Molecular Beam Epitaxy of group III nitride semiconductor nanowires

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Group of MBE Growth of Nitride Nanostructures
http://info.ifpan.edu.pl/Dodatki/WordPress/mbe2en/

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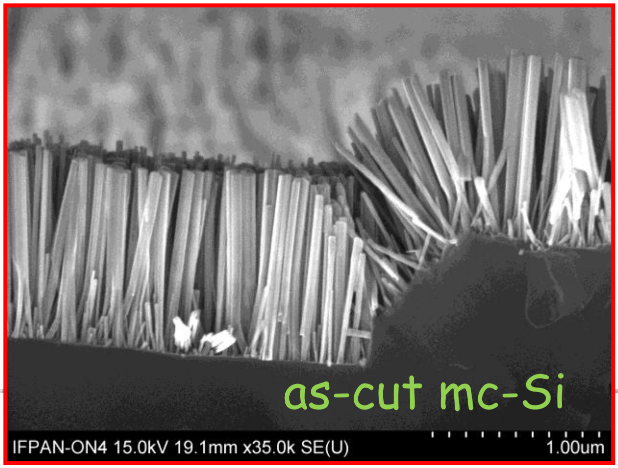
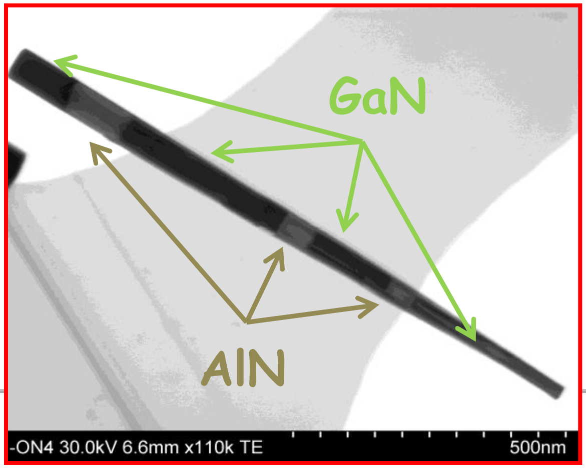
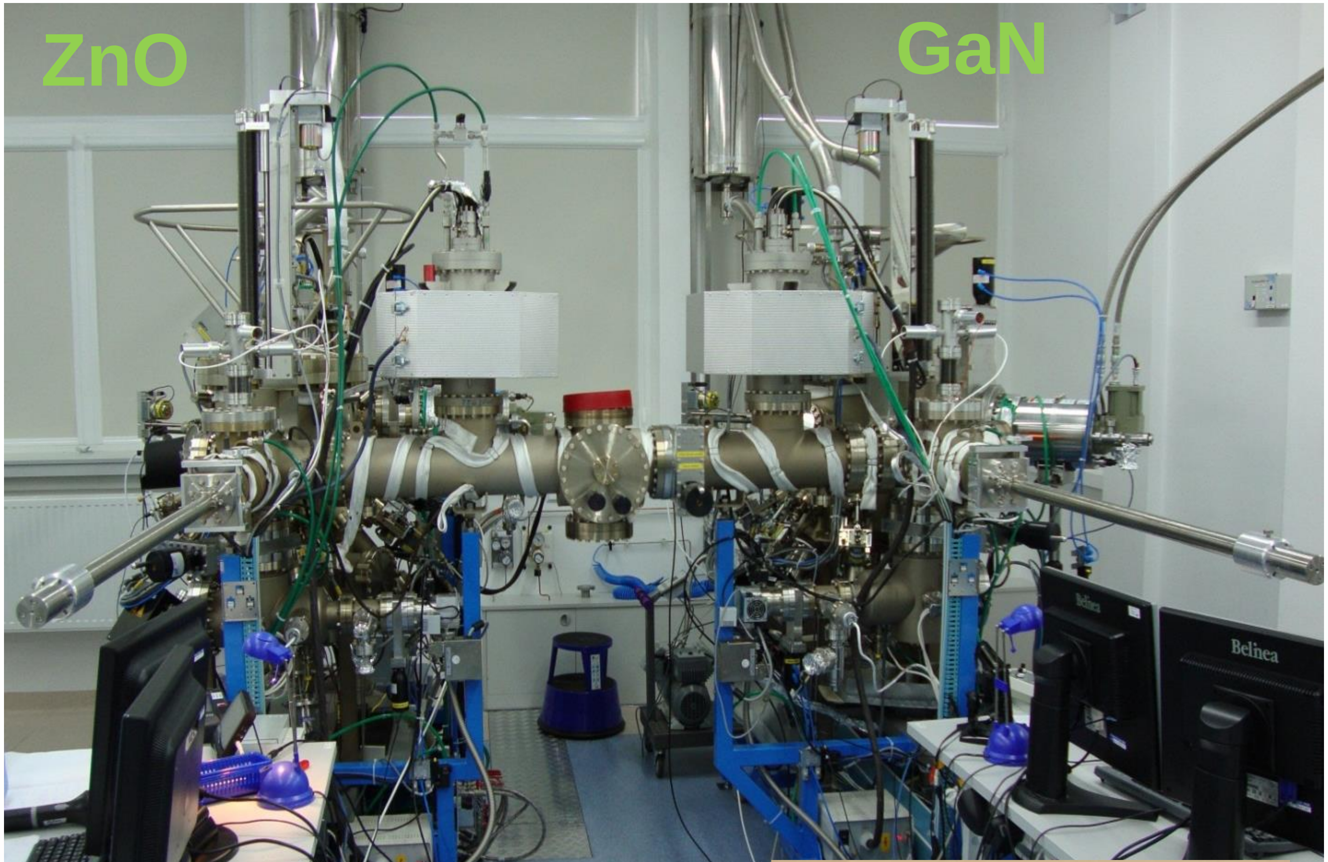




EAgLE
European Action towards Leading Centre
for Innovative Materials

Brussels, March 11th, 2015

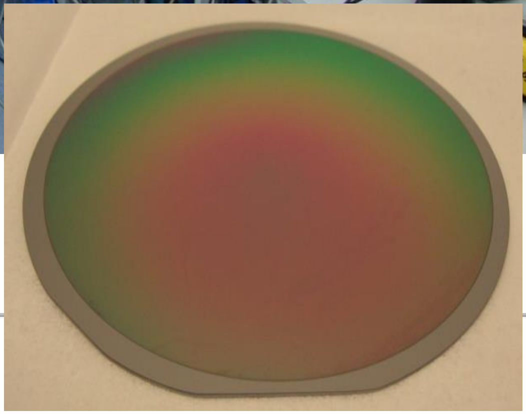
Plasma-Assisted MBE (PAMBE) Riber Compact 21



- optical pyrometer
- RHEED
- mass spectrometer
- reflectometry
- LayTec EpiCurve TT (temperature, curvature)
- kSpace RHEED software

SOURCES:

- Ga x2
- Al x2
- In
- RF nitrogen source
- Si x 2
- Mg
- Fe

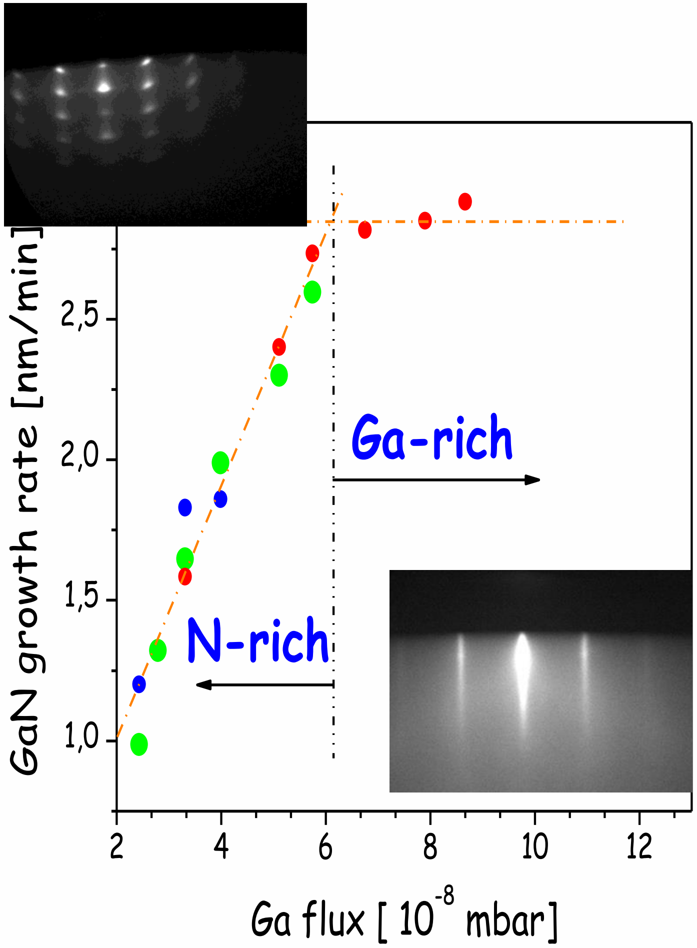


growth on
3″ substrates

PAMBE of GaN: growth conditions

MOVPE GaN: T ~ 1050°C
ammonia MBE GaN: T ~ 850°C

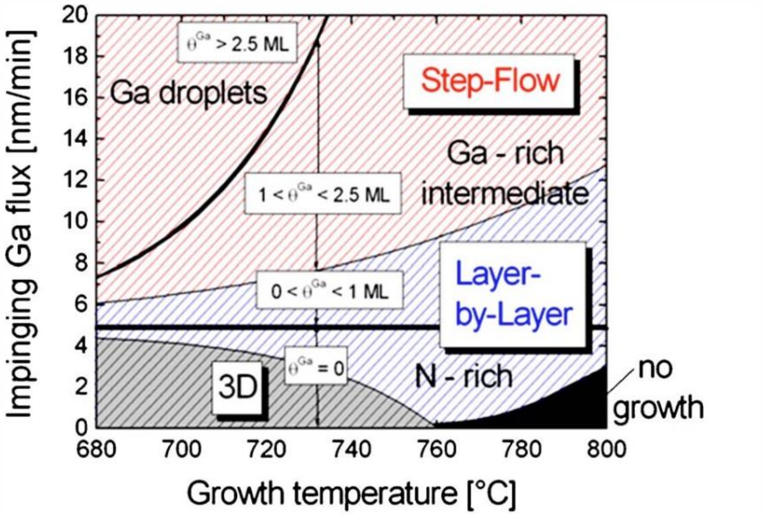
N-rich



PA MBE GaN: T ~ 700°C

Ga-rich

- Excess Ga on the surface during Ga-rich conditions
- Ga-rich conditions necessary for high-quality planar growth
- N-rich – 3D growth



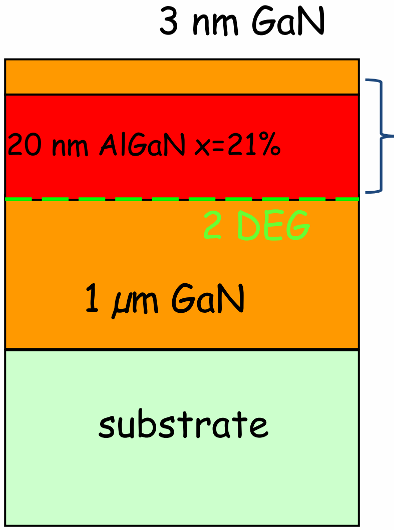
Koblmüller *et al.* Appl. Phys. Lett. **91**, 161904 (2007)

GaN growth rate up to 1 μ/h

ON 4.5 Group of MBE Growth of Nitride Nanostructures – research activity

1. AlGaN/GaN heterostructures on GaN/sapphire

typically on GaN/Al_2O_3 @RT: $n \sim 1\times10^{13}$ cm^{-2}; μ = 1500 – 1700 cm^2/Vs



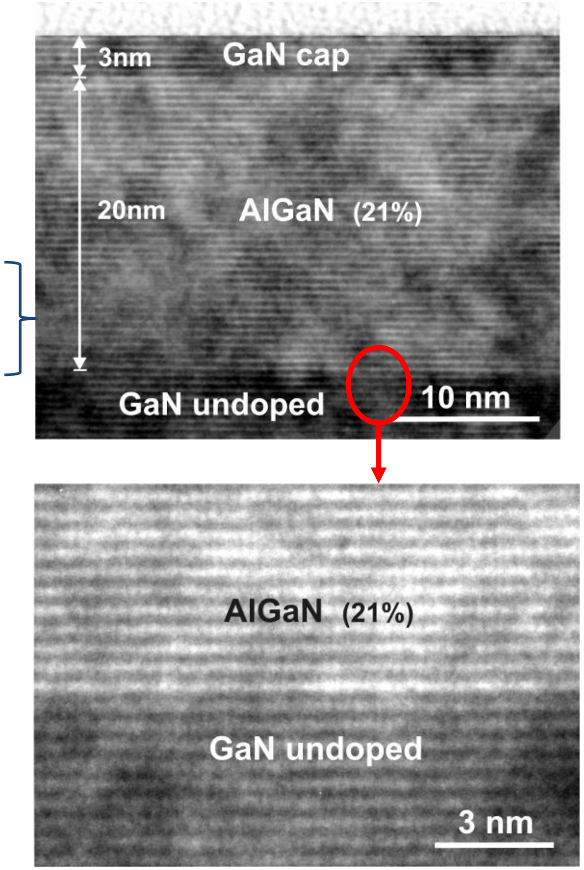
3 nm GaN

20 nm AlGaN x=21%

2 DEG

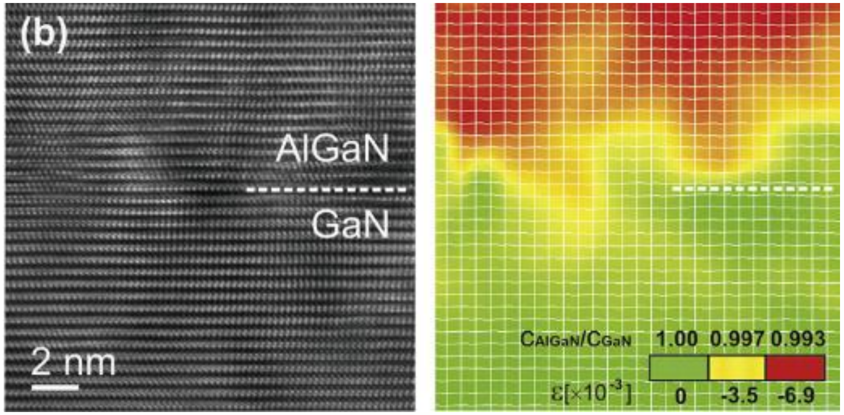
1 μm GaN

substrate



TEM

HR TEM



strain analysis at GaN/AlGaN interface

Borysiuk et al. JCG (2014)

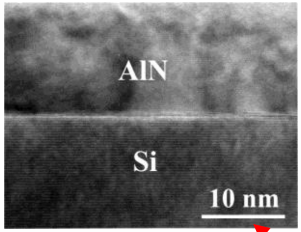
ON 4.5 Group of MBE Growth of Nitride Nanostructures – research activity

2. Al(Ga)N/GaN heterostructures on Si and bulk GaN

(AlGaN/GaN HEMTs on Ammono bulk GaN – new project)

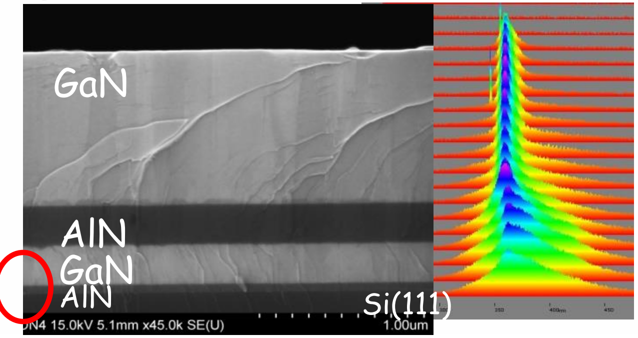
on Si(111)

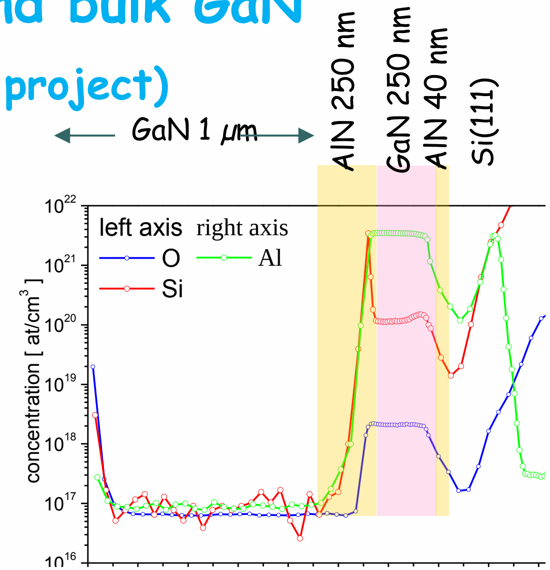
TEM



SEM

CL profiling

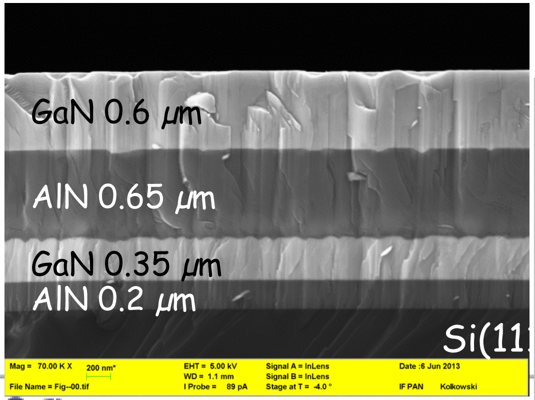


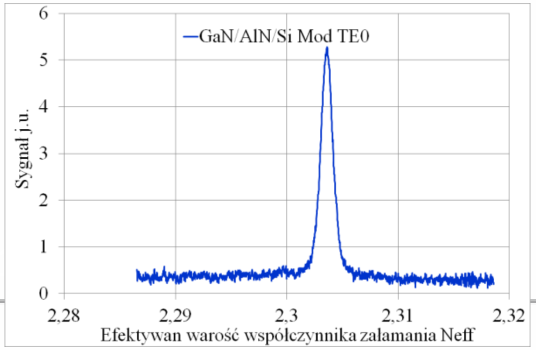


improvement of quality with thickness

optical waveguide GaN/AlN/Si

on bulk GaN

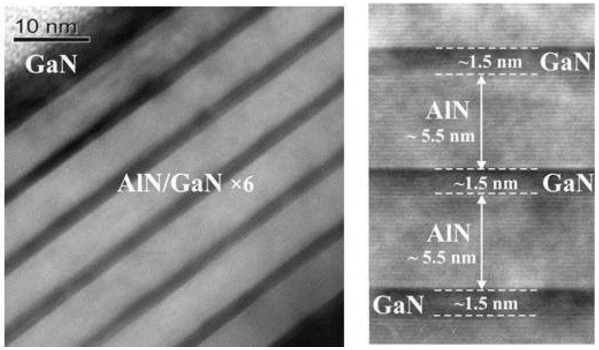




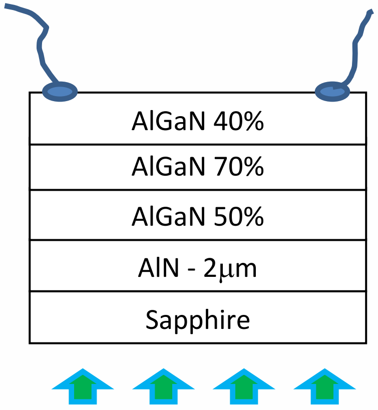
ON 4.5 Group of MBE Growth of Nitride Nanostructures – research activity

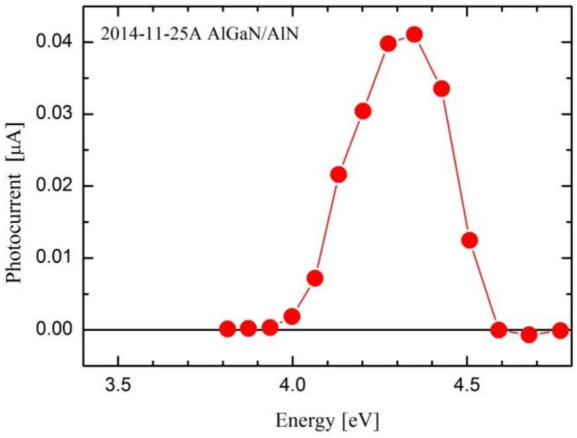
3. Al(Ga)N/GaN SLs & QWs

TEM



4. AlGaN/AlN selective photodetectors


AlGaN 40%
AlGaN 70%
AlGaN 50%
AlN - 2μm
Sapphire



5. III-N nanowires: physics and PAMBE growth technology

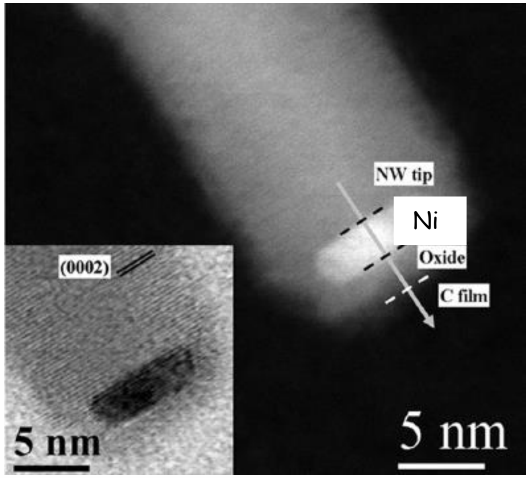
Questions:

- nucleation mechanism and kinetics; influence of substrate microstructure
- growth mechanism (axial vs. radial)
- doping
- ways of controlling in-plane and out-of-plane arrangements
- crystallographic perfection and optical properties
- ……

GaN nanowires – growth modes

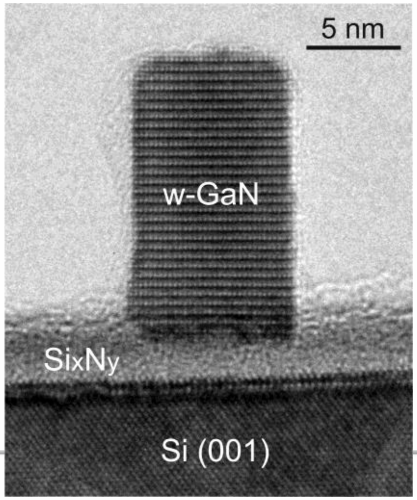
VLS on sapphire with Ni catalyst
0.3 nm Ni + 750°C

L. Lari, et al.
JCG **327** (2011)

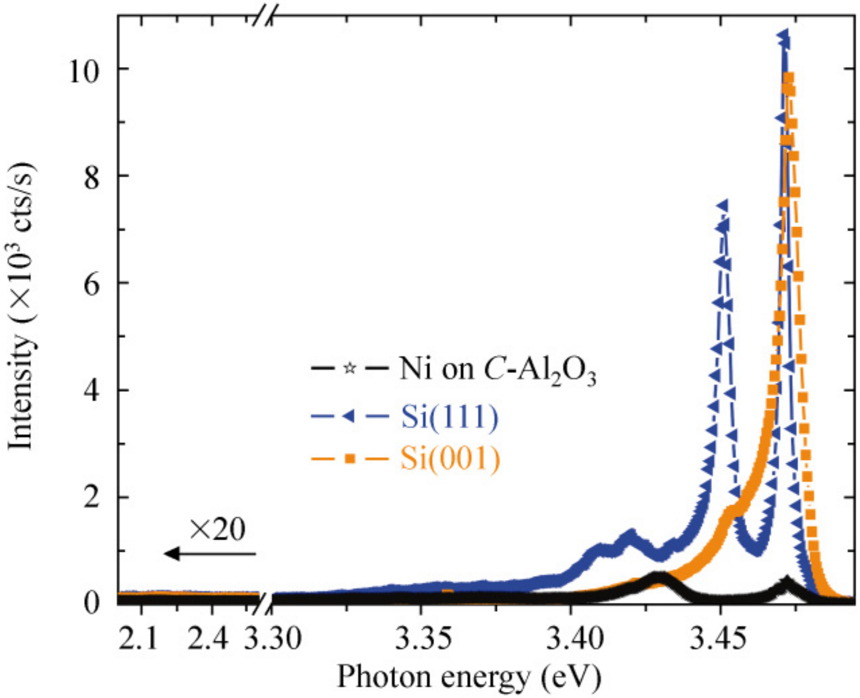


catalyst-free on Si(001)

J. Borysiuk, et al.
Nanotechnology
25 (2014) 135610



C, Cheze, et al. Nano Res **3** (2010)

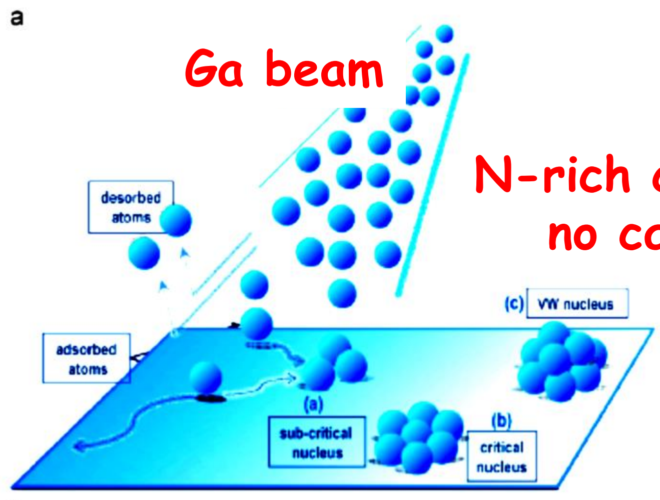


- D^0X = 3.472 eV for all cases
  (typical for strain-free GaN layers)
- PL intensity much lower (x 25) for GaN NWs grown with Ni – unintentional doping and defects (basal SFs)

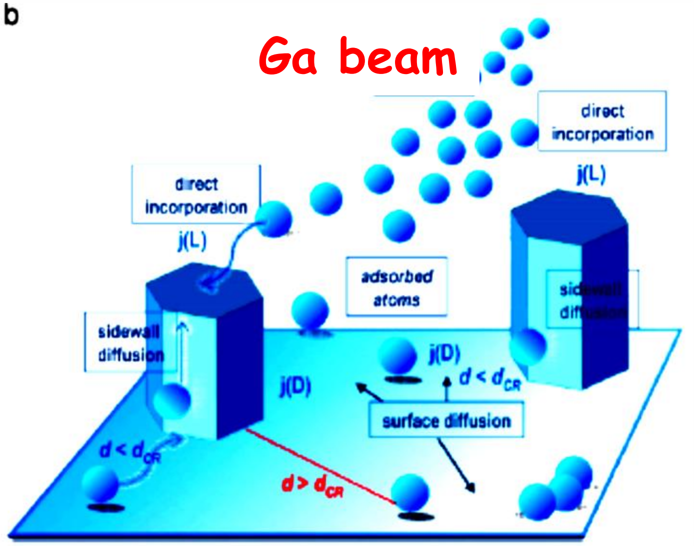
much better optical properties of GaN NWs grown catalyst-free

Brussels, March 11th, 2015

Mechanism of catalyst-free growth of GaN NWs



N-rich conditions
no catalyst



Ristic et al. JCG 310 (2008)

Two steps in growth of NWs:

1. self-induced nucleation (Volmer-Weber mechanism): adatoms migrate on the surface or desorb until stable critical nuclei are formed

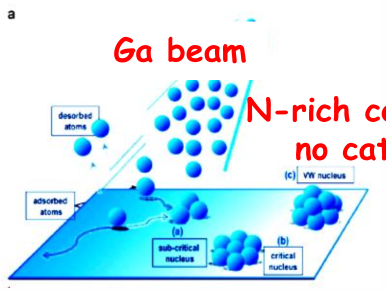
Influence of substrate microstructure on:

a. nucleation rate
b. arrangement and properties of NWs

2. growth of NWs by incorporation of Ga atoms from substrate surface around NW and directly from the Ga beam

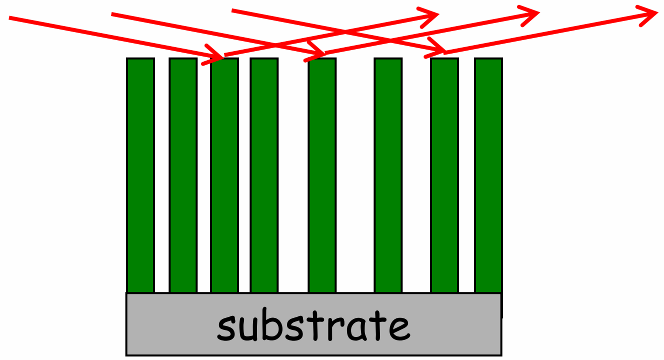
in situ monitoring of nucleation of NWs: RHEED

M. Sobańska, et al. (unpublished)



Ga beam

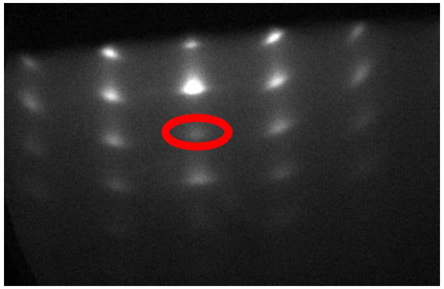
N-rich conditions
no catalyst

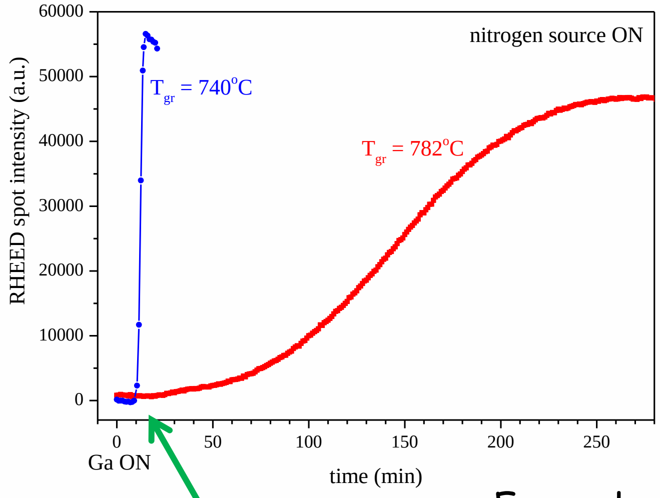


electron beam

RHEED pattern

substrate

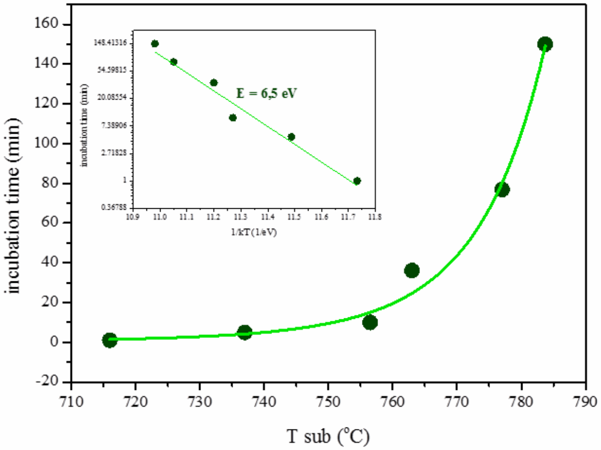




incubation time τ

$$\boxed{\tau \sim \exp(-E/kT)}$$

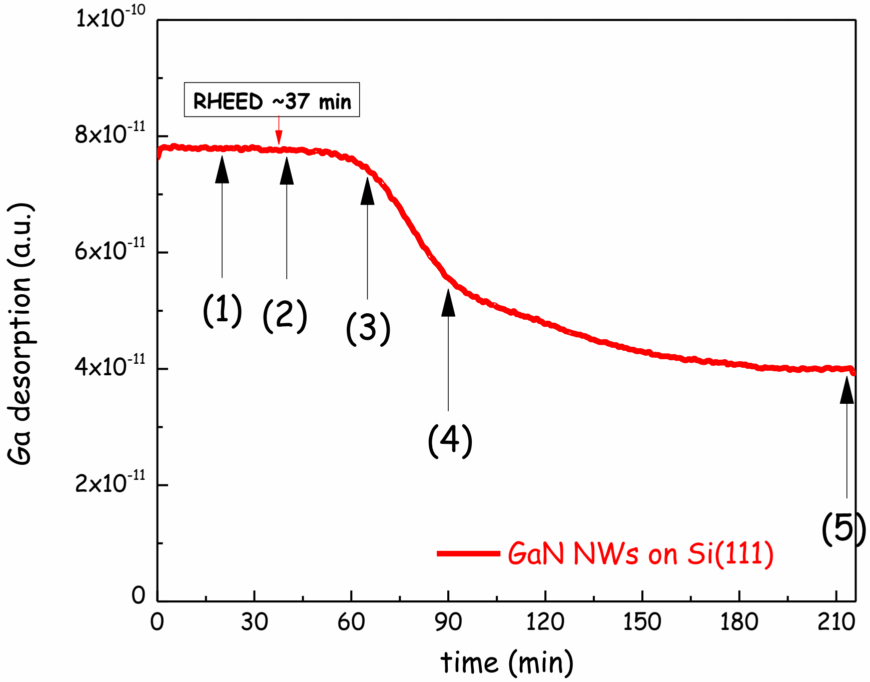
E – nucleation energy
(dependent on microstructure of the substrate, impurities, defects, ...)

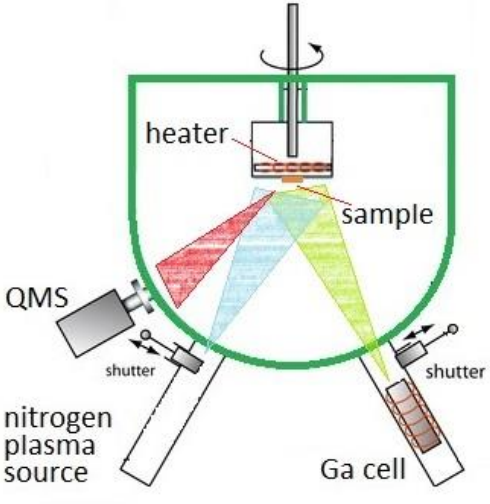


GaN NWs on a-Al_2O_3

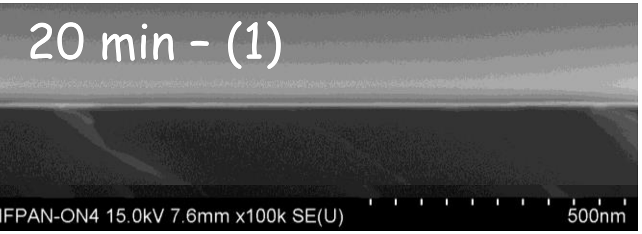
in situ monitoring: QMS i SEM

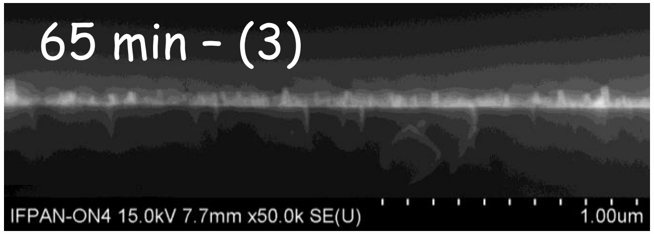
M. Sobańska, et al. (unpublished)

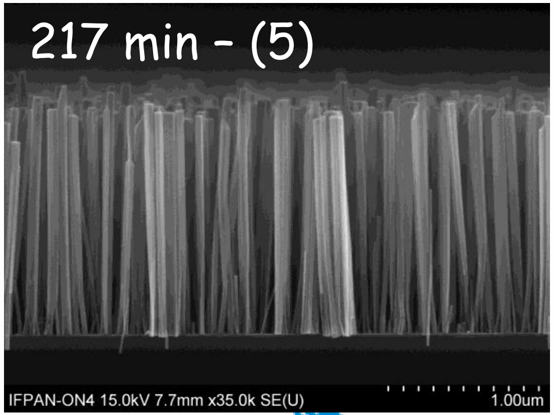


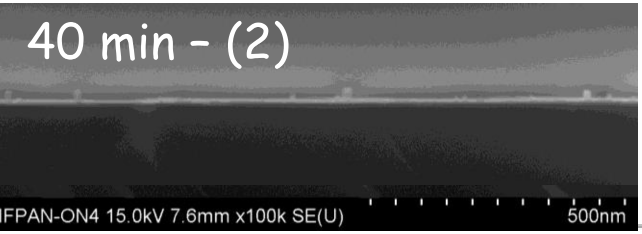


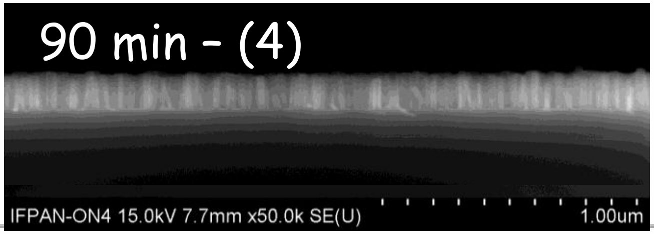
$$\Phi_{Ga} = \Phi_{gr} + \Phi_{out} \qquad \Phi_{QMS} \sim \Phi_{out}$$


20 min - (1)


65 min - (3)


217 min - (5)

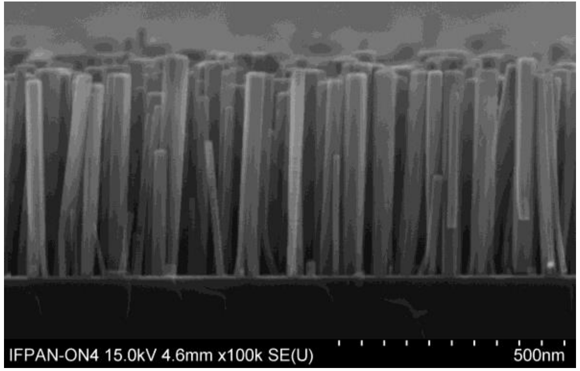

40 min - (2)

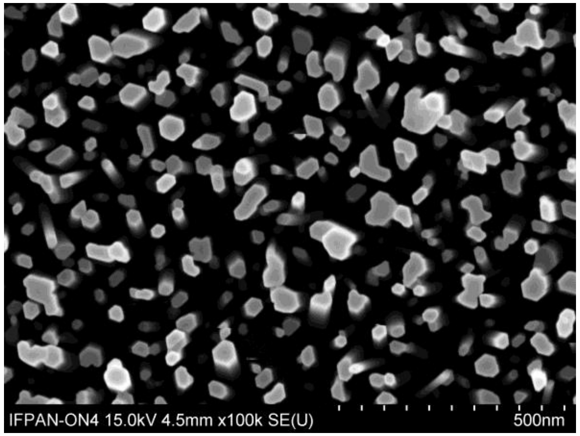

90 min - (4)

GaN NWs on Si(111) with Si_xN buffer: SEM and TEM

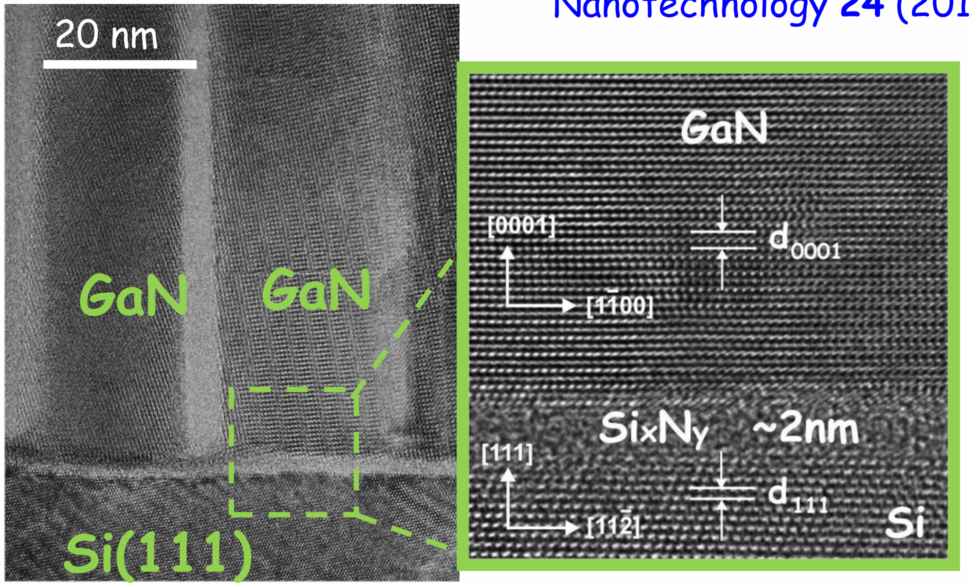
A. Wierzbicka, et al.
Nanotechnology **24** (2013) 035703

A. Reszka - SEM





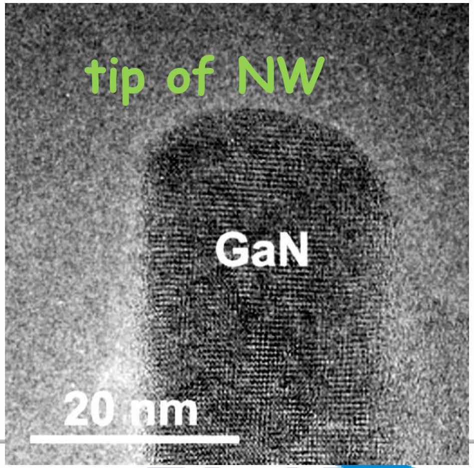
- Ø ~ 30 nm; L ~ 470 nm
- density ~ 250 μm^{-2} (~2.5×10^{10} cm^{-2})



TEM

- no defects at the GaN/Si_xN interface
- no wetting GaN layer

TEM

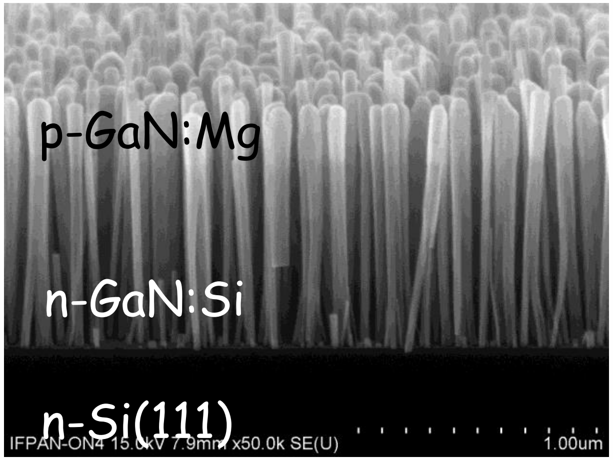


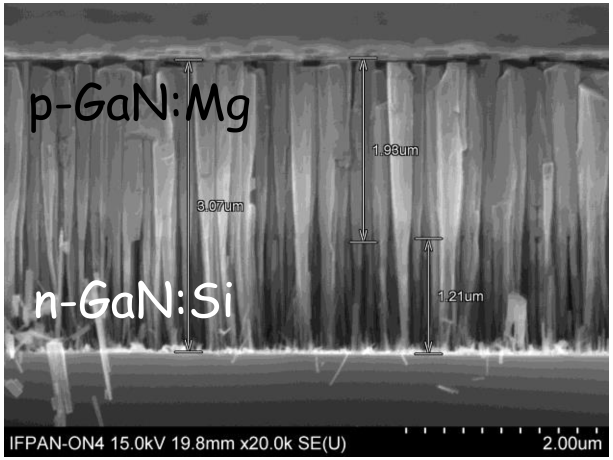
- uniform length
- N-polar
- very intense PL dominated by D^0X

NWs: examples of heterostructures

GaN p - n junction

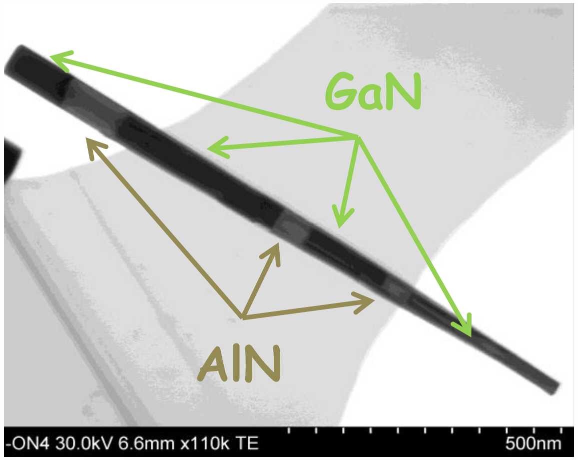
SEM

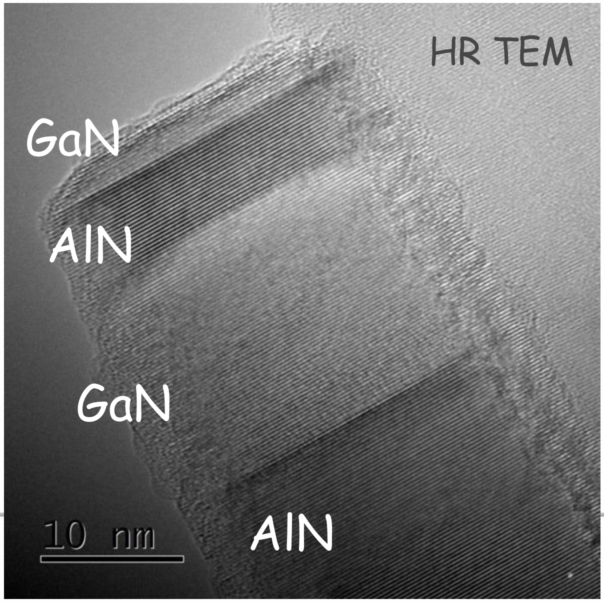




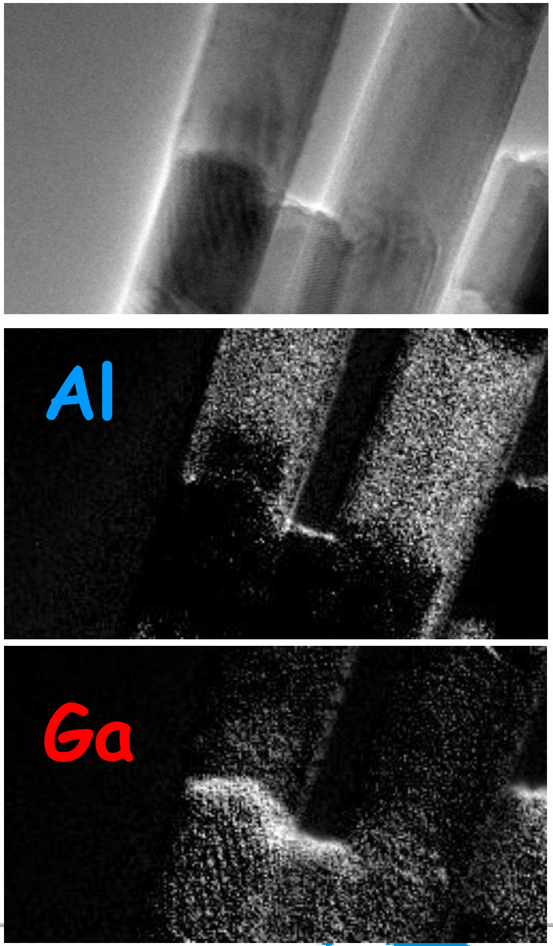
GaN/Al(Ga)N heterostructures

TE SEM





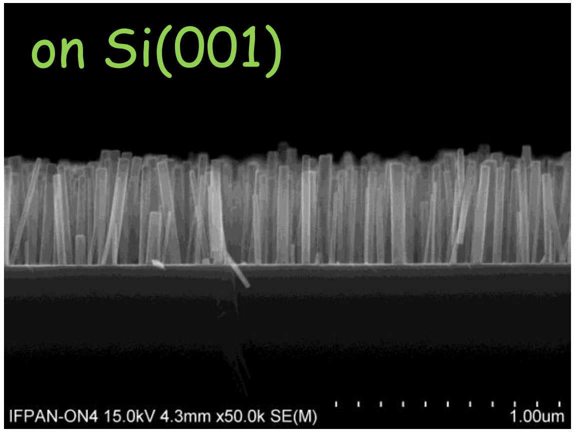
FTEM

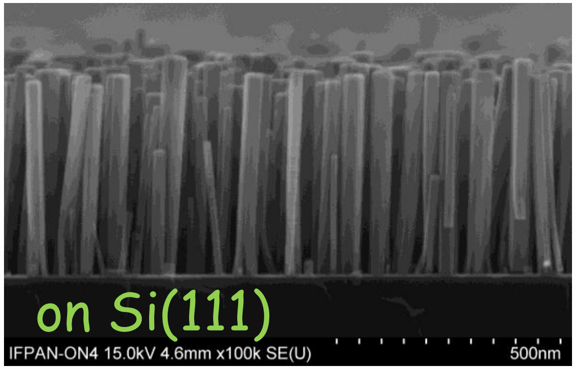


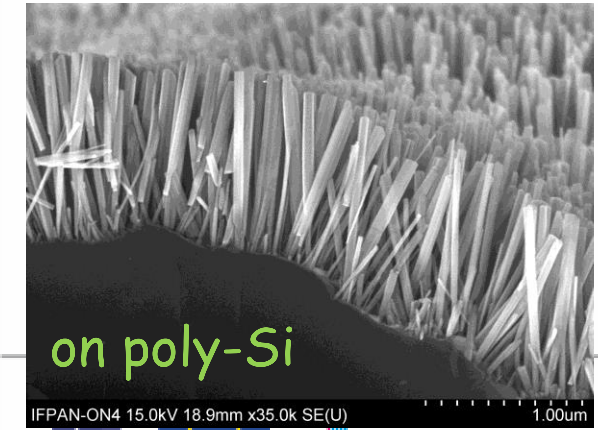
Unique feature of GaN nanowires on Si

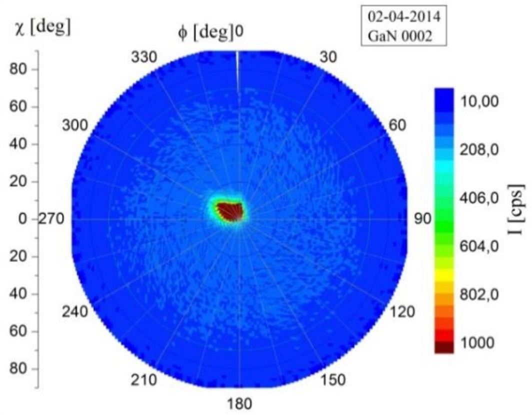
NWs always perpendicular to the surface of Si

if silicon nitride interlayer is present between GaN and Si


on Si(001)

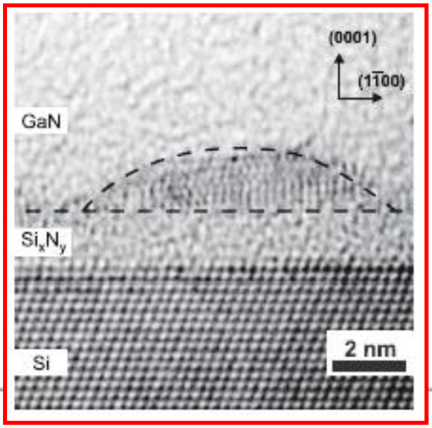

on Si(111)


on poly-Si

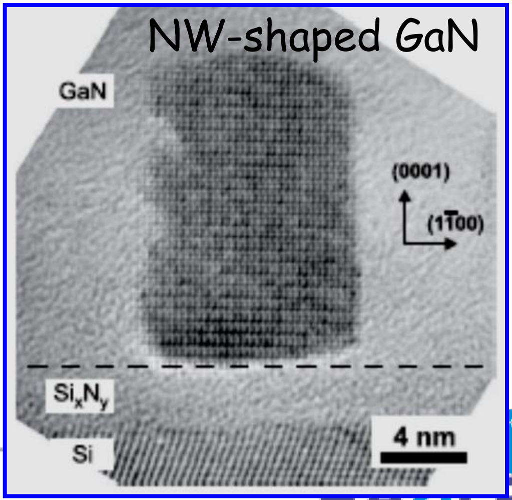


XRD pole figures

tilt = ±2.5°



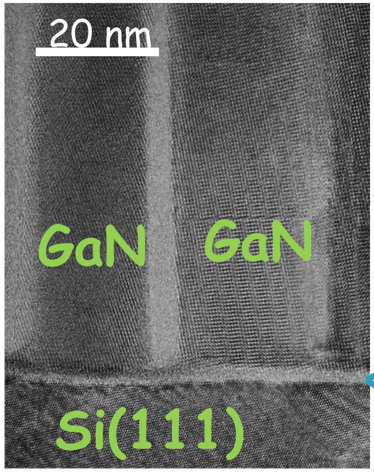
shape change



Consonni et al. PRB **83** (2011)

Arrangement on Si (111) substrate: twist

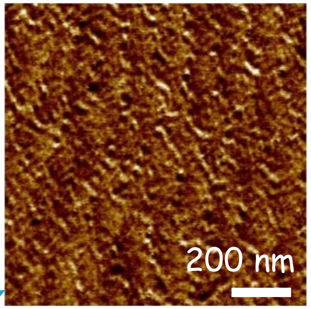
A. Wierzbicka, et al.
Nanotechnology **24** (2013) 035703



in-situ
2 nm Si_xN
(<150 °C)

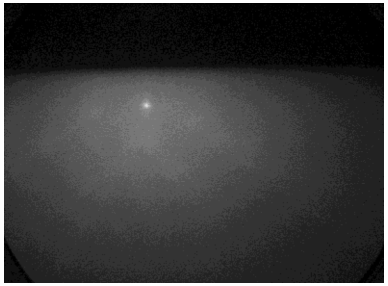
amorphous Si_xN layer

E. Łusakowska - AFM

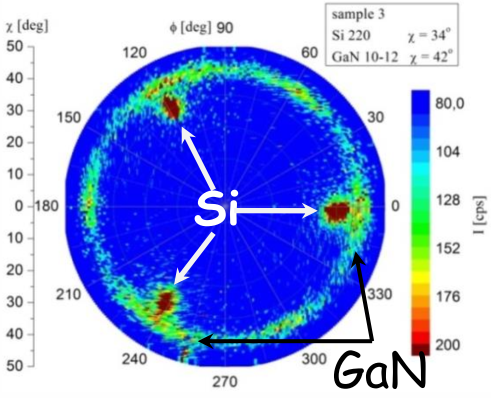


RMS = 0.15 nm

RHEED



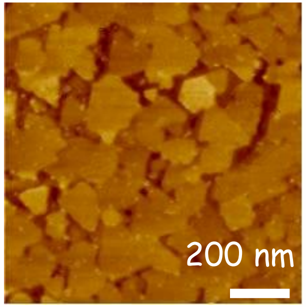
XRD pole figures



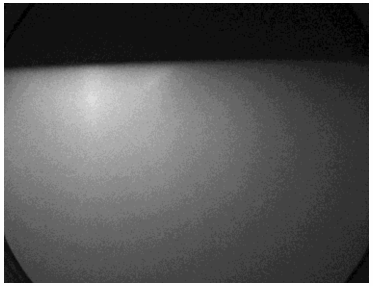
random twist of NWs

in-situ
2 nm Si_xN
(850 °C)

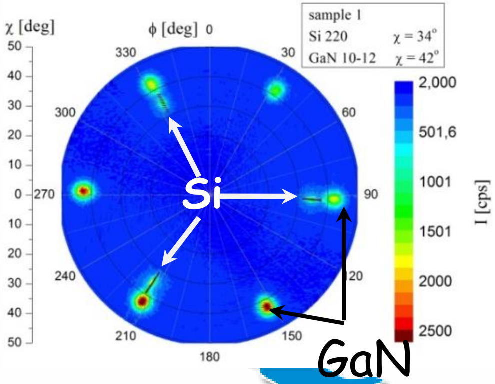
1 nm deep groves;
~150-200 nm hex islands
RMS = 0.47 nm



RHEED



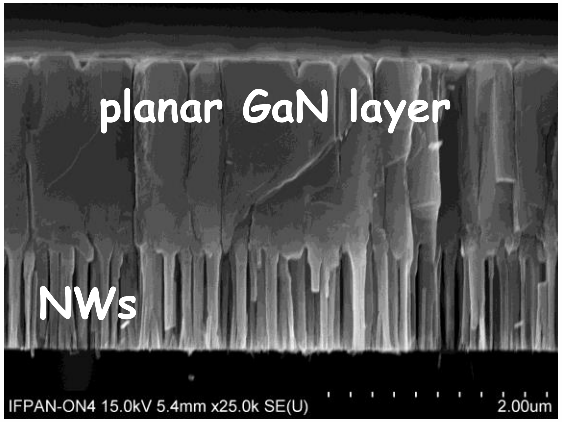
epitaxial alignment GaN to Si
(as in planar GaN/Si(111))

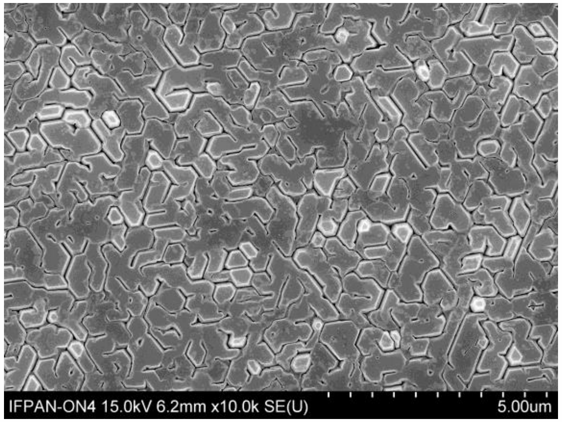


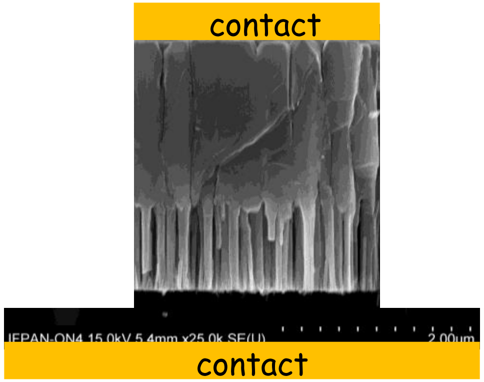
"partially" amorphous Si_xN layer

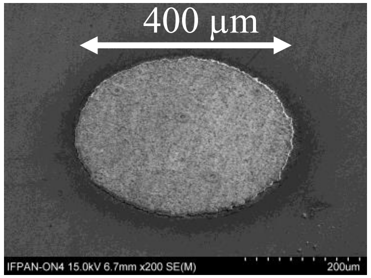
Is coherence of twist important? Planarization of NWs.

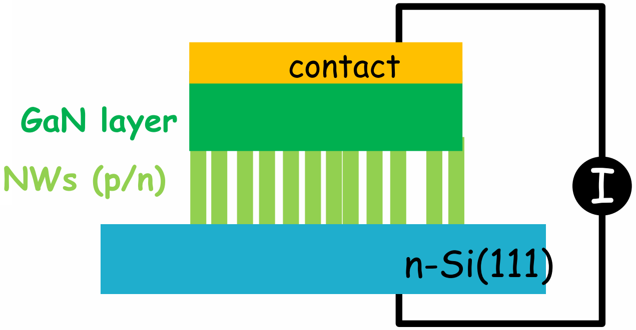
alignment to the substrate important in fully-overgrown structures











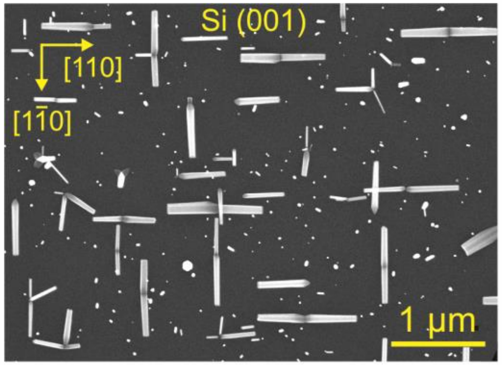
- high sensitivity, but long reaction time due to a high density of NWs
- optimization of mesa diameter and/or density of NWs are needed to speed up gas exchange in the sensor

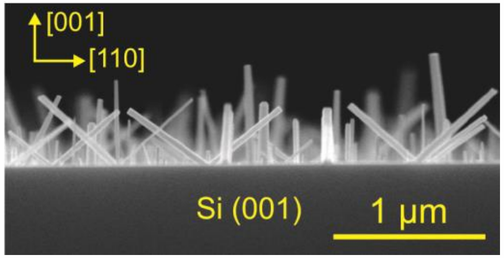
processing R. Kruszka, K. Gołaszewska - ITE

Unusual inclined GaN NWs on Si(001) substrate

J. Borysiuk, et al. Nanotechnology **25** (2014) 135610

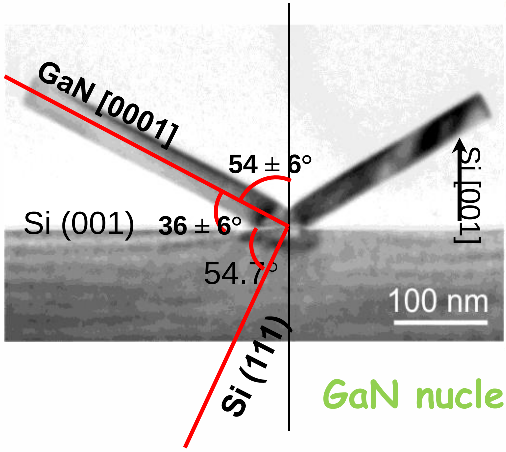
Occasionally 2 types of NWs found on Si(001): vertical (standard) and inclined

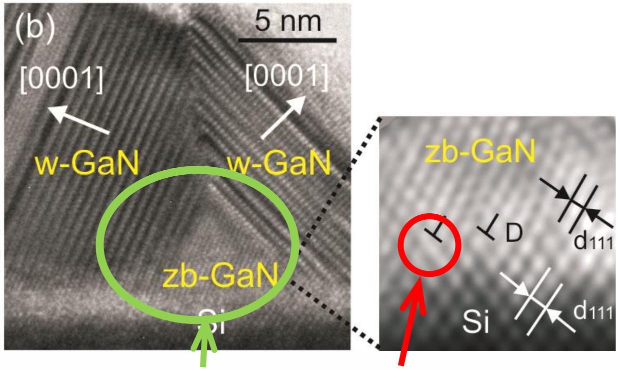




inclined NWs:

- exhibit fourfold symmetry pattern on the substrate
- are longer and thicker than their vertical neighbors
- are perpendicular to the Si (111) planes (TEM and XRD)
- are Ga-polar
- grow from Ga droplet in contact with substrate (no Si_xN layer)

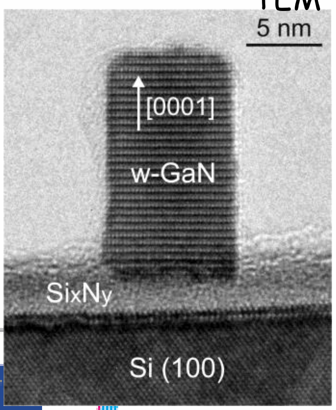




GaN nucleates in zb-form

dislocation

TEM



standard NWs:

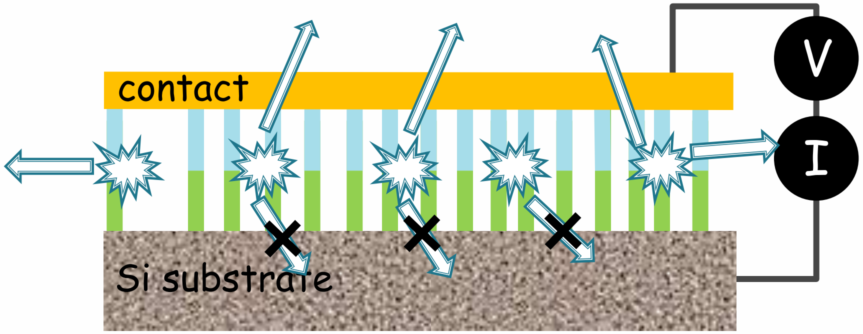
- ~2 nm Si_xN
- GaN NWs without defects

EAgLE

Brussels, March 11th, 2015

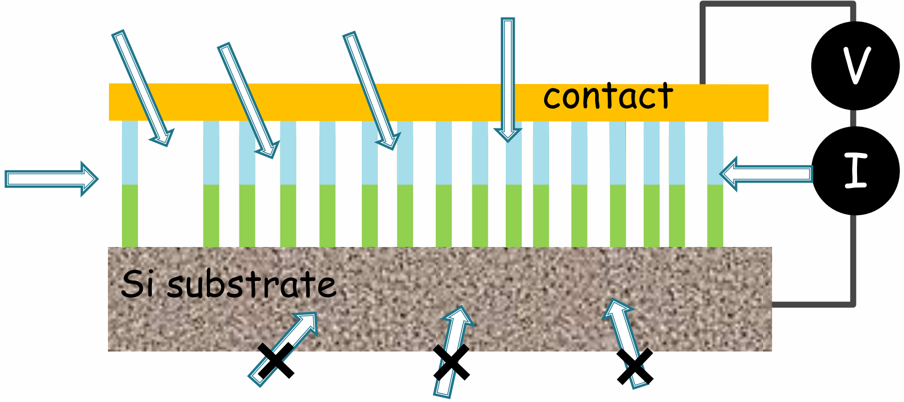
Is silicon the best substrate for growth of GaN NWs?

GaN NWs LED (p-n)



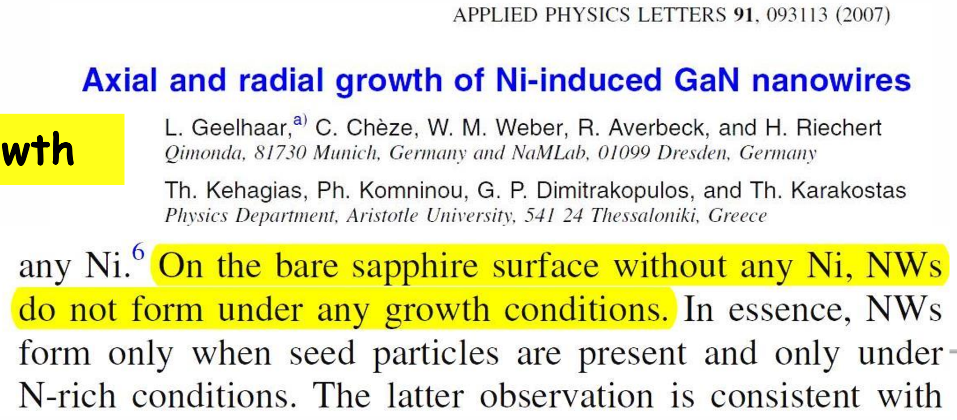
in LED large part of generated light is absorbed by Si substrate

GaN NWs photodetector



in photodetector light reaches the active layer (NWs) only through the upper contact

- optical access to NWs difficult
- Si incorporated to GaN NWs at very high growth temperatures
- substrate transparent and inert to Ga needed —> sapphire



APPLIED PHYSICS LETTERS **91**, 093113 (2007)

Axial and radial growth of Ni-induced GaN nanowires

L. Geelhaar,[a] C. Chèze, W. M. Weber, R. Averbeck, and H. Riechert
Qimonda, 81730 Munich, Germany and NaMLab, 01099 Dresden, Germany

Th. Kehagias, Ph. Komninou, G. P. Dimitrakopulos, and Th. Karakostas
Physics Department, Aristotle University, 541 24 Thessaloniki, Greece

any Ni.[6] On the bare sapphire surface without any Ni, NWs do not form under any growth conditions. In essence, NWs form only when seed particles are present and only under N-rich conditions. The latter observation is consistent with

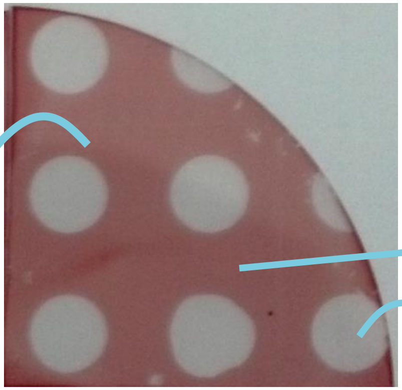
catalyst-free growth

PAMBE of GaN NWs on sapphire

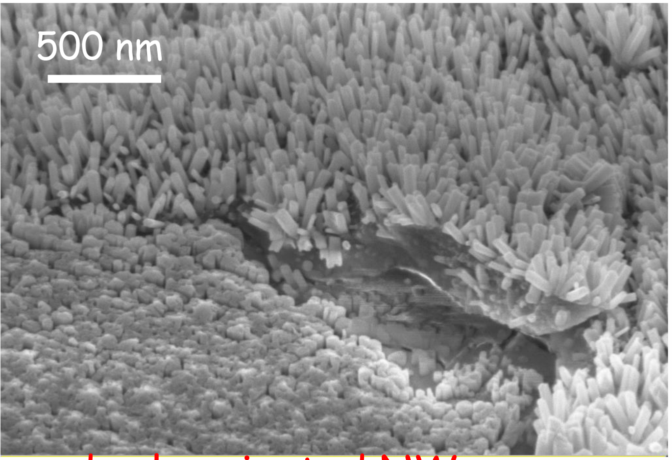
M. Sobanska, et al. JAP **115** (2014) 043517

the same conditions as for our standard growths of GaN NWs on Si

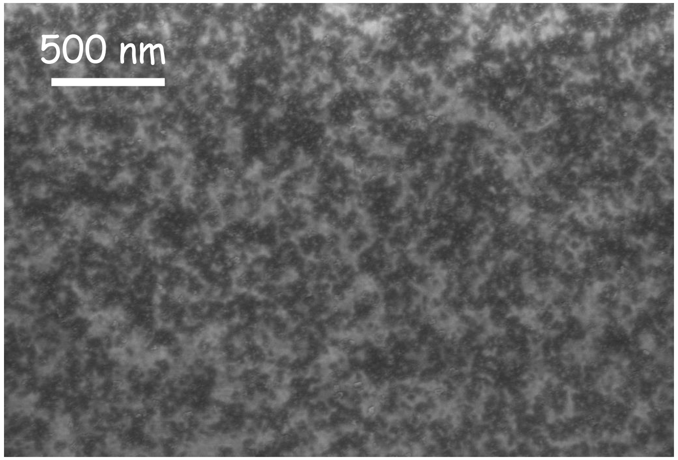
crystalline Al_2O_3



intentional scratch

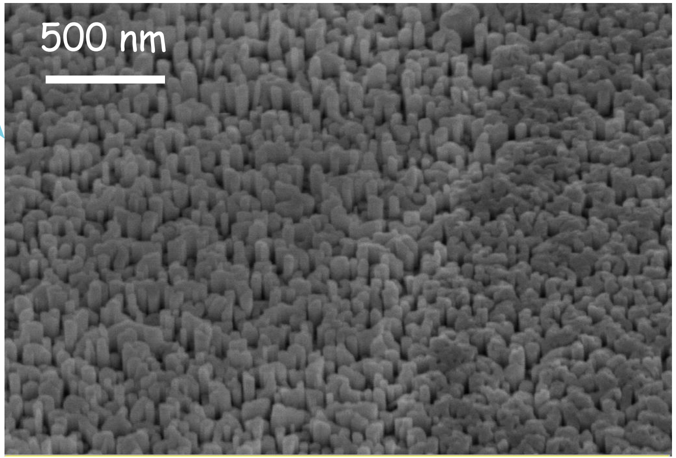


randomly oriented NWs



no NWs present

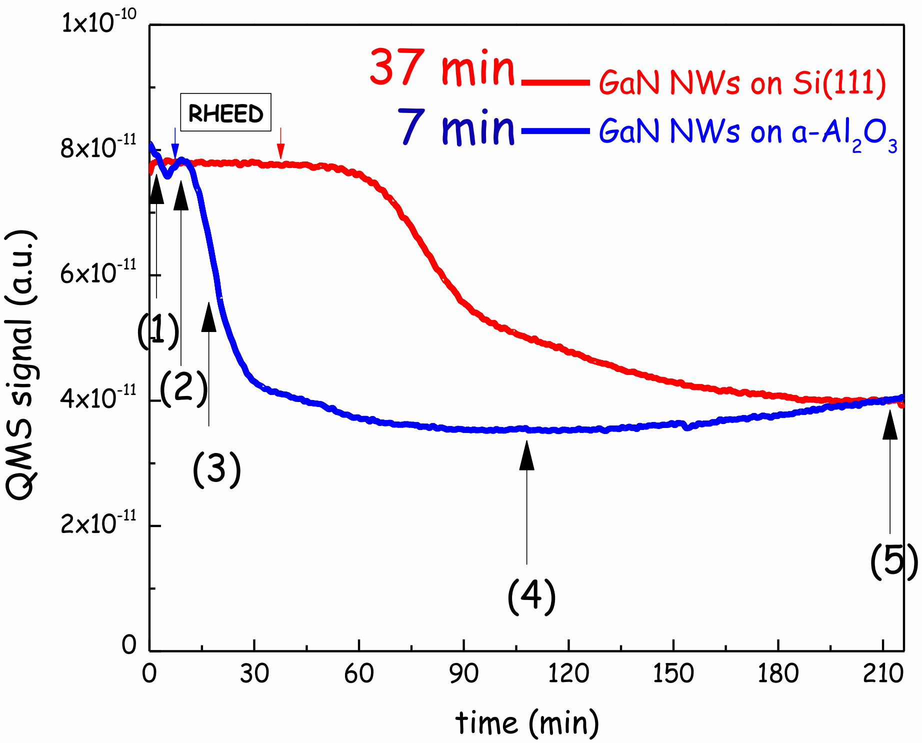
20 nm thick amorphous Al_2O_3



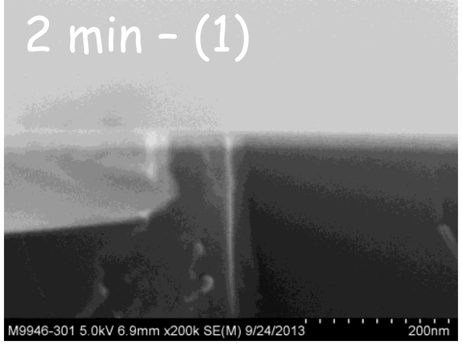
nicely organized NWs

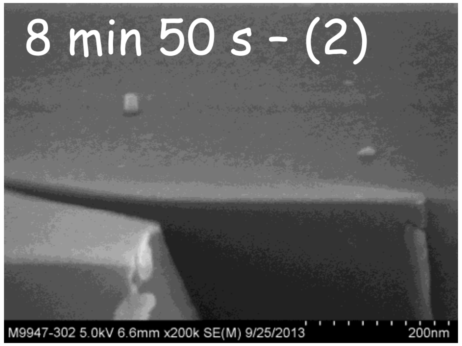
substrate microstructure matters !!!

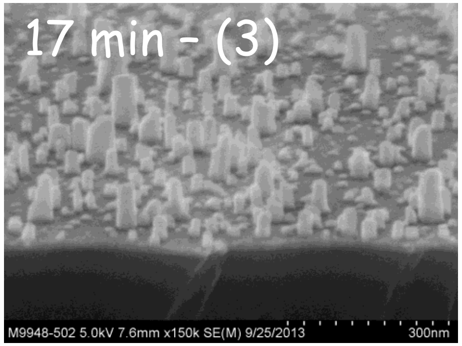
GaN NWs on a-Al_2O_3/Si: QMS and SEM

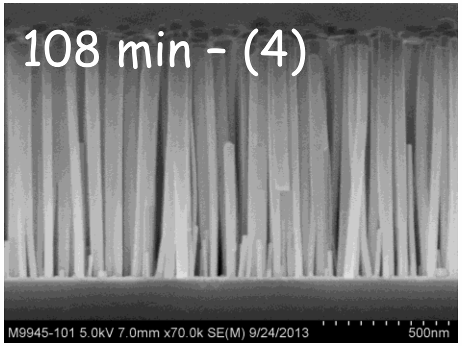


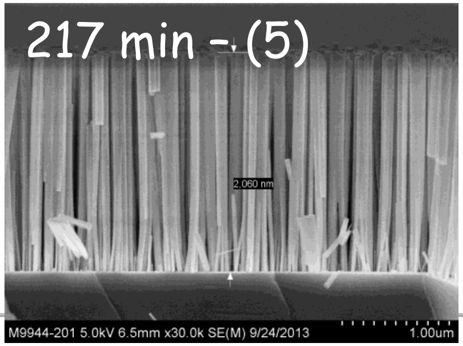
M. Sobanska, et al. (unpublished)









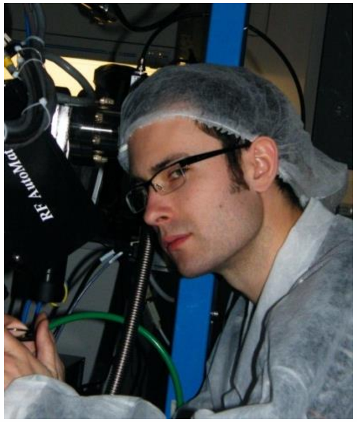


→ nucleation rate of NWs significantly enhanced by amorphous microstructure of the substrate

The team

Mgr Marta Sobańska – MBE

Mgr Kamil Kłosek – MBE



Dr Jola Borysiuk – TEM

Mgr Andrzej Cabaj

Mgr Giorgi Tchutchulashvili

Dr Ola Wierzbicka – XRD

+ many external partners

new cooperations most welcome