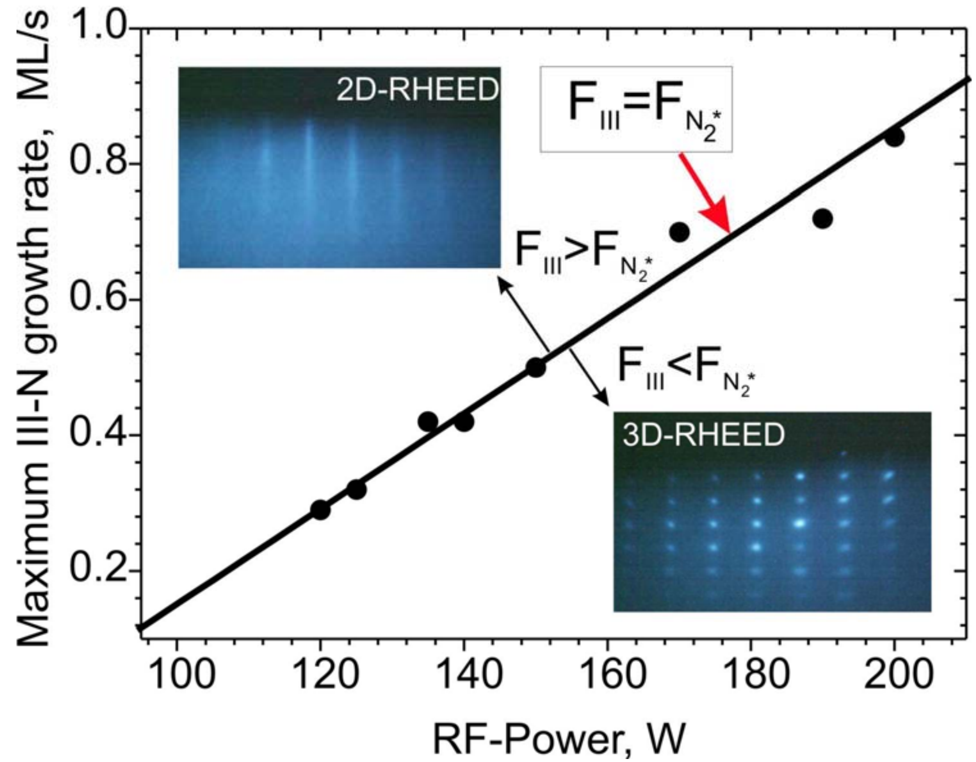
Peculiarities & Advantages of Plasma-Assisted MBE of AlGaN



- High vacuum growth conditions
  - → *No parasitic gas-phase reactions (Al+NH_3)*
- Hydrogen- and carbon-free growth environment
  - → *Easy Mg doping without post-growth treatment*
- Rapid change of growth atom fluxes
- Low growth temperature (700-800°C)
  - \+ *Sharp interfaces with atomic resolution*
  - – *Complexity of the 2D step-flow growth*
- Growth under different stoichiometric conditions:
  - *nitrogen-rich (III/N<1) →* ***3D growth***
  - *metal-rich (III/N≥1) →* ***2D growth***
- Variable polarity growth:
  - Ga-polar and N-polar depending on growth nucleation

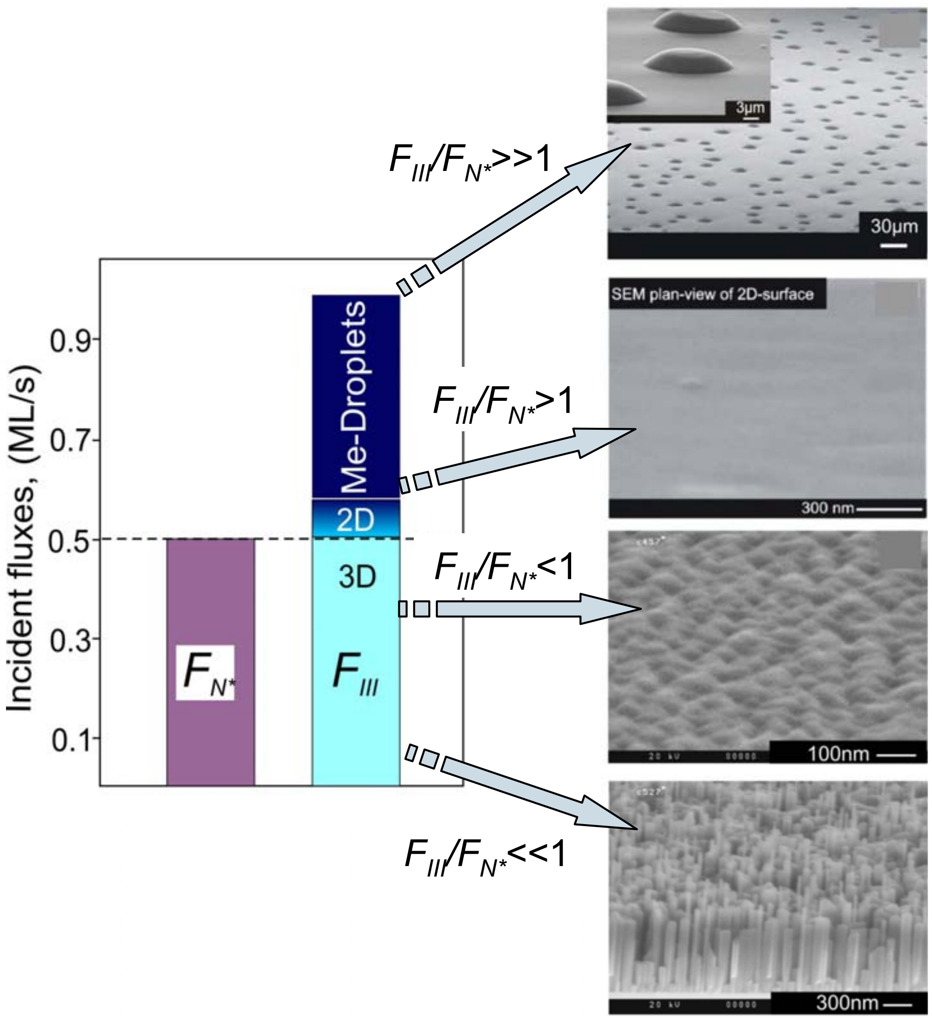
Linear control of plasma-activated nitrogen flux



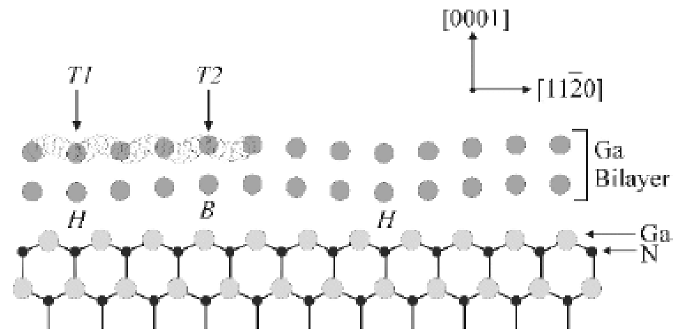


Jmerik et al. , Techn. Phys. Lett. 33,333 (2007)

Stoichiometrical conditions in PA MBE of III-nitrides

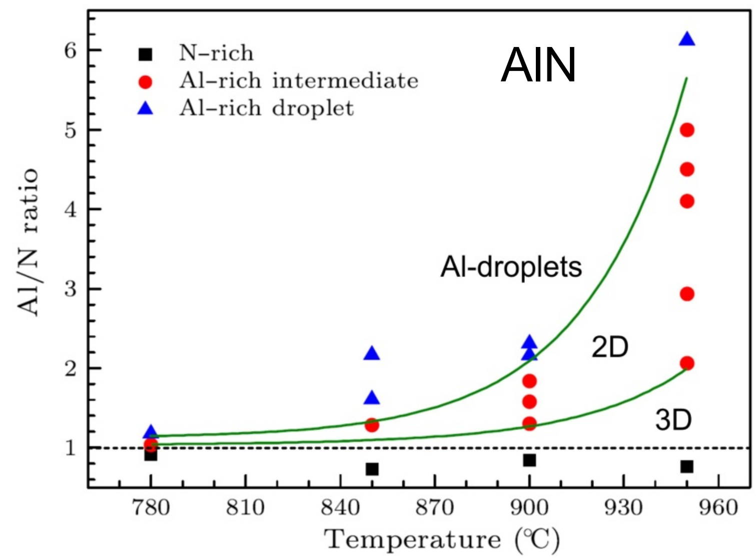


Ga-rich PA MBE of GaN



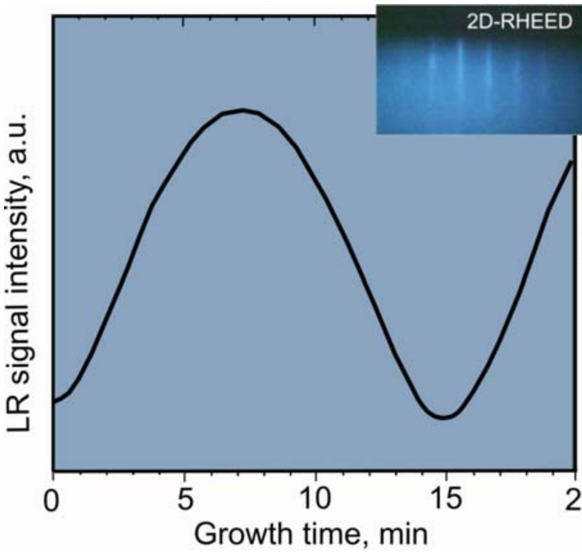
Heying et al., J. Appl. Phys. 88, (2000), 4.

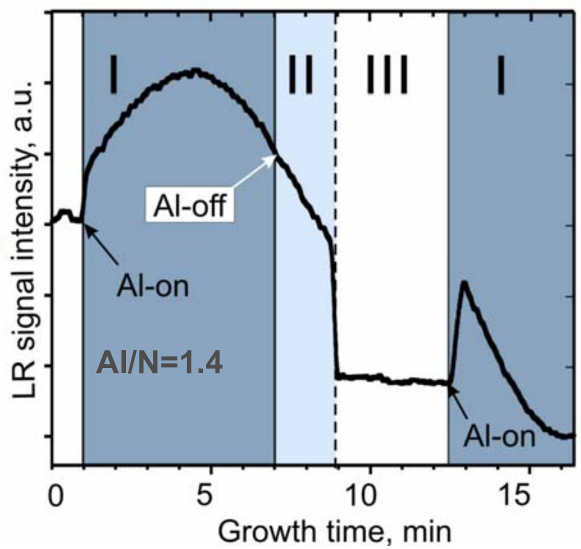
Northrup et al., Phys.Rev.B, 61, (2000), 9932.

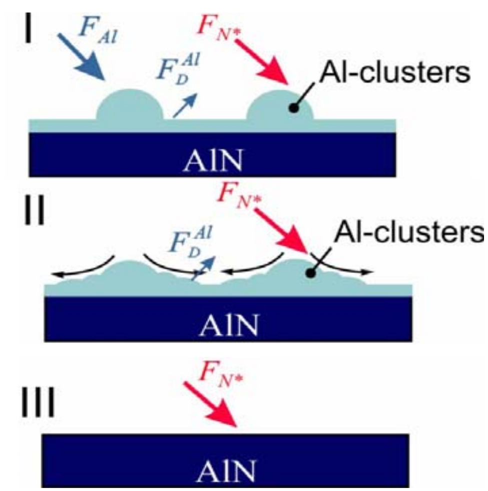


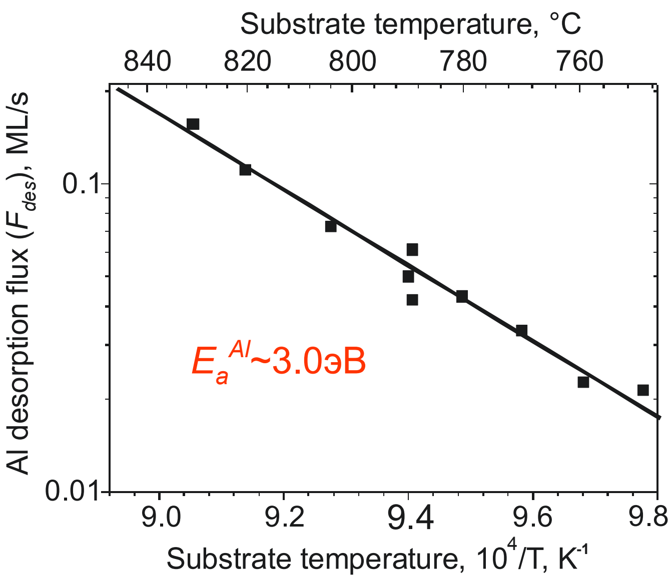
Pan et al., Chin.Phys.Lett., 28, (2011), 068102.

Al-rich growth of thick AlN layers with periodically supplied Al-flux and continuous N-flux









$$F_D^{Al}(T_S) = \frac{F_{Al} \cdot t_I}{t_I + t_{II}(T_S)} - F_{N*}$$

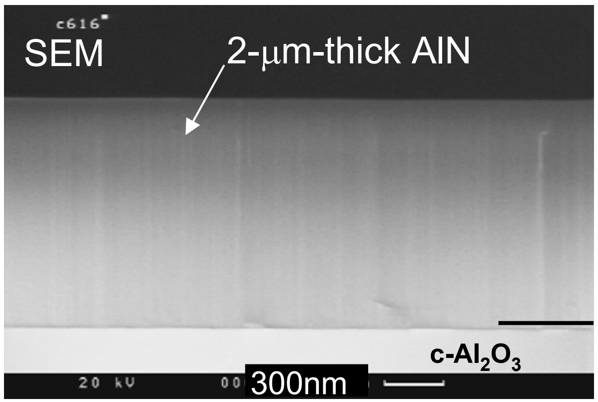
$$F_D^{Al} = A \cdot \exp\left(-\frac{E_a^{Al}}{kT_S} \right)$$

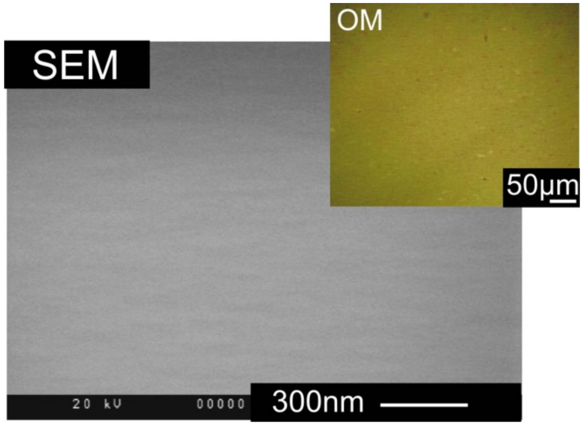
Jmerik et al., J. Cryst. Growth 354, 188 (2012)

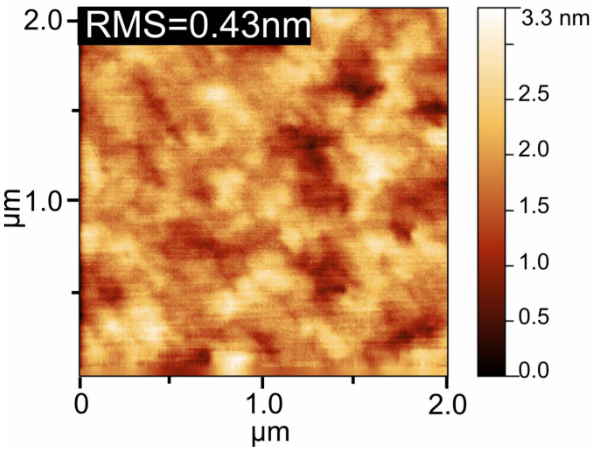
2-µm-thick AlN layers with atomically smooth and droplet-free surface

Pulsed Al-supplying mode: T_S=730°C F_{Al}/F_N=1.4

t_I=3min; t_{II}=45s; t_{III}=45s

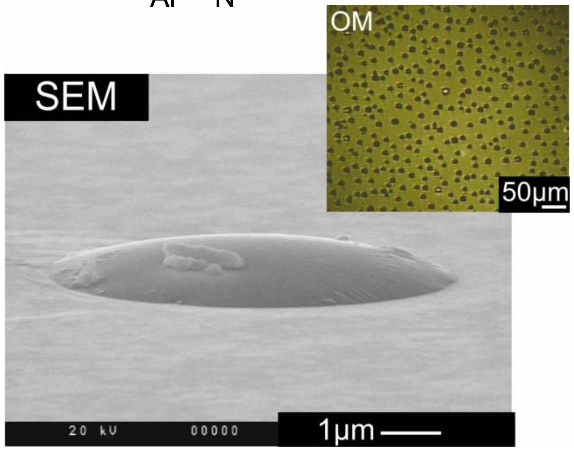






Continuous Al-supplying mode: T_S=730°C F_{Al}/F_N=1.4

Al droplets n~10^5 cm^{-2}



Polarities of $Al_xGa_{1-x}N$ (x=0-1) layers grown by PA MBE

III-polar AlGaN(0001)

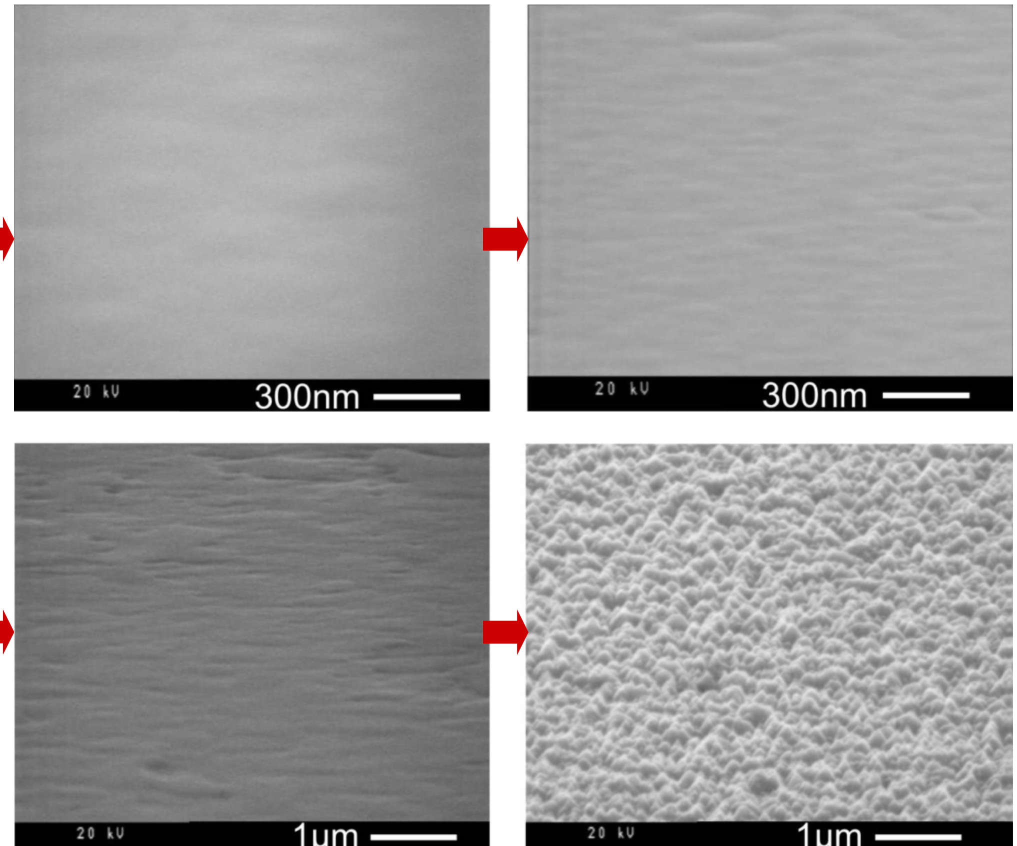
Buffer layer/substrate	***Al-content***
c-Al_2O_3	0.2<x<1
3µm-GaN(0001)-MOCVD	0 <x< 1
300nm-AlN(0001)-PA MBE	0 <x< 1

N-polar AlGaN(000$\bar{1}$)

Buffer layer/substrate	*Al-content*
c-Al_2O_3	0 <x< 0.2
500nm-GaN(000$\bar{1}$)-PA MBE	0 <x< 1

SEM images of the AlGaN surfaces after growth

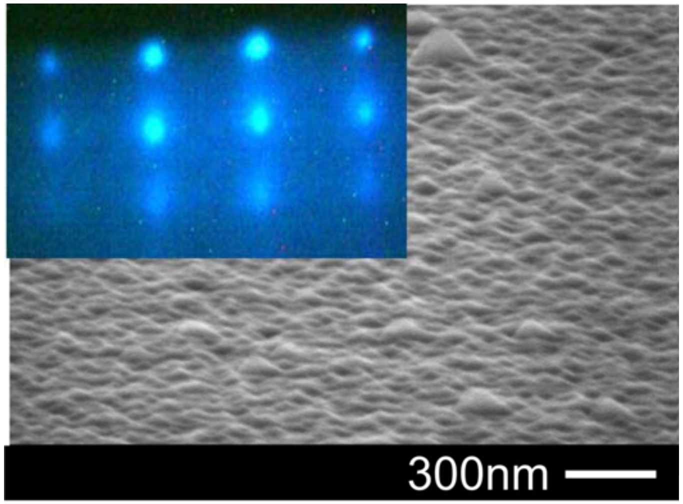
After 10-minutes etching in 0.2M KOH at 300K



Both polarities of $Al_xGa_{1-x}N$(0<x<1) can be grown by PA MBE

Mizerov et al., Semiconductors, 43, 1096 (2009)

AlGaN layers with different morphologies and Al-content grown at both N- and Ga-rich conditions



N-rich $Al_xGa_{1-x}N$

F_{III}/F_N=0.9

T_S=700°C

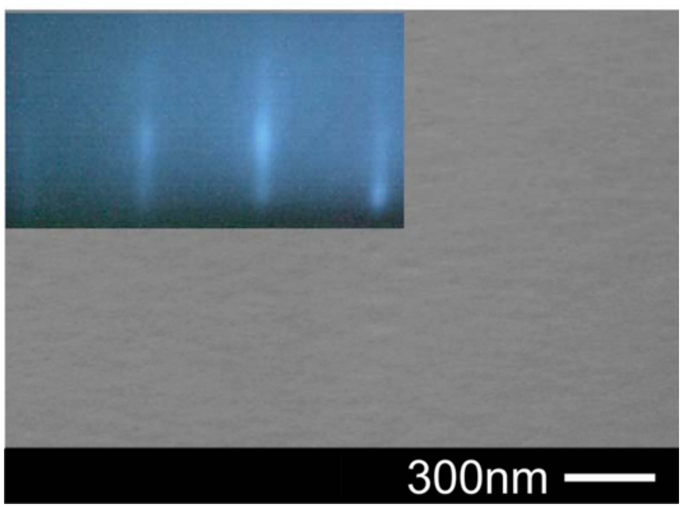
F_N=0.5ML/s

$F_{Al}/F_N=0.7\neq x$

x depends on

- Substrate temperature
- Stress in heterostructures
- Growth rate

Mizerov et al., J. Cryst. Growth 323, 686 (2011).



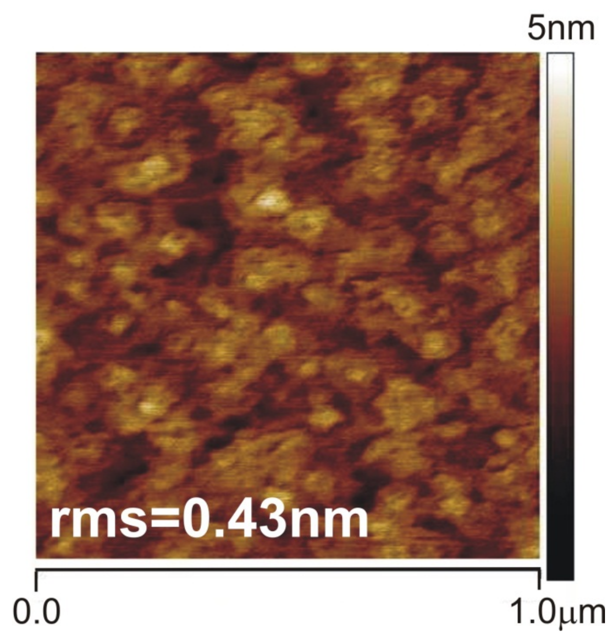
Ga-rich $Al_{0.7}Ga_{0.3}N$

F_{III}/F_N=1.8

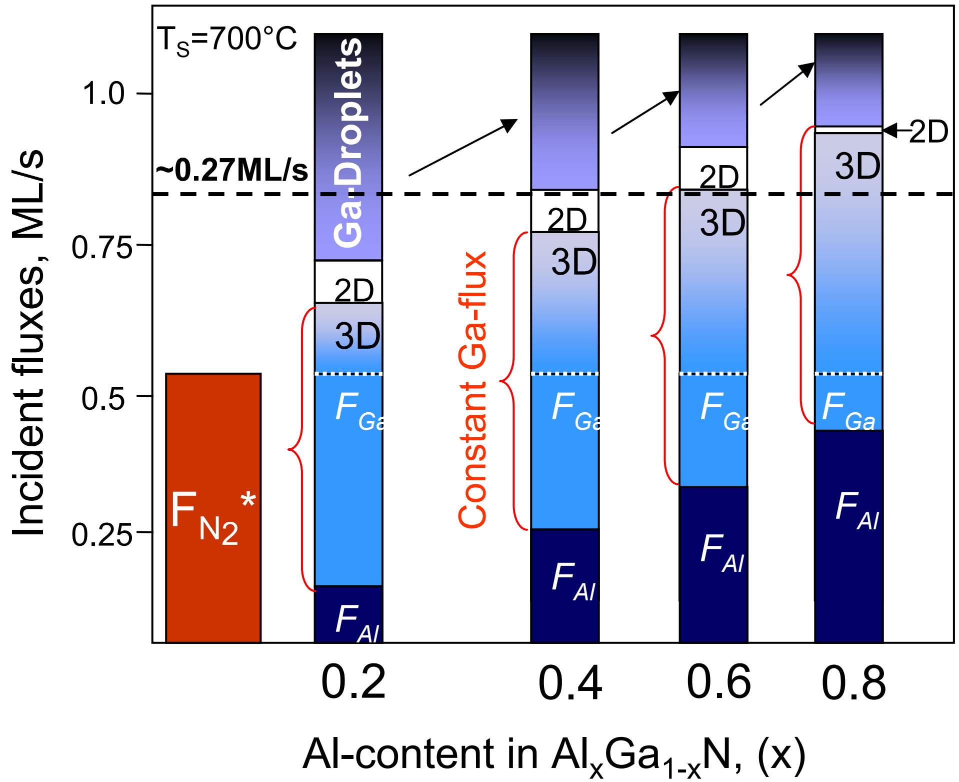
T_S=700°C

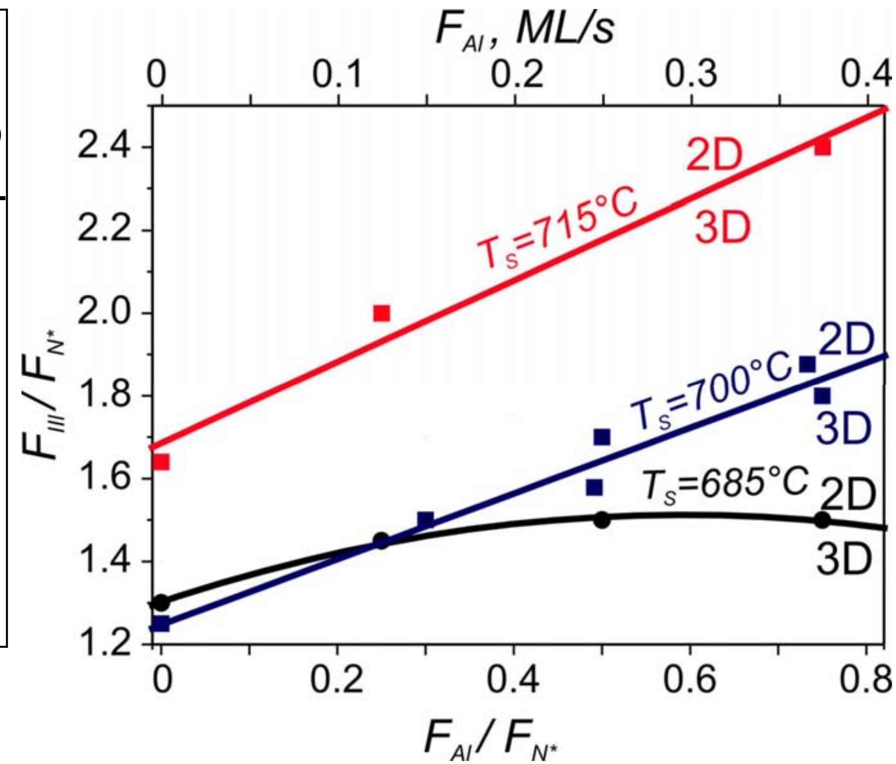
$F_N=v_g$=0.5ML/s

F_{Al}/F_N=x=0.7



3D-2D phase diagram of PA MBE growth of $Al_xGa_{1-x}N$ (x=0-0.8) layers in Ga-rich conditions





$x=F_{Al}/F_N$
(x=0.1-1) at $F_{III}/F_{N2}>1$

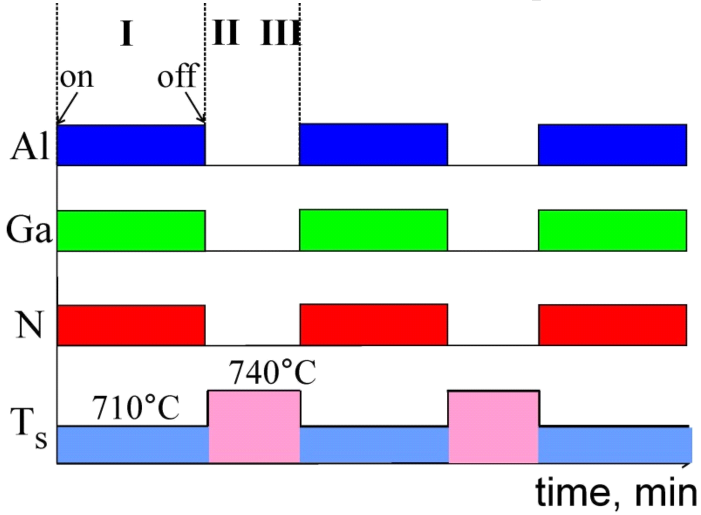
$E_{Al\text{-}N}>E_{Ga\text{-}N}$, $F_D^{Al}=0$

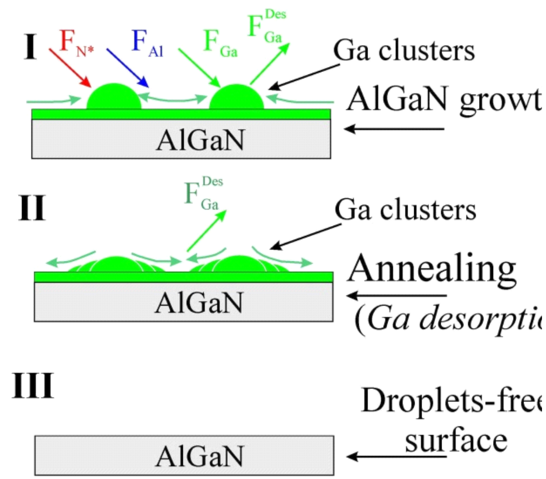
3D→2D transition occurs at constant F_{Ga}

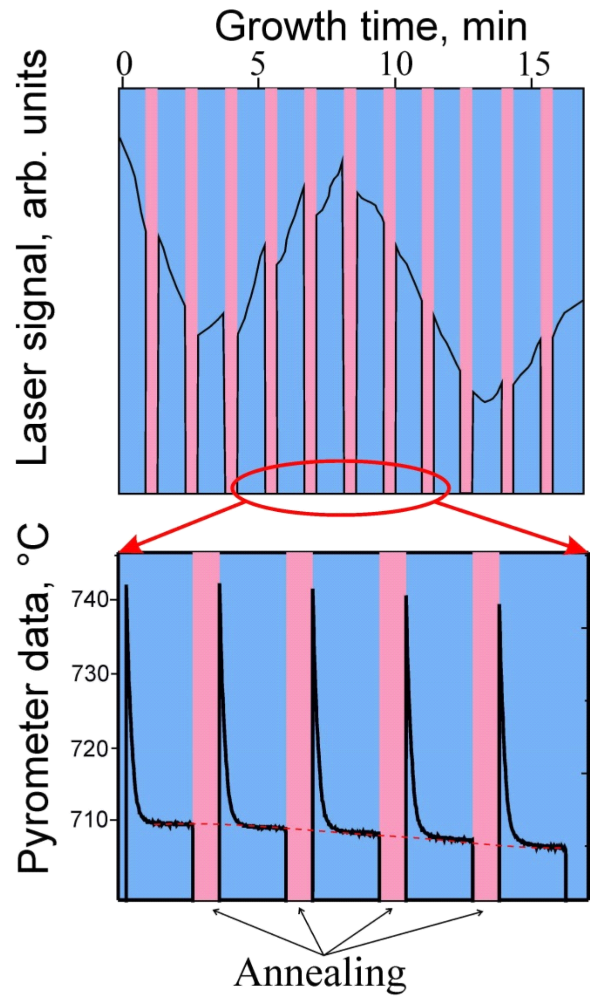
Growth kinetics is determined by Ga/N ratio and T_S but independent of the aluminum flux ($F_{Al}<F_N$)

Mizerov et al., JCG, 323, 68 (2011)
Jmerik et al., PSS A 210, 439 (2013)

Metal-rich growth of thick 2D-AlGaN layers with temperature and flux modulated epitaxy

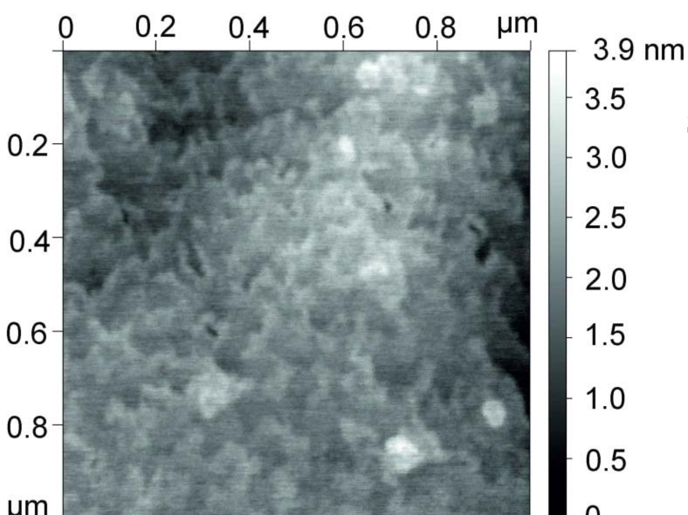






by closing the main shutter

AFM images of the $Al_{0.61}Ga_{0.39}N$ layer



rms=0.47 nm

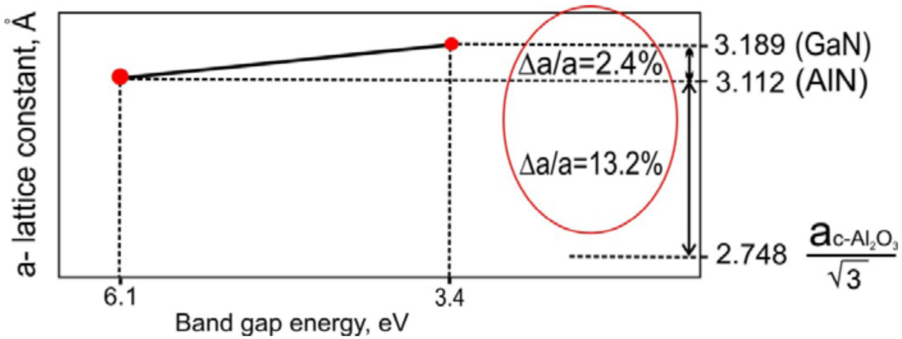
Special cares:

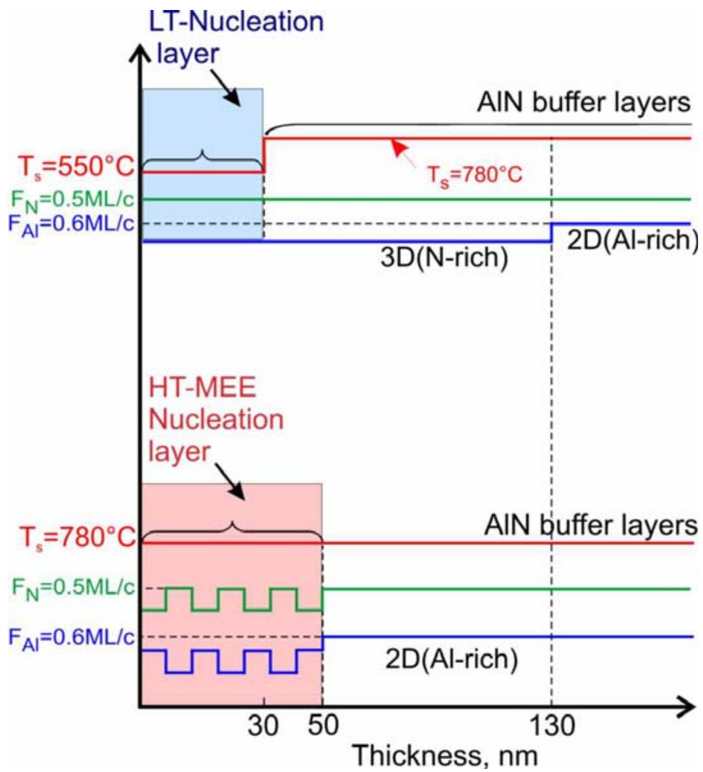
- Interruption under N results in GaN periodical insertions
- Growth of AlGaN on overheated wafer leads to Al-rich AlGaN periodical insertions

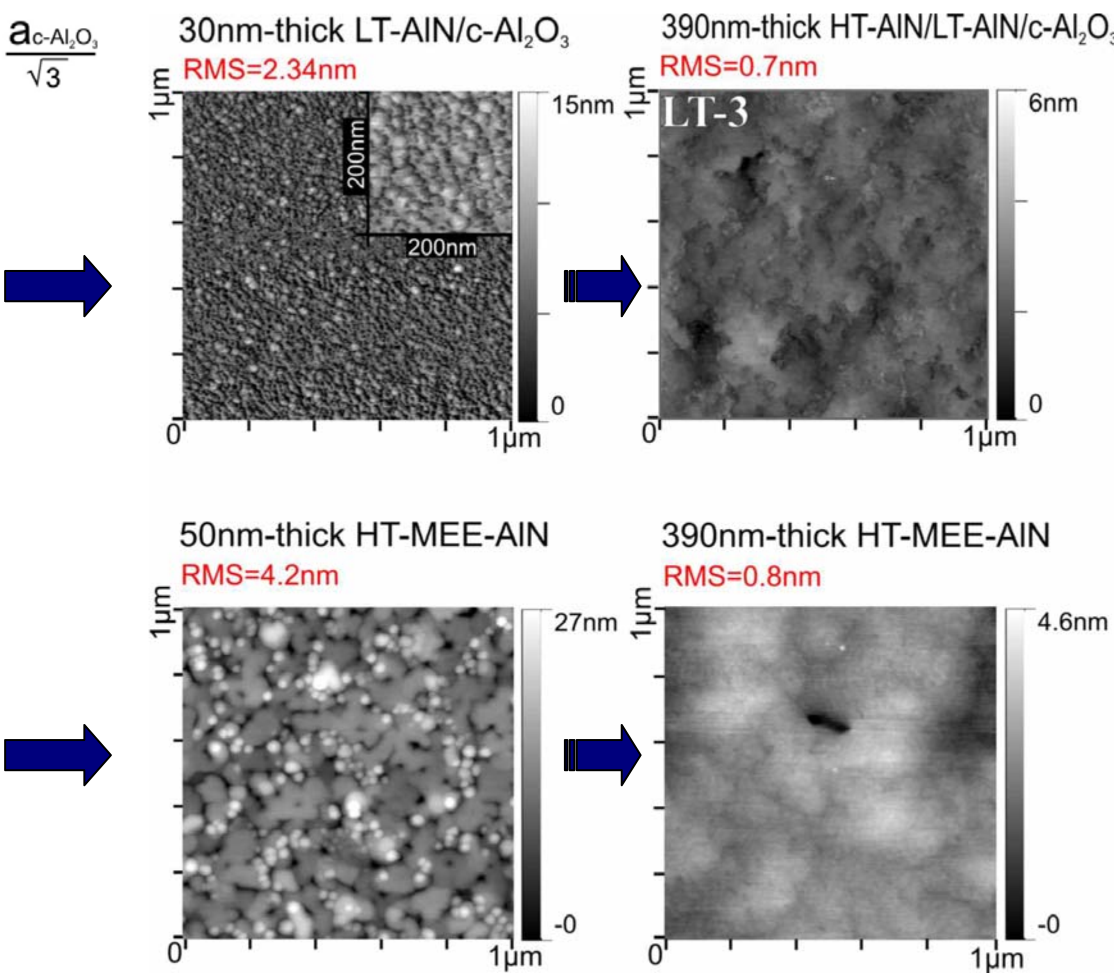
Outline

- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
- PA MBE growth and surface morphology control of III-Nitrides
  - Al-rich growth of thick AlN/c-Al_2O_3 buffer layers
  - Growth kinetics of AlGaN layers (2D-3D transition)
- Dislocation control and filtering in AlGaN/AlN/c-Al_2O_3 heterostructures
- Sub-monolayer Digital Alloying growth of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ QWs
- Strain engineering in AlGaN QW heterostructures to prevent TE/TM switching of photoluminescence polarization
- Low-threshold optically pumped QW laser structures in the 258-303 nm range
- LEDs and solar-blind p-i-n photodiodes
- Conclusions

Growth of AlN nucleation layers on c-Al2O3 substrates at the different substrate temperatures & stoichimetric conditions



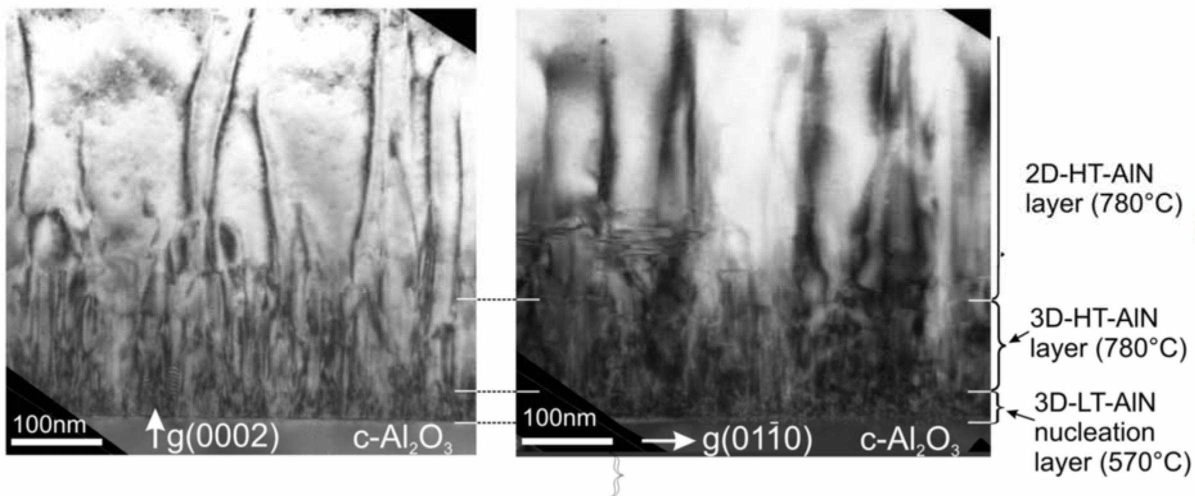




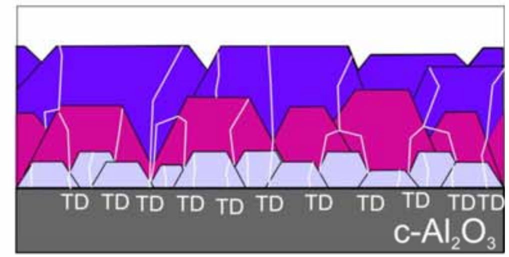
Nechaev et al., MBE-2012, J. Cryst. Growth, online 5 January 2013

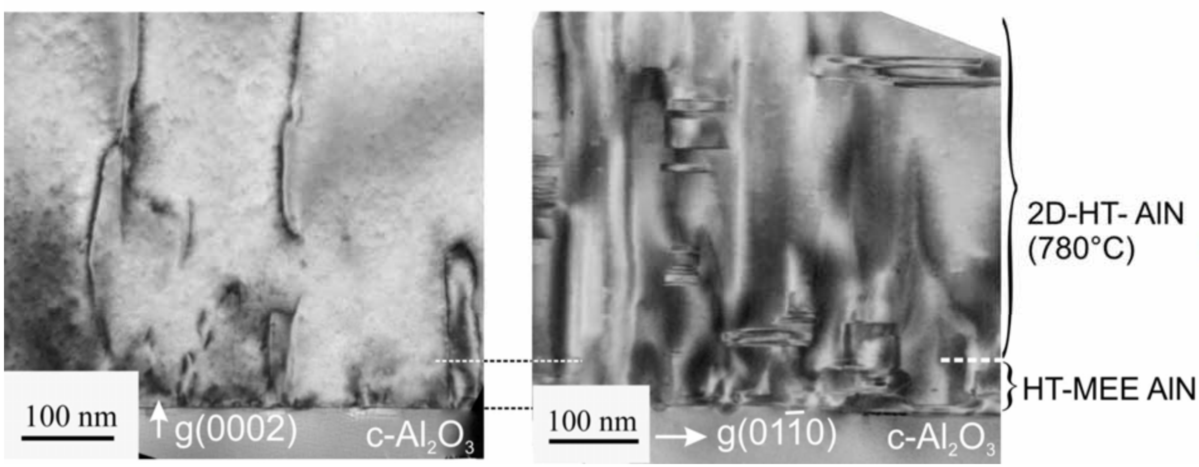
Lowering the TDs density in AlN/c-Al_2O_3 heterostructure by changing stoichiometric conditions 3D→2D

screw & mixed | edge

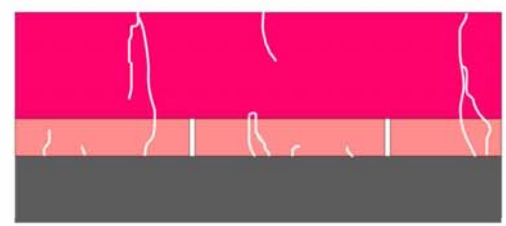


N_{TD}~10^{10}cm^{-2}



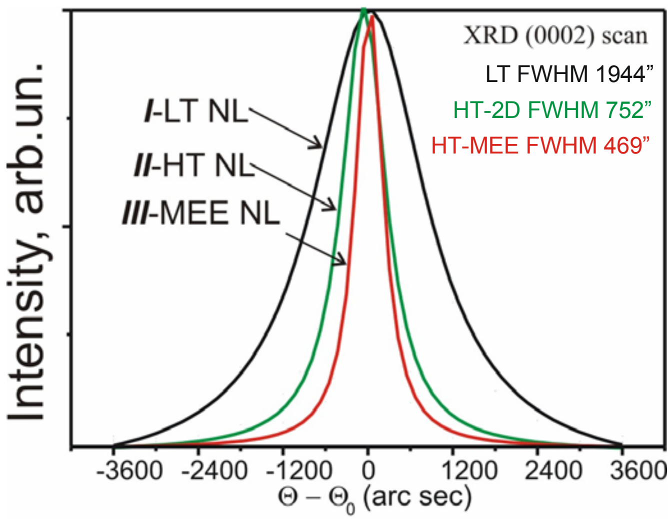


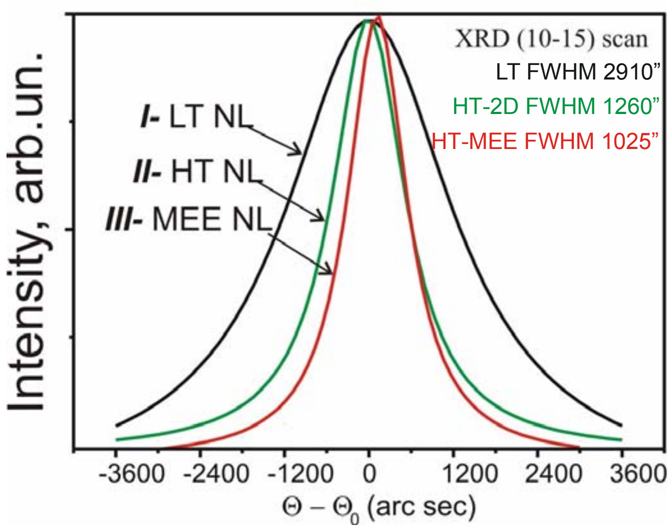
N_{TD}<10^{10}cm^{-2}

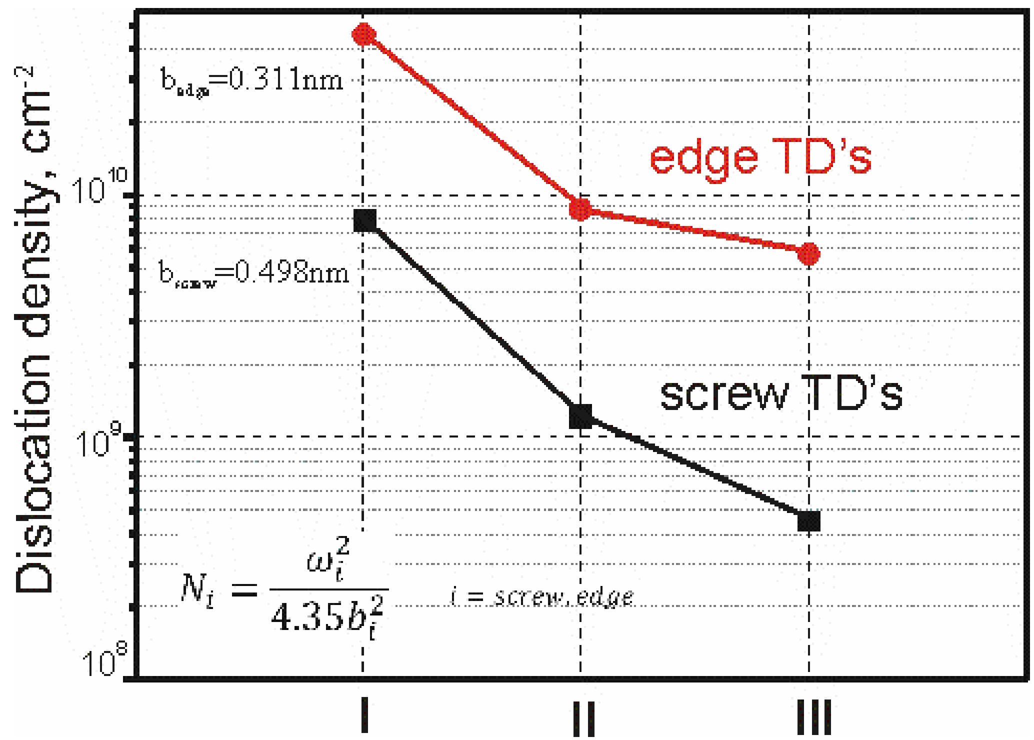


TDs density in 390-nm-thick AlN/c-Al203 heterolayers with different nucleation layers (NL)

XRD rocking curves





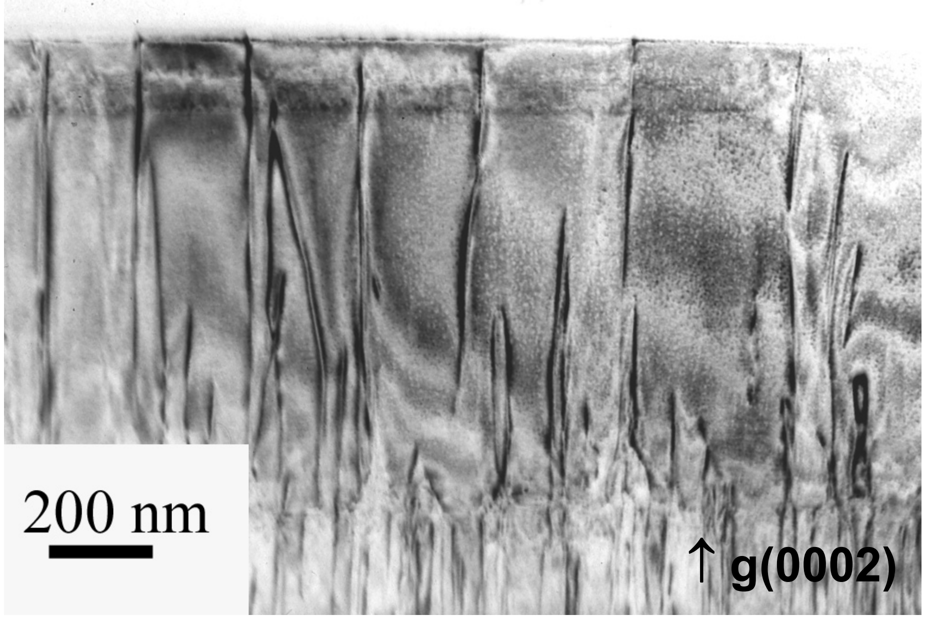


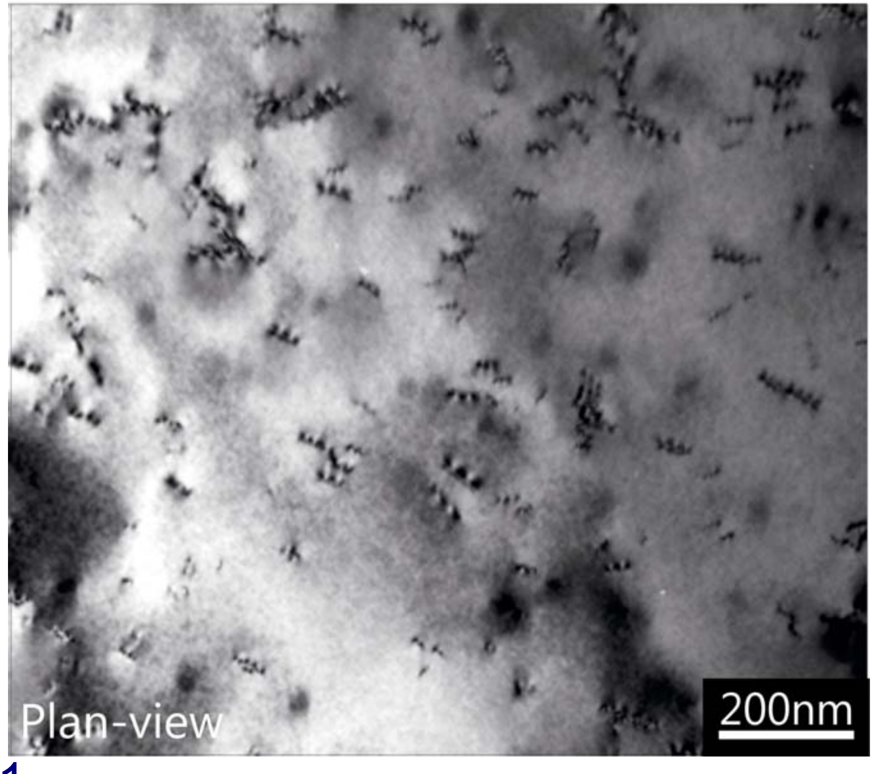
I – **Low T (570ºC) 30-nm-thick AlN-NL+ pulse-AlN-BL(360nm)**

II – **High T (760ºC) 30-nm-thick AlN-NL + pulse-AlN-BL(360nm)**

III – **MEE of 50-nm-thick HT-AlN + pulse-AlN-BL(340nm)**

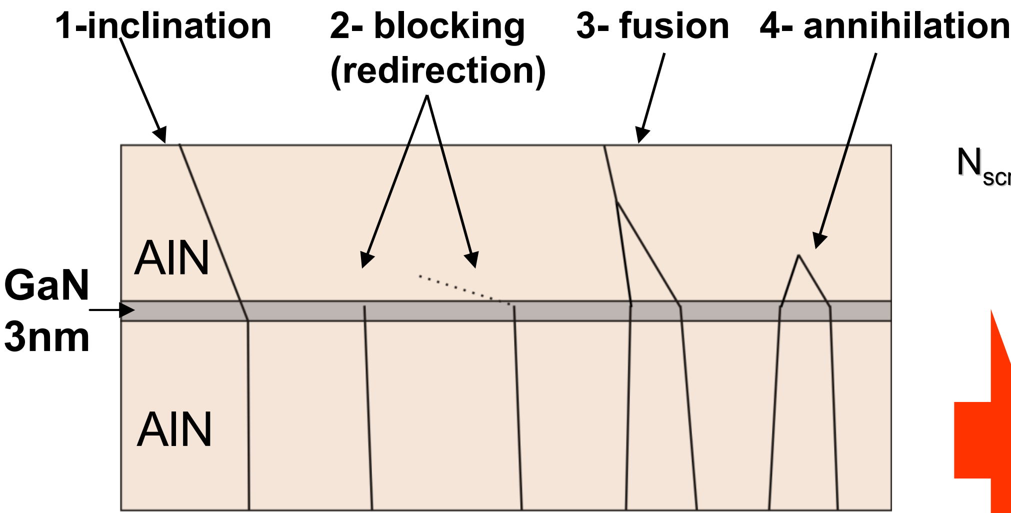
General TEM view of $AlGaN/AlN/c\text{-}Al_2O_3$ SQW structure with NL grown in regime III



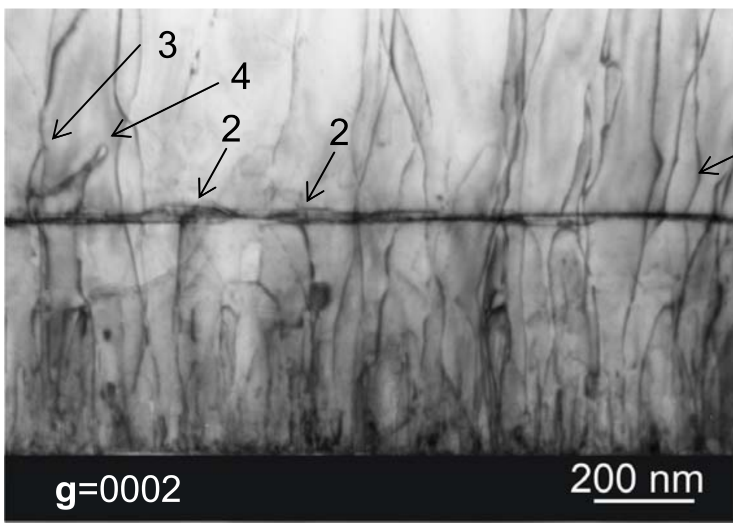


TDD Screw: ~$4 \cdot 10^8$cm^{-2}
Edge & Mixed: ~$6 \cdot 10^9$cm^{-2}

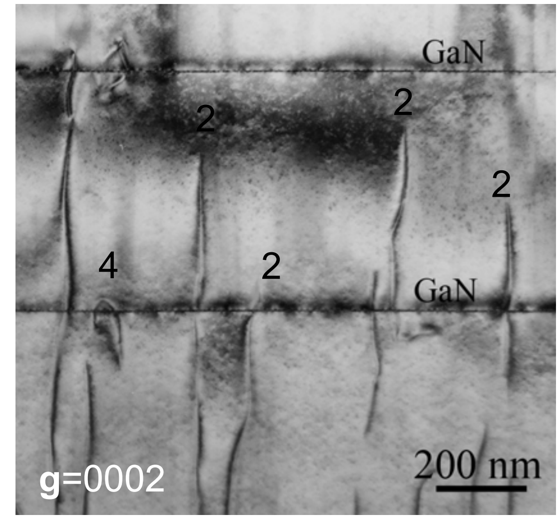
Filtering TD densities in thick AlN buffer layers by multiple compressively-strained 3nm-thick GaN layers



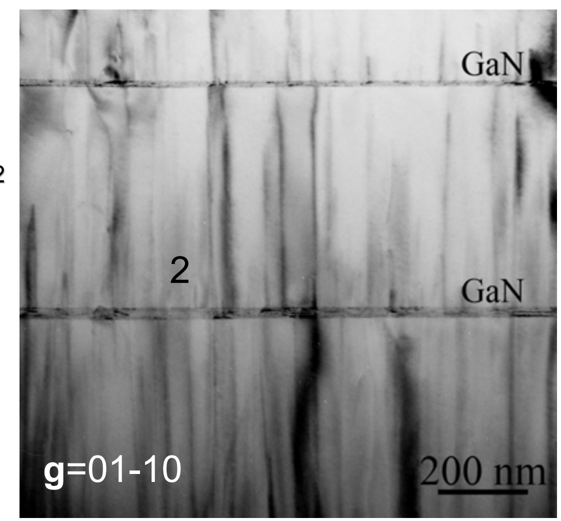
AlN 2D mode



N_{screw}=3.5·10^{9}см$^{-2}$



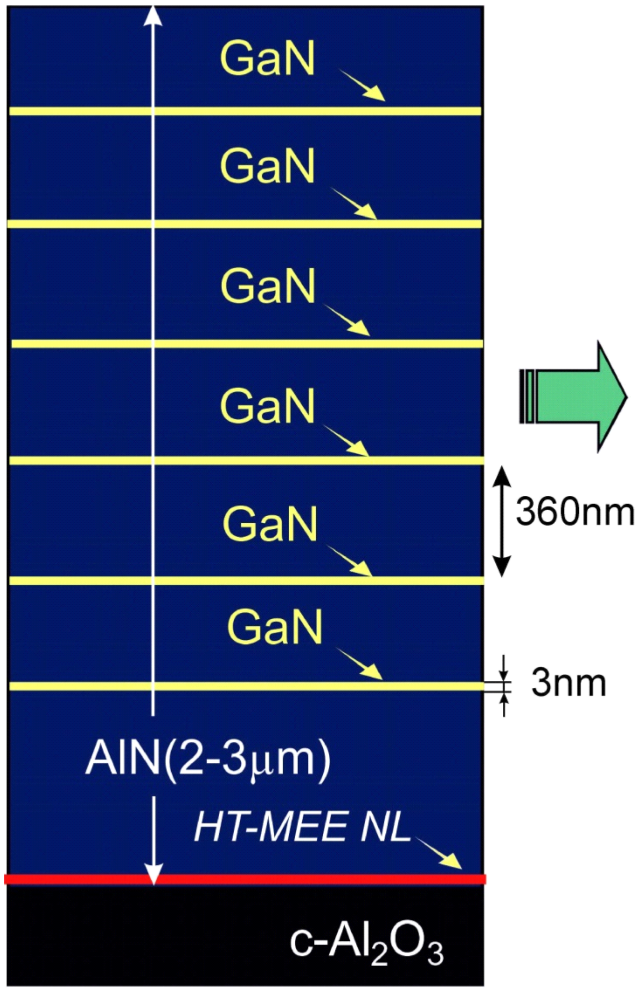
N_{edge}~10^{10}см$^{-2}$

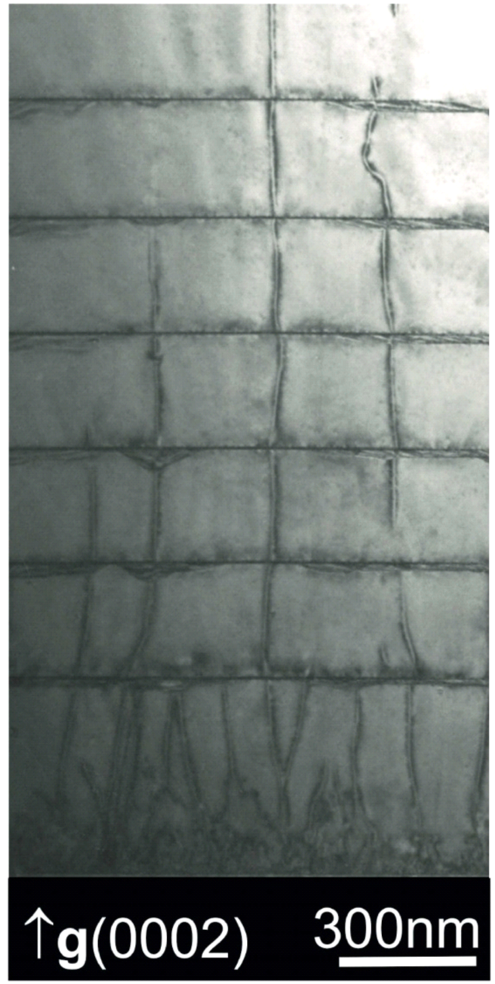


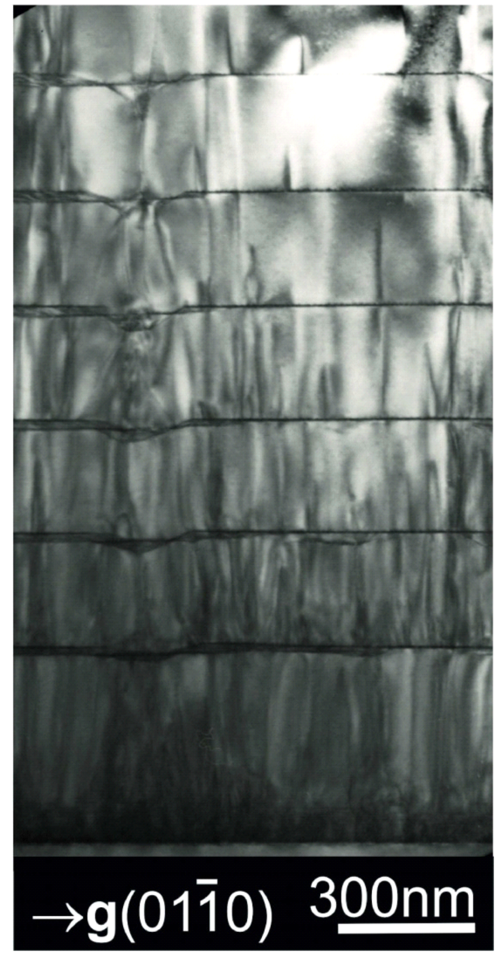
MOVPE results

J. Bai et al., Appl. Phys. Lett. **88**, 051903 (2006).
H. Jiang et al., Appl. Phys. Lett. **87**, 241911 (2005).

Filtering TDs in thick AlN buffer layers by multiple compressively-strained 3nm-thick GaN layers

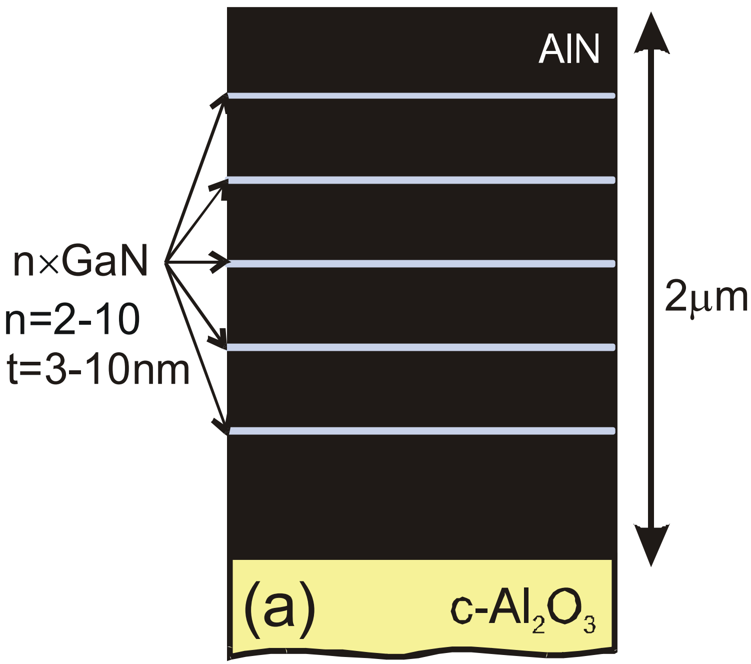




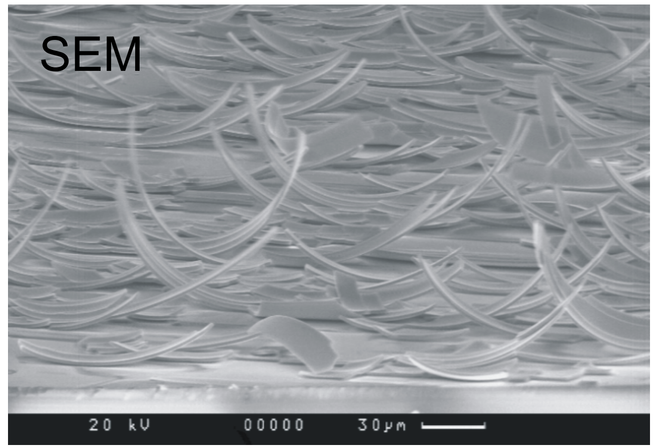


Nechaev et al. "Nanophysics and Nanoelectronics", 2014

Microscope images of the 2-µm-thick GaN/AlN heterostructures with GaN interlayers of non-optimized design and growth conditions

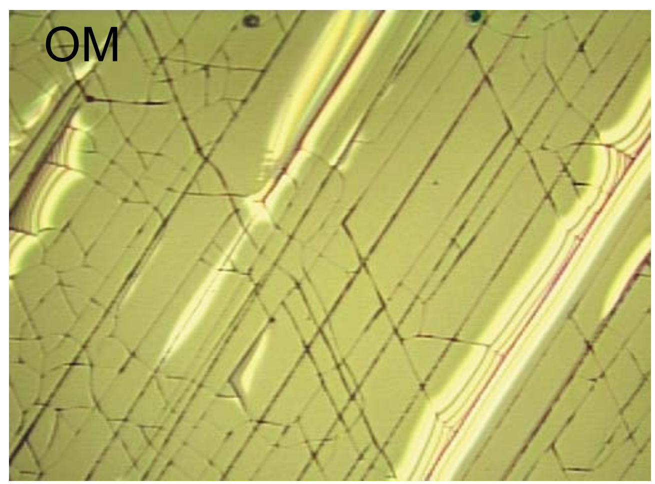


detachment



- 2D GaN growth mode
- multiple GaN interlayers above 6 interlayers
- for interlayer spacing smaller than 150nm even above 3 interlayers

cracking

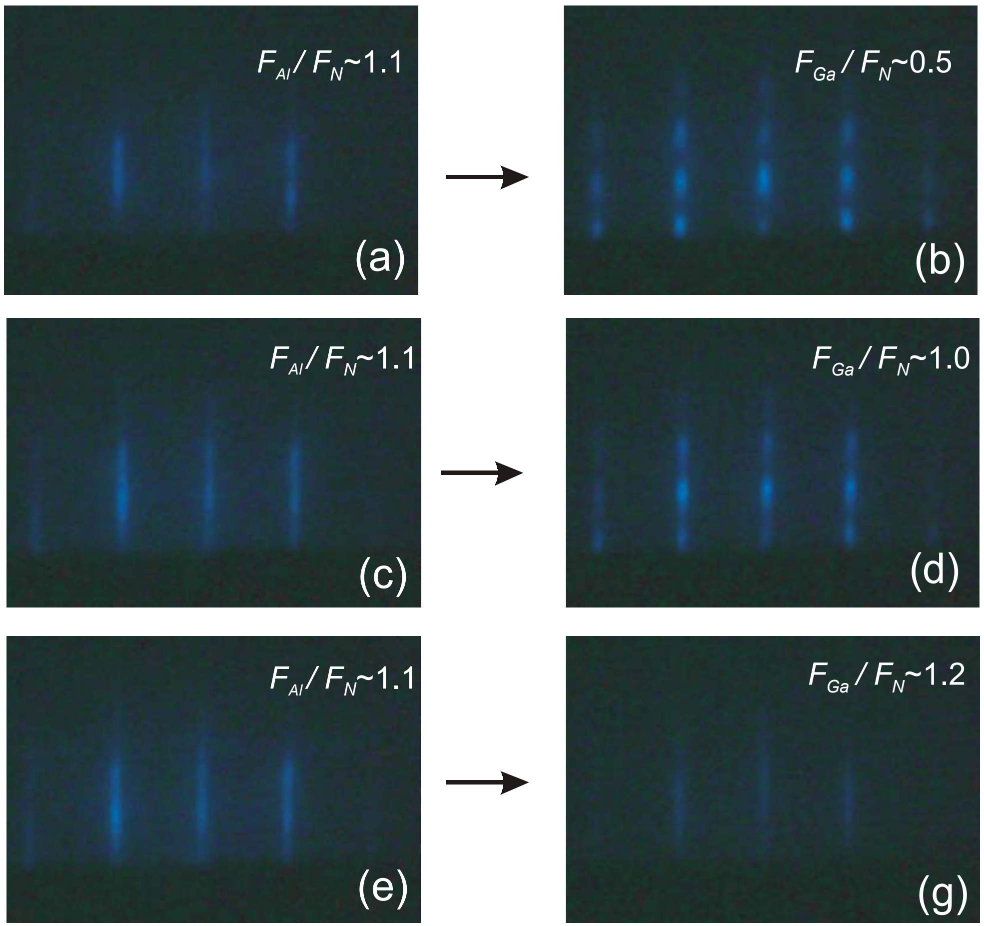


- 3D GaN growth mode
- multiple GaN interlayers at small spacing below 150 nm

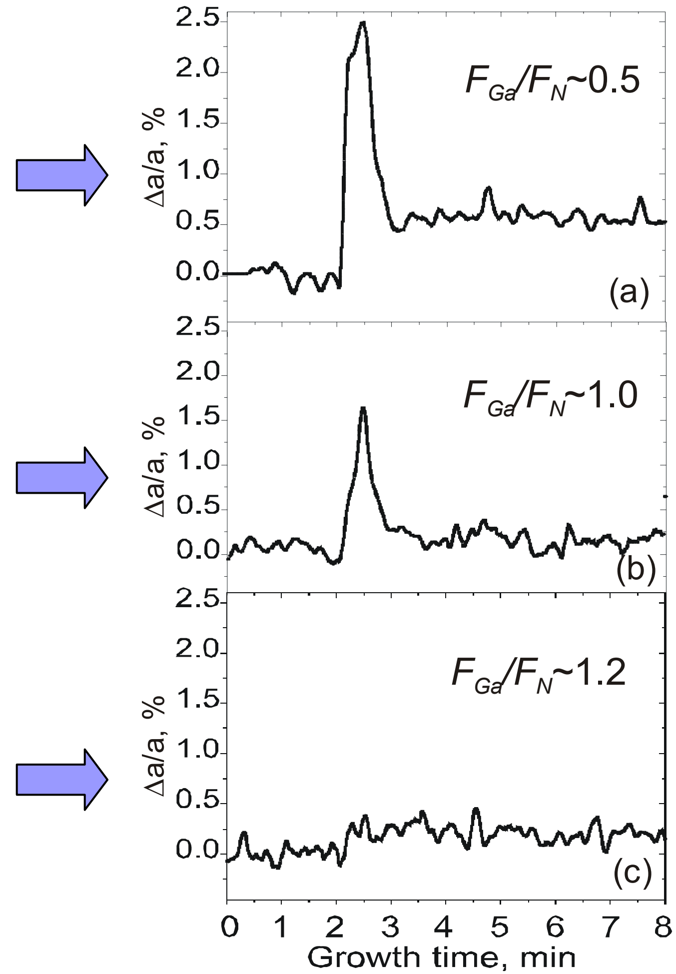
Strain relaxation versus surface morphology of 3-nm-thick GaN interlayers in 2D AlN buffer

RHEED patterns during growth

Al-rich AlN buffer **GaN interlayer**

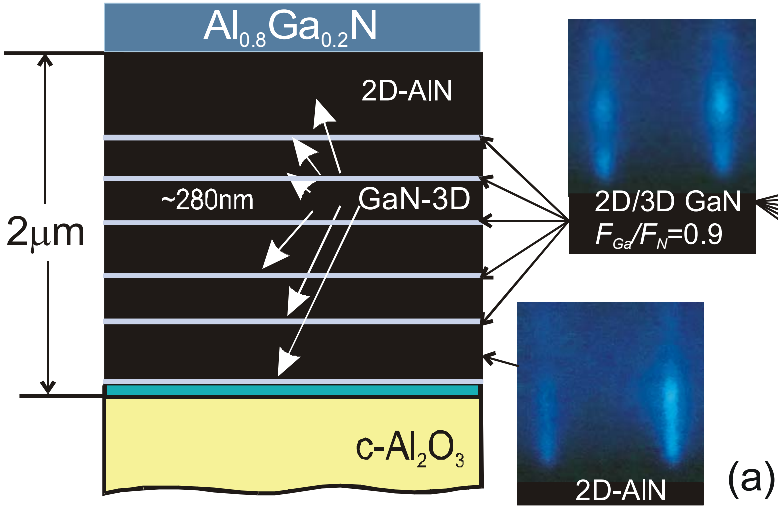


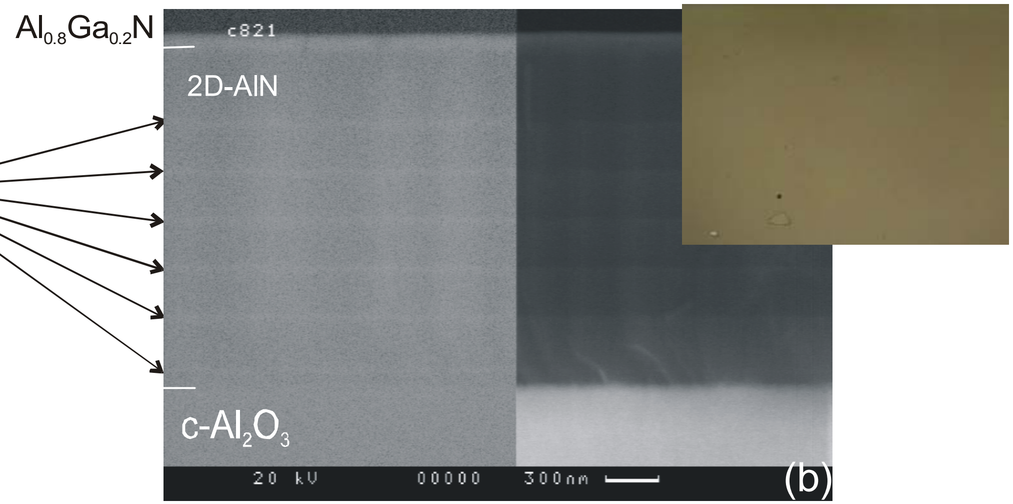
Temporal changes of a-lattice constant during growth of GaN interlayers

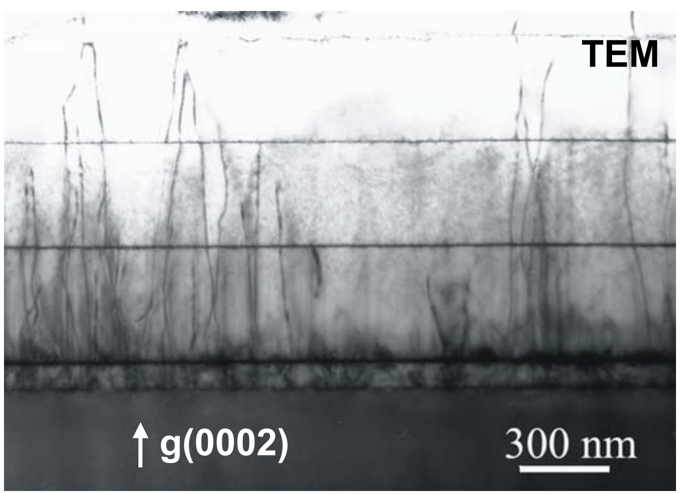


In accordance with model by Daudin's group
[Phys. Rev. B **63**, 245307 (2001), J. Appl. Phys. **95**, 1127 (2004)]

Structural property of $Al_{0.8}Ga_{0.2}N$(100nm)/AlN(2μm)/c-Al_2O_3 heterostructure grown on optimized AlN/GaN buffer



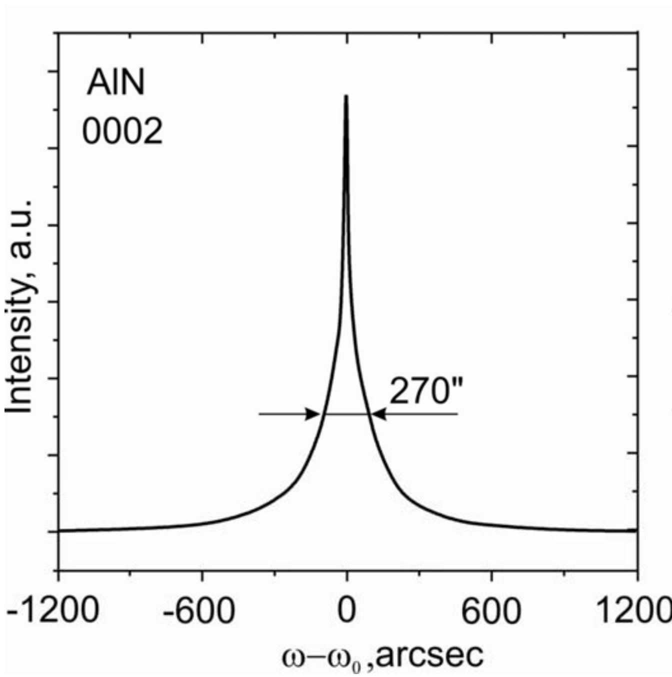




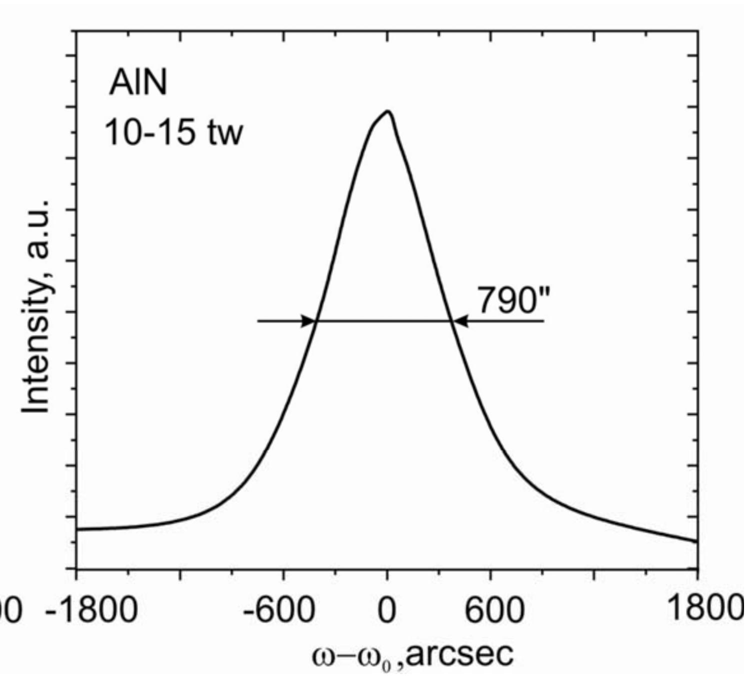
- Metal-flux modulated Al-rich growth of 260-nm-thick AlN layers separated by six 3-nm-thick GaN interlayers grown under the slightly N-rich conditions (F_{Ga}/F_N~0.9).
- Screw&mixed TD density reduced to ~10^8 cm^{-2}

XRD rocking curves of AlN buffer layer in SQW structure grown on c-sapphire at optimized AlN/GaN buffer structure design and growth conditions

symmetric (0002) reflex



skew-symmetric (10-15tw) reflex



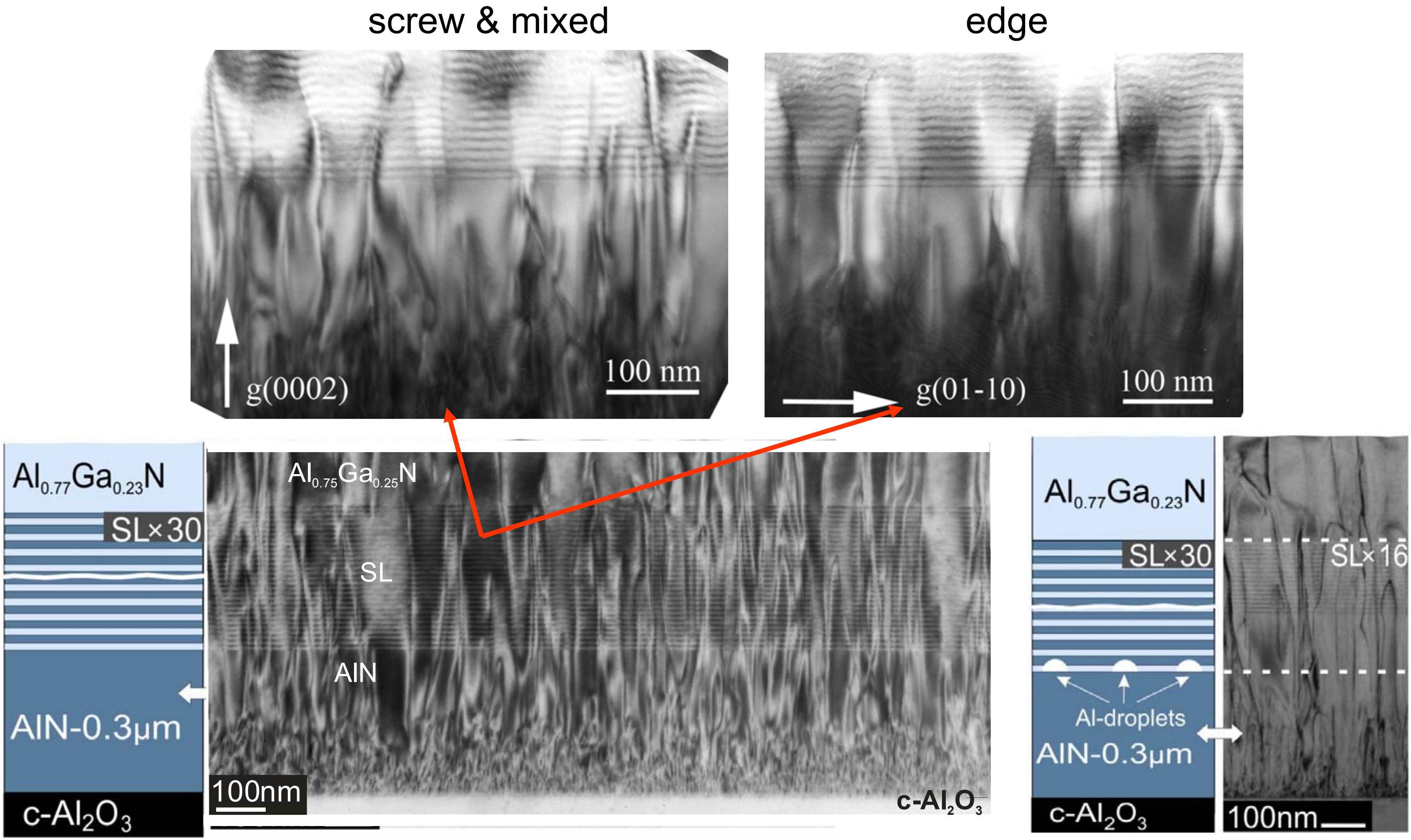
Screw TD : ~$1.5 \cdot 10^{8}$cm^{-2}

Edge & Mixed TD : ~$3 \cdot 10^{9}$cm^{-2}

$$N_{TD} = w^2/4.35b^2$$

AlN:
b = 0.498 nm (for screw TD)
b = 0.311 nm (for edge TD)

Suppression of TDs by using 30x{$Al_{0.77}Ga_{0.23}N$/AlN}/AlN superlattices (T = 10nm, x_{av}= 0.9)

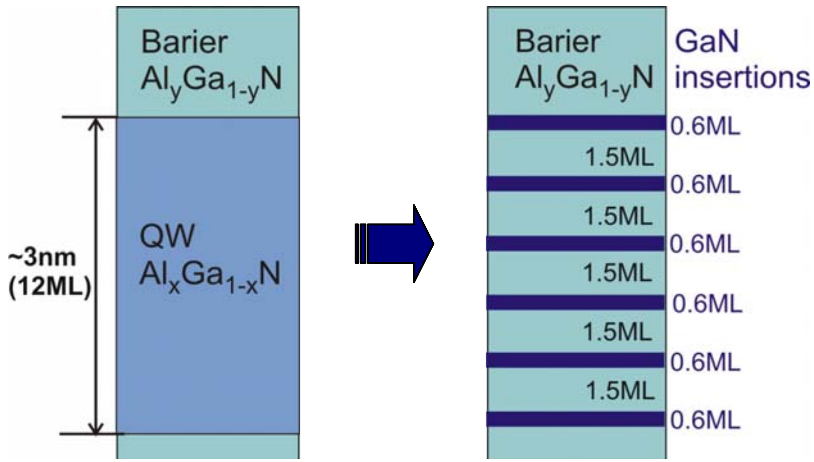


Outline

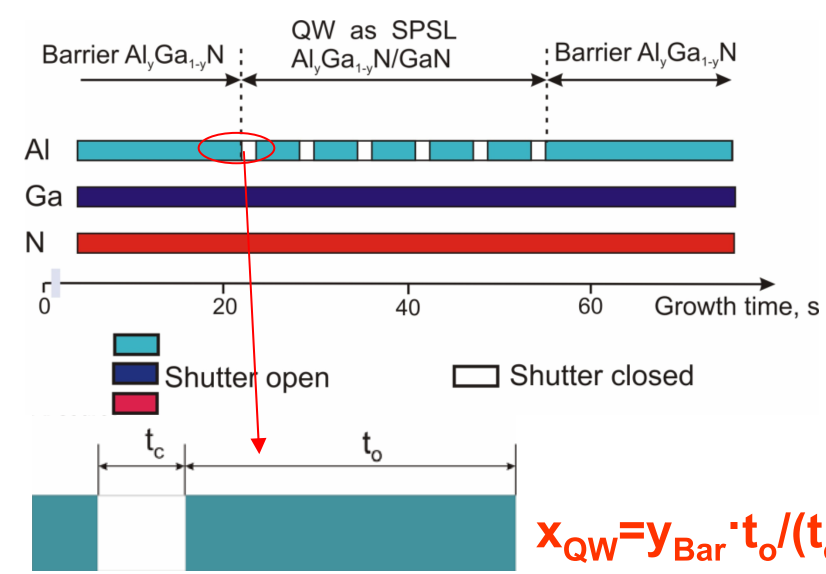
- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
- PA MBE growth and surface morphology control of III-Nitrides
  - Al-rich growth of thick AlN/c-Al_2O_3 buffer layers
  - Growth kinetics of AlGaN layers (2D-3D transition)
- Dislocation control and filtering in AlGaN/AlN/c-Al_2O_3 heterostructures
- Sub-monolayer Digital Alloying growth of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ QWs
- Strain engineering in AlGaN QW heterostructures to prevent TE/TM switching of photoluminescence polarization
- Low-threshold optically pumped QW laser structures in the 258-303 nm range
- LEDs and solar-blind p-i-n photodiodes
- Conclusions

Submonolayer Digital Alloying (SMDA) growth of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ MQW heterostructures

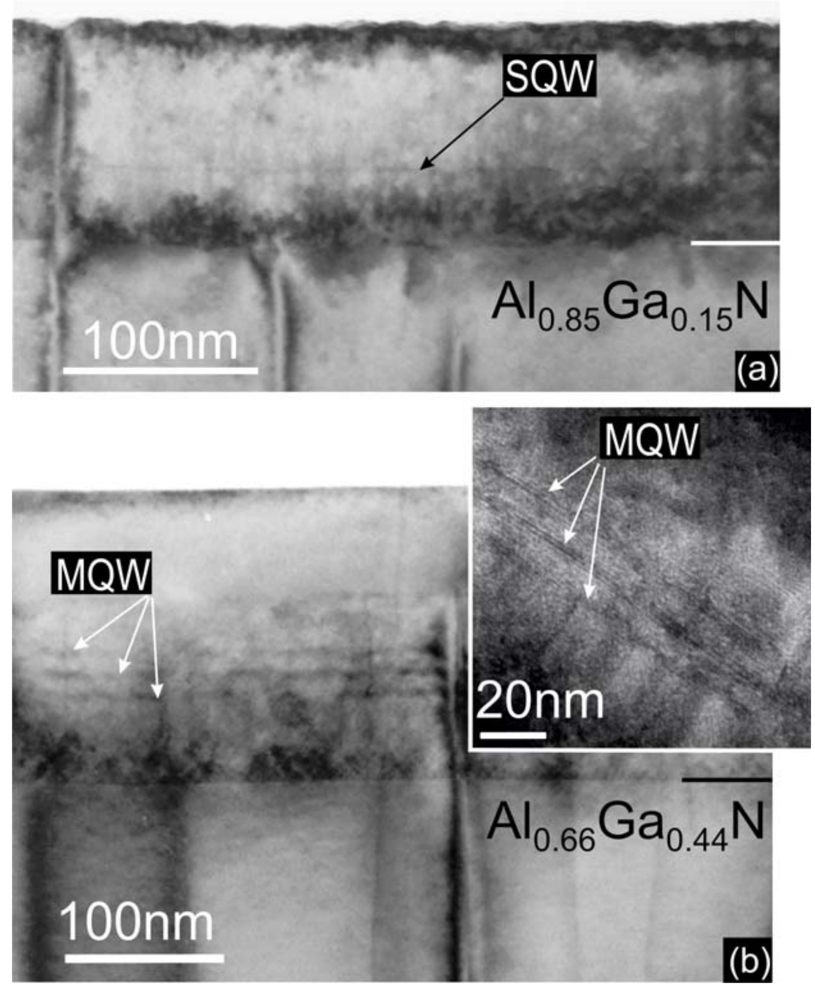
Standard QW / SMDA QW



Shutter control of Al content in AlGaN QW

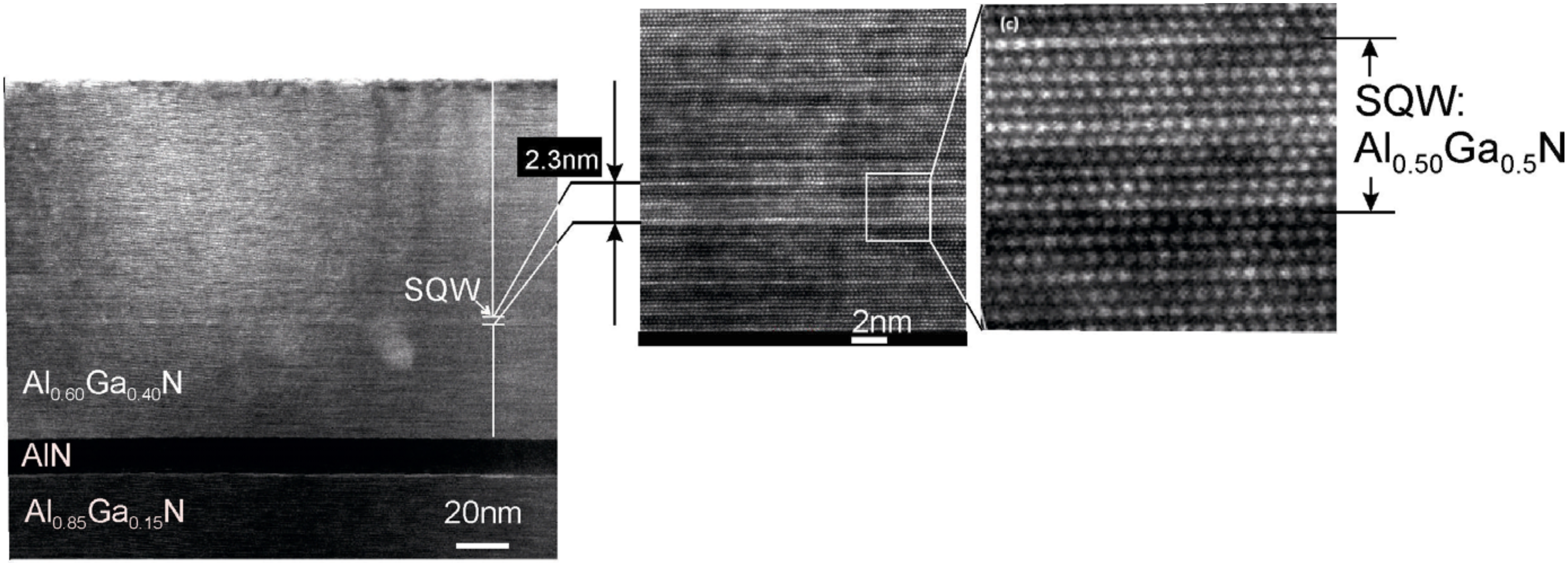


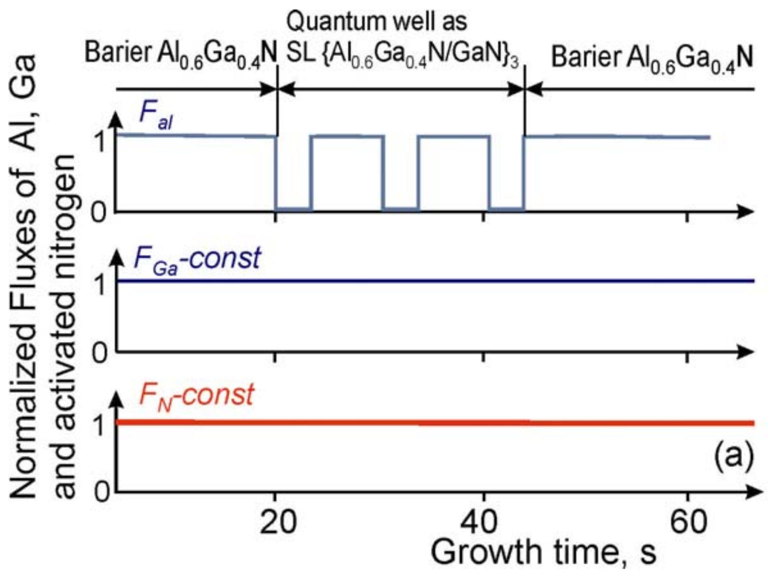
$$x_{QW}=y_{Bar}\cdot t_o/(t_o+t_c)$$

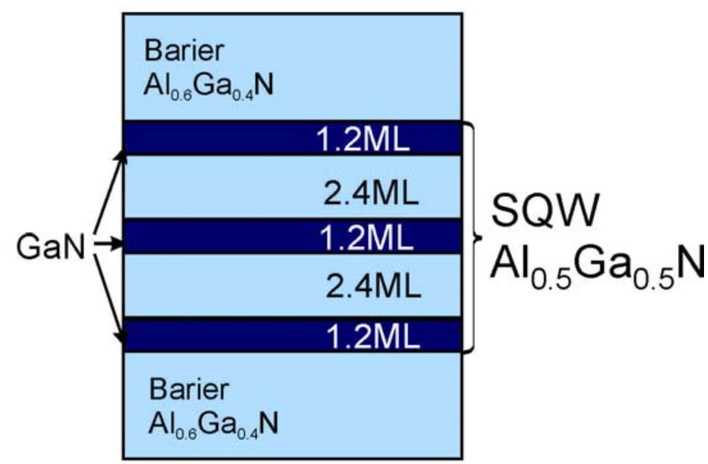


Jmerik et al., Semiconductors ***42****, 1452, (2008), PSS A* ***210****, 439(2013).*

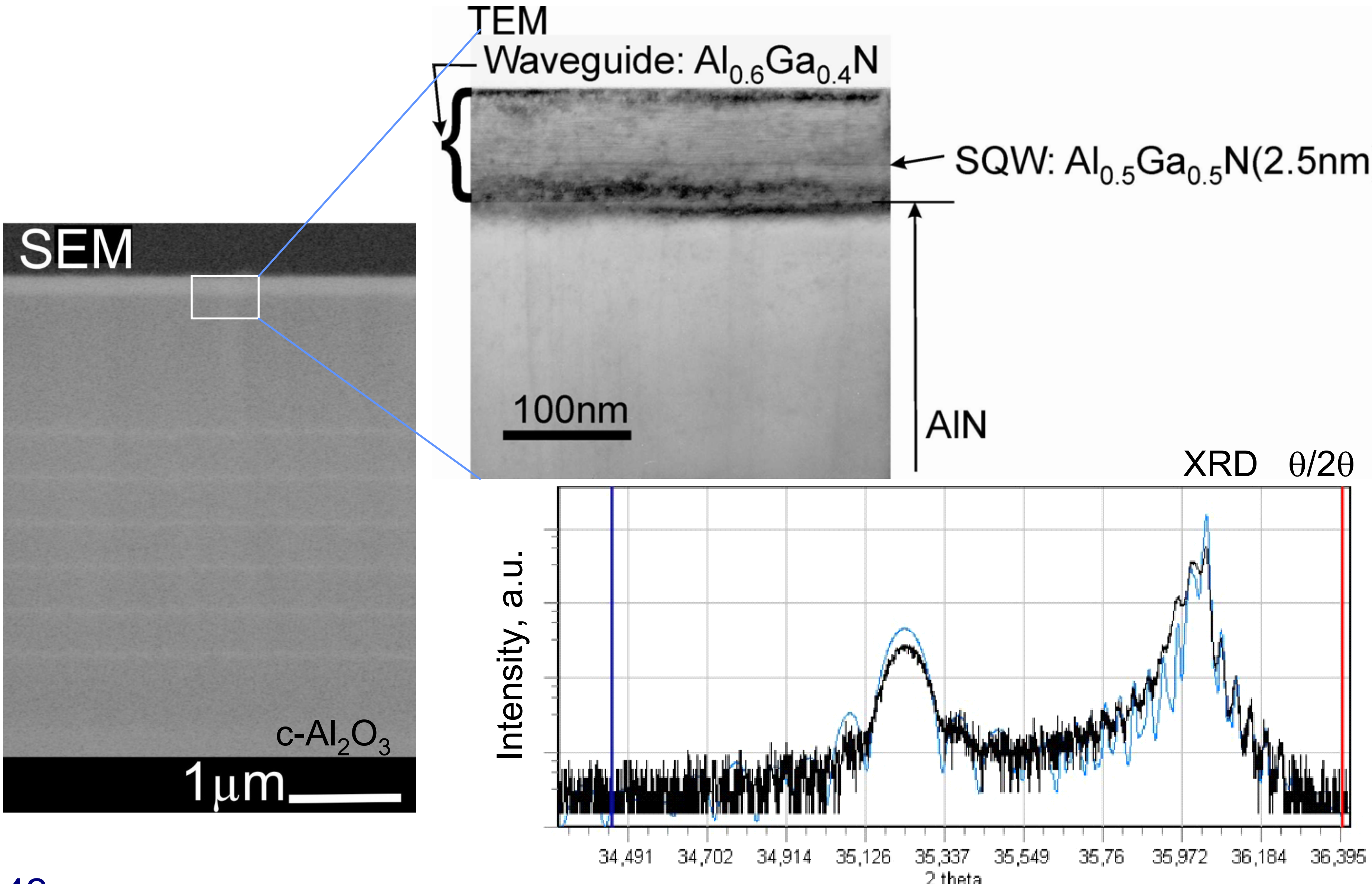
HAADF STEM and HRTEM images of AlGaN-based SQW heterostructure



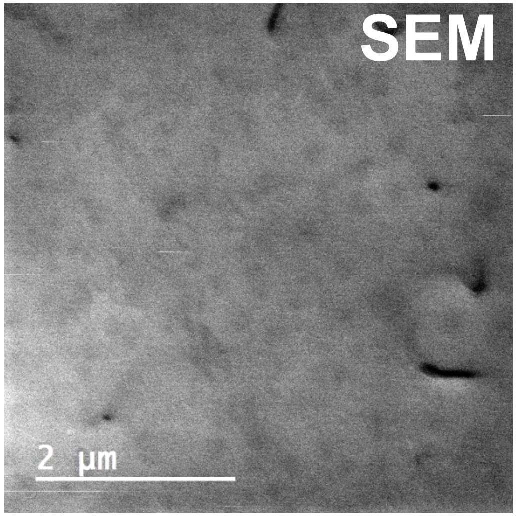


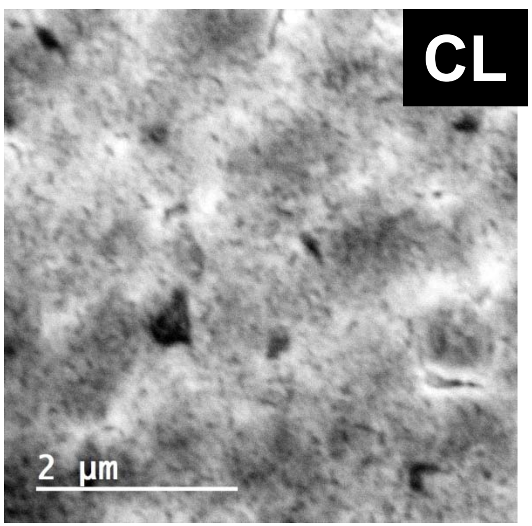


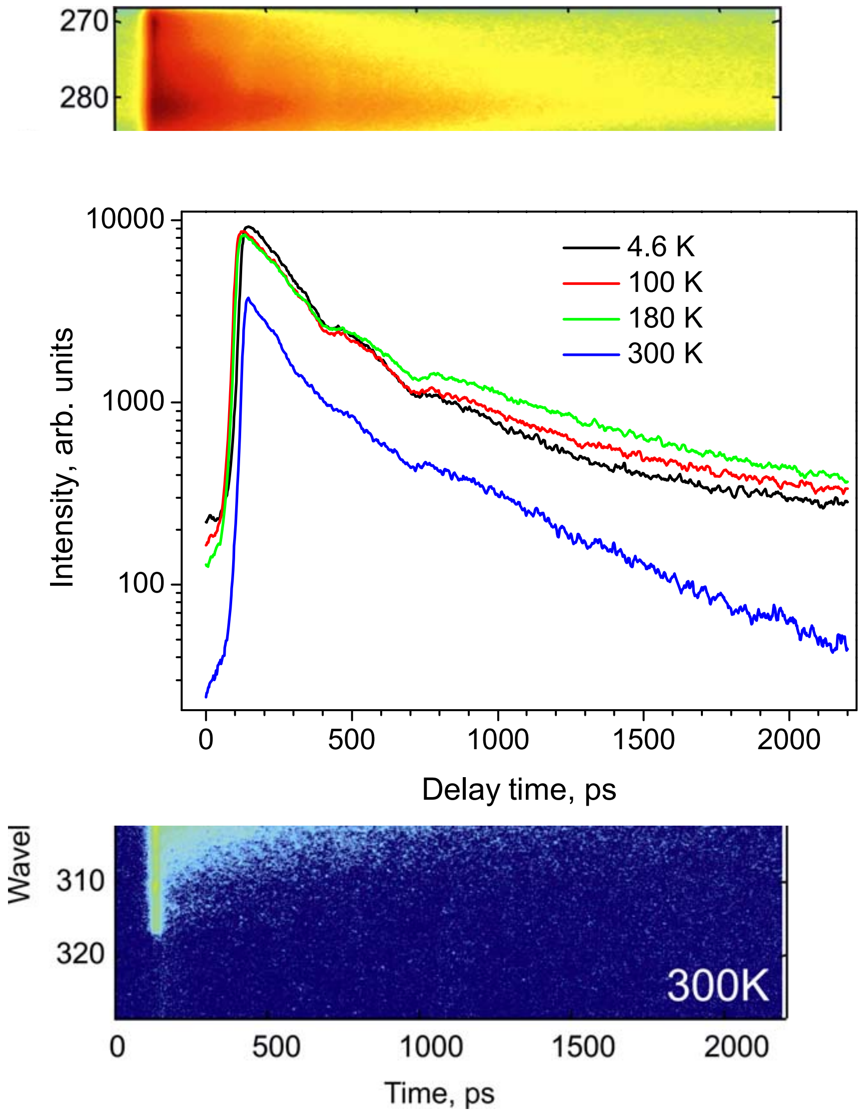
Structural properties of AlGaN-based SQW heterostructure grown on c-Al_2O_3



CL and TRPL spectra of $Al_{0.5}Ga_{0.5}N(2.5nm)/Al_{0.6}Ga_{0.4}N$ SQW





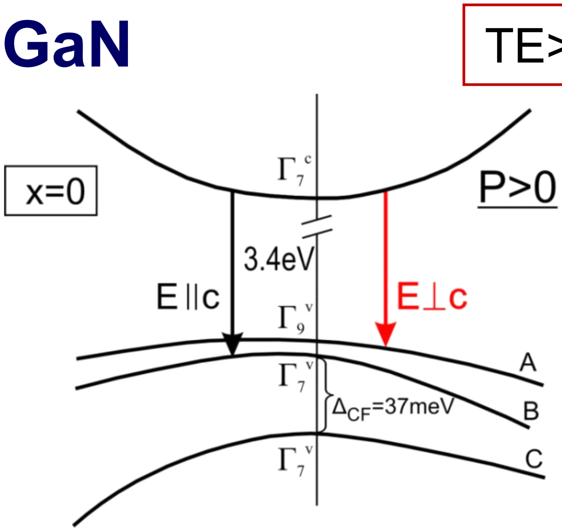


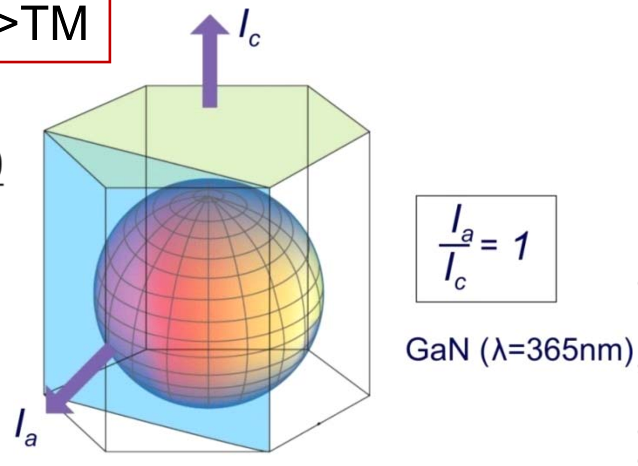
Outline

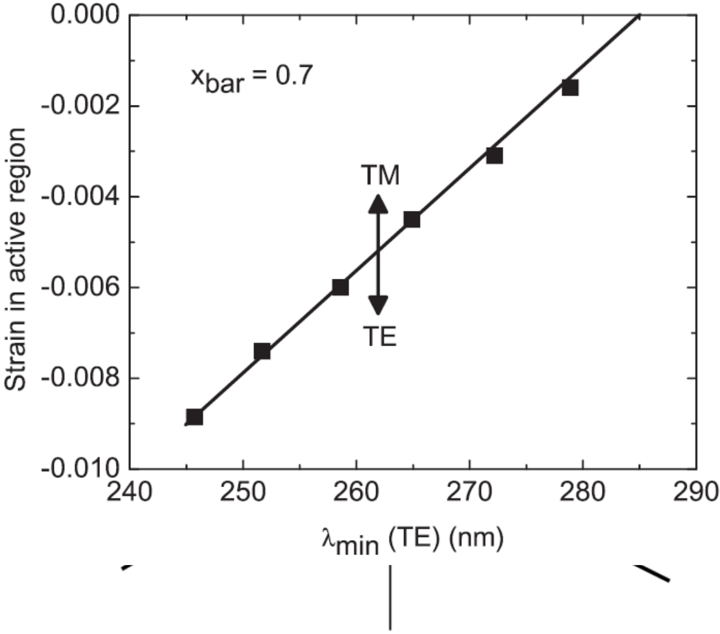
- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
- PA MBE growth and surface morphology control of III-Nitrides
  - Al-rich growth of thick $AlN/c\text{-}Al_2O_3$ buffer layers
  - Growth kinetics of AlGaN layers (2D-3D transition)
- Dislocation control and filtering in $AlGaN/AlN/c\text{-}Al_2O_3$ heterostructures
- Sub-monolayer Digital Alloying growth of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ QWs
- **Strain engineering in AlGaN QW heterostructures to prevent TE/TM switching of photoluminescence polarization**
- Low-threshold optically pumped QW laser structures in the 258-303 nm range
- LEDs and solar-blind p-i-n photodiodes
- Conclusions

Valence band structure of $Al_xGa_{1-x}N$(x=0-1) alloys and anisotropic polarization of output UV radiation from GaN&AlN

GaN

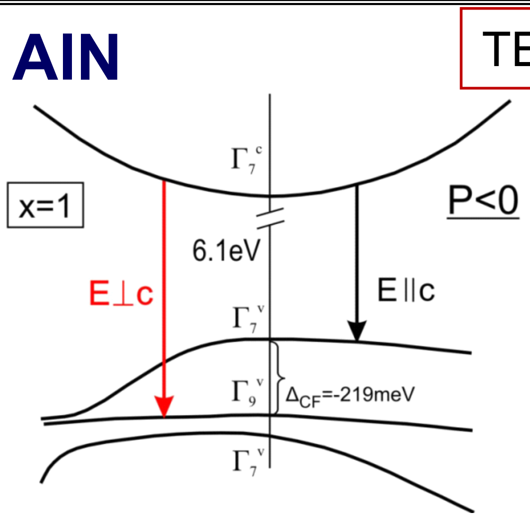


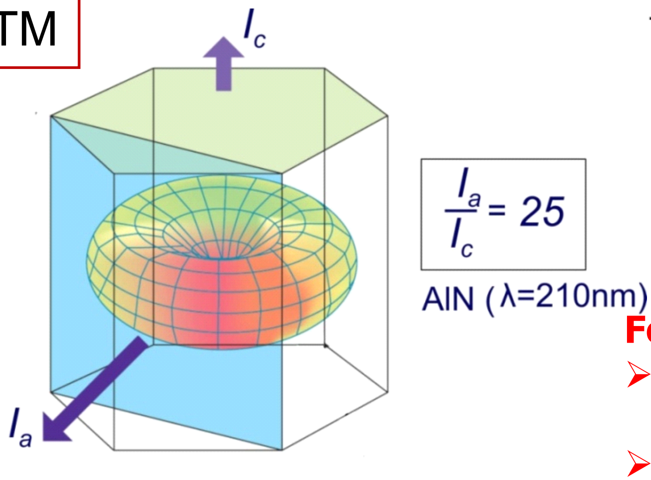




*Northrup et al., Appl.Phys.Lett. **100**, 021101 (2012)*
*Durnev &Karpov, Phys.Stat.Solidi B**250**, 180(2013)*

AlN





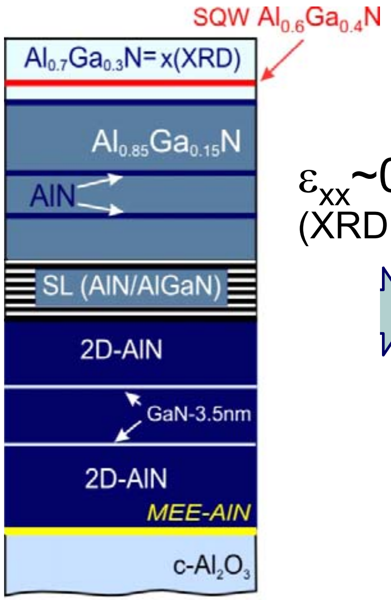
*Nam et al., APL **84**, 5264 (2004).*

*Taniyasu et al., APL **90**, 261911 (2007).*

For TE plarization:

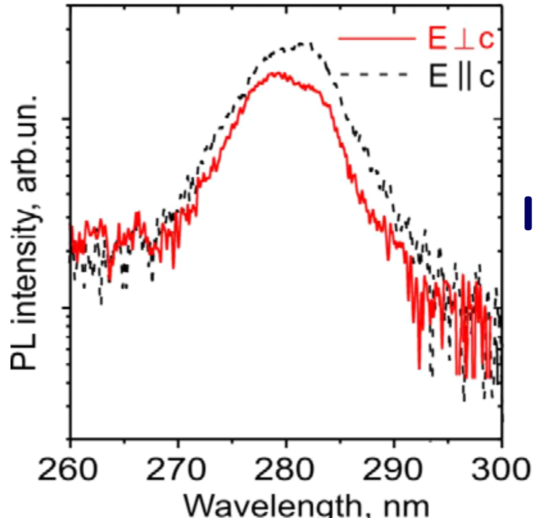
- Efficient light extraction from mid-UV LEDs normally to c-plane
- Higher differential gain in the mid-UV laser cavity due to the higher reflectivity coefficient

PL spectra of AlGaN-based heterostructures with the different compressive strains on c-Al_2O_3

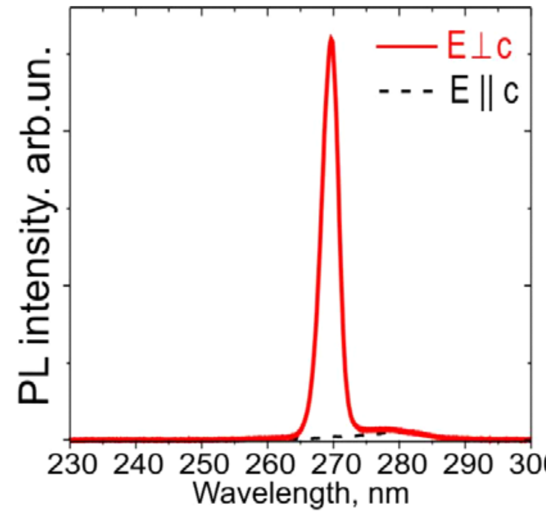


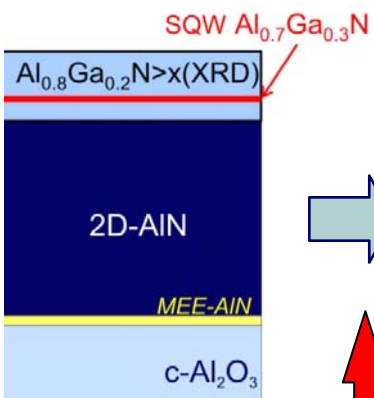
ε_{xx}~0
(XRD)

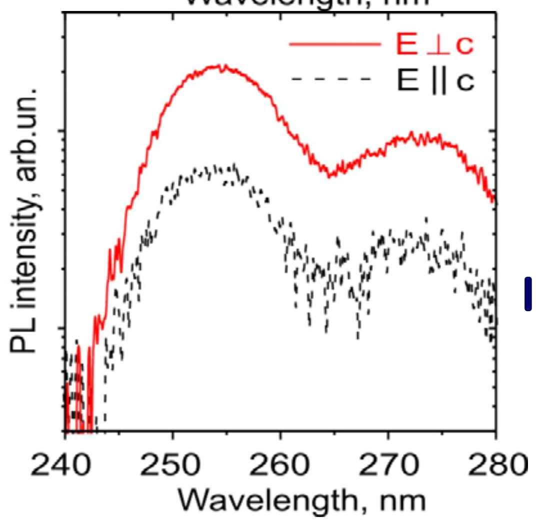
Spontaneous PL spectra

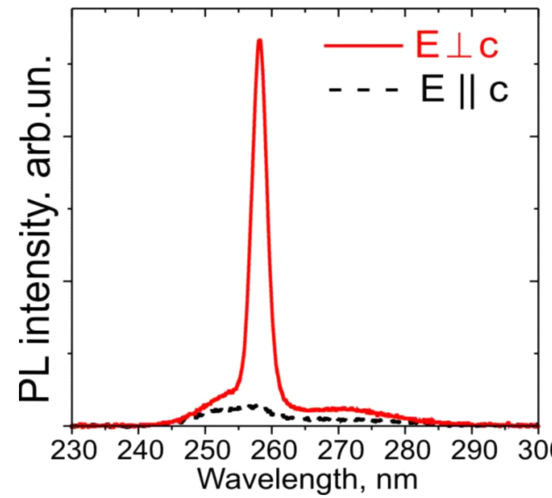


Stimulated PL spectra









*Lutsenko et al., Physics of Solid State , **55**(10), 2058, 2013*

ε_{xx}~−0.7-0.8% in the $Al_xGa_{1-x}N$ SQW corresponds to theoretical estimations of the compressive strain necessary for suppression of the valence band crossover for x > 0.7

*Northrup et al., Appl. Phys. Lett. **100**, 021101 (2012).*

Kinetic limitations for generation of threading dislocations

Misfit dislocations generation rates $\left(\frac{dN}{dt}\right)$ **to be influenced by the:**

- Stress due to misfit strain (τ_{eff})
- Density of nucleation sites (N_0) $\rightarrow$ **2D** $\rightarrow$ ***Metal-rich PAMBE !***
- Growth temperature (T) $\rightarrow$ ***Low T (<800°) PA MBE !***

This can be described by the semiempirical expression :

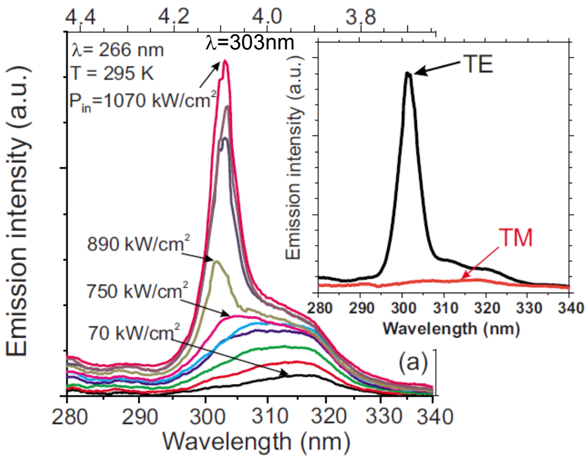
$$\frac{dN}{dt} = B \cdot N_0 \left(\frac{\tau_{eff}}{\mu}\right)^n \exp\left(-\frac{E_a}{kT}\right)$$

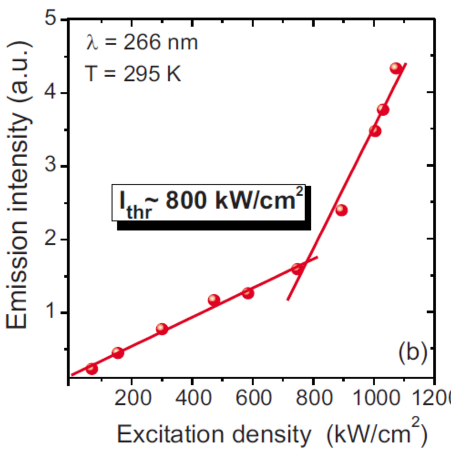
Houghton, J.Appl.Phys. 70, (1991), 2136

Outline

- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
- PA MBE growth and surface morphology control of III-Nitrides
  - Al-rich growth of thick AlN/c-Al_2O_3 buffer layers
  - Growth kinetics of AlGaN layers (2D-3D transition)
- Dislocation control and filtering in AlGaN/AlN/c-Al_2O_3 heterostructures
- Sub-monolayer Digital Alloying growth of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ QWs
- Strain engineering in AlGaN QW heterostructures to prevent TE/TM switching of photoluminescence polarization
- Low-threshold optically pumped QW laser structures in the 258-303 nm range
- LEDs and solar-blind p-i-n photodiodes
- Conclusions

Optically pumped mid-UV lasing in AlGaN heterostructures grown by PA MBE (previous results)



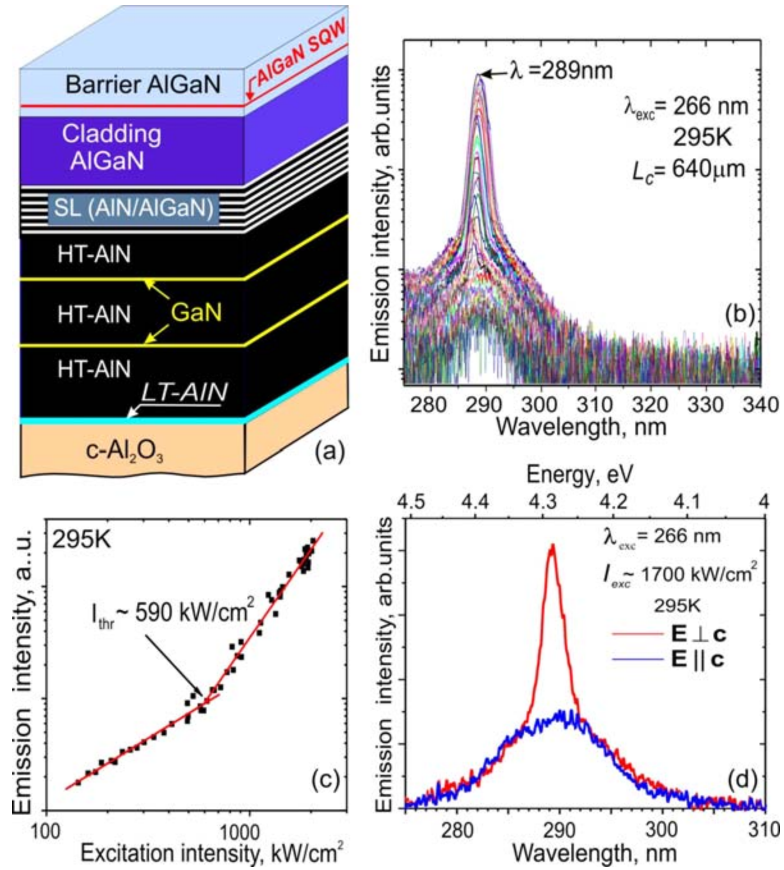


APPLIED PHYSICS LETTERS **96**, 141112 (2010)

Low-threshold 303 nm lasing in AlGaN-based multiple-quantum well structures with an asymmetric waveguide grown by plasma-assisted molecular beam epitaxy on c-sapphire

V. N. Jmerik,[1,a)] A. M. Mizerov,[1] A. A. Sitnikova,[1] P. S. Kop'ev,[1] S. V. Ivanov,[1] E. V. Lutsenko,[2] N. P. Tarasuk,[2] N. V. Rzheutskii,[2] and G. P. Yablonskii[2]
[1]*Ioffe Physical-Technical Institute, RAS, St. Petersburg 194021, Russia*
[2]*Stepanov Institute of Physics of NAS Belarus, Independence Ave. 68, Minsk 220072, Belarus*

(Received 28 January 2010; accepted 2 March 2010; published online 8 April 2010)



Phys. Status Solidi A **210**, No. 3, 439–450 (2013) / **DOI** 10.1002/pssa.201300006

physica status solidi a
applications and materials science

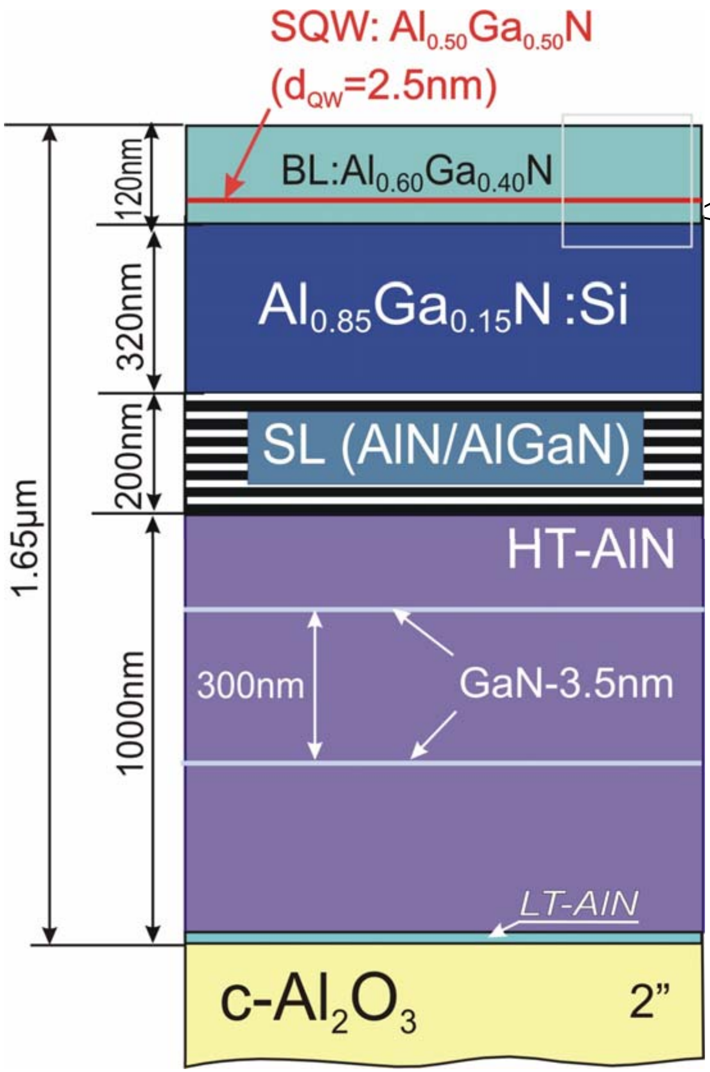
Feature Article

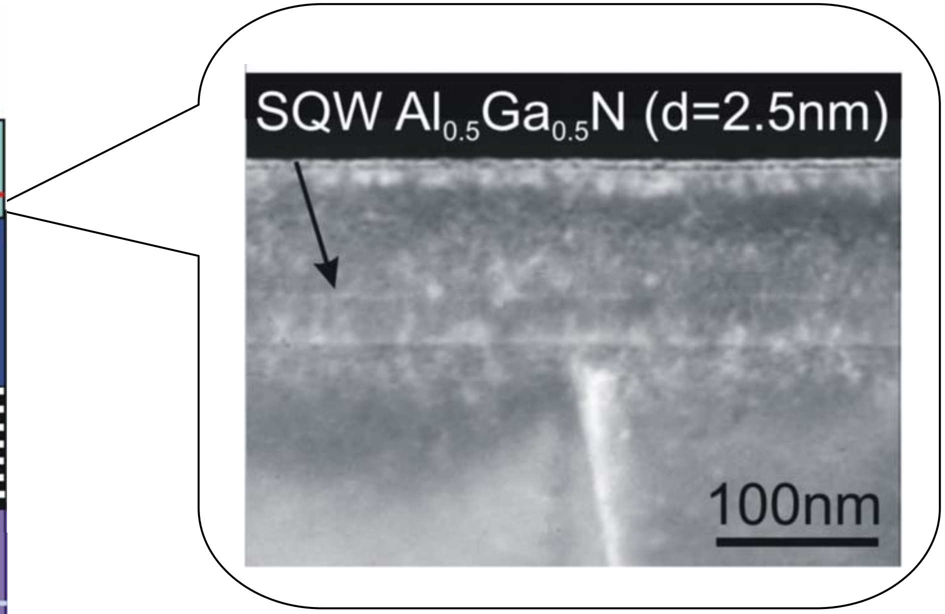
Plasma-assisted molecular beam epitaxy of AlGaN heterostructures for deep-ultraviolet optically pumped lasers

V. N. Jmerik[*,1], **E. V. Lutsenko**[2], **and S. V. Ivanov**[1]
[1]Ioffe Physical-Technical Institute of RAS, Polytekhnicheskaya 26, St. Petersburg 194021, Russia
[2]Stepanov Institute of Physics of NAS Belarus, Independence Ave. 68, Minsk 220072, Belarus

Received 15 January 2013, revised 5 February 2013, accepted 6 February 2013
Published online 4 March 2013

Design and TEM image of AlGaN-based SQW structure optimized for sub-300nm UV-lasing



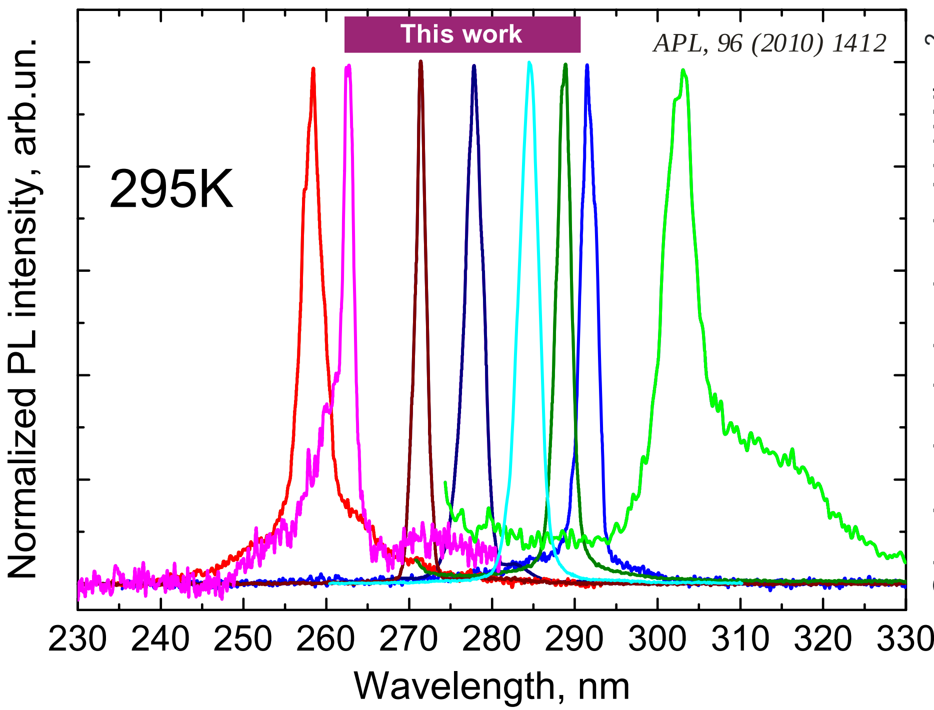


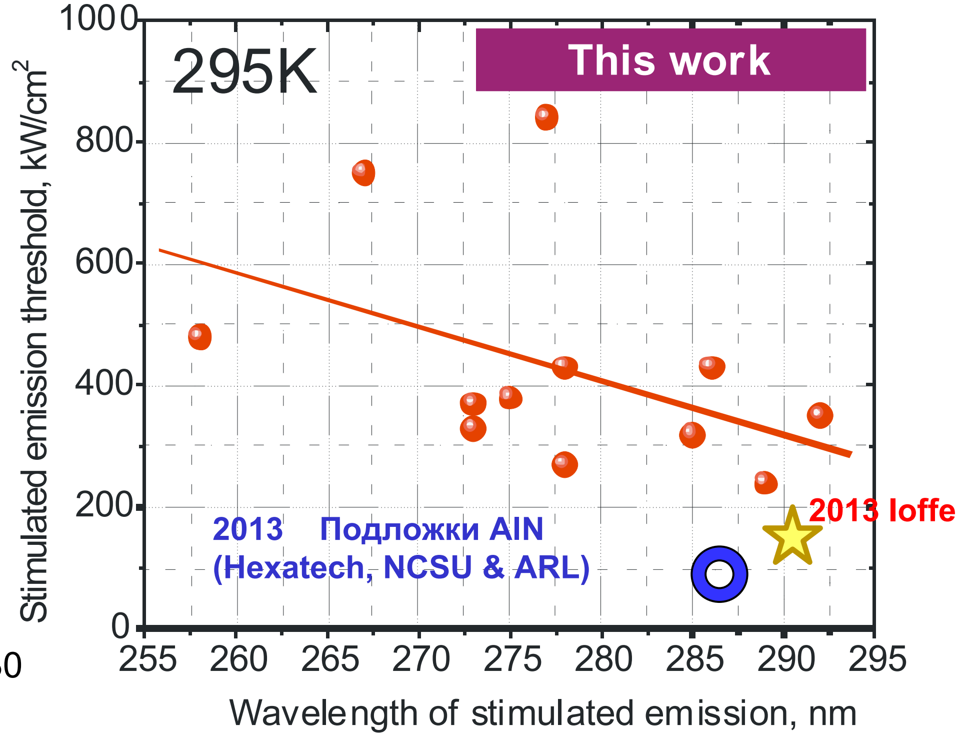
Key factors

- Reduction of TDs density (10^8-10^9cm^{-2}) by using (1-3)-µm thick AlN buffer with incorporated optimized 3-nm-thick GaN layers and AlGaN/AlN SL, grown under the optimized conditions.
- Employing a SQW structure with optimum QW thickness <3 nm and slightly inhomogenious morphology facilitating appearance of localization states.

Stimulated emission in the sub-300nm range in AlGaN SQW SCH grown by PA MBE on c-Al_2O_3

Edge PL in cleaved-facets laser chips





Feature paper, Jmerik et al., phys. stat. sol. (a) 210, 439 (2013)

- Advanced AlGaN SQW and MQW structures grown by PA MBE on c-sapphire demonstrate optically-pumped stimulated emission within the 255-300 nm wavelength range with typical threshold power densities of 240-480 kW/cm^2 (295K) and TE polarization.
- The lowest SE threshold power density achieved at 289 nm was 150 kW/cm^2.

Outline

- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
- PA MBE growth and surface morphology control of III-Nitrides
  - Al-rich growth of thick AlN/c-Al_2O_3 buffer layers
  - Growth kinetics of AlGaN layers (2D-3D transition)
- Dislocation control and filtering in AlGaN/AlN/c-Al_2O_3 heterostructures
- Sub-monolayer Digital Alloying growth of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ QWs
- Strain engineering in AlGaN QW heterostructures to prevent TE/TM switching of photoluminescence polarization
- Low-threshold optically pumped QW laser structures in the 258-303 nm range
- **LEDs and solar-blind p-i-n photodiodes**
- Conclusions

Electrical properties of as-grown PAMBE $Al_xGa_{1-x}N$:Mg

GaN - $Al_{0.15}Ga_{0.85}N$

C-V (300K): p-type p = 3×10^{18} cm^{-3}

Hall (250K): p-type p = 1×10^{18}cm^{-3}, μ_H = 3 cm^2/Vs

Seebeck (300K): p-type

$Al_{0.42}Ga_{0.58}N$

C-V (300K): compensated, although at the reverse bias above 5V p-type conductivity was observed

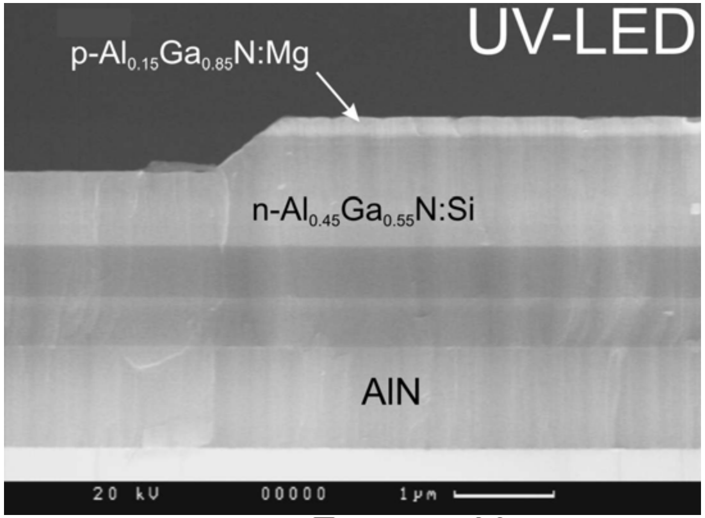
Hall (250K): p-type p = 4×10^{17} cm^{-3} μ_H = 1.4 cm^2/Vs

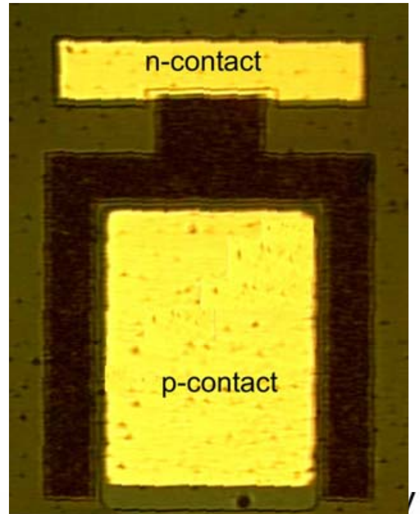
Seebeck (300K): p-type

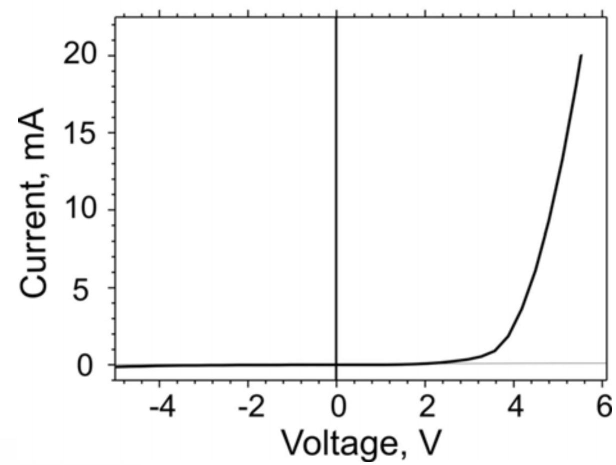
This is the first observation of p-conductivity by Hall effect in MBE-grown $Al_xGa_{1-x}N$ with x>0.3

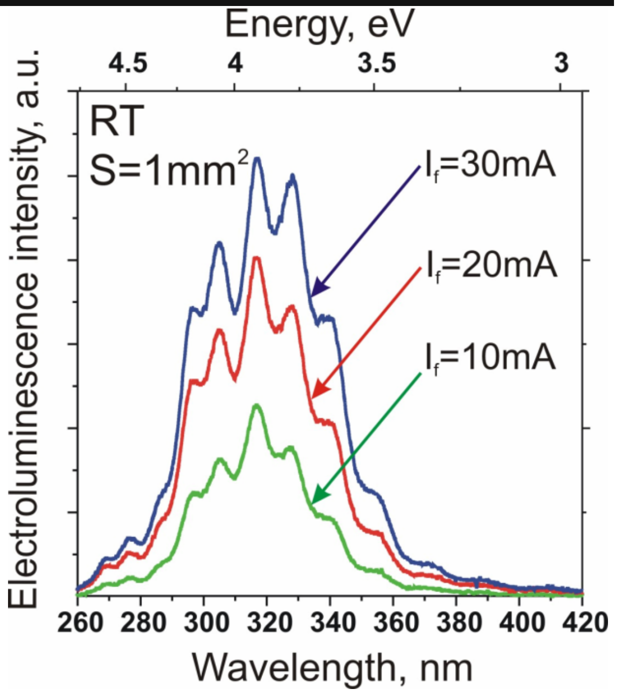
Komissarova et al., Montreux, 2008, pss(c) 6, S466 (2009)

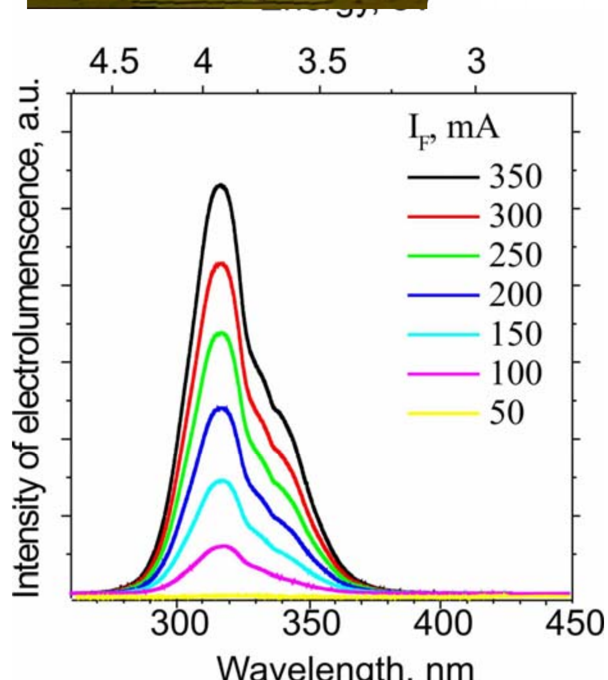
Design and characteristics of UV LED







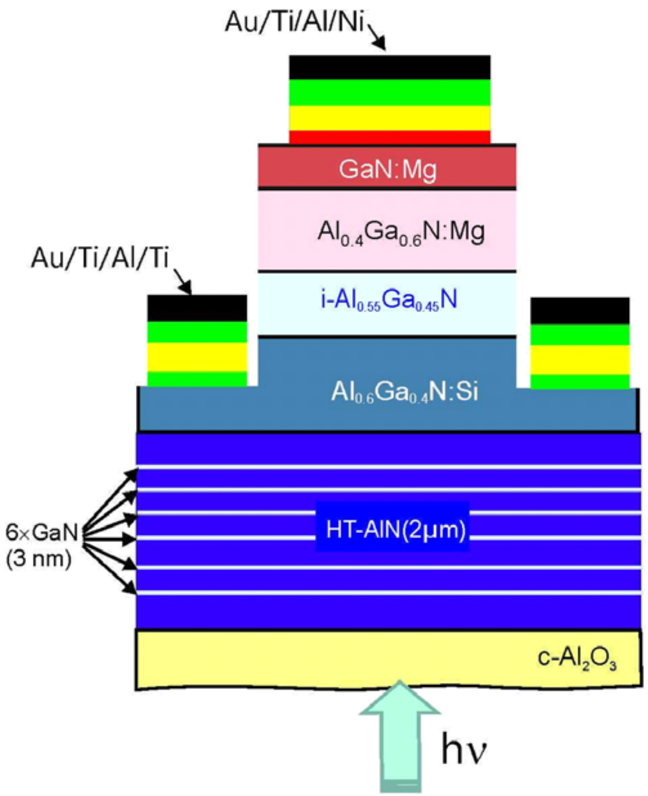




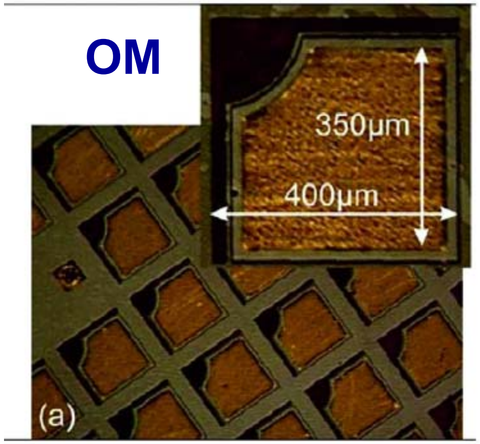
λ = 300-350 нм

P_{out}~ 0.5 мВт

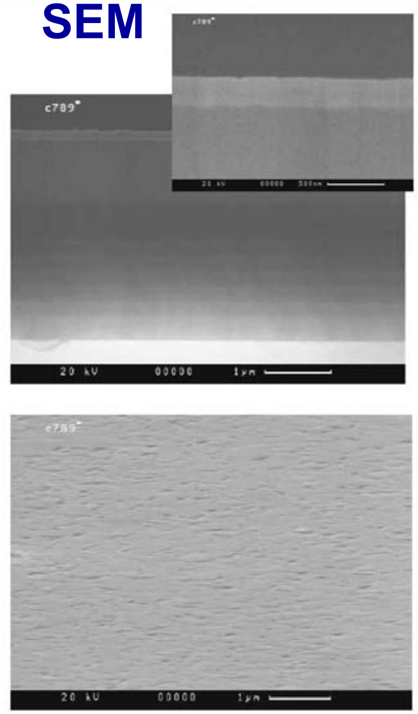
Development of solar-blind p-i-n UV-photodiode

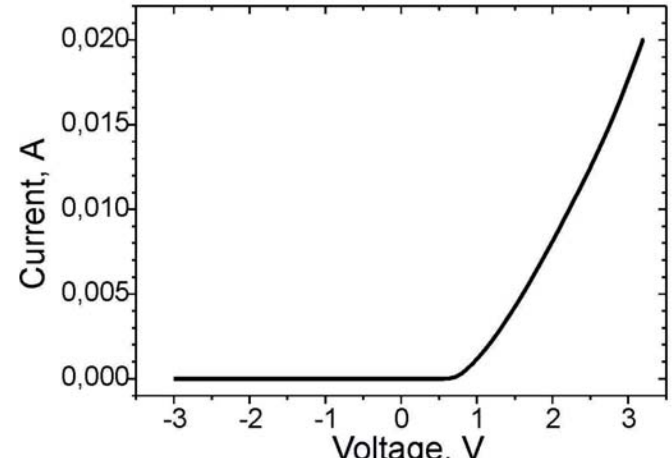


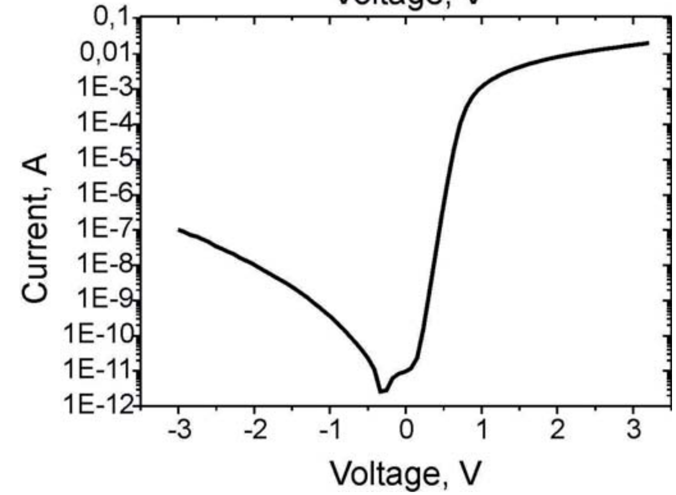
OM



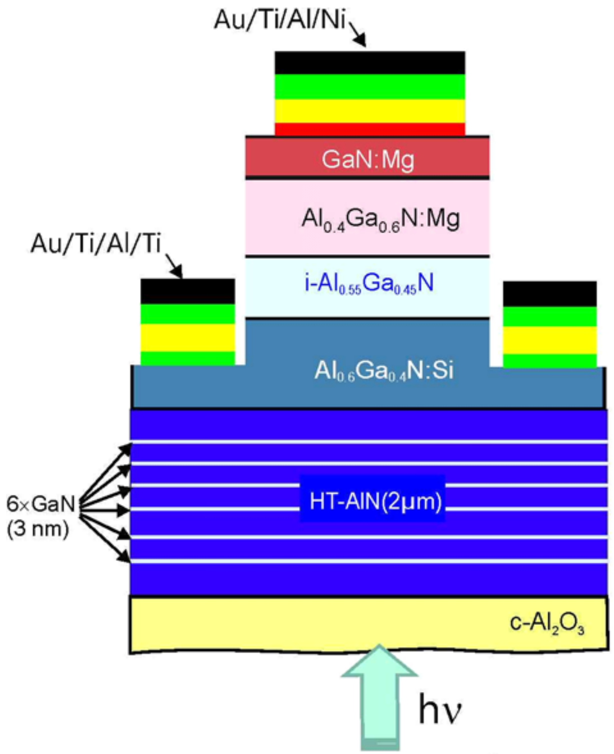
SEM

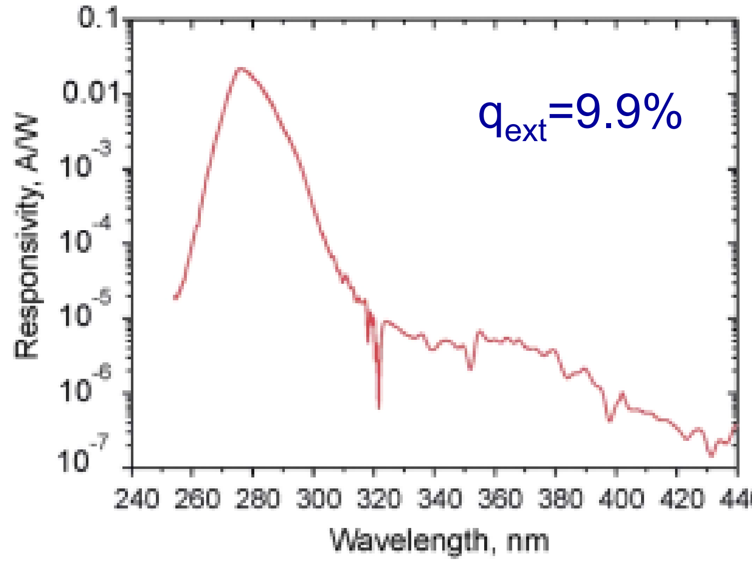




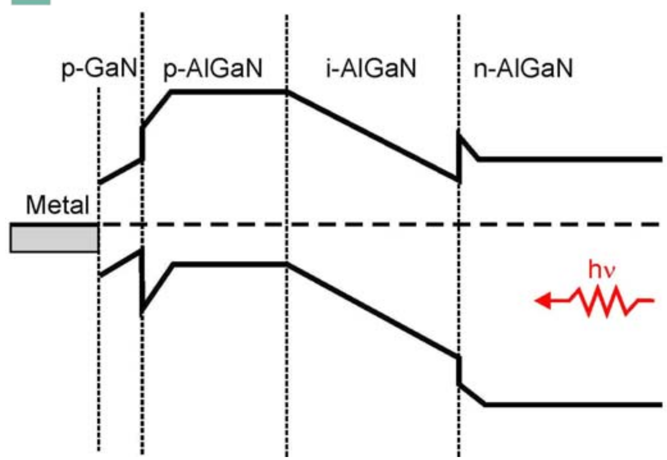


Manufacturing both Schottky and p-i-n UV-photodiodes with the different level of Mg-doping





[Mg]= $6{\cdot}10^{18}$-$2{\cdot}10^{19}$cm^{-3}



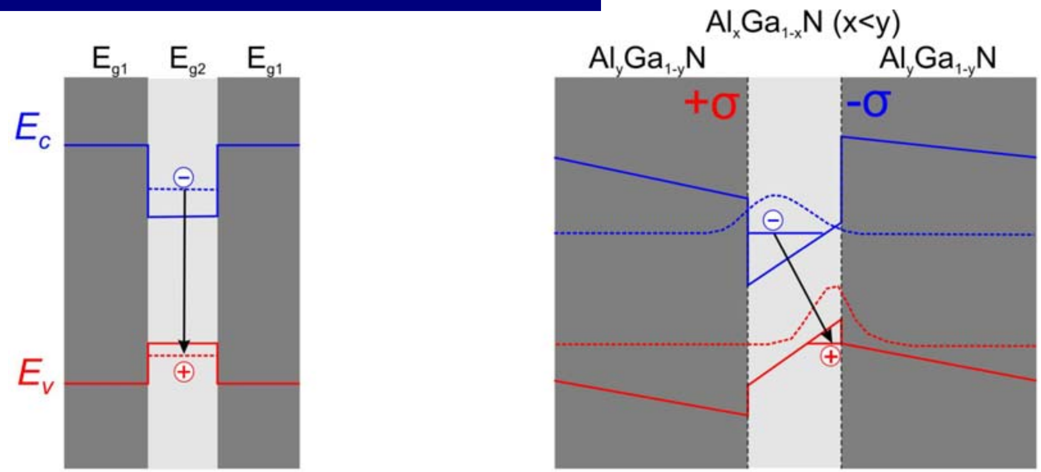
Conclusions

- Advanced PA MBE growth technology of several-micron-thick AlN buffer layers with atomically-smooth and droplet-free surface morphology on c-Al_2O_3 substrates has been developed, which employs pulsed supplied Al-flux under the quantitative control by laser reflectometry
- 2D-3D phase diagram of PA MBE of $Al_xGa_{1-x}N$ epilayers (x=0.2-1) on c-Al_2O_3 substrates under the group III-rich conditions has been elucidated and substrate-temperature modulated epitaxy has been proposed to avoid Ga droplet formation.
- The most optimum combination of GaN interlayer parameters to maintain the 2D and cracking-free morphology of GaN/AlN buffer layers is as follows: mixed 2D-3D growth mode (streaky-dotty RHEED pattern), thickness of about 3nm, and interlayer spacing above 250 nm. TEM analysis has exhibited positive effect of the GaN insertions providing (i) inclination of both screw and edge TDs and (ii) blocking of vertical propagation of TDs due to bending in c-plane.
- Threading dislocations reduction and filtering using HT-MEE nucleation layer, optimized ultra-thin GaN interlayers in AlN buffer layer and strained AlN/AlGaN SL resulted in reduction of TD density in the active region grown atop down to 1.5×10^8 and 3×10^9 cm^{-2} for screw and edge types, respectively. Lowest reported values for PA MBE.
- AlGaN SQW and MQW structures have been fabricated by SMDA technique, which demonstrate RT PL within the wavelength range of 230-320 nm, PL decay time around 1 ns up to RT and intensity reduction just by 2.5 times from 77 to 300K.
- Pseudomorphic growth of AlxGa1-xN/AlN (x>0.5) heterostructures has been implemented on c-Al_2O_3 substrates to suppress transition from TE to TM polarization of photoluminescence as the wavelength decreases.
- Advanced AlGaN SQW and MQW structures grown by PA MBE on c-sapphire demonstrate optically-pumped stimulated emission within the 255-300 nm wavelength range with typical threshold power densities of 240-480 kW/cm^2 (295K) and TE polarization. The lowest laser threshold power density achieved at 289 nm was 150 kW/cm^2.
- Mid-UV LEDs and solar-blind photodiodes have been demonstrated.

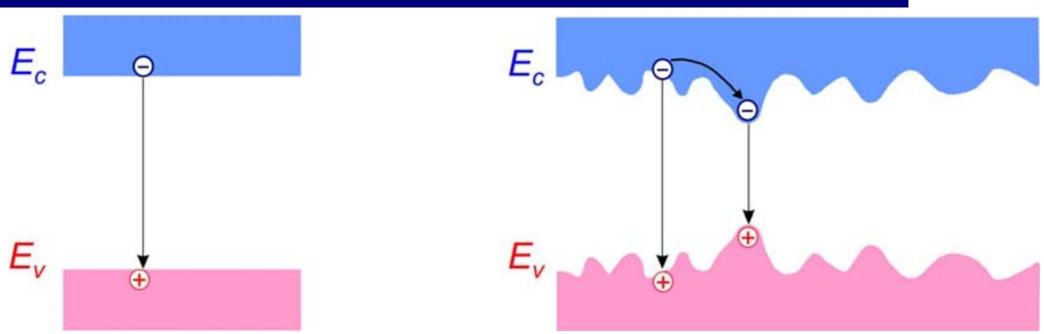
Thank you for the attention

Main effects determining the light emission mechanisms in AlGaN-based (0001) QWs

Quantum –confined Stark effect



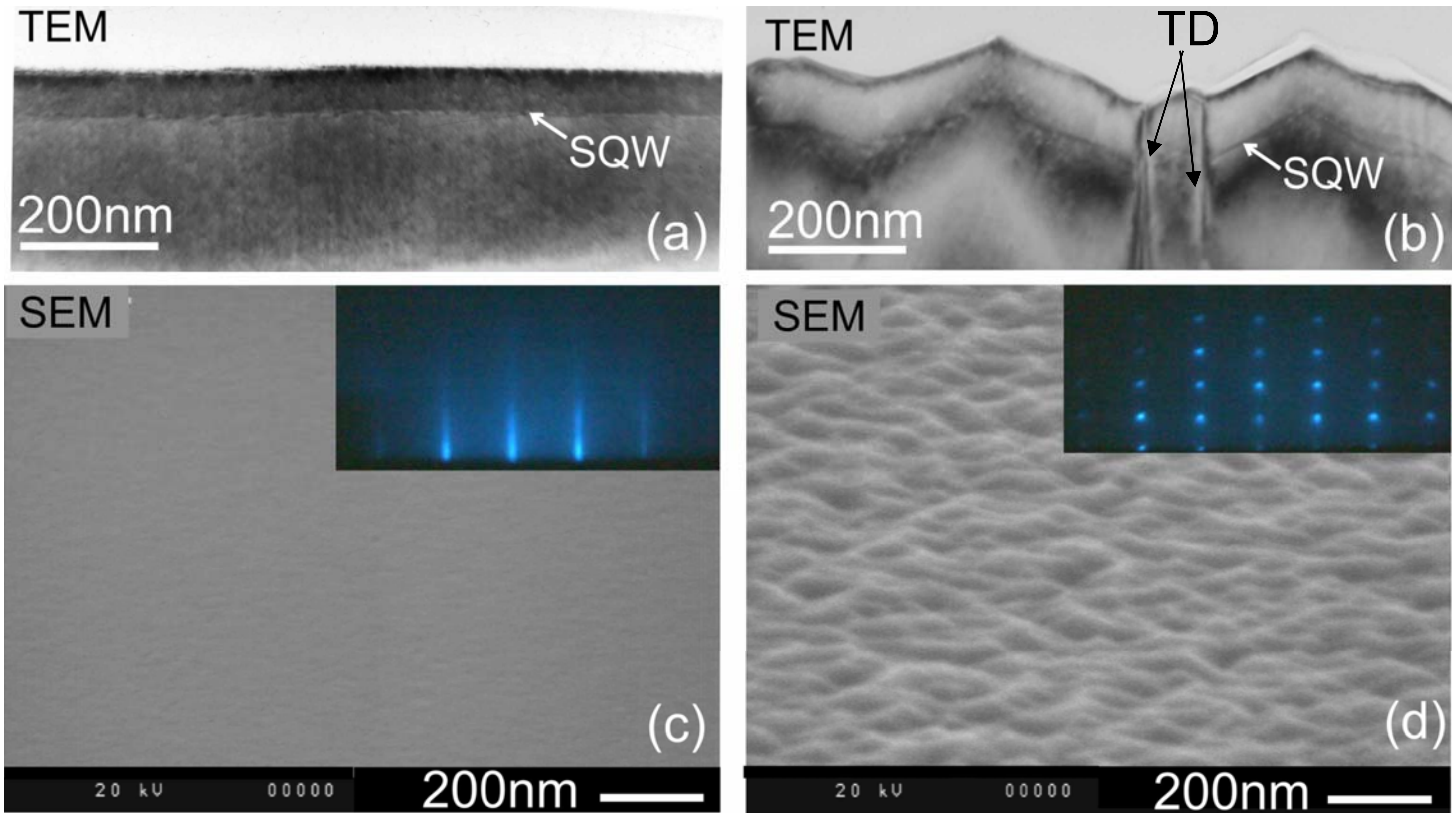
Localized states due to potential fluctuations *(compositional inhomoheneities)*



Varied technological parameters:

- Al-composition in
  Barrier layers: y=0.4-0.6
  QWs: x=0.3-0.5
- Thickness of QW: 2.5-6nm
- Morphology: plane vs corrugated
- Growth temperature: 670-730°C

6-nm-thick $Al_{0.3}Ga_{0.7}N/Al_{0.4}Ga_{0.6}N$ SQW structures with plane and corrugated morphology grown by SMDA

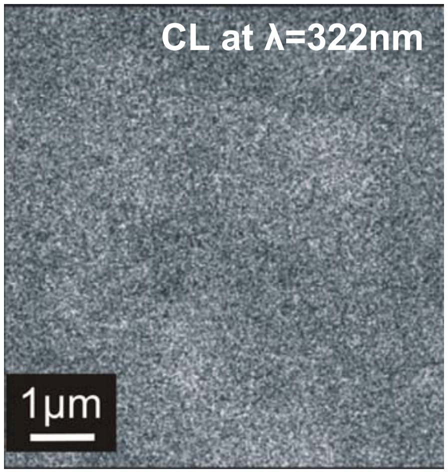


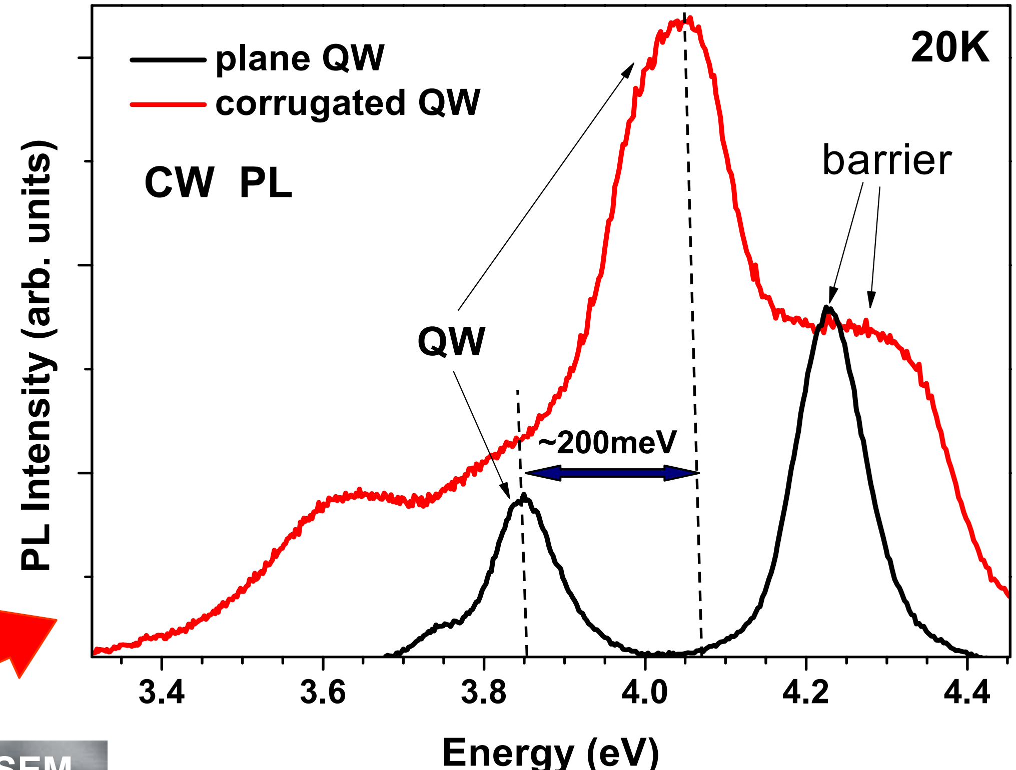
2D AlN buffer growth mode 3D AlN buffer growth mode

For both structures N_D~10^{10} cm^{-2}

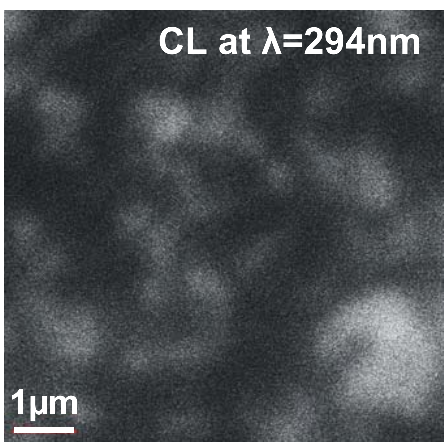
CL images and cw-PL spectra of the AlGaN SQW structures with different morphologies

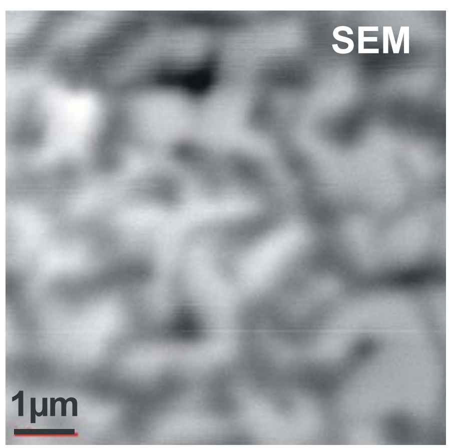
Plane QW morphology





Corrugated QW morphology





- **4 times stronger PL emission in the corrugated QW at 20K**
- **200 meV red shift of PL peak in planar QW**

Suppressed QCSE?

Shevchenko et.al., Semiconductors, 46, 8, 1022 (2012)