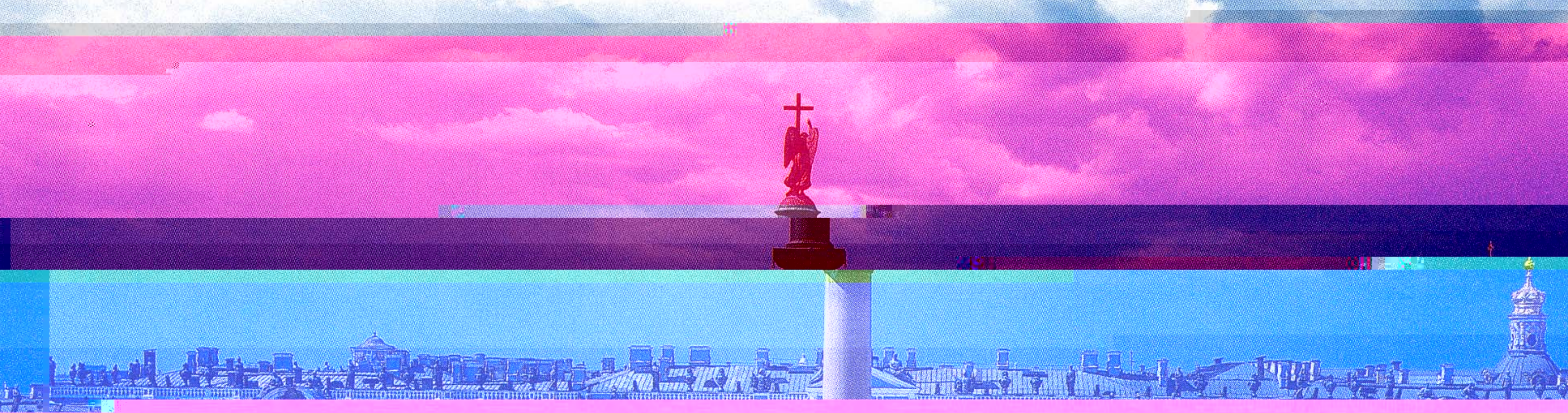
SWEDEN
FINLAND
NORWAY
RUSSIA
UKRAINE
KAZAKHSTAN
MONGOLIA
FRANCE
SPAIN
TURKEY
IRAQ
IRAN
CHINA
JAPAN



Mariinskii theater

Pushkin

Hermitage

Pavlovsk

Russian Museum

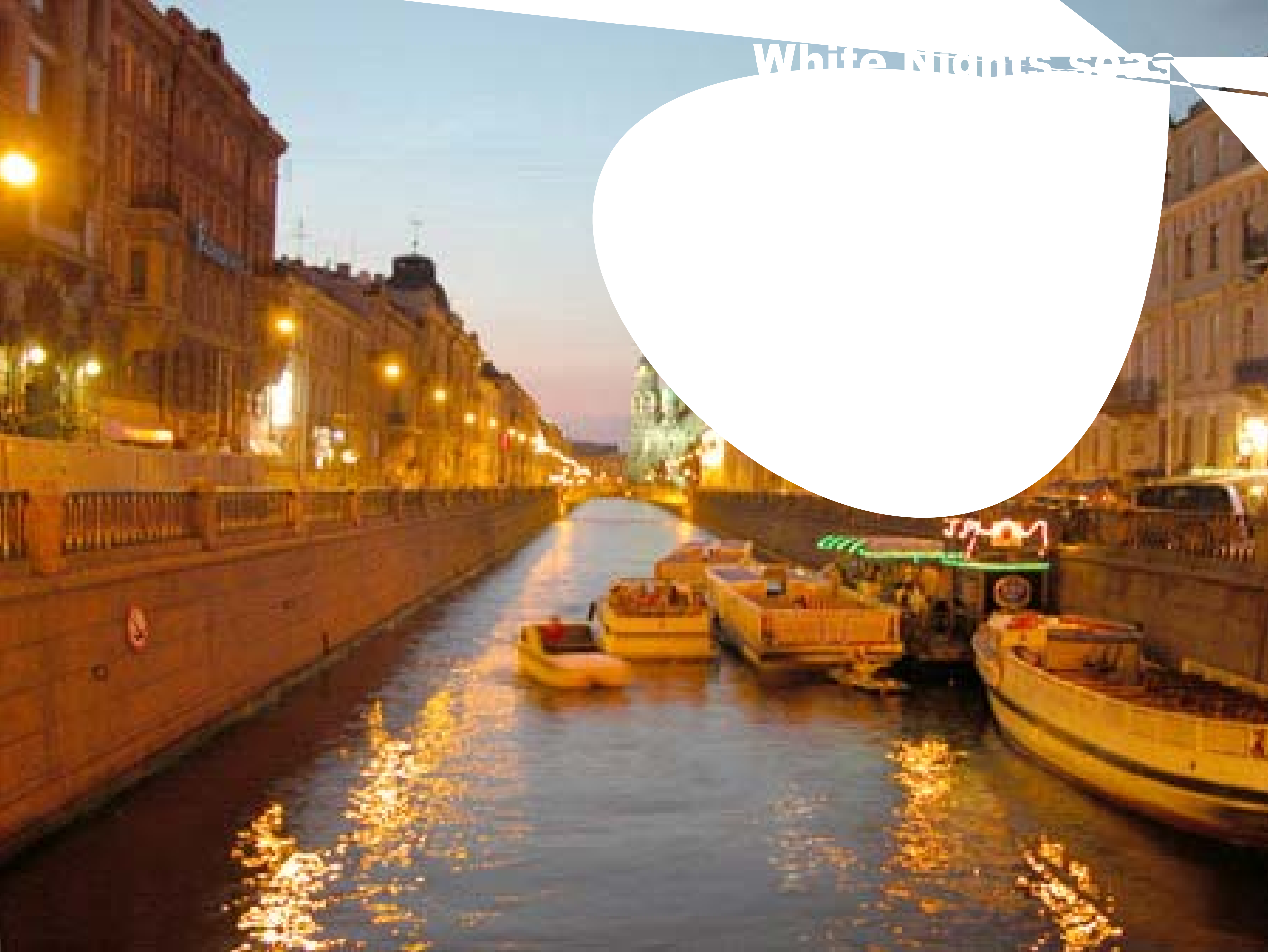
Peterhof

Palaces and Squares of St. Petersburg

Parks and Palaces of St. Petersburg Suburbs

Treasures of A

White Nights seas



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 :
L. D. Landau, P. L. Kapitsa,
I. E. Tamm,

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

Division

Ioffe Institute of RAS

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

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 ( );
- 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 ( );
- hybrid III-V/II-VI structures with a heterovalent interface in the active region for mid-IR applications, solar cells, and spintronics ( );
- 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 ( ).

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

<u>*Acknowledgments*</u>

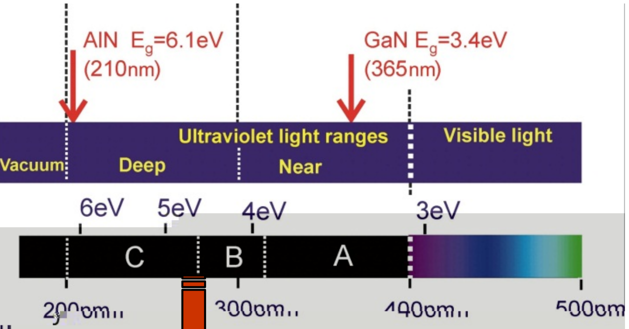
V.N. Jmerik, D.V. Nechaev, T.A. Komissarova, E.A. Shevchenko, A.A. Toropov, A. A. Sitnikova, V.V. Ratnikov, M.A. Yagovkina

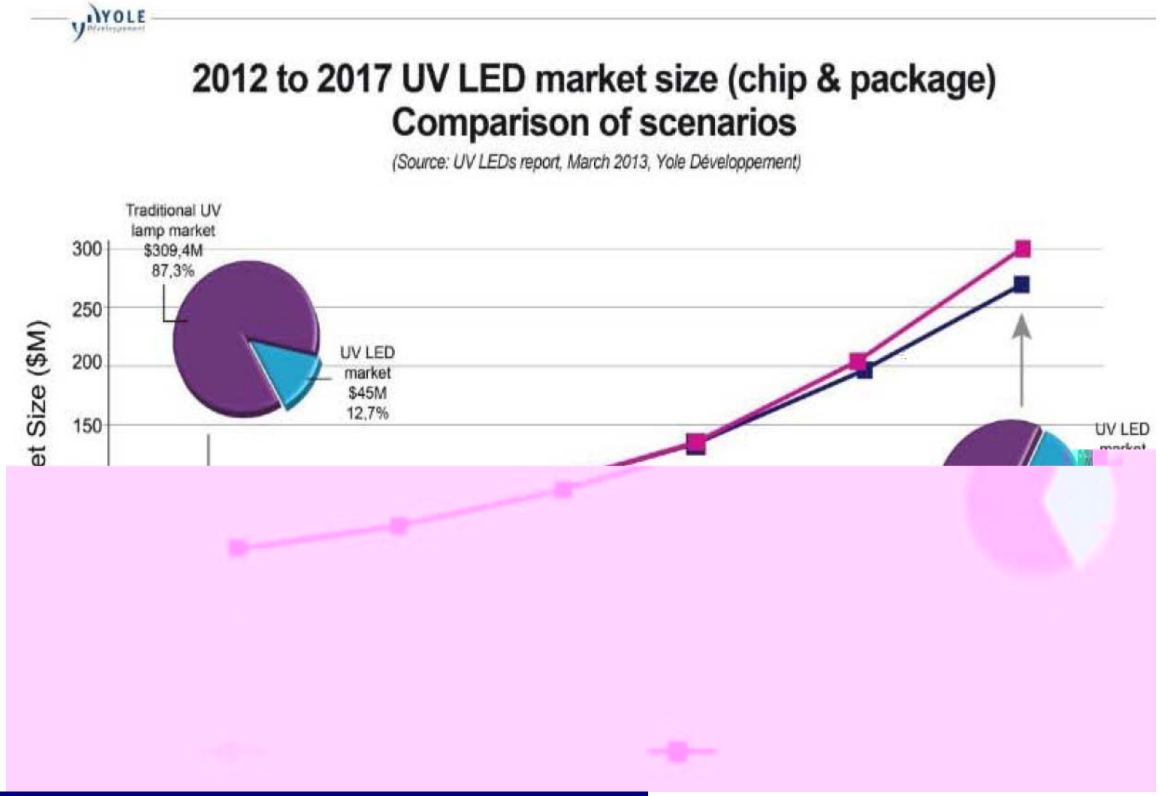
Ioffe Physical-Technical Institute of RAS, Polytekhnicheskaya 26, St. Petersburg 194021, Russia

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

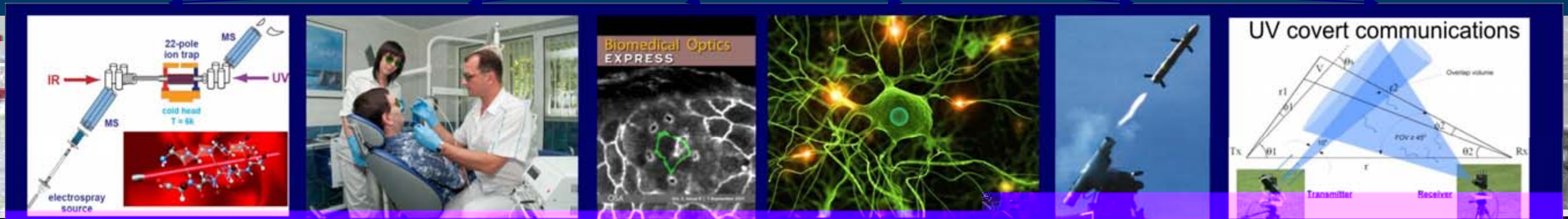
Stepanov Institute of Physics of NAS Belarus, Independence Ave. 68, Minsk 220072, Belarus

- 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)
-

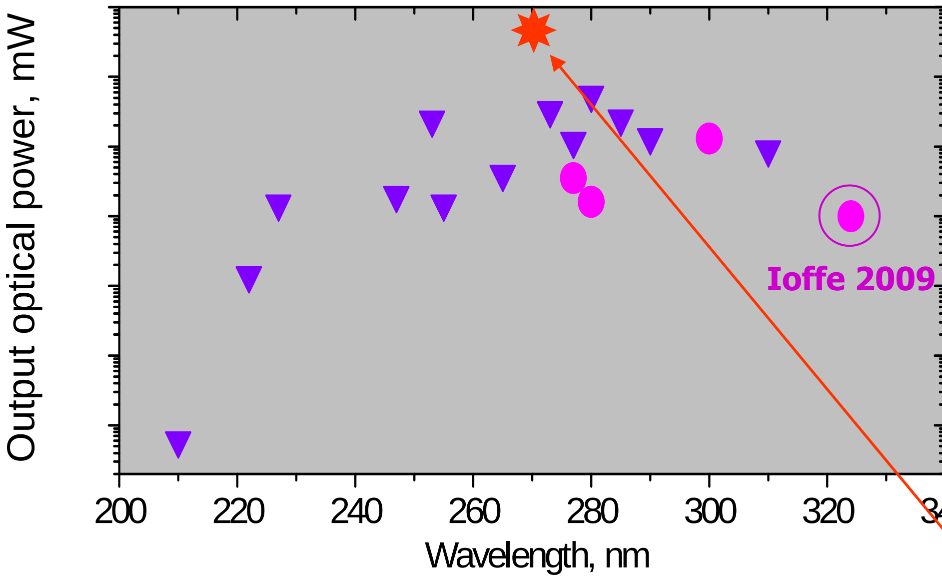


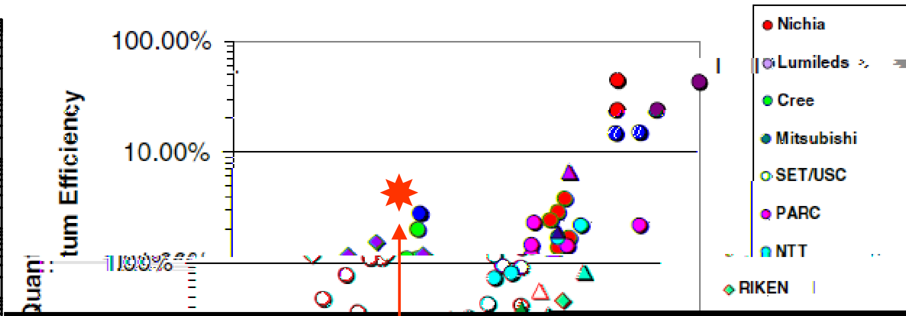


Main applications of UV-lasers



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





[redacted]

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

MOCVD ▼

MBE ●

SET	Crystal IC
USC	NU
Riken	NTT
SNL	TU

BU

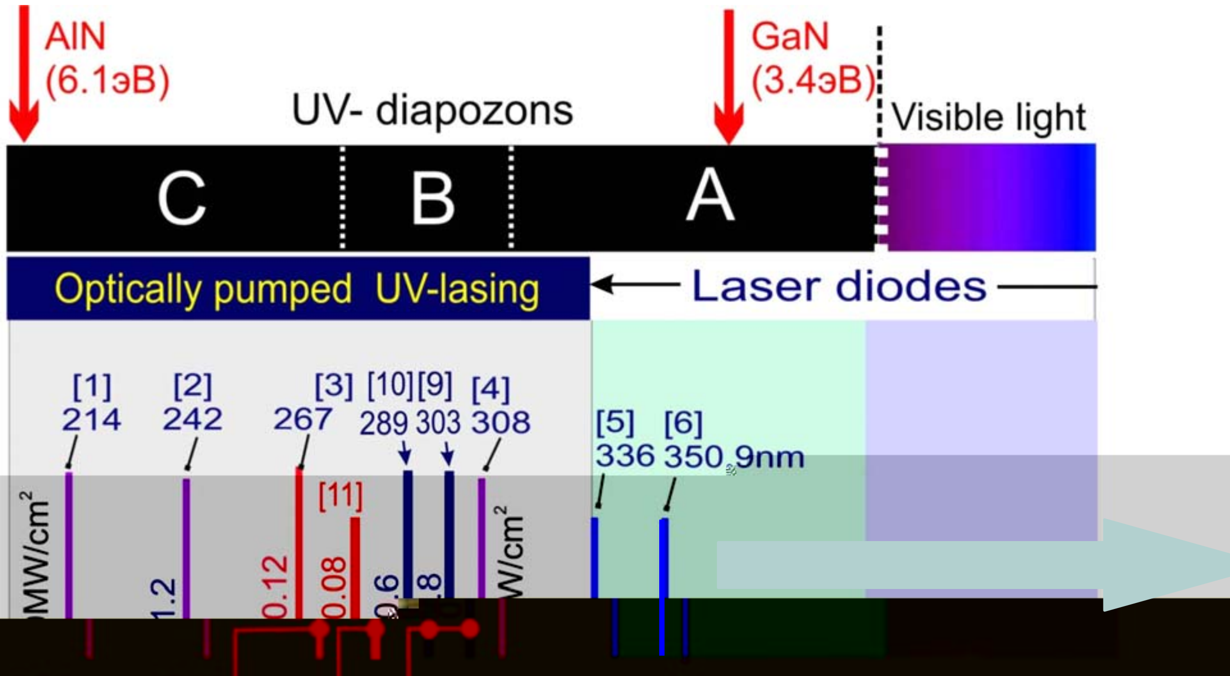
TTU

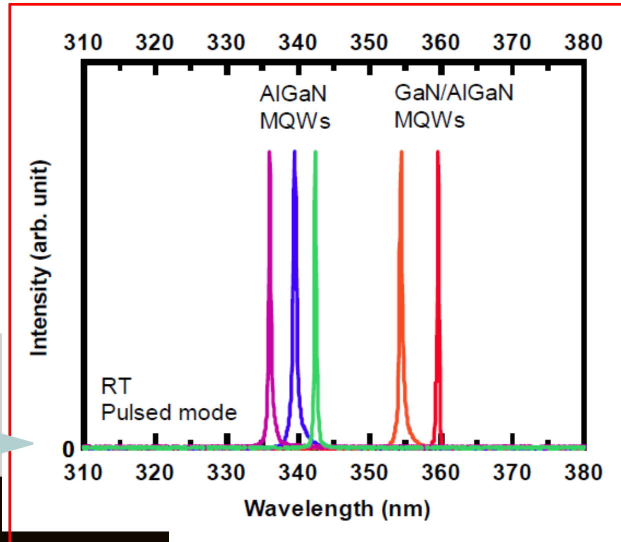
ARL

IOFFE, *Stepanov*

Pseudomorphic single-chip UV LED
:
λ = 271nm, P_{out} = 60mW CW,
EQE = 4.9%, WPE = 2.5%

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

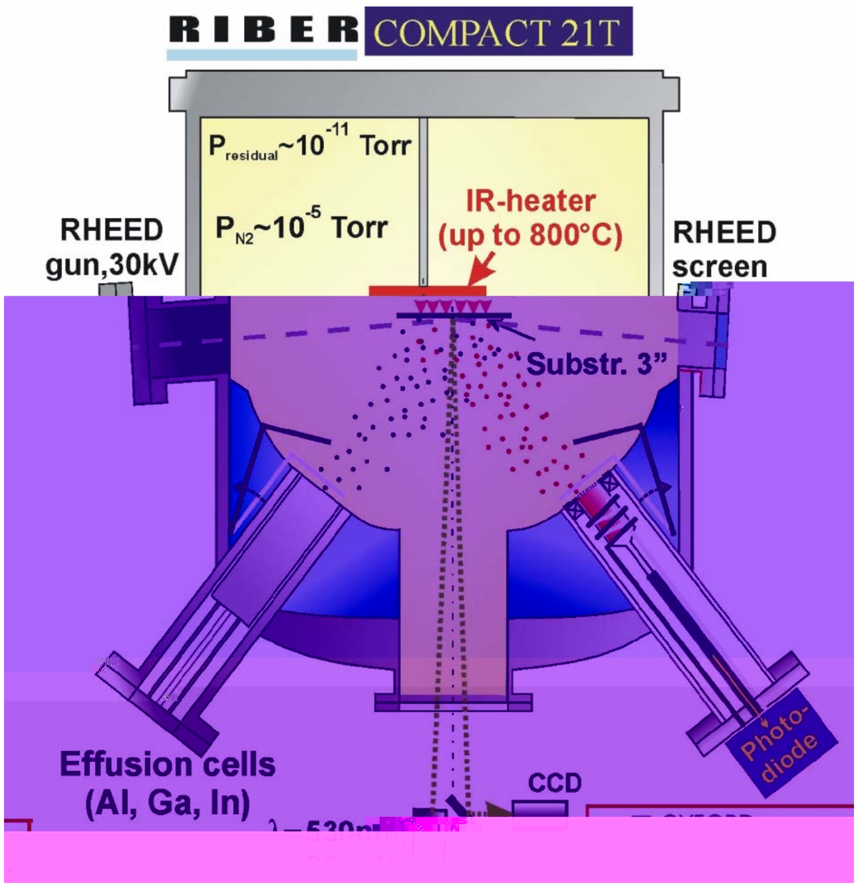




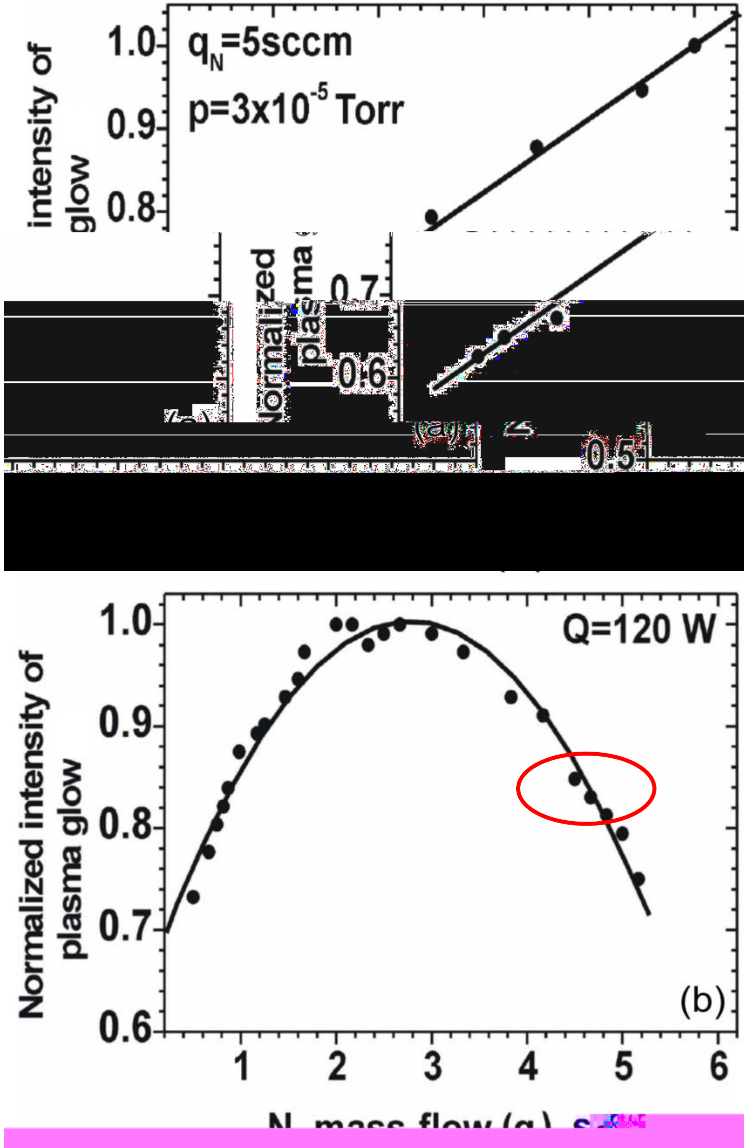
AlGaN-based Laser Diodes (MOCVD):

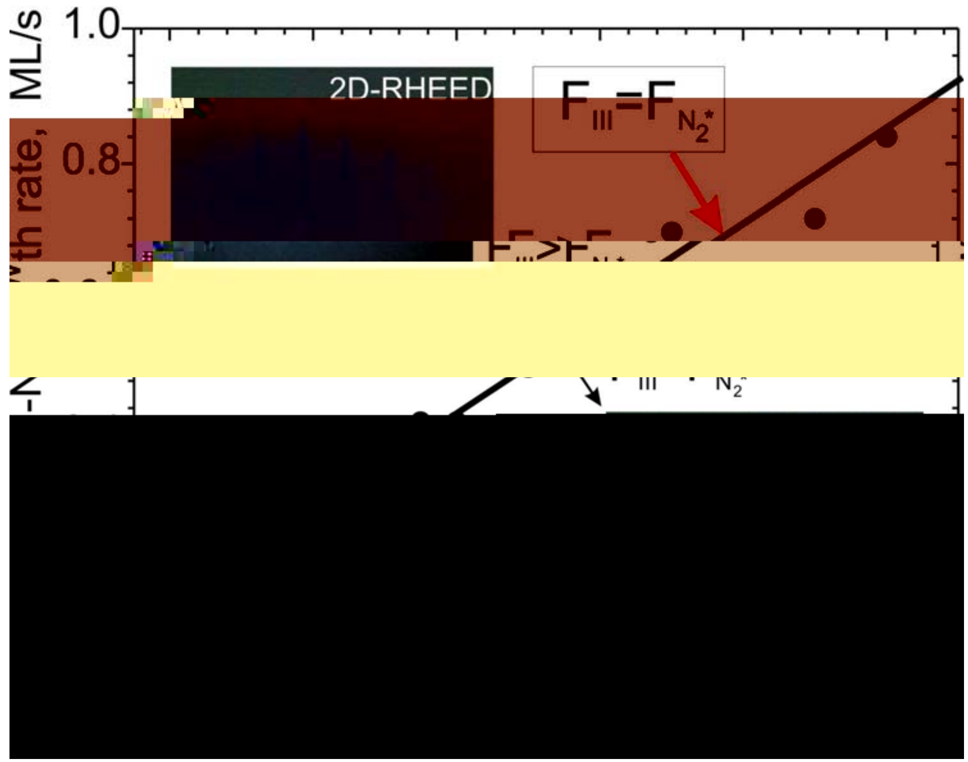
[6] Iida et al., .

- 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



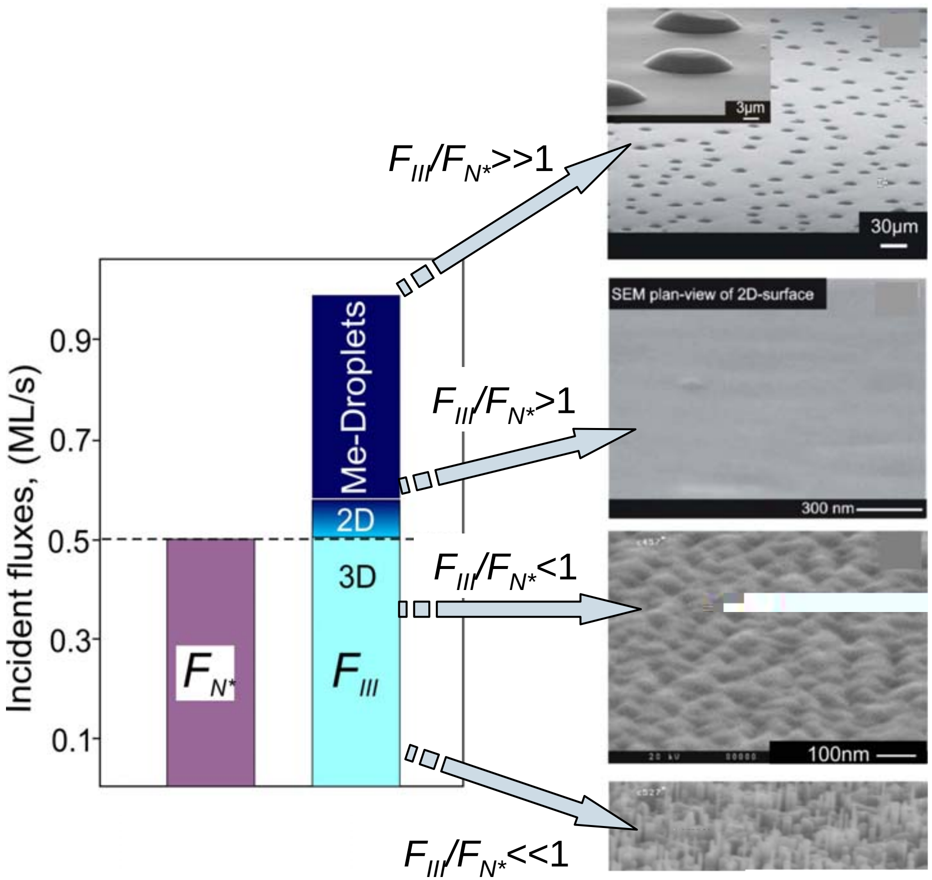
- High vacuum growth conditions
  - → *No parasitic gas-phase reactions ($Al+NH_3$)*
- Hydrogen- and carbon-free growth environment
  - → *Easy Mg doping without post-growth treatment*
- Rapid change of growth atom fluxes
- Low growth temperature (700-800°C)
  - *+ Sharp interfaces with atomic resolution*
  - *– 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

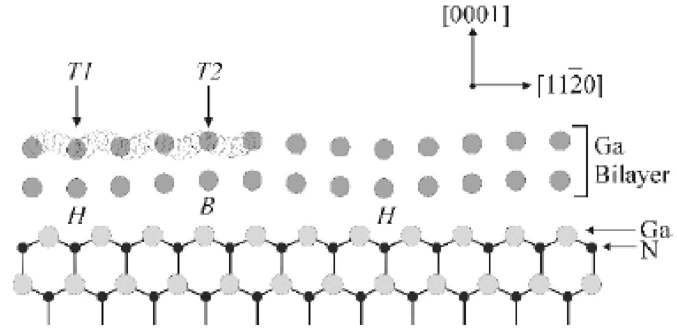




Jmerik et al. , Techn. Phys. Lett. 33,333 (2007)

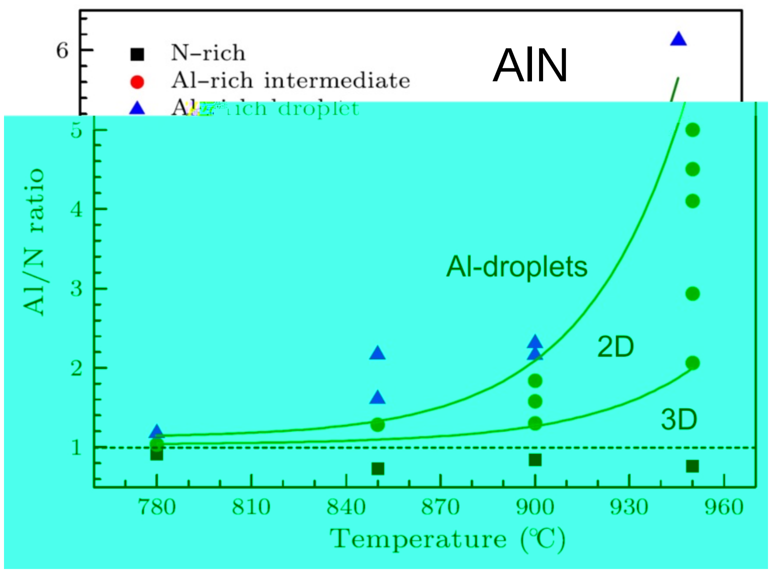
Ga-rich PA MBE of GaN



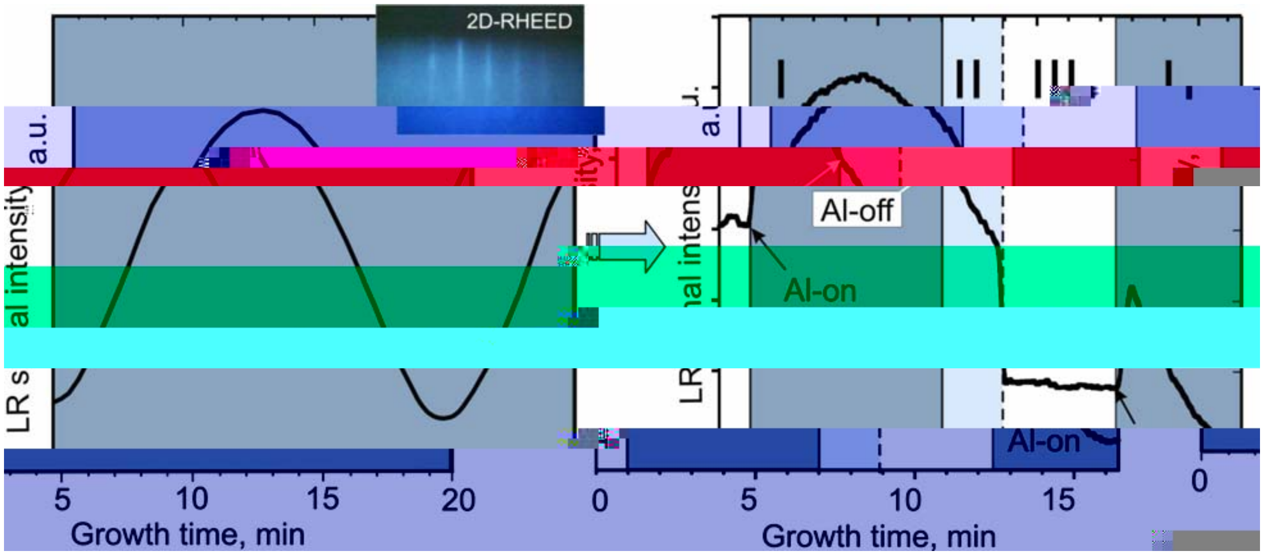


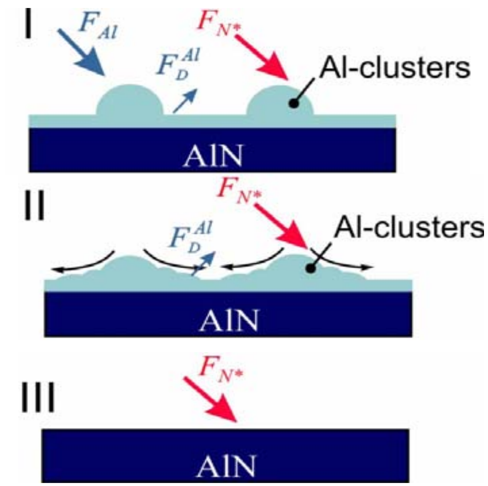
Heying et al., J. Appl. Phys. 88, (2000), 4.

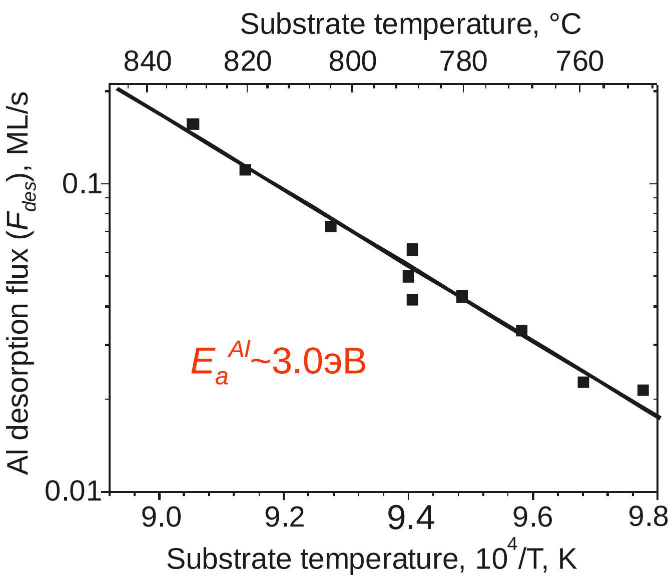
Northrup et al., Phys.Rev.B, 61, (2000), 9932.



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







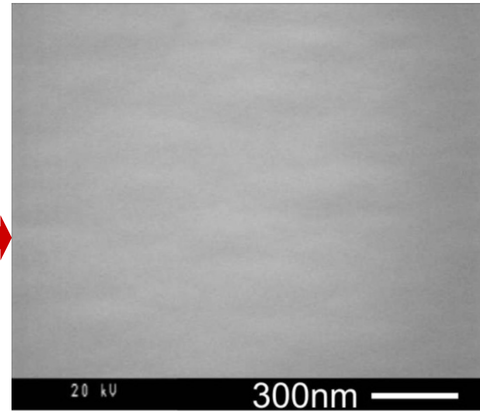
$$F_D^{Al}(T_S) \quad \frac{F_{Al} \quad t_I}{t_I \quad t_{II}(T_S)} \quad F_{N*}$$

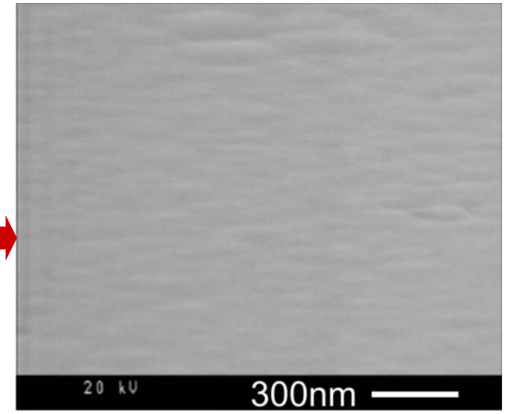
$$F_D^{Al} \quad A \ \exp \quad \frac{E_a^{Al}}{kT_S}$$

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

III-polar AlGaN(0001)

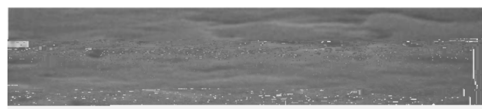
Buffer layer/substrate	***Al-content***
c-Al_2O_3	0.2<x<1
3 m-GaN(0001)-MOCVD	0 <x< 1
300nm-AlN(0001)-PA MBE	0 <x< 1

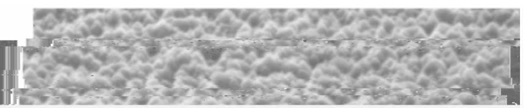




N-polar AlGaN($000\bar{1}$)

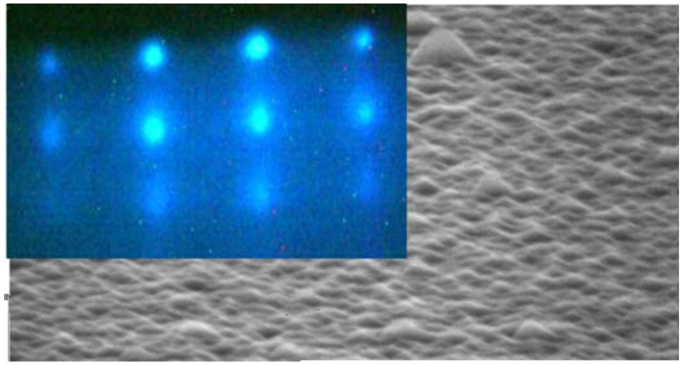
Buffer layer/substrate	*Al-content*
c-Al_2O_3	0 <x< 0.2
500nm-GaN($000\bar{1}$)-PA MBE	0 <x< 1





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

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



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

$F_{III}/F_N=0.9$

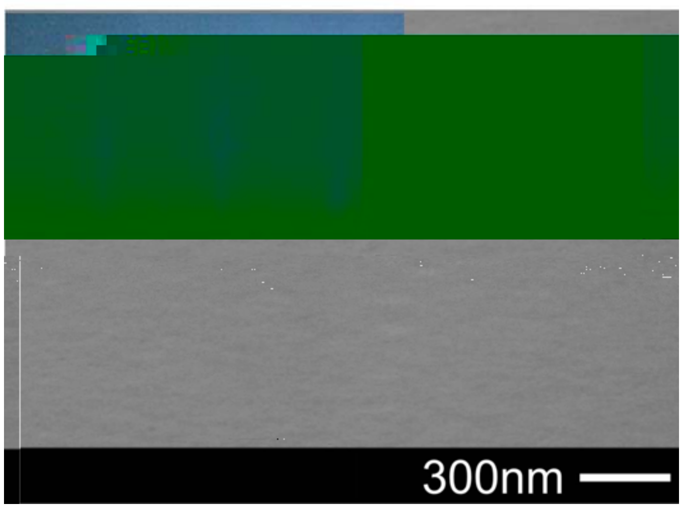
$T_S=700°C$

$F_N=0.5ML/s$

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

- Substrate temperature
- Stress in heterostructures
- Growth rate

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



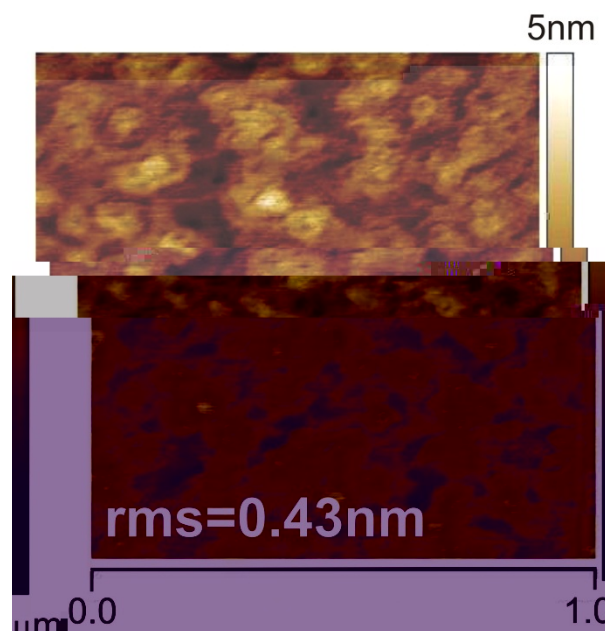
Ga-rich $Al_{0.7}Ga_{0.3}N$

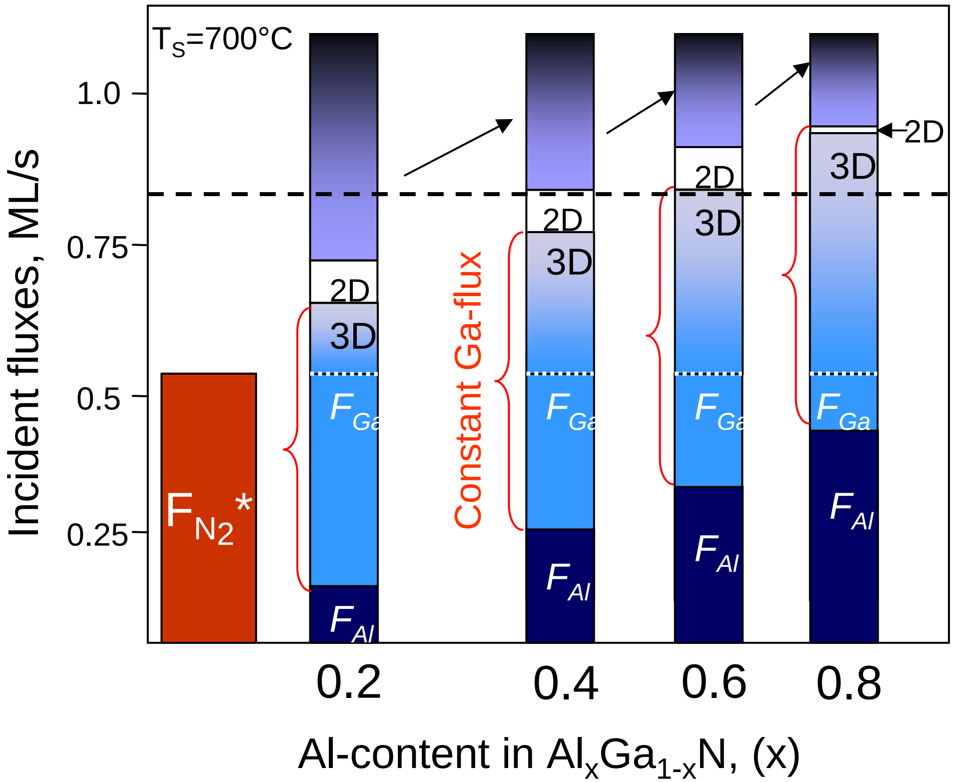
$F_{III}/F_N=1.8$

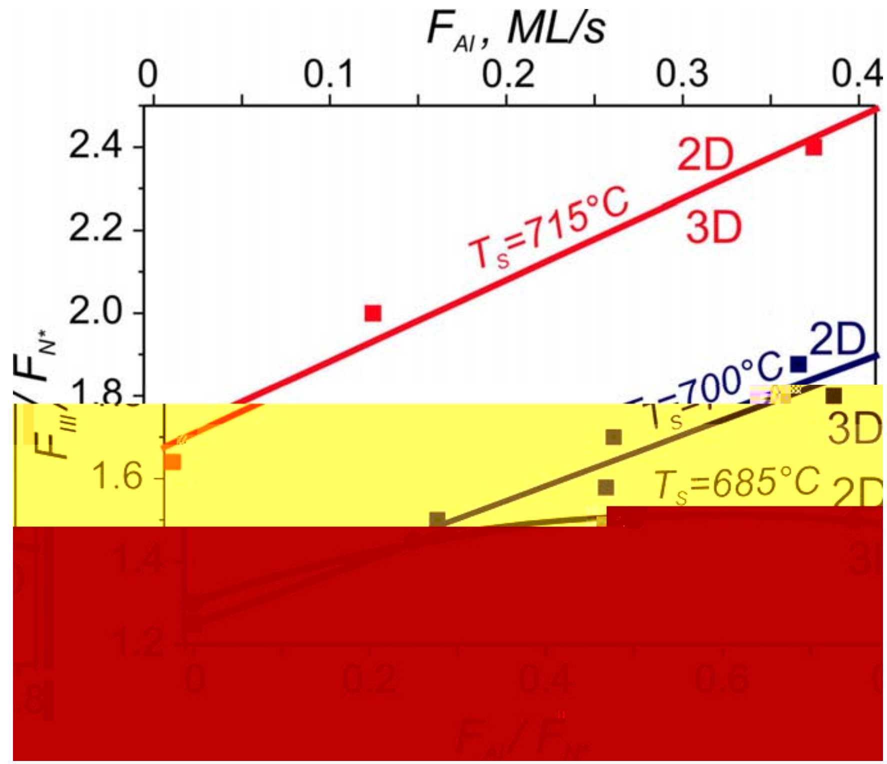
$T_S=700°C$

$F_N=v_g=0.5ML/s$

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







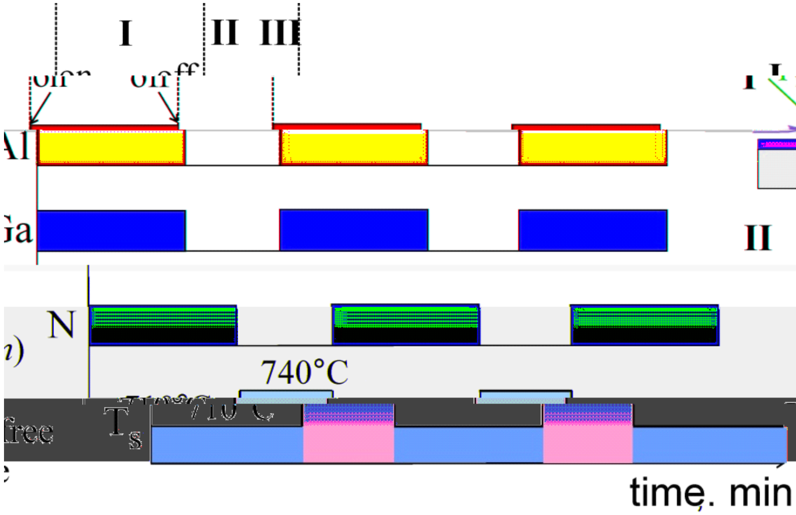
$x = F_{Al} / F_N$
$(x=0.1\text{-}1)$ at $F_{III}/F_{N2}>1$

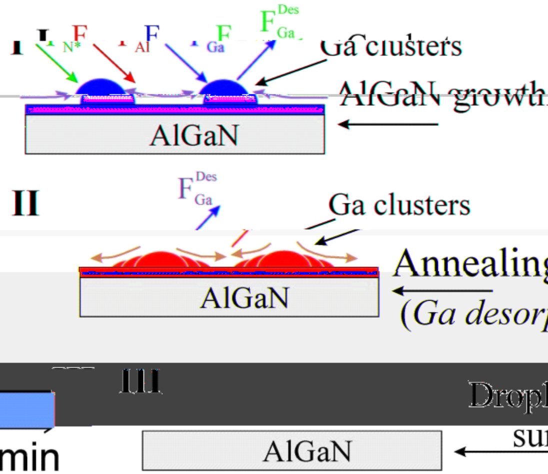
$E_{Al\text{-}N} > E_{Ga\text{-}N}$, $F_D^{Al}=0$

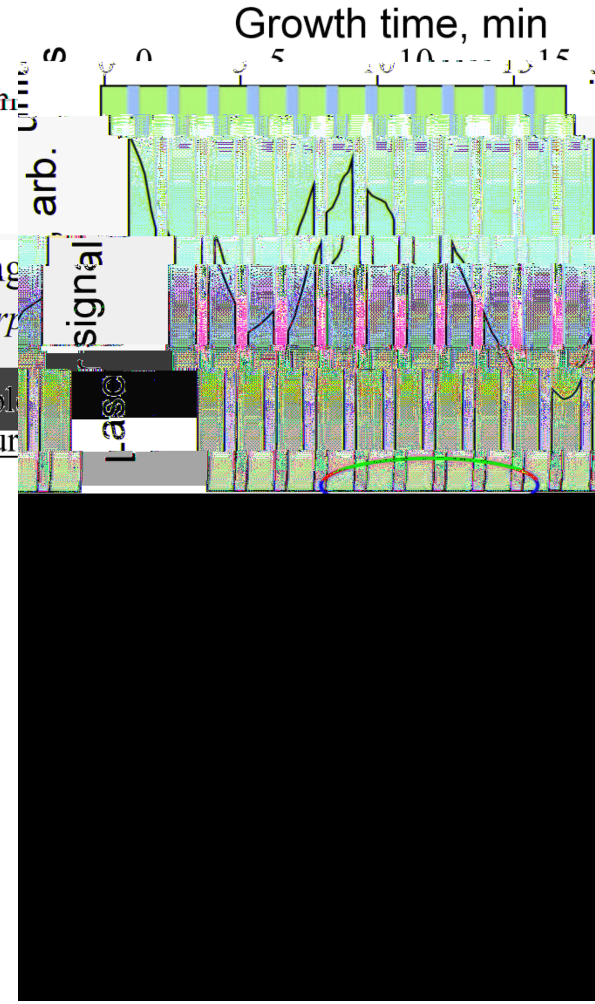
3D → 2D transition occurs at constant F_{Ga}

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

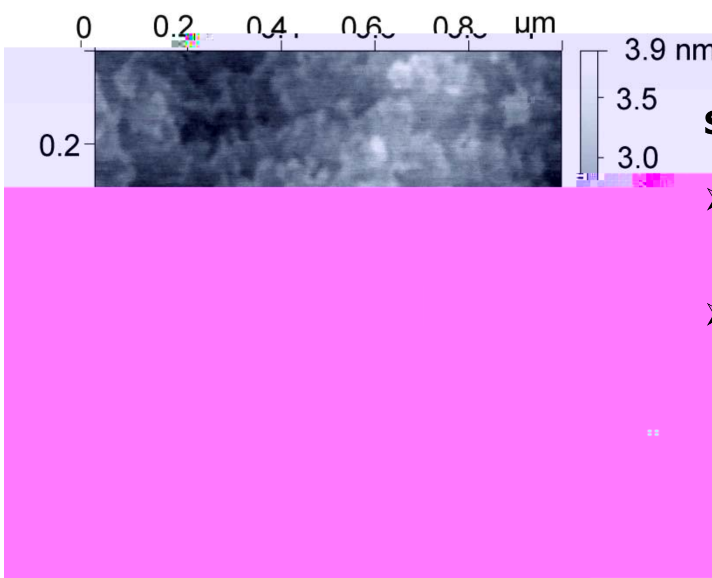
Mizerov et al., JCG, 323, 68 (2011)
Jmerik et al., PSS A 210, 439 (2013)







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



Special cares:

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

by closing the main shutter

- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
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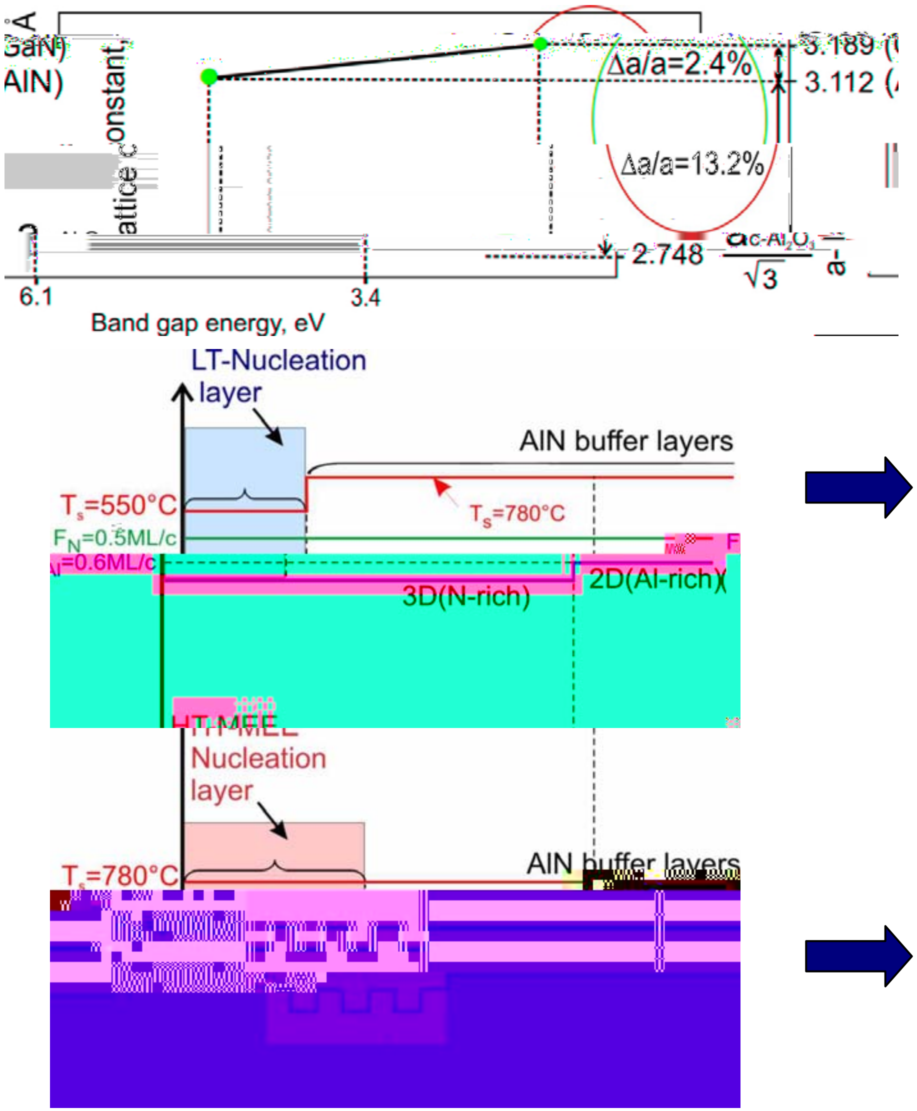
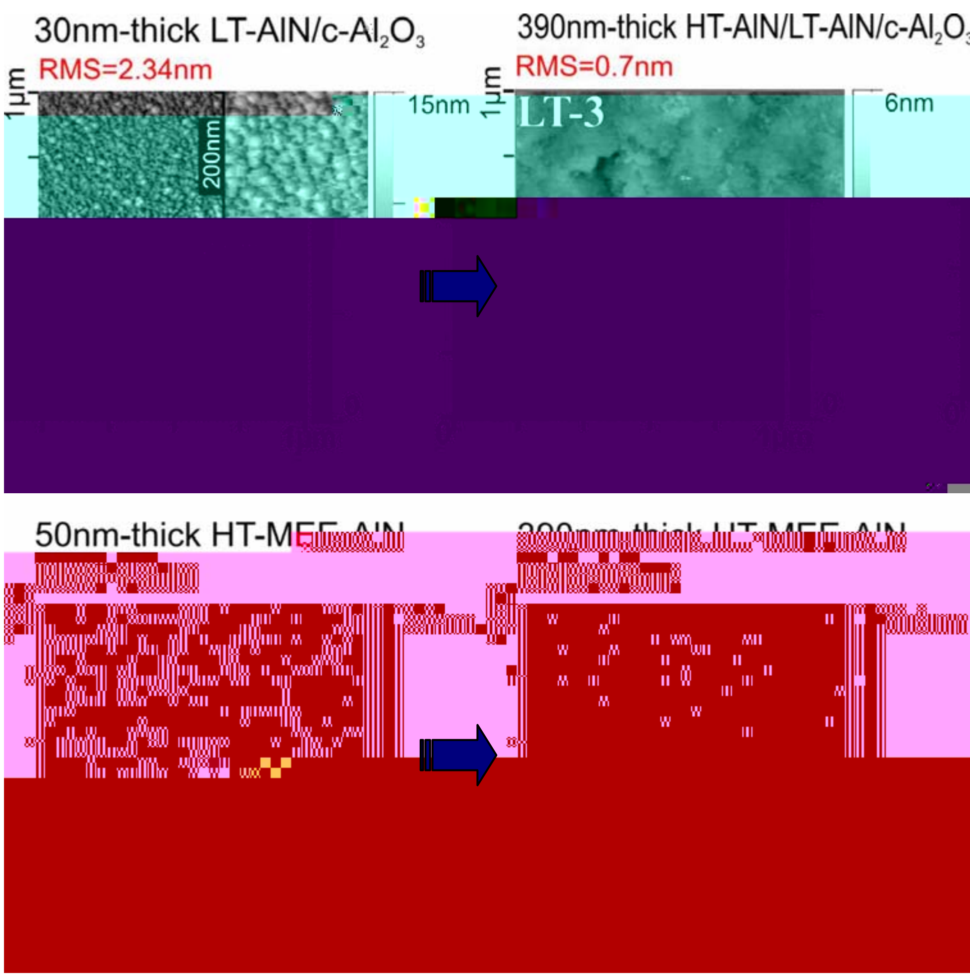


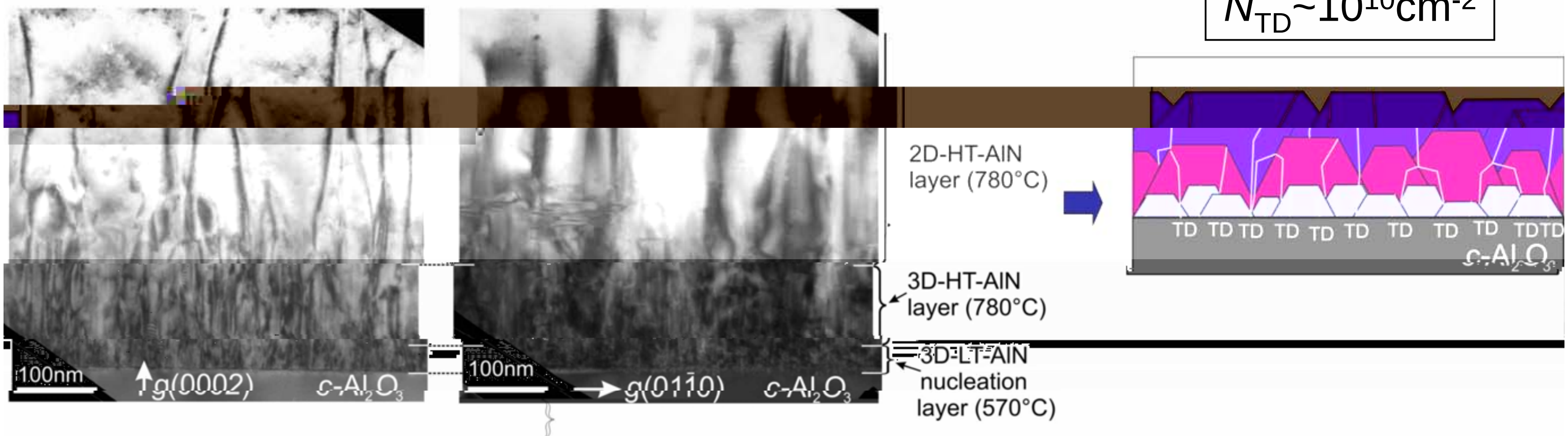


Nechaev et al., MBE-2012, J. Cryst. Growth, online 5 January 2013

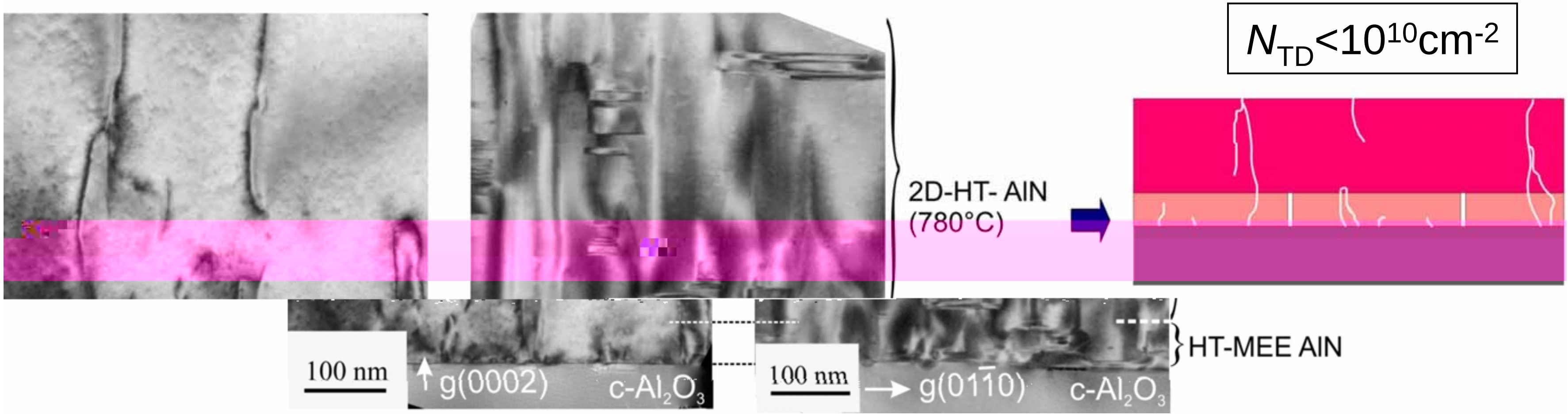
→

screw & mixed　　　　edge

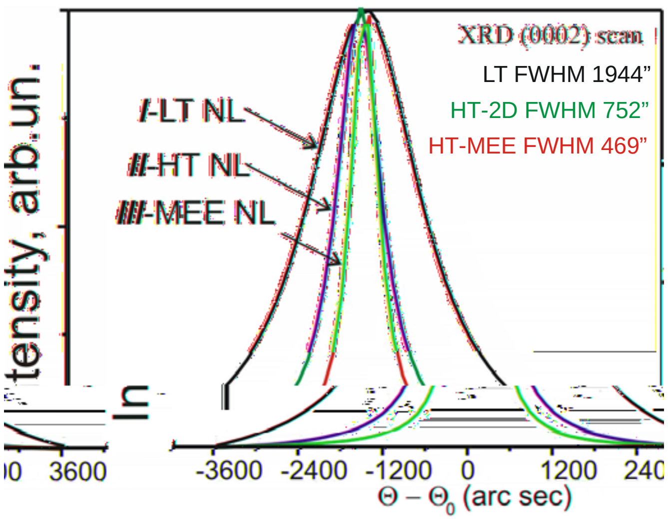
N_{TD}~10^{10}cm^{-2}

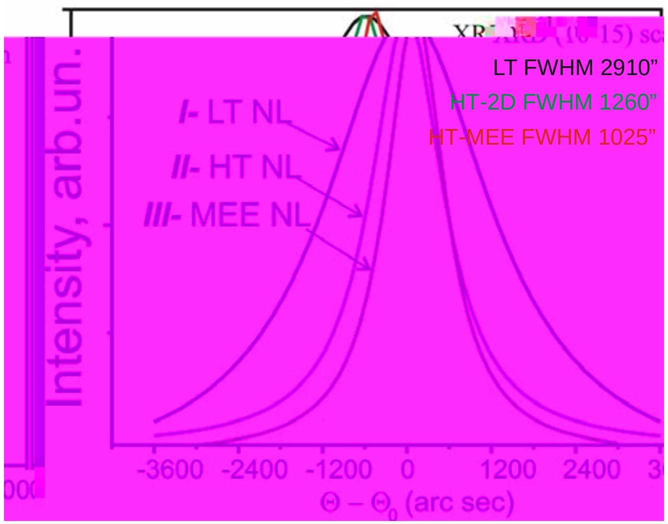


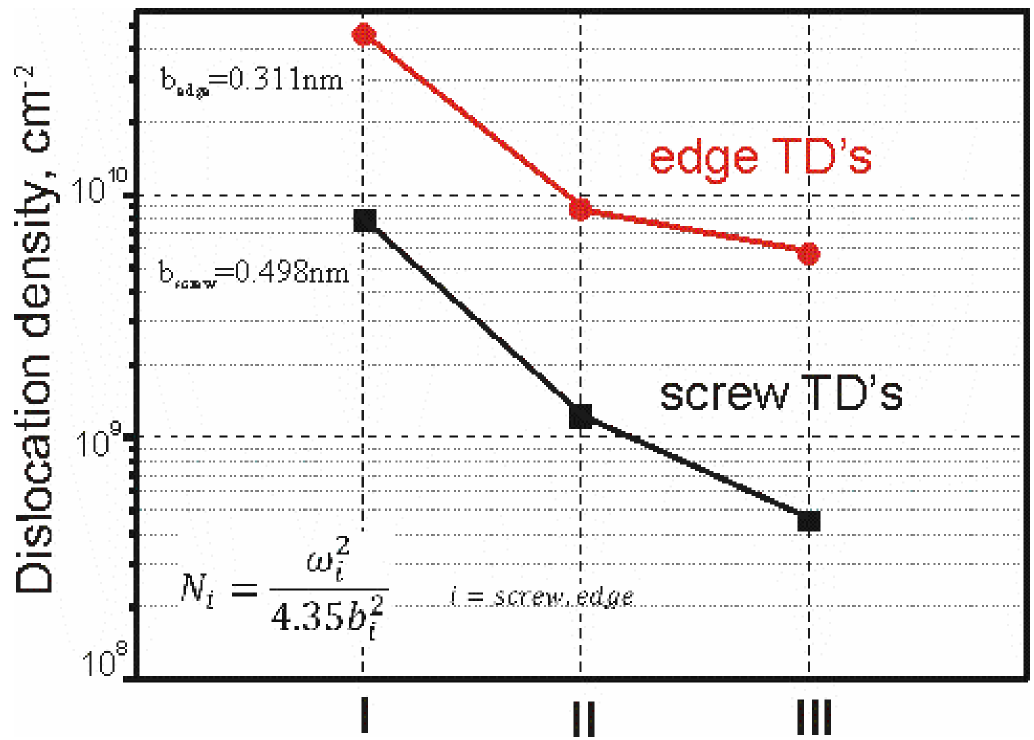
N_{TD}<10^{10}cm^{-2}

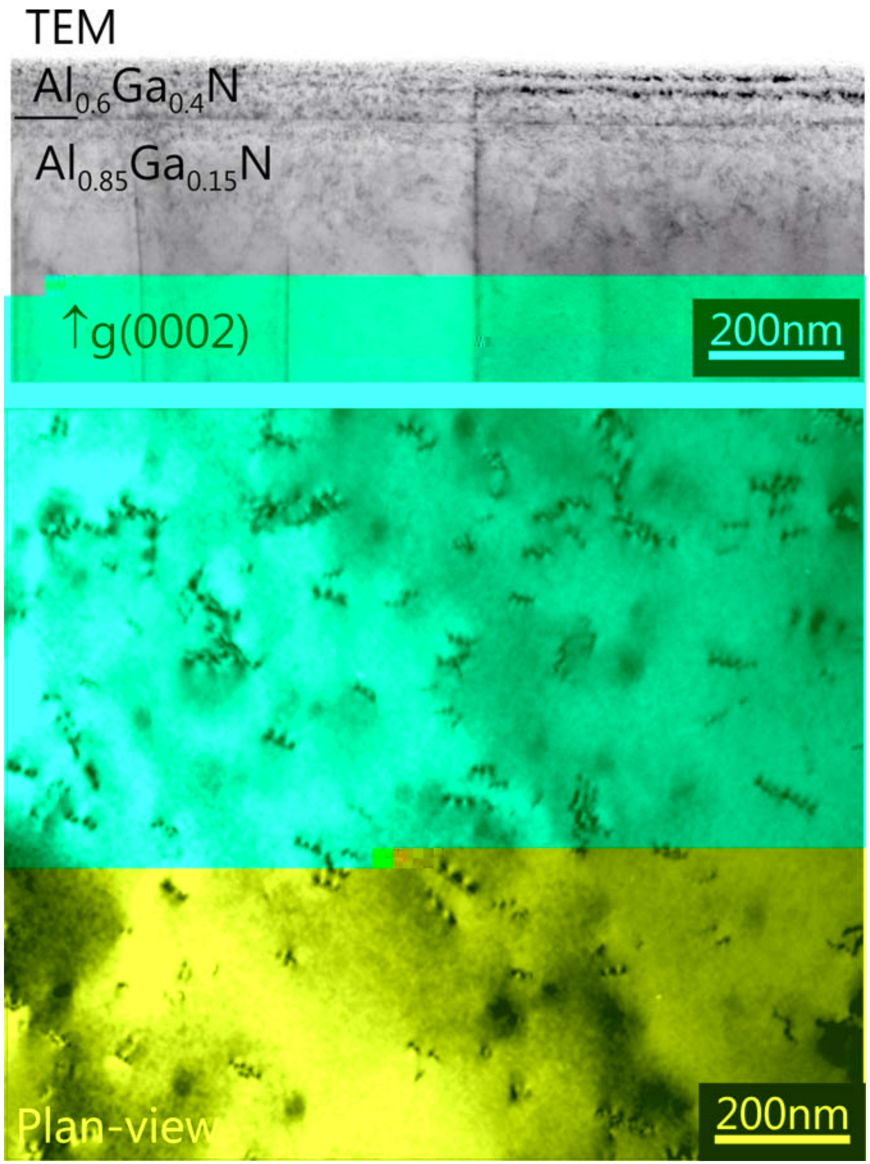


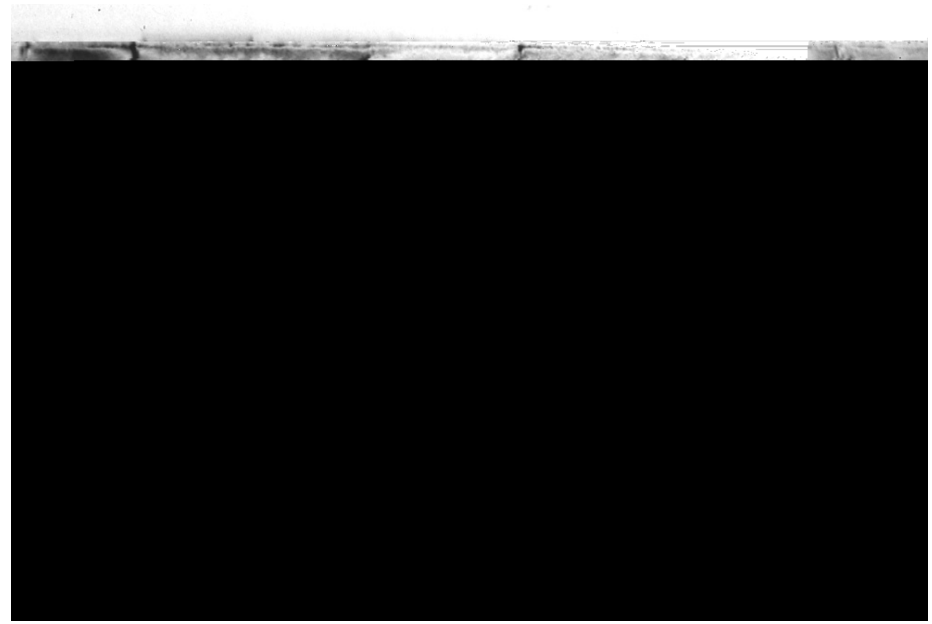
XRD rocking curves





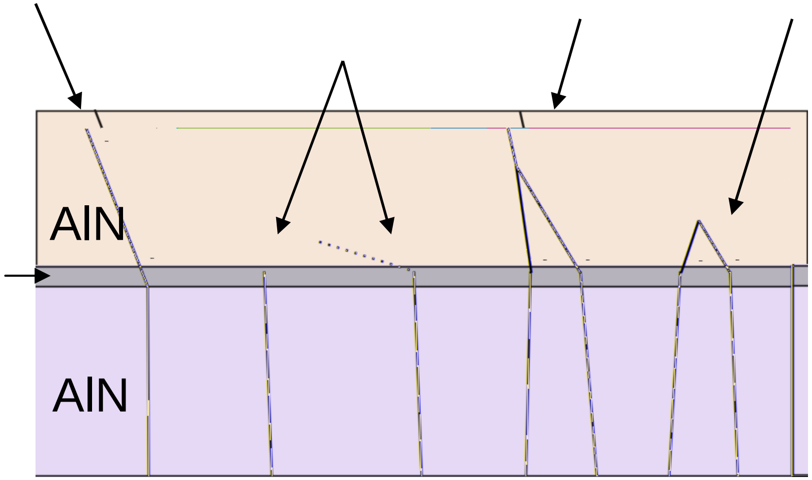




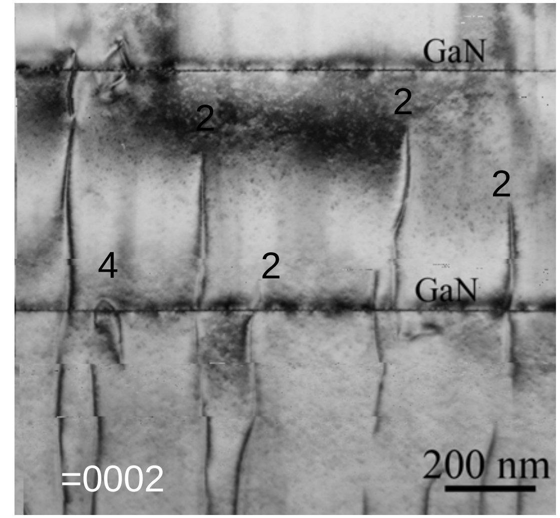


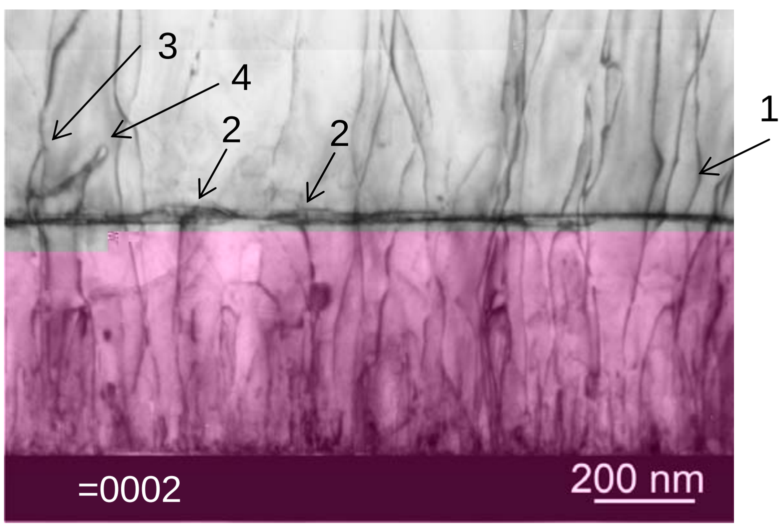
~4 10^{8}cm^{-2}

Edge & Mixed: ~6 10^{9}cm^{-2}

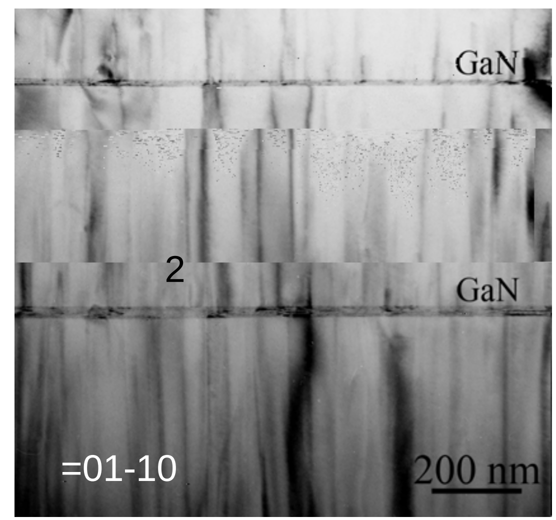


N_{screw}=3.5·10^{9}см$^{-2}$





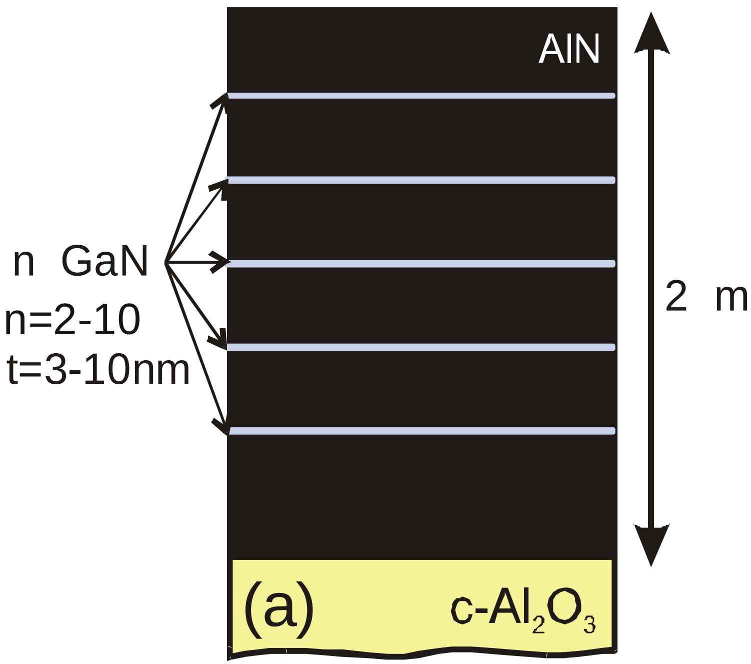
N_{edge}~10^{10}см$^{-2}$

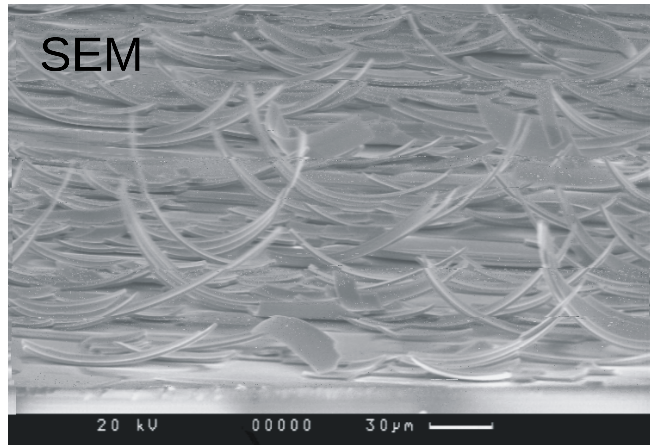


J. Bai et al., Appl. Phys. Lett. **88**, 051903 (2006).
H. Jiang et al., Appl. Phys. Lett. **87**, 241911 (2005).

[redacted]

Nechaev et al. "Nanophysics and Nanoelectronics" , 2014

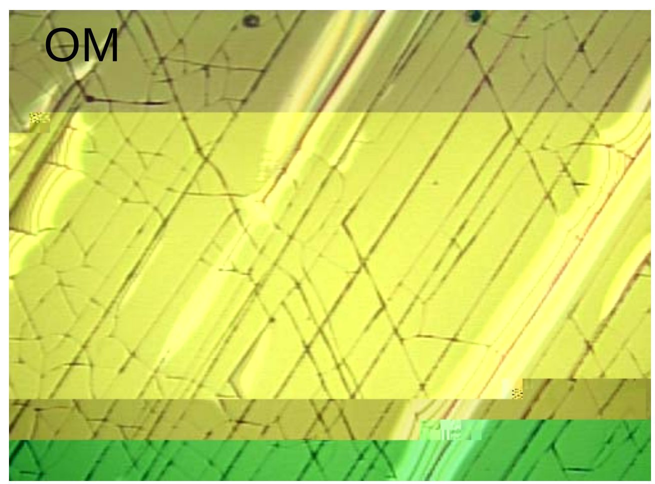




- 2D GaN growth mode

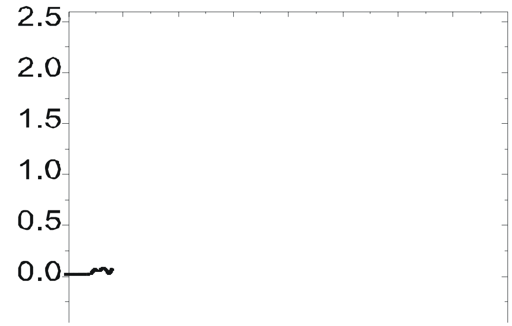
- multiple GaN interlayers above 6 interlayers

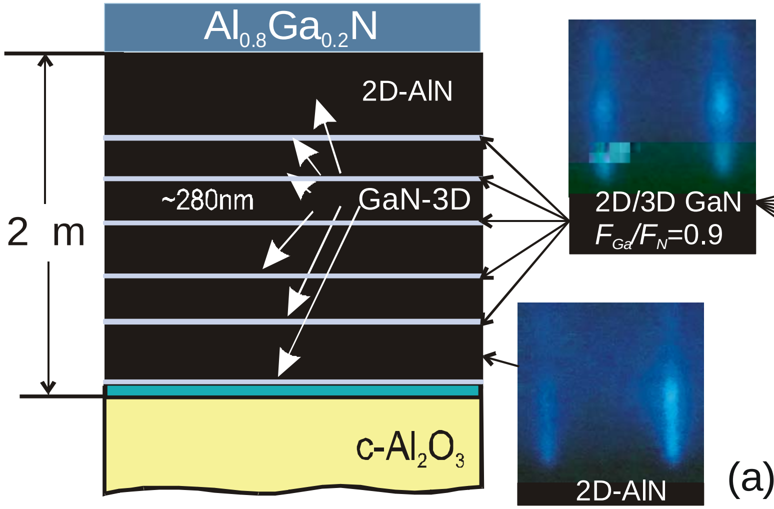
- for interlayer spacing smaller than 150nm even above 3 interlayers

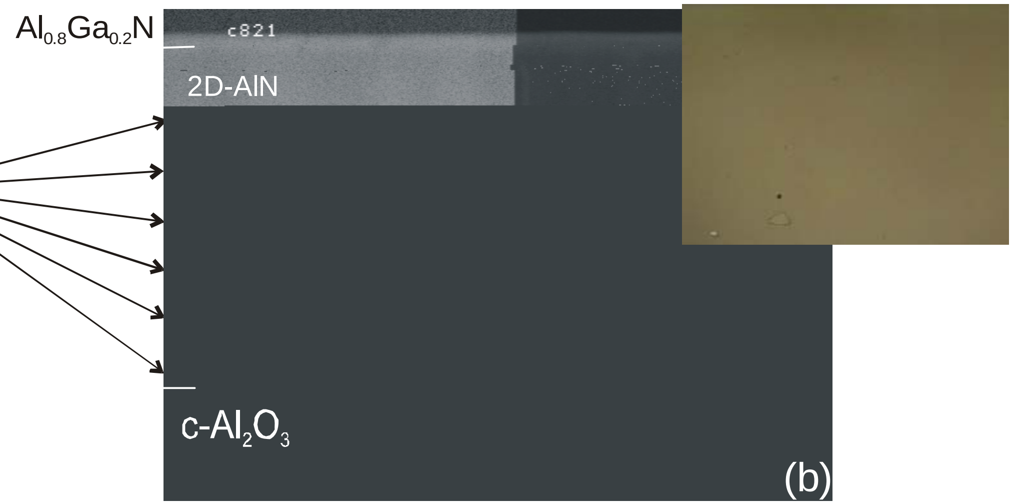


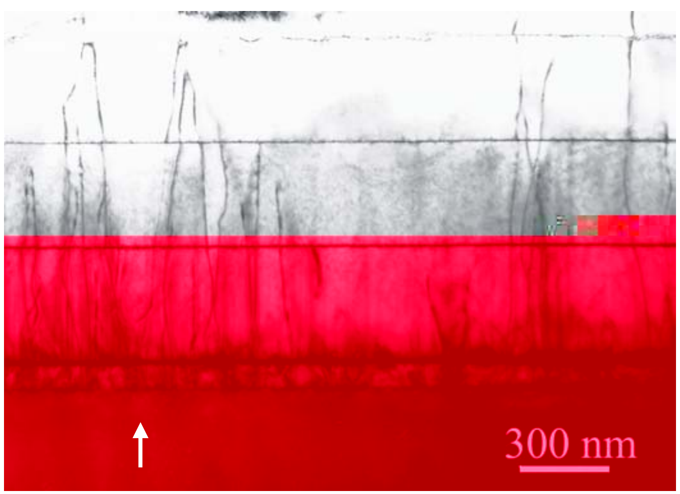
- 3D GaN growth mode

- multiple GaN interlayers at small spacing below 150 nm

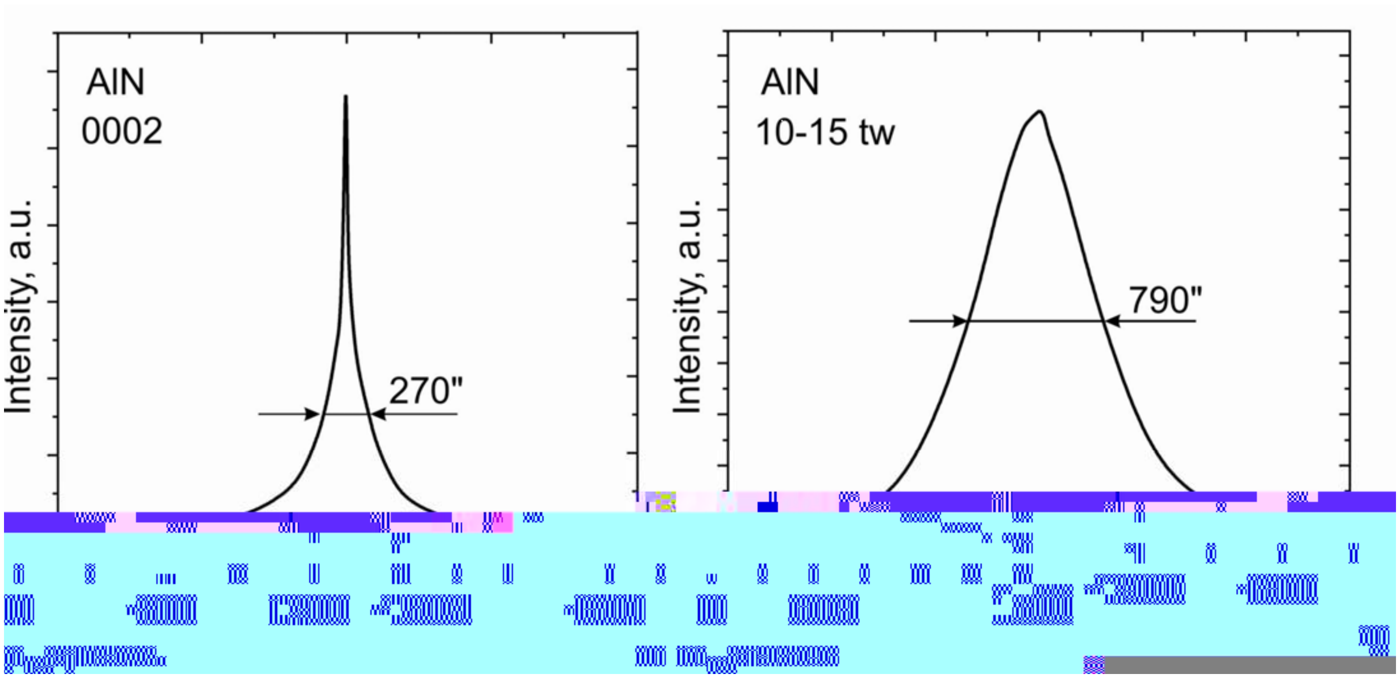

2.5
2.0
1.5
1.0
0.5
0.0


Al0.8Ga0.2N
2D-AlN
~280nm
GaN-3D
2 m
c-Al2O3
2D/3D GaN
FGa/FN=0.9
2D-AlN
(a)


Al0.8Ga0.2N
c821
2D-AlN
c-Al2O3
(b)


300 nm

symmetric (0002) reflex skew-symmetric (10-15tw) reflex



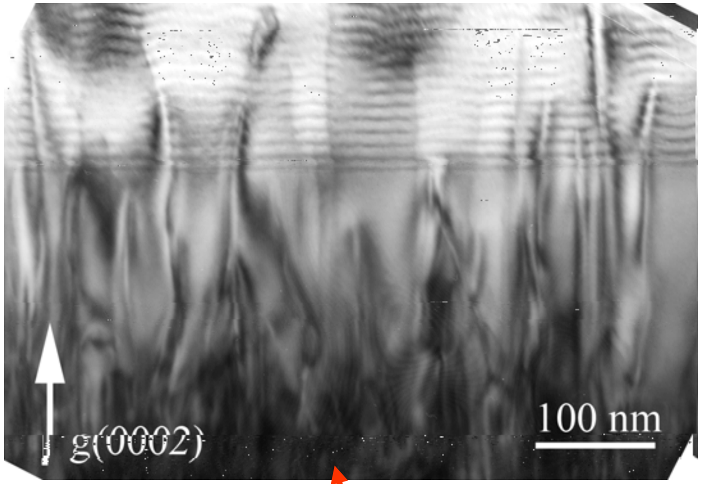
~1.5 $10^8 cm^{-2}$ **Edge & Mixed : ~3 $10^9 cm^{-2}$**

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

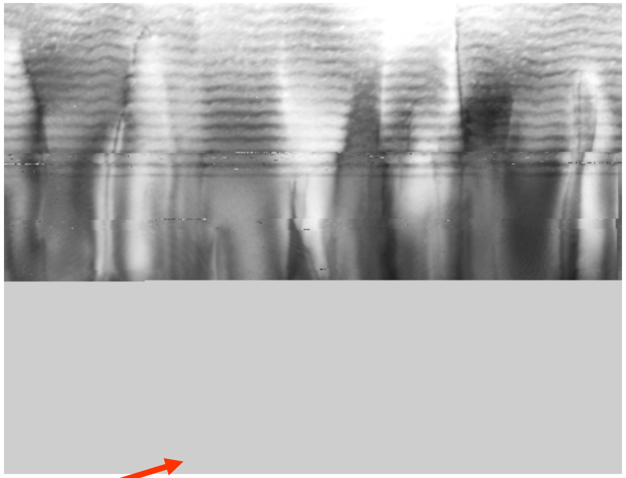
= 0.498 nm (for screw TD)
= 0.311 nm (for edge TD)

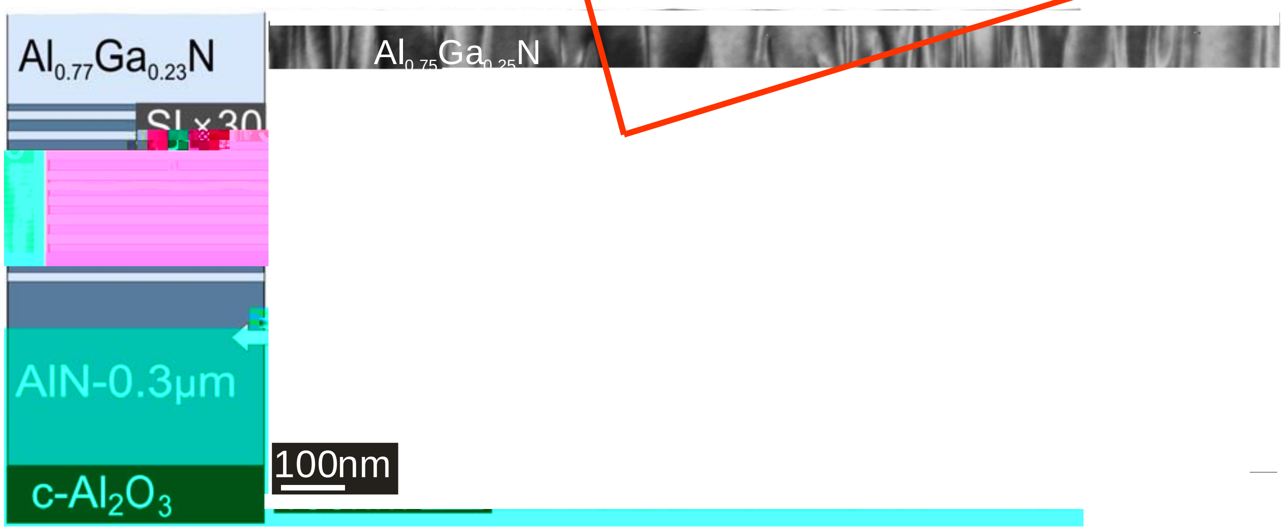
T x_{av}

screw & mixed



edge





- Applications of UV-optoelectronics and state-of-the-art of AlGaN-based UV LED and laser structures obtained by both MOVPE and PA MBE
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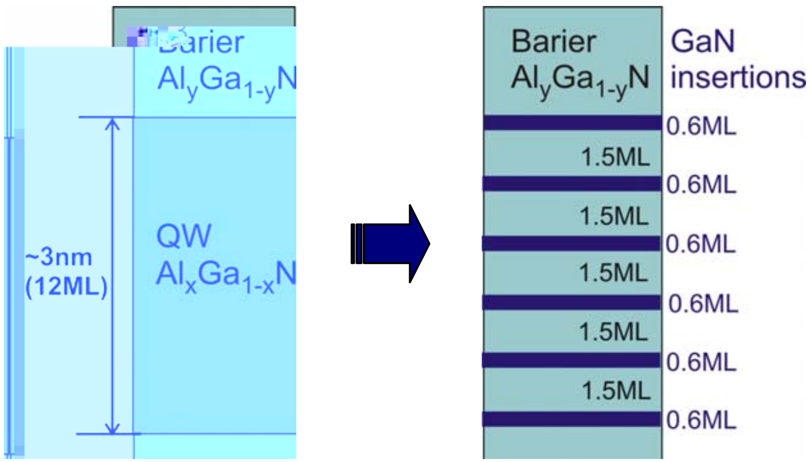
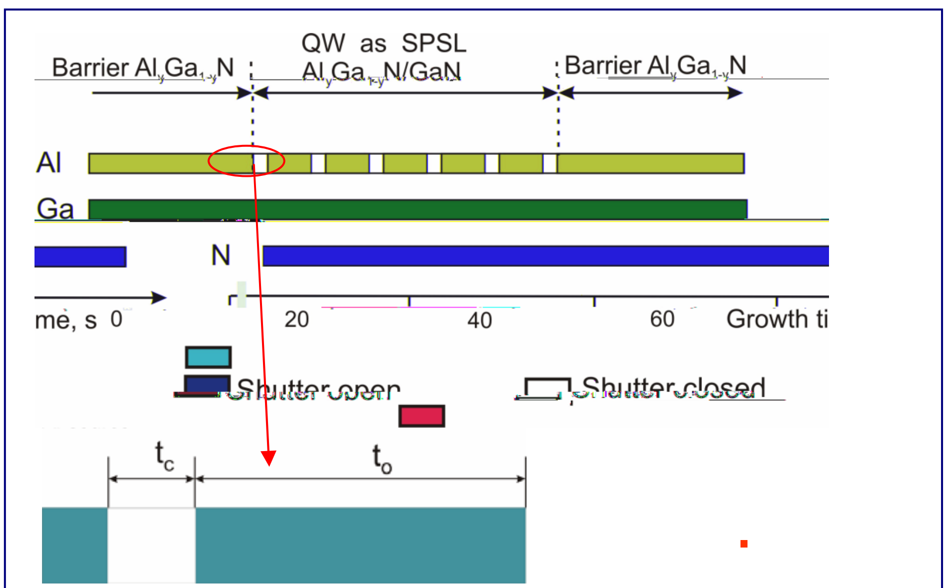
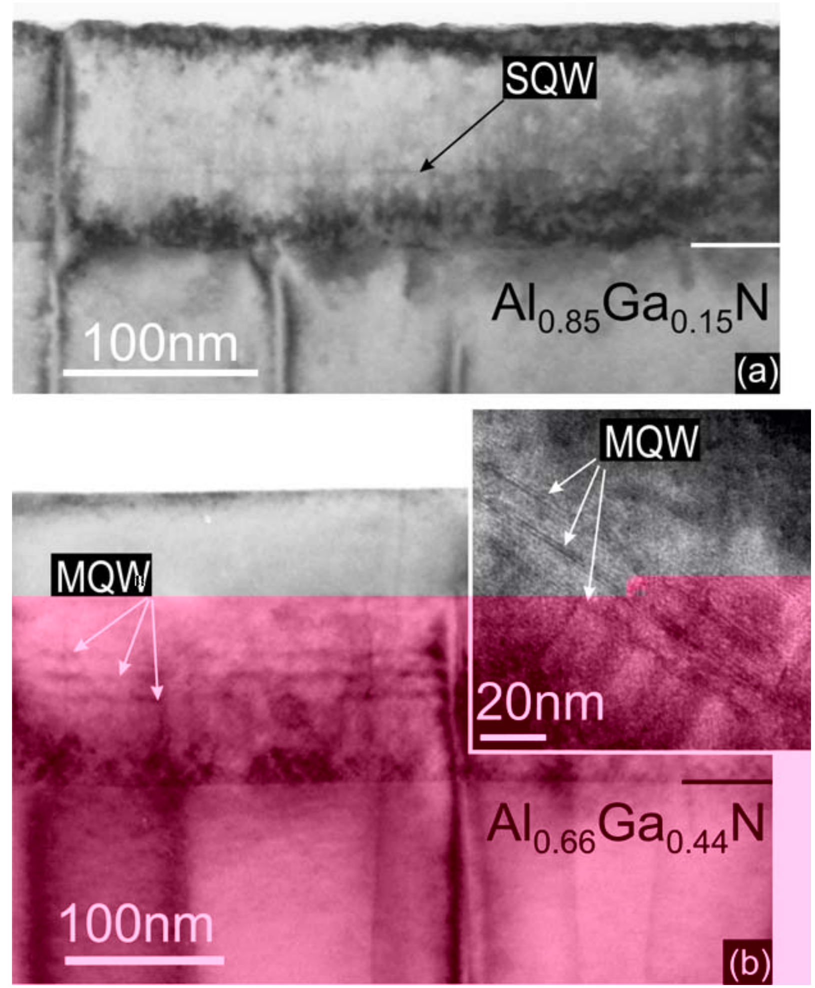
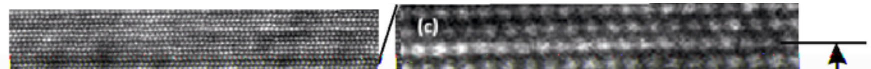
- Conclusions





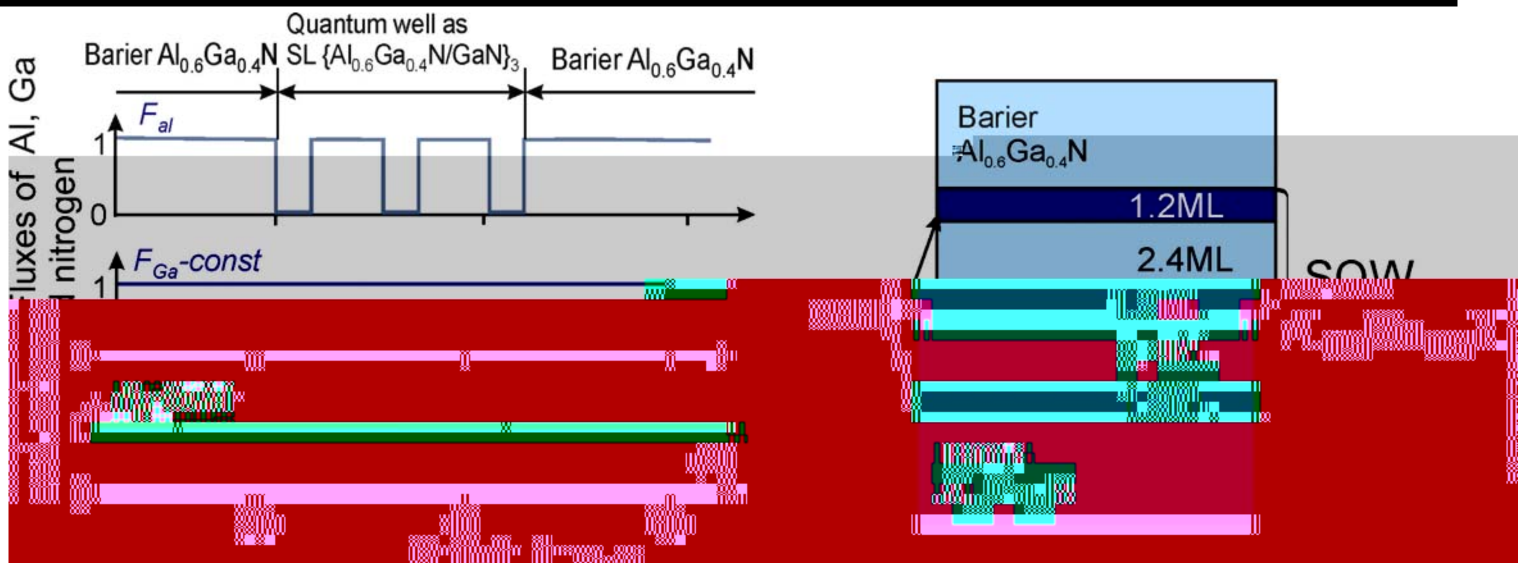


*Jmerik et al., Semiconductors **42**, 1452 2008), PSS A **210**, 2013).*

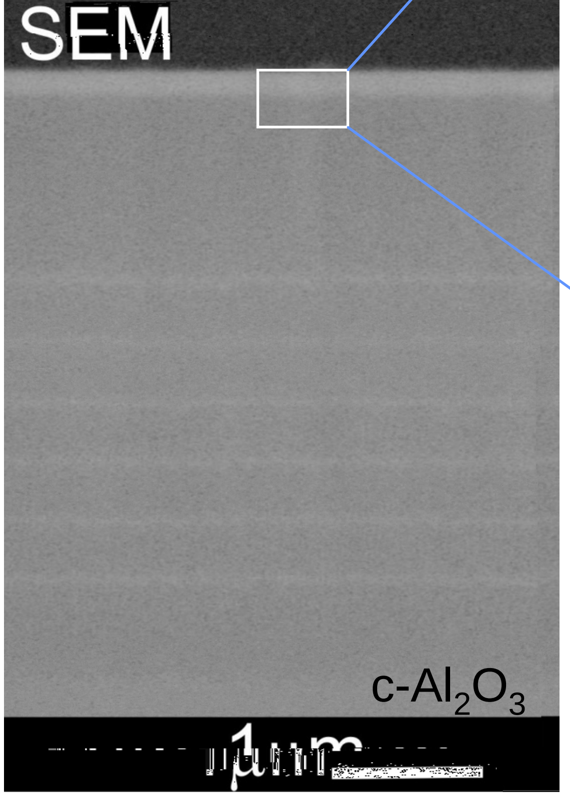


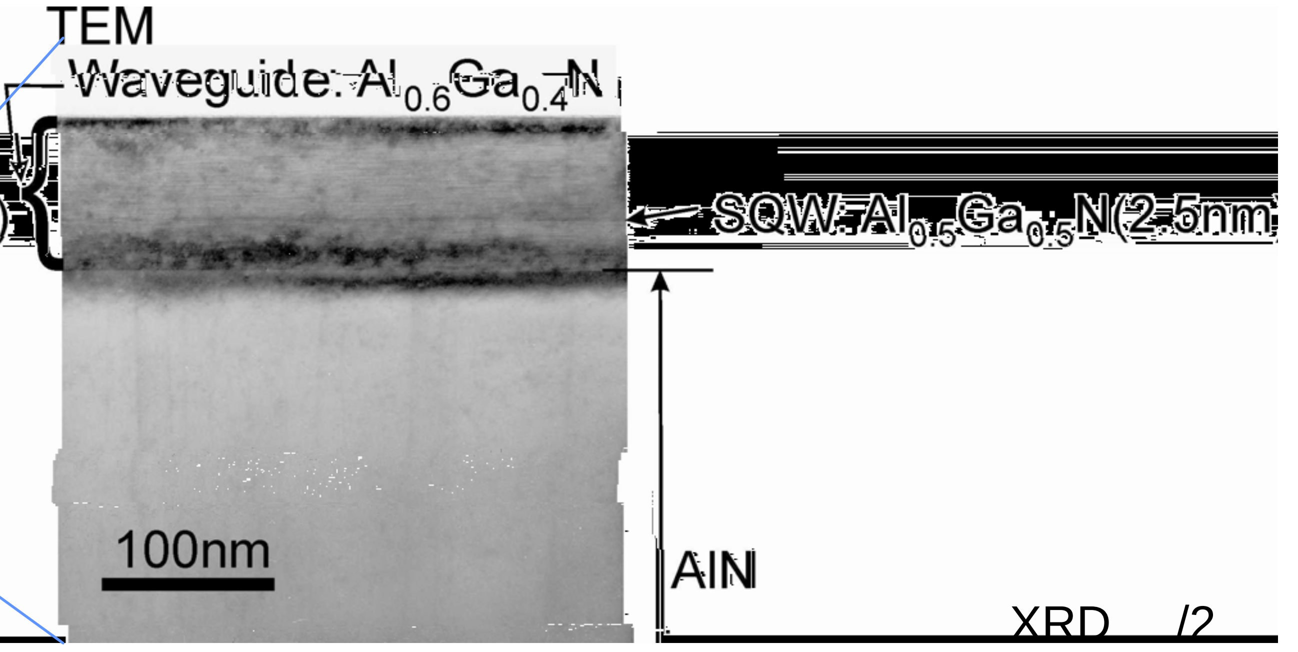
(c)

[redacted]

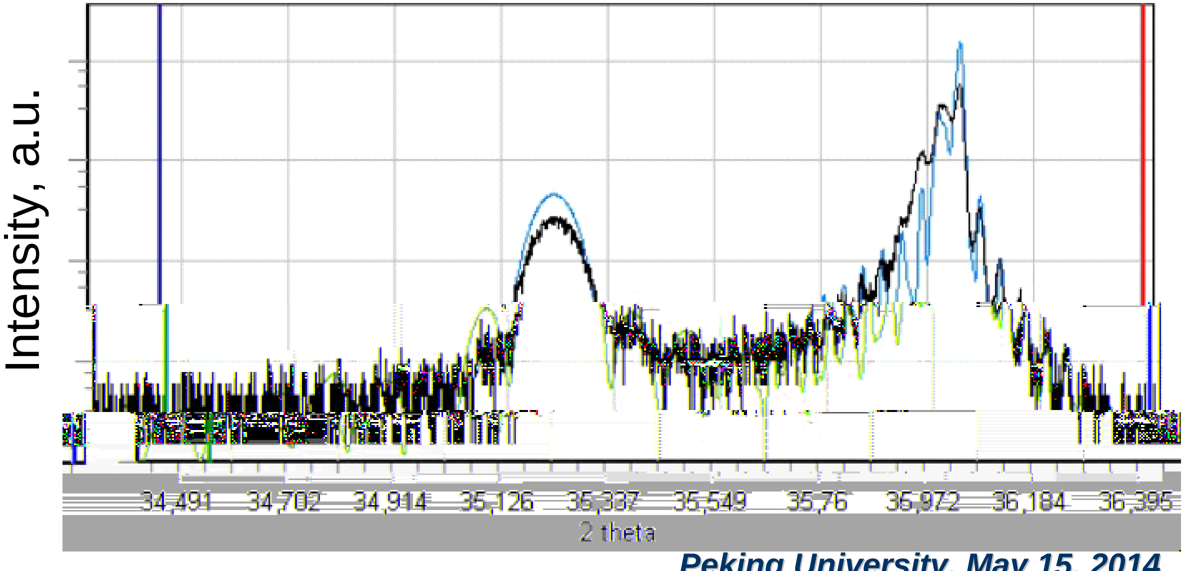


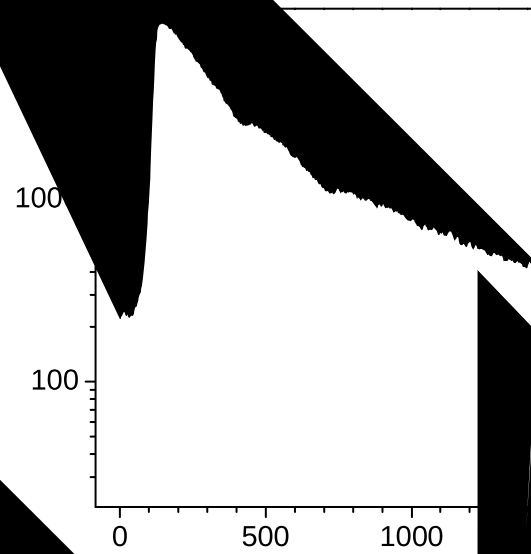
Quantum well as
Barier Al0.6Ga0.4N
SL {Al0.6Ga0.4N/GaN}3
Barier Al0.6Ga0.4N
F_al
F_Ga-const
1
0
1
Barier
Al0.6Ga0.4N
1.2ML
2.4ML


SEM
c-Al_2O_3
1μm


TEM
Waveguide: $Al_{0.6}Ga_{0.4}N$
SQW: $Al_{0.5}Ga_{0.5}N$(2.5nm)
100nm
AlN

XRD /2


Intensity, a.u.
34.491
34.702
34.914
35.126
35.337
35.549
35.76
35.972
36.184
36.395
2 theta


100
0
500
1000

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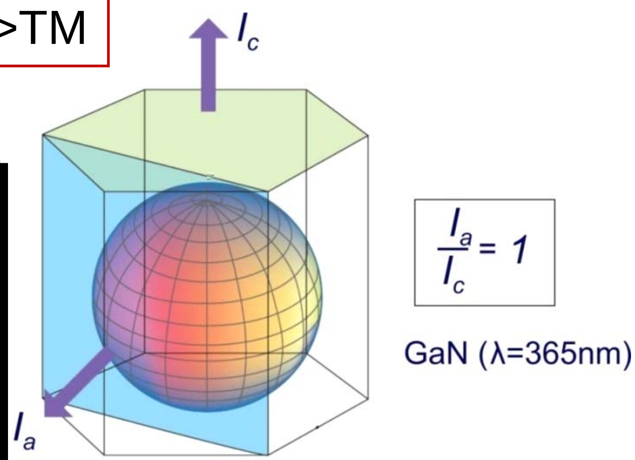
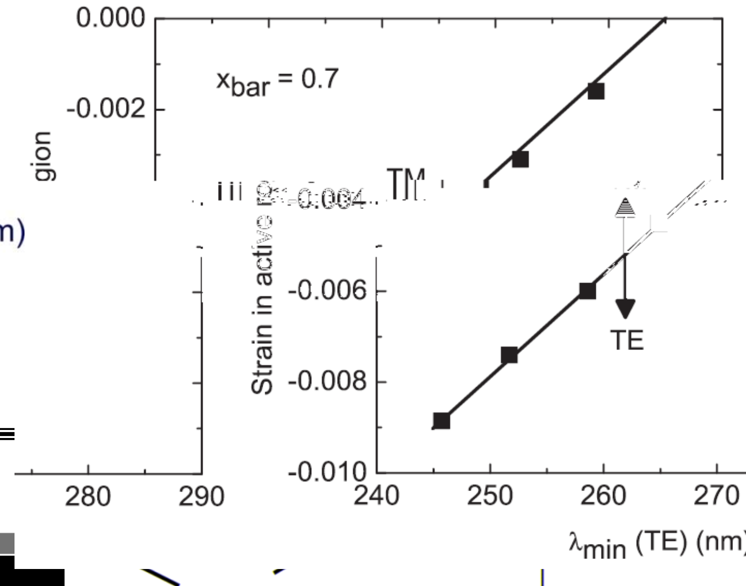
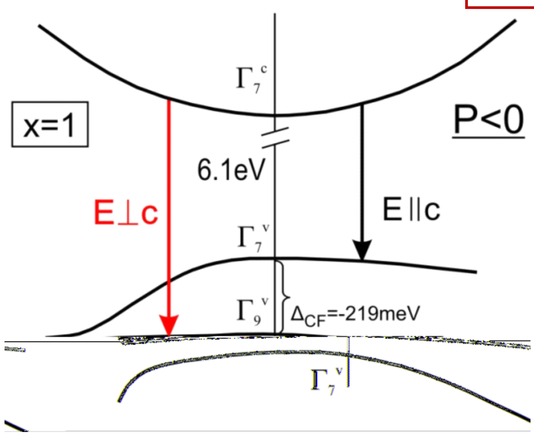
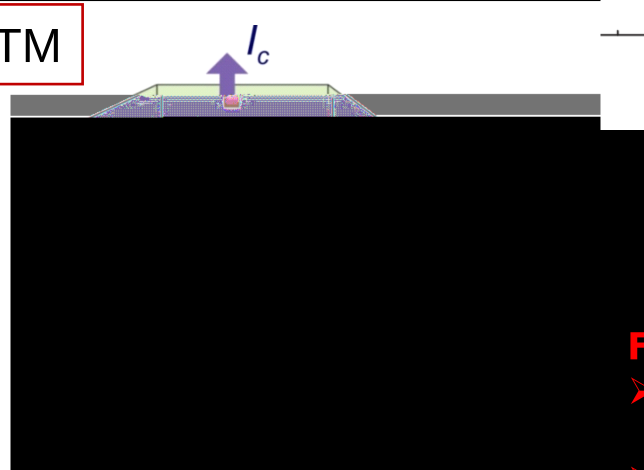
TE>TM





TE<TM





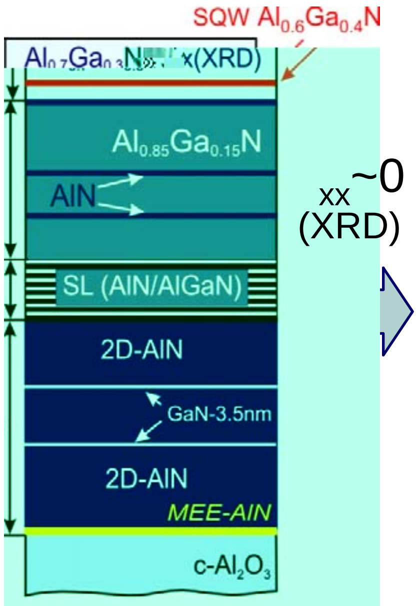
Northrup et al., Appl.Phys.Lett. ***100****, 021101 (2012)*
*Durnev &Karpov, Phys.Stat.Solidi B****250****, 180(2013)*

For TE plarization:

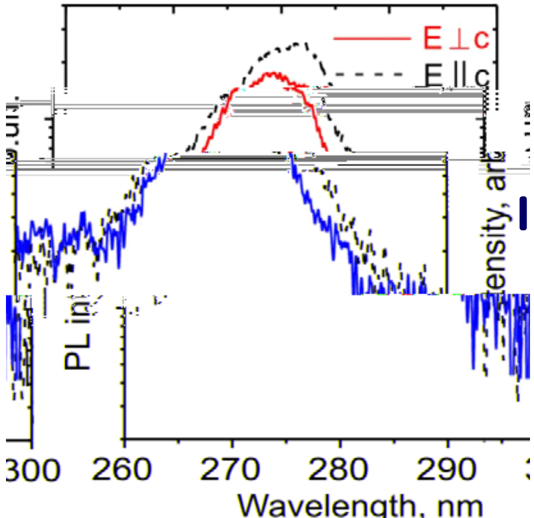
- Efficient light extraction from mid-UV LEDs normally to c-plane
- Higher differential gain in the mid-UV laser cavity due to the higher reflectivity coefficient

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

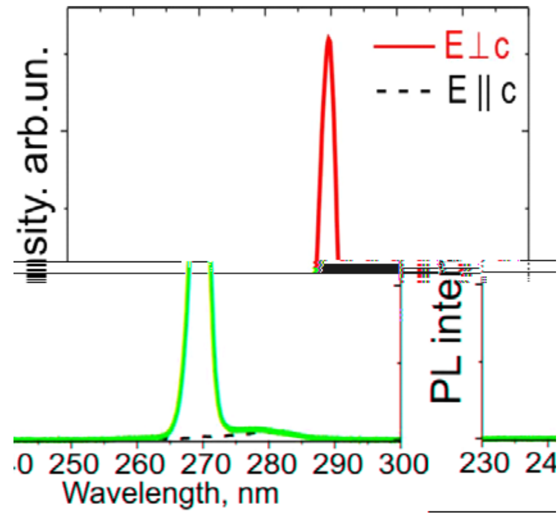
Taniyasu et al., APL ***90****, 261911 (2007).*

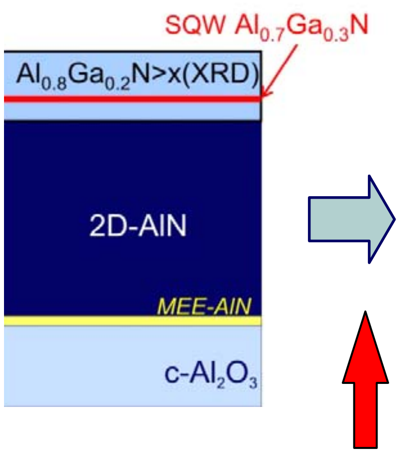


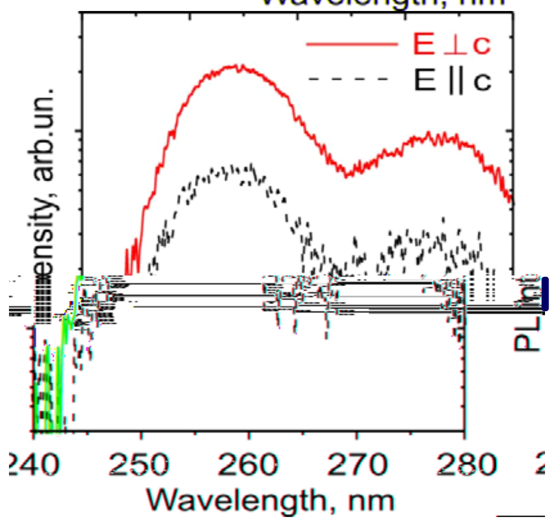
Spontaneous PL spectra

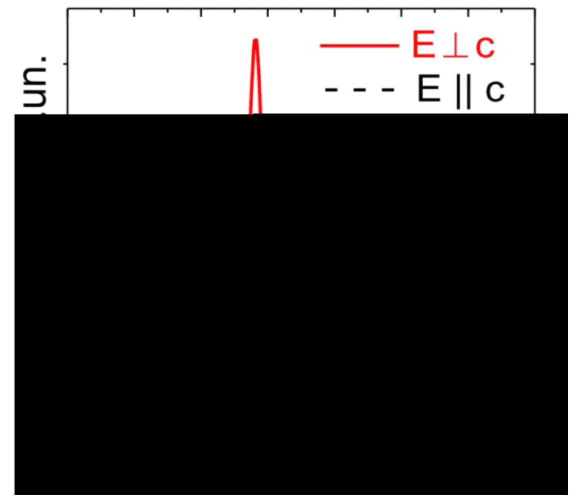


Stimulated PL spectra









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

$_{xx}$~−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).*

$$\frac{dN}{dt}$$

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

This can be described by the semiempirical expression :

$$\frac{dN}{dt} \quad B \; N_0 \; \frac{{}_{eff}}{}^{\,n} \exp \; \frac{E_a}{kT}$$

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

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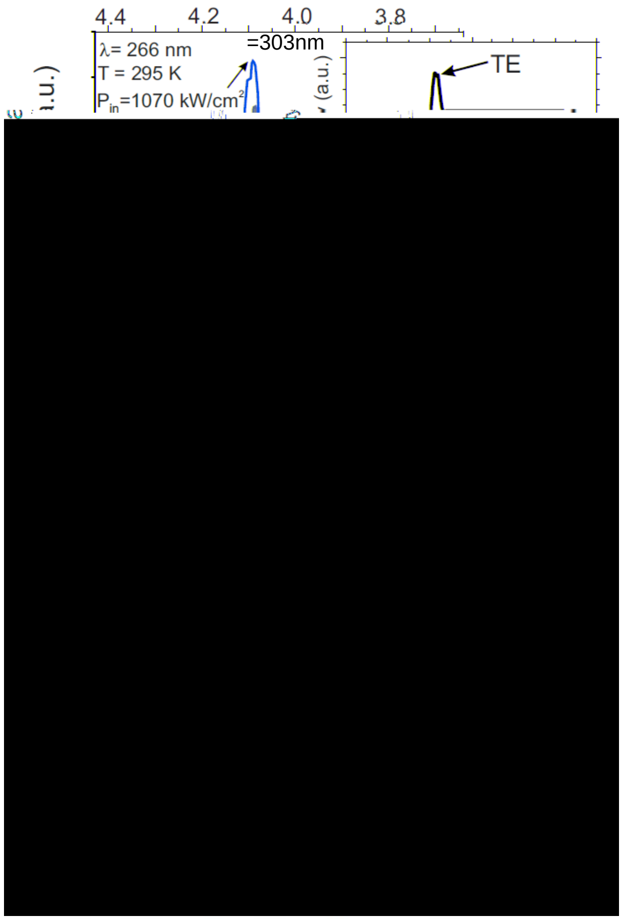
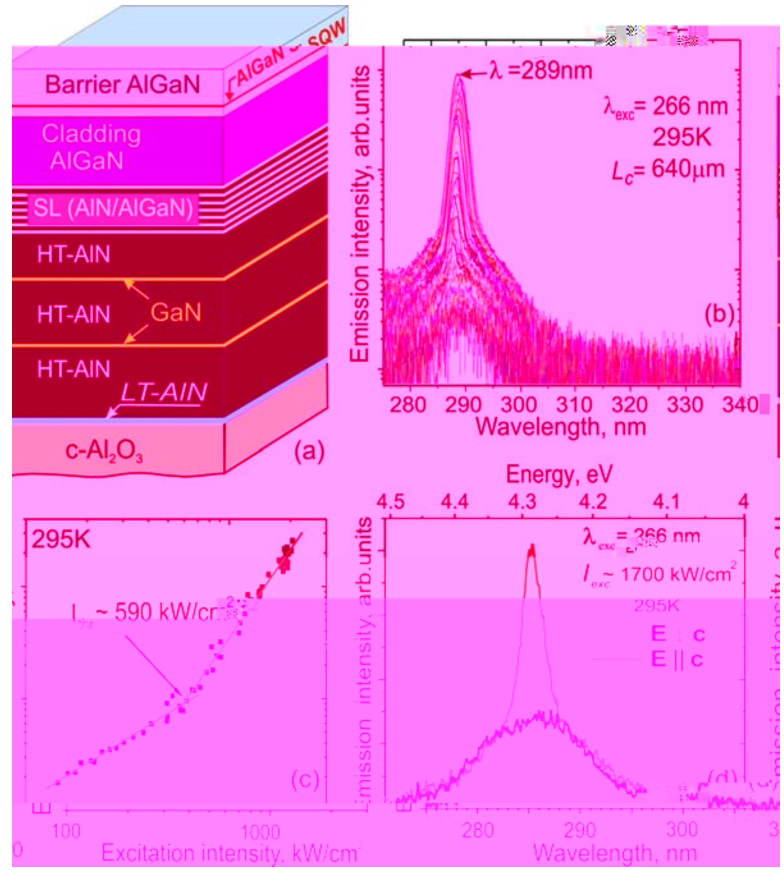


APPLIED PHYSICS LETTERS **96**, 141112 (2010)

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]



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

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www.pss-a.com
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]

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

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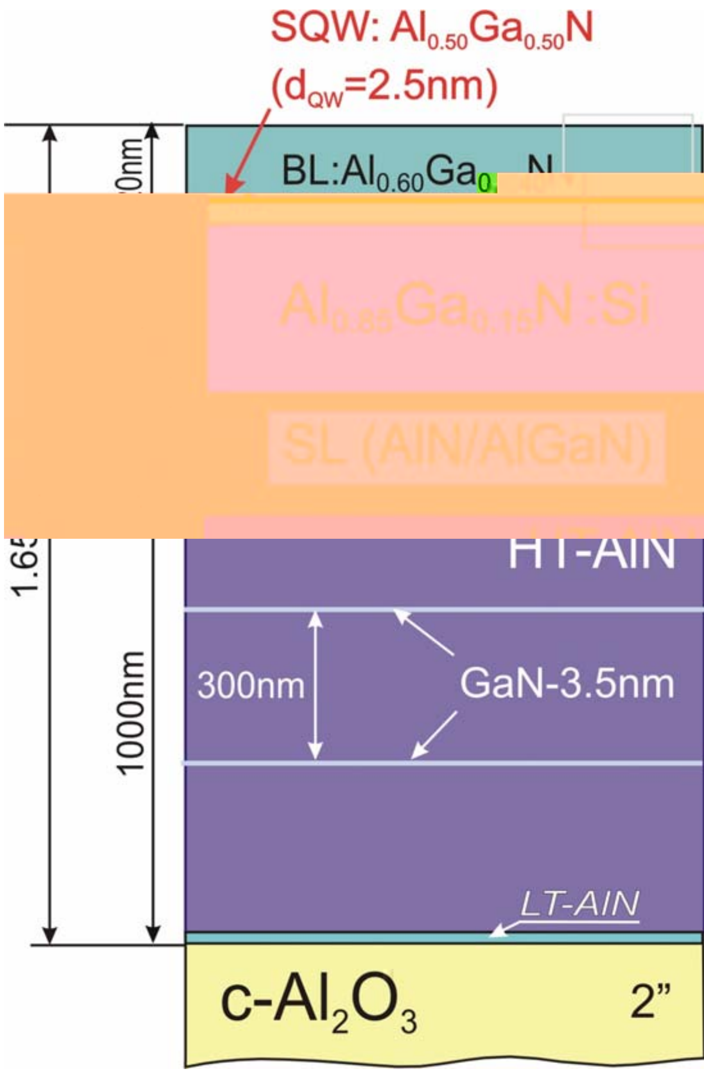
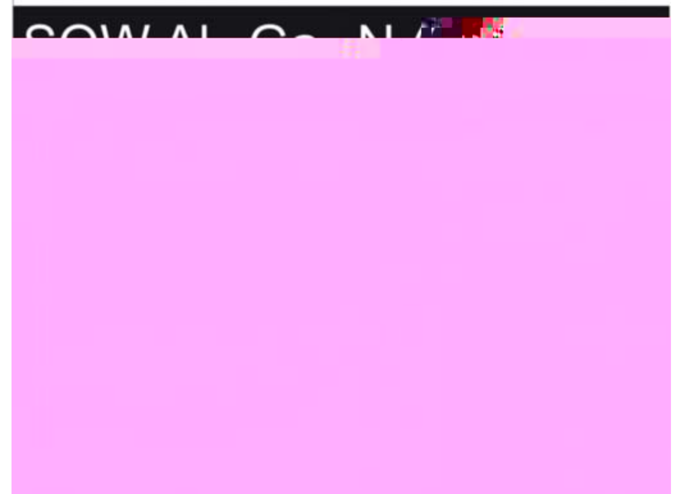
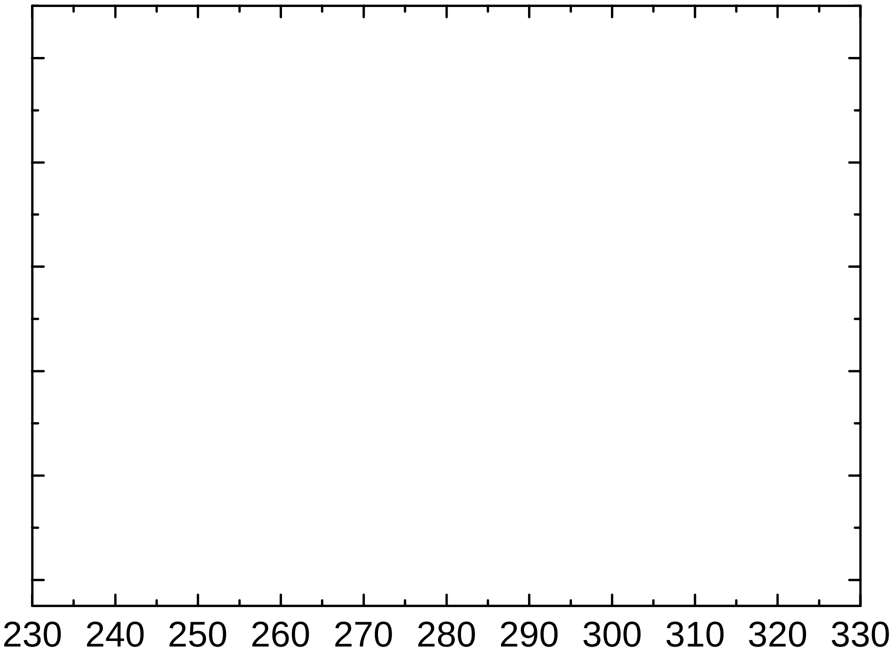
Published online





- Reduction of TDs density (10^8-$10^9 cm^{-2}$) 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.


230 240 250 260 270 280 290 300 310 320 330

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- Conclusions

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

$Al_{0.42}Ga_{0.58}N$

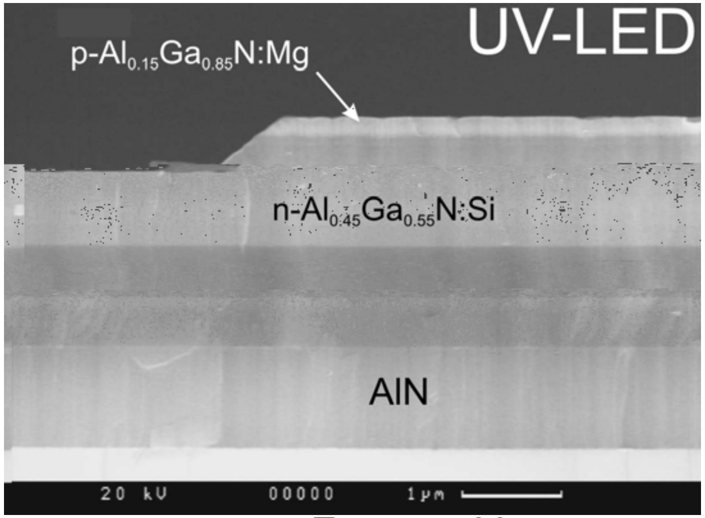
C-V (300K): compensated, although at the reverse bias above 5V p-type conductivity was observed

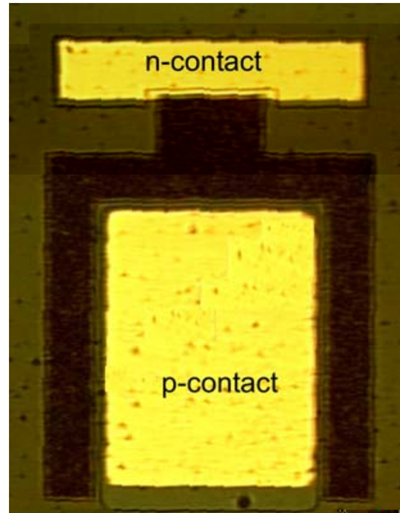
Hall (250K): p-type p = 4×10^{17} cm^{-3} μ_H = 1.4 cm^2/Vs

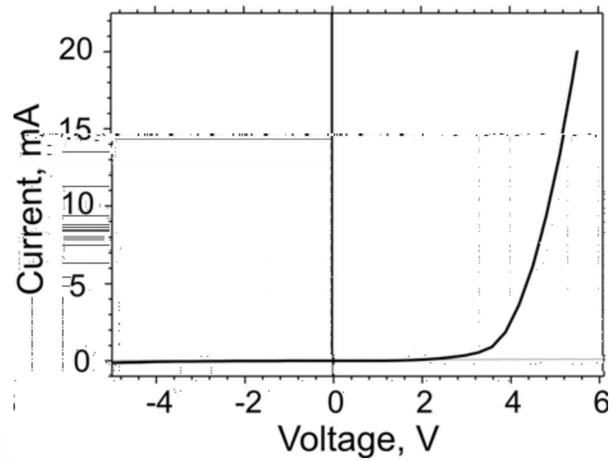
Seebeck (300K): p-type

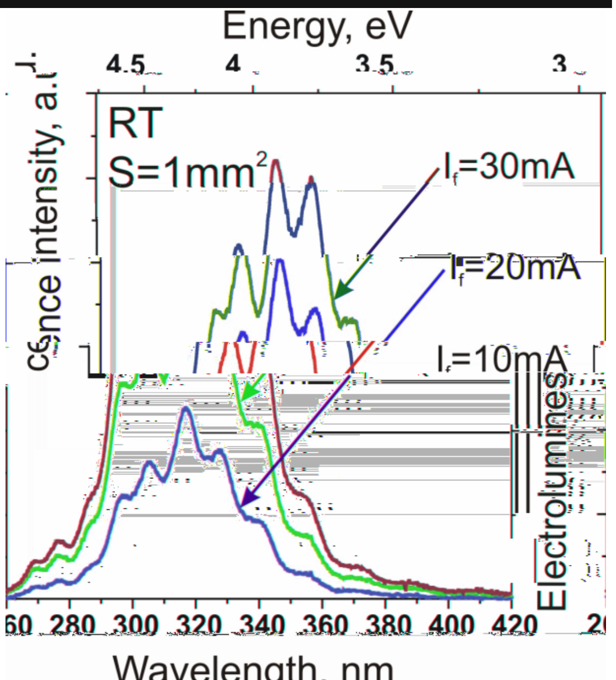
This is the first observation of p-conductivity by Hall effect in MBE-grown $Al_xGa_{1-x}N$ with x>0.3

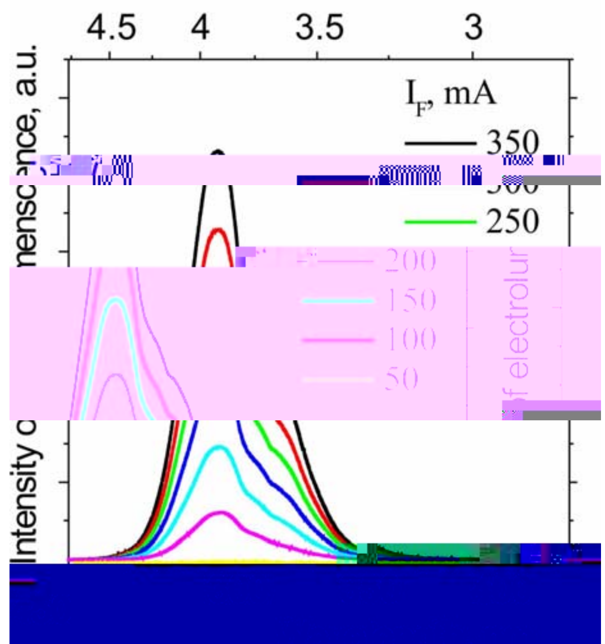
Komissarova et al., Montreux, 2008, pss(c) 6, S466 (2009)





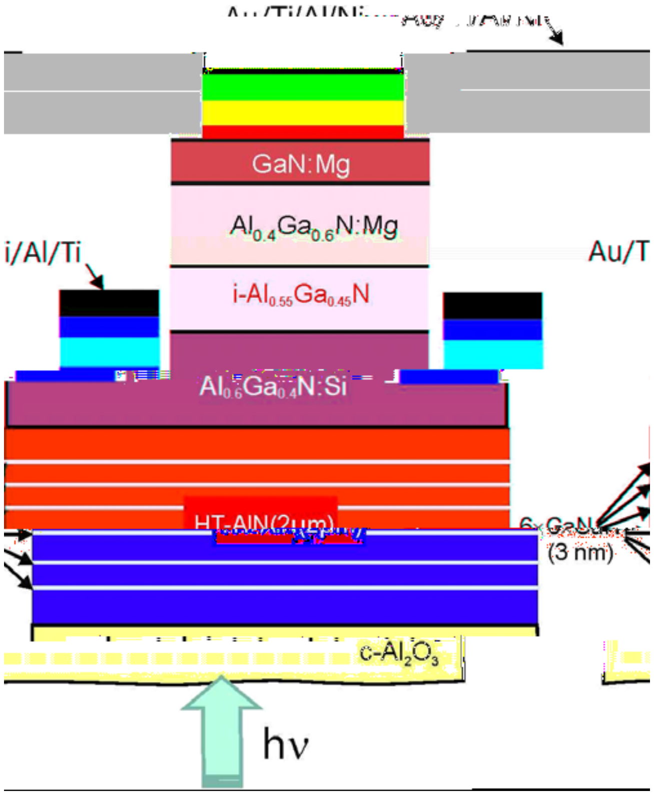


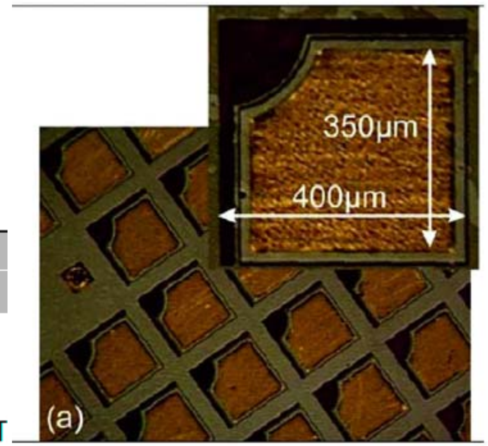


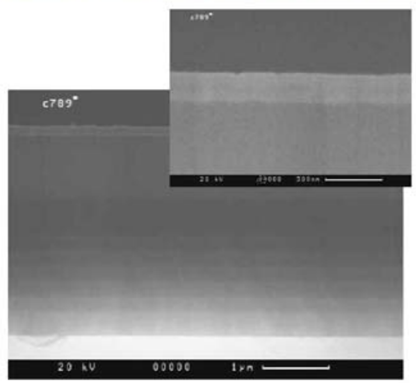


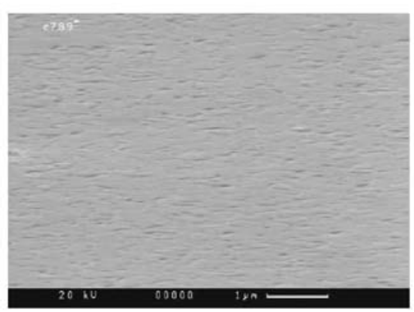
λ = 300-350 нм

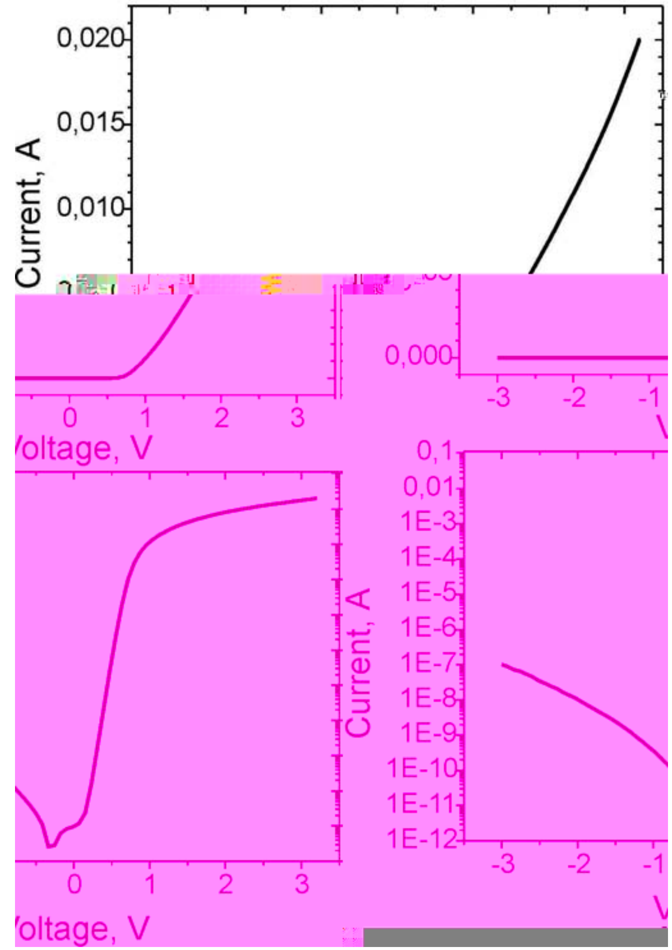
P_{out}~ 0.5 мВт


GaN:Mg
Al0.4Ga0.6N:Mg
i-Al0.55Ga0.45N
Al0.6Ga0.4N:Si
HT-AlN(2μm)
c-Al2O3
(3 nm)
hν

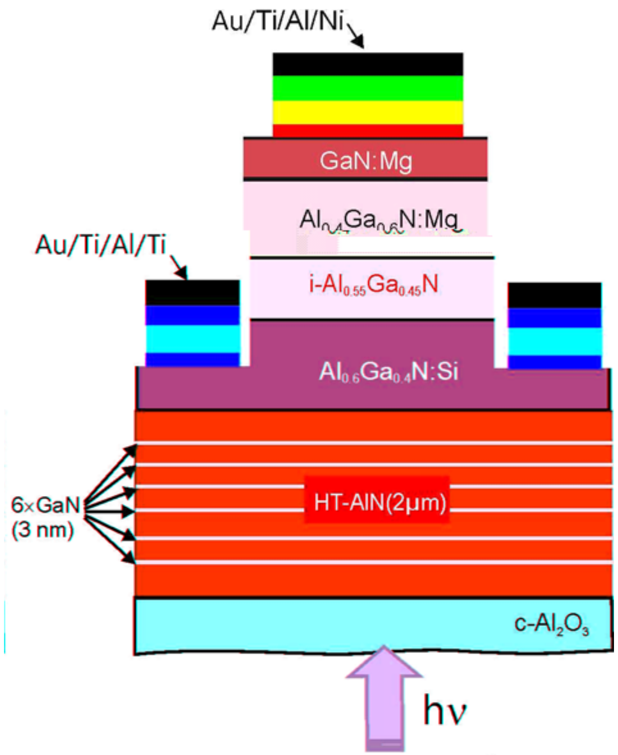

350μm
400μm
(a)

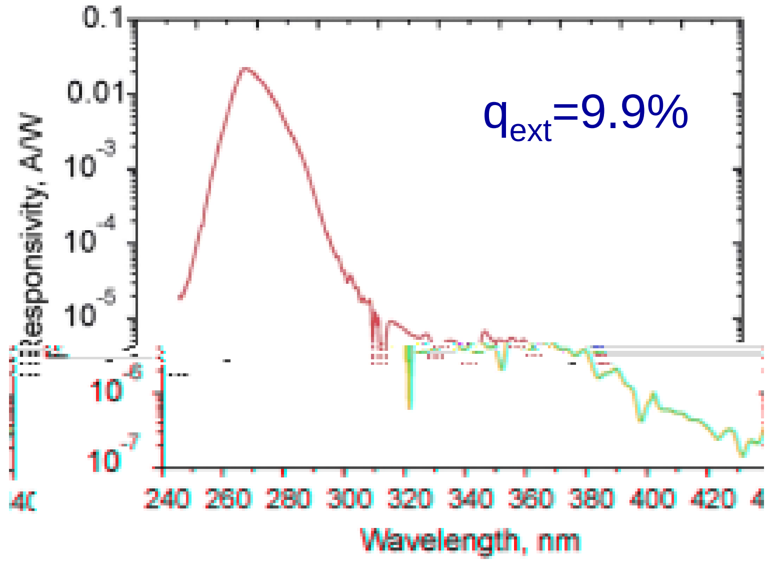


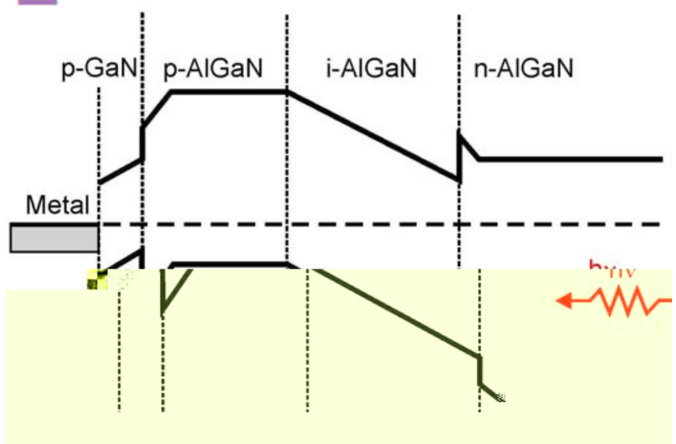



0,020
0,015
0,010
Current, A
0,000
Voltage, V
0,1
0,01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
Current, A
Voltage, V

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



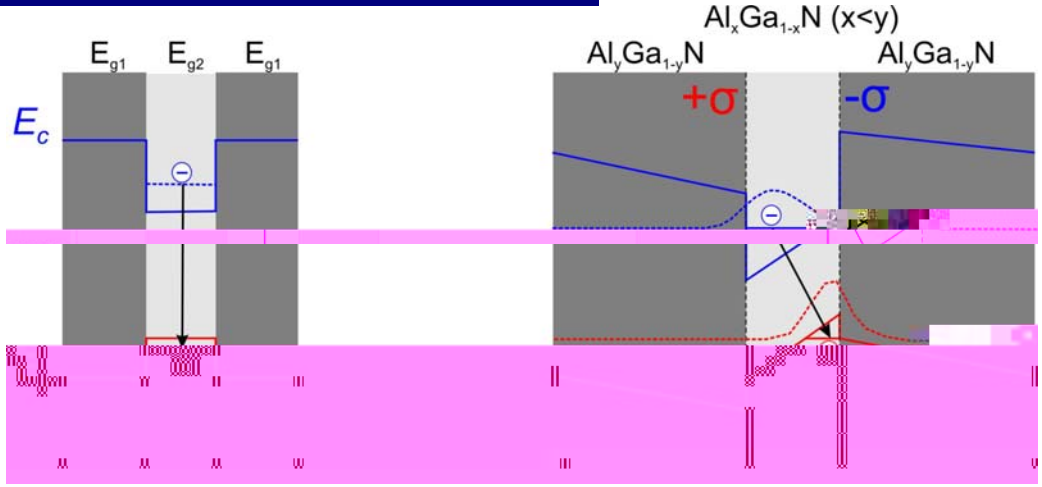




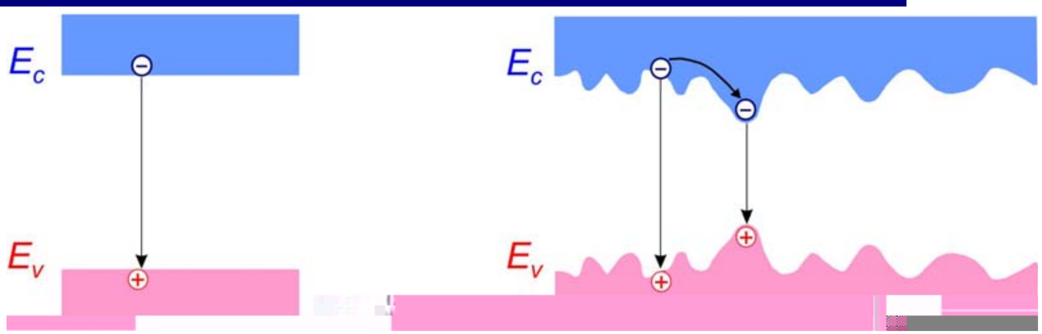
[Mg]= 6 10^{18}-2 10^{19}cm^{-3}

- 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.

Quantum –confined Stark effect



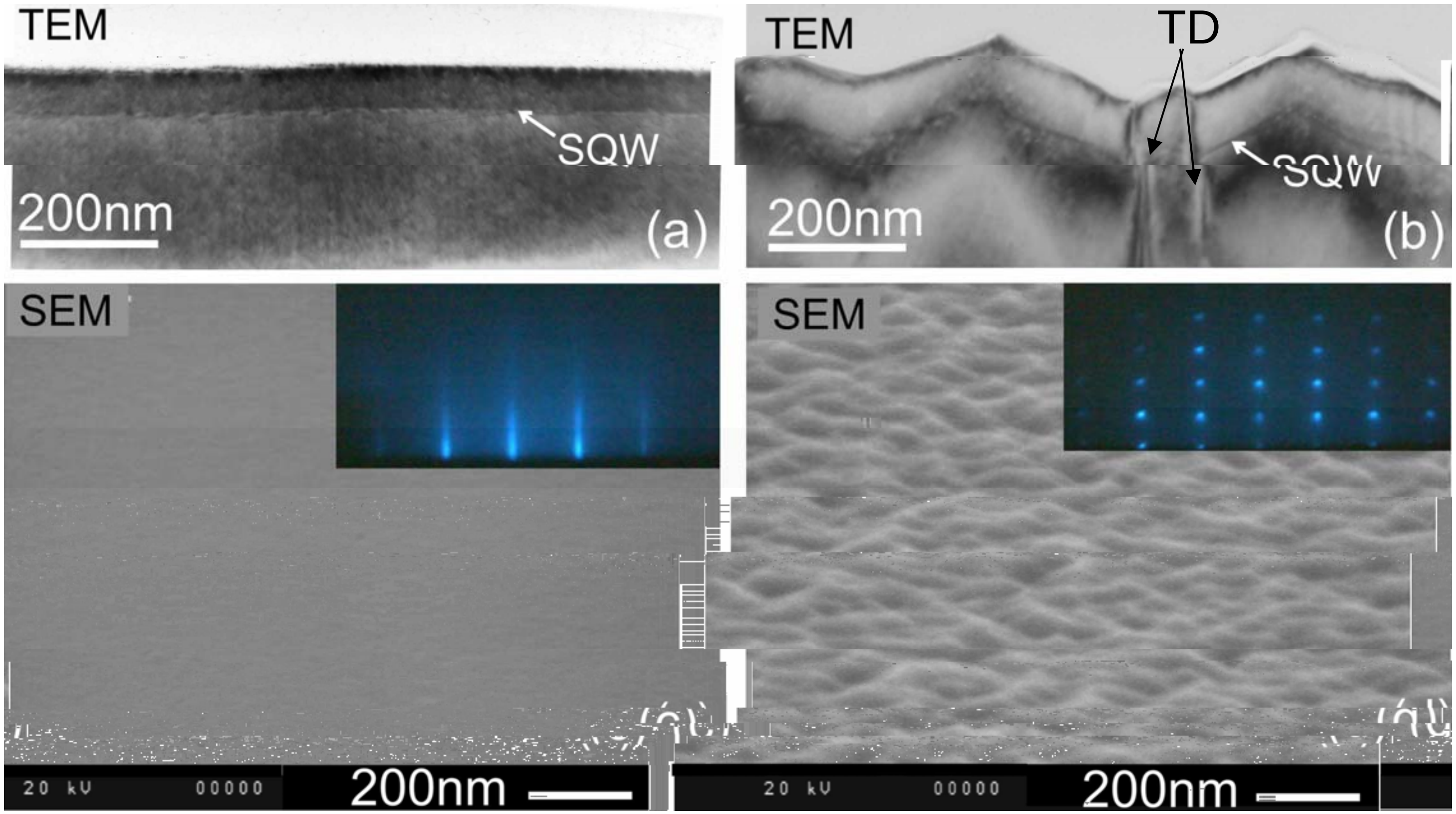
Localized states due to potential fluctuations *(compositional inhomoheneities)*



- 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

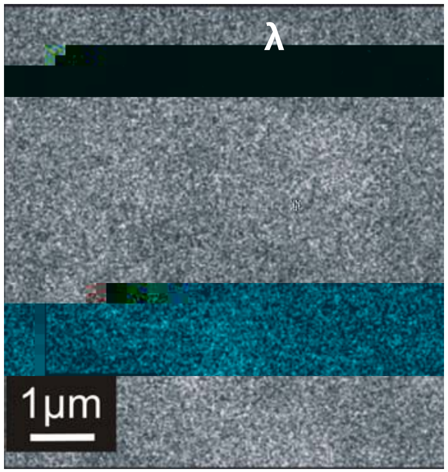


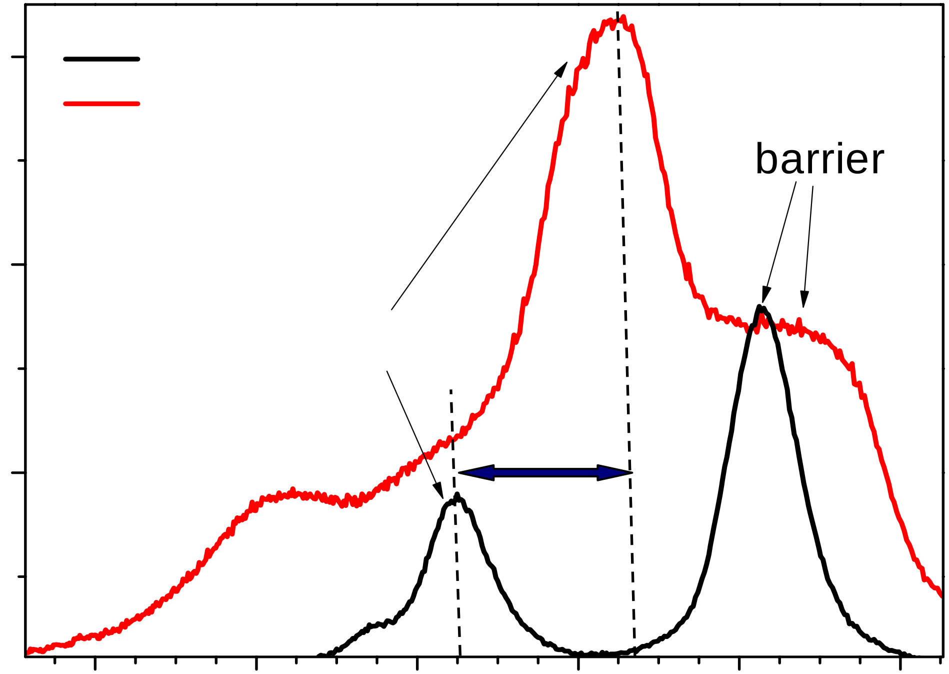
2D AlN buffer growth mode

3D AlN buffer growth mode

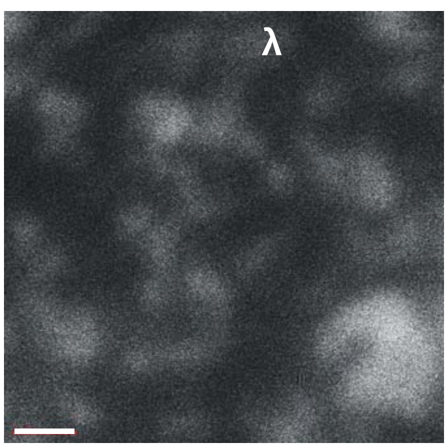
For both structures N_D~10^{10} cm^{-2}

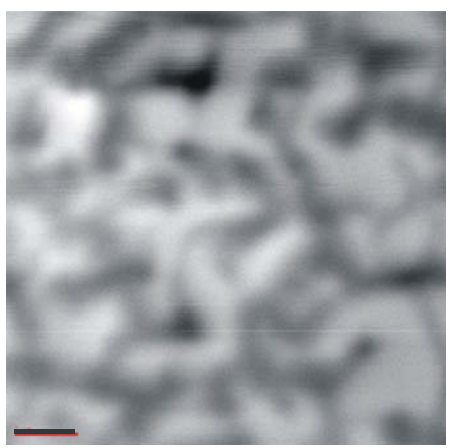
Plane QW morphology





Corrugated QW morphology





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