ESTEC-ESA - Wide Band Gap Technology Meeting,

17 - 18 October 2001

"ATHENA"-ESA Contract Status

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INTEC

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http://www.intec.rug.ac.be

Outline

- **Introduction to ATHENA-project**
  - main - CCN1 - structure

- **GaN developments**
  - WPs - collaborations - CCN2
  - MOVPE of GaN
  - growth on sapphire
  - non planar growth and other substrates
  - 2DEGs
  - HEMTs

ESA-ATHENA: Main contract

- **ATHENA = Development of advanced technologies for low-defect hetero-epitaxial growth of GaN and InGaAs**
- **Objectives**
  - Development of new substrates and advanced growth technologies for low defect epitaxial layers
    - (In)(Al)GaN
    - InGaAs
  - Applications
    - AlGaN microwave power devices
    - InGaAs extended wavelength detectors
  - Delivery of demonstrator devices
- **Period**
  - 1/4/2000 - 30/9/2003

ESA-ATHENA: CCN1

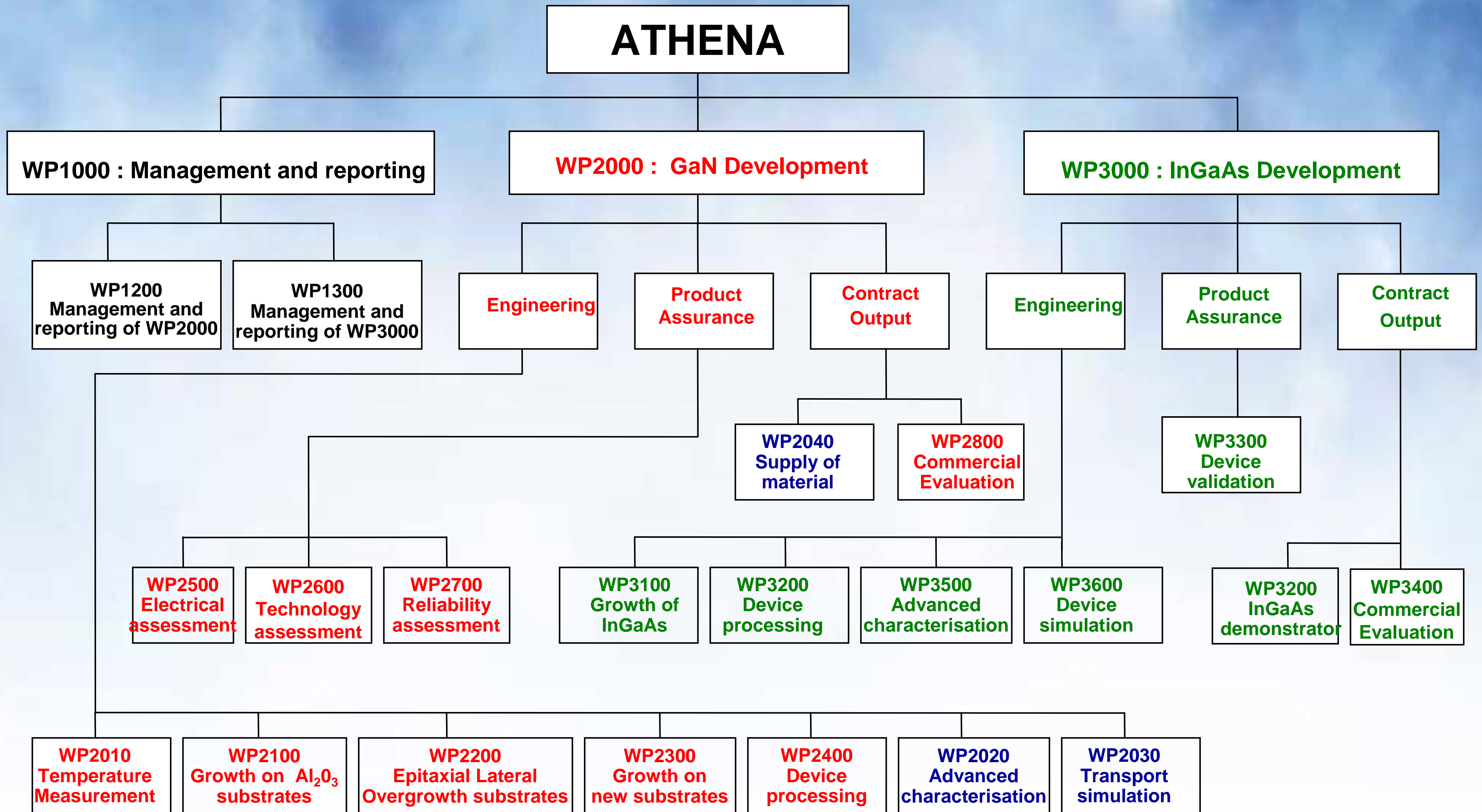
Objectives

- Advanced material characterisation
  - HR-XRD, TEM, SIMS, …
- Transport simulation of AlGaN/GaN 2-DEG
- Supply of GaN material for process and device development
- Extra substrates for reproducibility tests

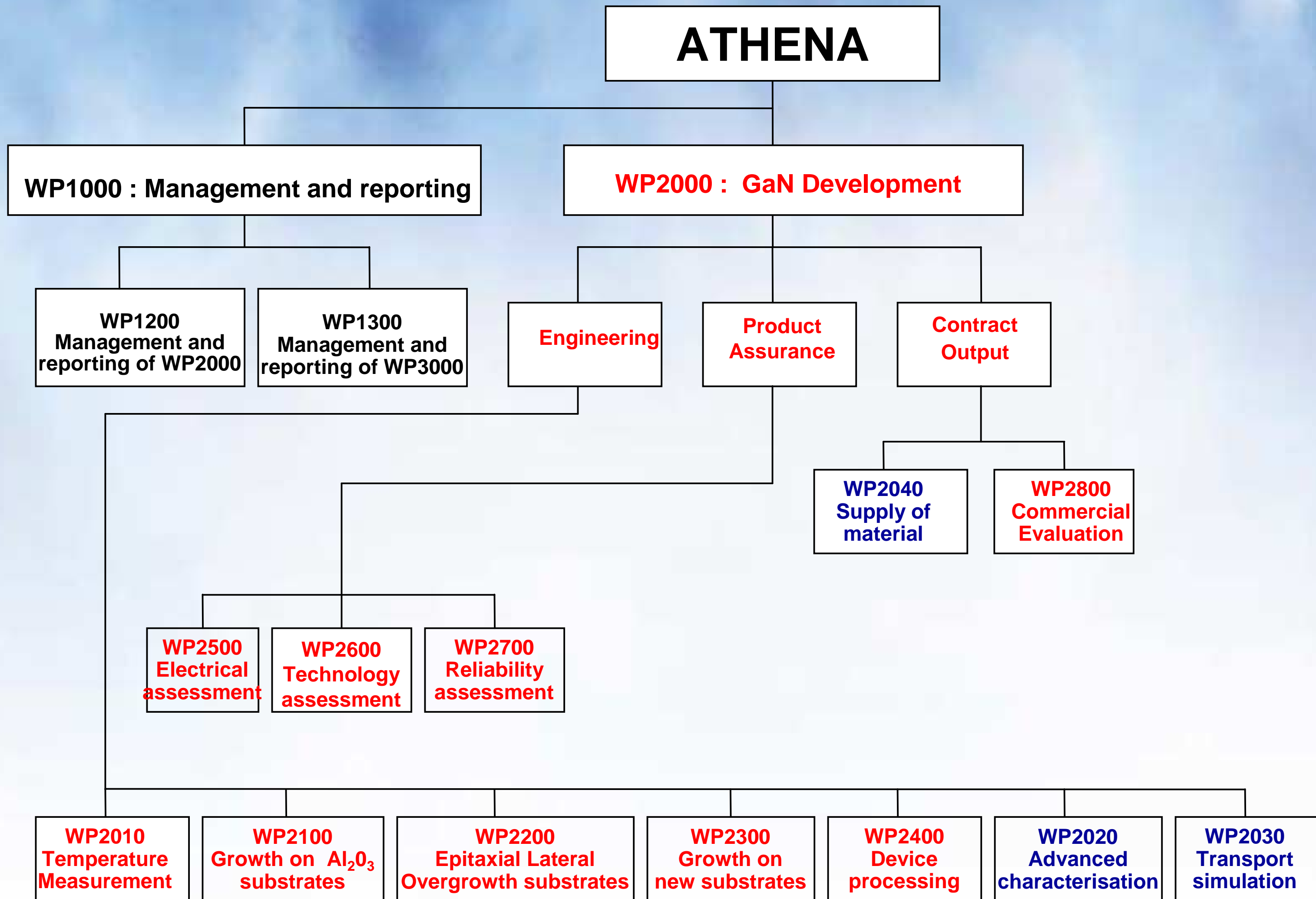
Structure of ATHENA project

- **WP1000: Management**
- **WP2000: Development of GaN layers**
  - *Partners*:
    - IMEC (B)
    - Marconi Caswell Limited (MCL, UK),
    - Thomas Swan Scientific Equipment Ltd. (TSSEL, UK)
    - Umicore (B)
  - *Activities*:
    - Epitaxial growth of GaN-layers
    - GaN device processing
    - GaN device validation
- **WP3000: Development of InGaAs layers**
  - *Partners*: IMEC, Umicore
  - *Activities:*
    - Epitaxial growth of InGaAs-layers
    - InGaAs device processing
    - InGaAs device validation

Structure of ATHENA project (WBS)



Structure of ATHENA project (WBS)



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WP2000: GaN Development (1)

- **Epitaxial growth**
  - WP2100: Growth on Al_2O_3-substrates (IMEC)
  - WP2200: Epitaxial lateral overgrowth structures (IMEC)
  - WP2300: Growth on new substrates (IMEC, Umicore)
  - WP2010: Temperature measurement (TSSEL)
    (high spatial resolution temperature monitoring)
- **CCN1**
  - WP2020: Advanced characterisation (IMEC)
  - WP2030: Transport simulation (IMEC)
  - WP2040: Supply of material (IMEC)

WP2000: GaN Development (2)

- **WP2400: Device processing (MCL)**
  - Processing & characterisation of AlGaN/GaN HEMTs
  - Feedback on material quality
- **Device validation (MCL)**
  - WP2500: Electrical assessment
  - WP2600: Technology assessment
  - WP2700: Reliability assessment
- **WP2800: Commercial Evaluation (All)**

ESA-ATHENA

Main collaborations

- *Etching, contacts, HEMT-process*
  - Madrid Polytechnic University (UPM)
  - COBRA, TUEindhoven
  - Laboratory INTEC-Hannover
  - IEMN
- *Transport modelling*
  - LSPES, University of Lille (Prof. J.-L. Farvacque)
- *Cryogenic Transport measurements:*
  - University College, London (J.J. Harris et al)
- *TEM*
  - EMAT, RUCA Antwerp
  - Cambridge University
- *PL*
  - CRHEA-Valbonne

ESA-ATHENA: CCN2

Some changes within ATHENA in 2002

- Transfer of GaN growth activities from Gent to Leuven
- Replacement of MCL by QinetiQ for GaN device processing
- Start up of device processing activity in IMEC (Leuven)

Future contact information

- IMEC vzw
  Kapeldreef 75, B-3001 Leuven, Belgium

- Contact persons:
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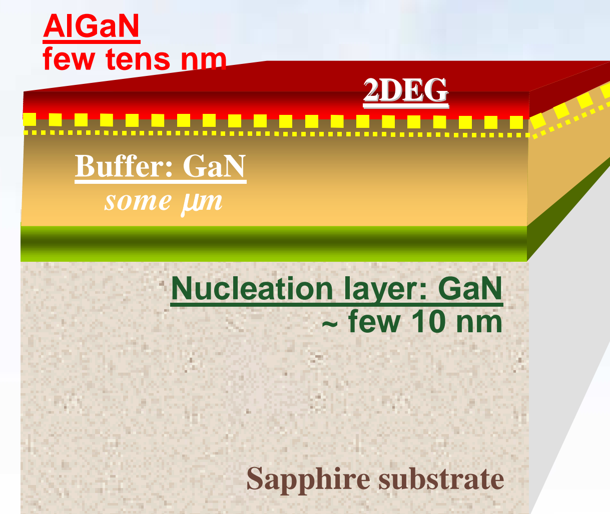
  - Marianne Germain (marianne.germain@imec.be)
  - Maarten Leys (maarten.leys@imec.be)
  - Staf Borghs (borghs@imec.be)

WP2000: GaN development (1)

Objectives for GaN based layers

- Application for power device (HEMT)
- Best Specifications:
  - Electron sheet density: ~ 2 x 10^{13} cm^{-2}
  - 2DEG mobility (300K): ~ 1400 cm^2/V.s
  - Al% uniformity on 2” wafer: 2%
  - Doping uniformity: 5%
  - Structural quality of GaN:
    - X-Ray (000n) FWHM: < 200 arcsec
    - Dislocation density (ELO): < 10^6 cm^{-2}
  - Sheet resistance of buffer: > 10 MΩ



WP2000: GaN development (2)

Material requirements

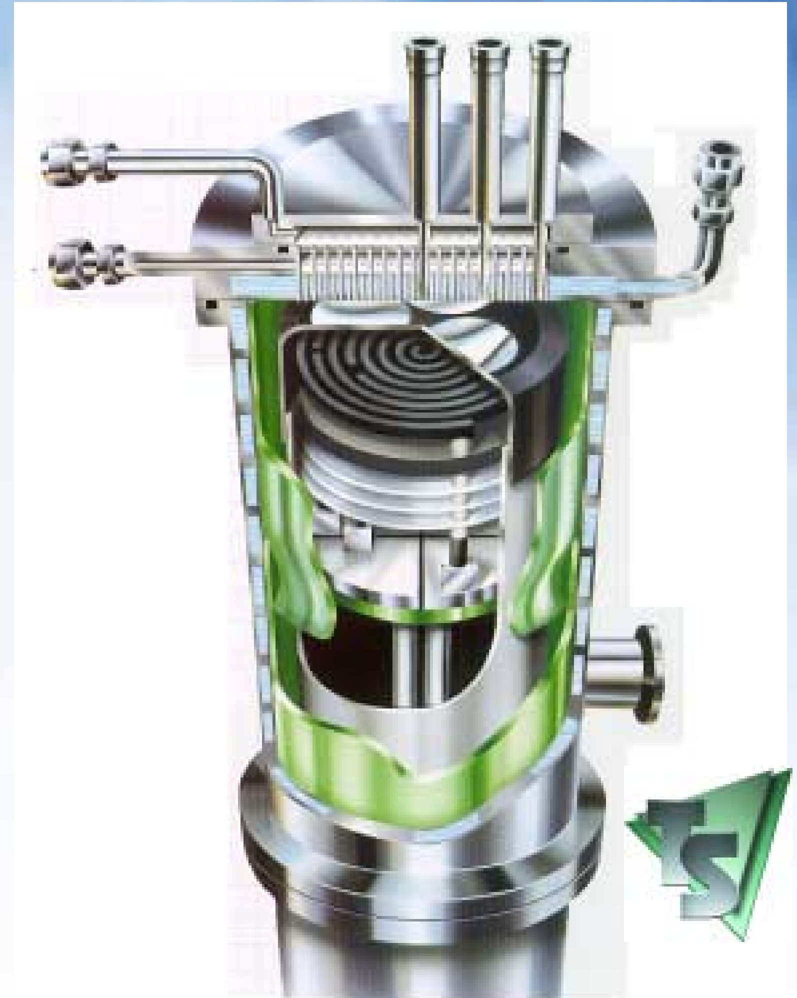
- Low point defect and impurity levels
- Low dislocation density / increase of sub-grain size
- Insulating GaN material available
- AlGaN-GaN HEMT optimum architectures:
  - AlGaN (homogeneity, piezo and spontaneous polarisations, modulation doping)
  - reduce interface roughness (smooth morphology)
  - undoped or Si doped channel (?)
  - possibly GaN or InGaN QW (?)

WP2000: growth environment

Thomas Swan 3x2” MOVPE-reactor

close-coupled showerhead (CCS) technology

- Vertical water cooled chamber
- Rotating disk to improve uniformity of thickness and alloy composition
- Showerhead injection for more efficient gas mixing
- 3-zone heating for more uniform temperature distribution



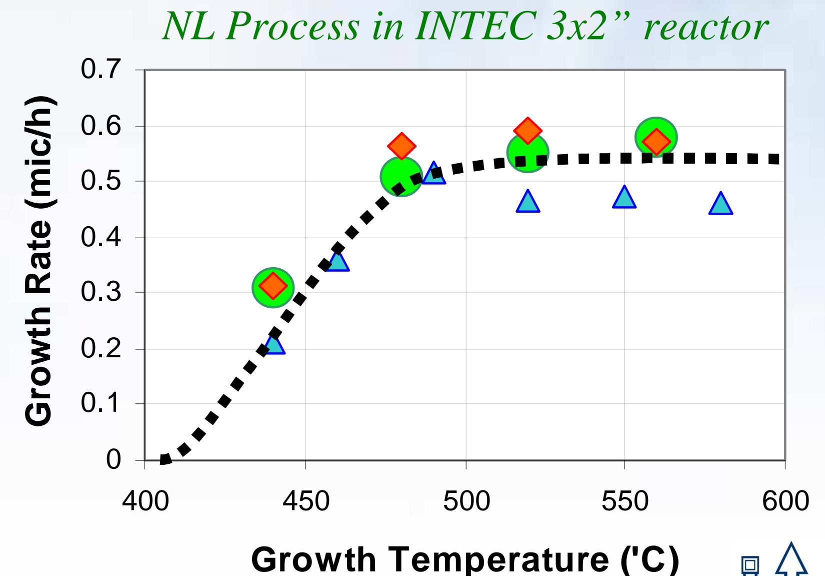
WP 2100 - Growth on Al_2O_3: program

- **Issues addressed in the growth program**
  - Engineering the epitaxy
    - Nucleation Layer (NL)
    - optimum parameters: growth temperature (Tg), growth rate (Vg), V/III are different for different reactors
    - reduce defects: background and threading dislocations
  - Control the conductivity
    - control of n type material behaviour ("Dislocation Wall effect")
    - control the *insulating* character of GaN layers
  - Ternary compound AlGaN
  - AlGaN-GaN interfaces
  - 2DEG characterisation and optimisation
  - Uniformity over 2" wafers
  - Reproducibility between susceptor pockets and from run to run
- ***Some realisations are presented hereafter….***

WP 2100 - Growth on Al_2O_3 : nucleation

Nucleation Layer

- Growth :
  - select growth rate in the saturation regime
  - impact on NL surface roughness and sapphire wetting
- Recrystallisation time :
  - control strain, stochiometry, microstructure
  - NL surface roughness
  - condition the residual conductivity…
- Optimum thickness :
  - 20 - 80 nm explored
  - optimum at 22-30 nm
- Other : Pressure, V/III, Vg
  - pressure: effect on sub-grain diameter...



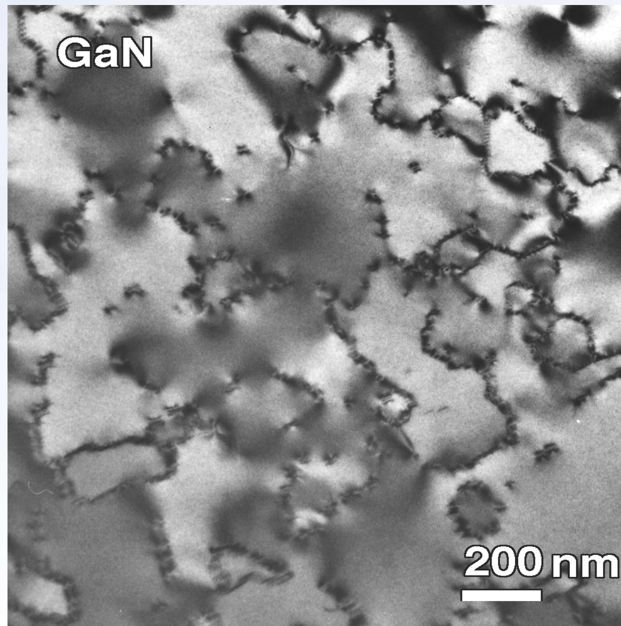
WP 2100 - peculiarity of the microstructure

Threading dislocation density: 2 examples

Old process in 1x2" Reactor

(PV- TEM: O. Lebedev, EMAT)

[dislo] ~ 2.10^{10} cm^{-2}

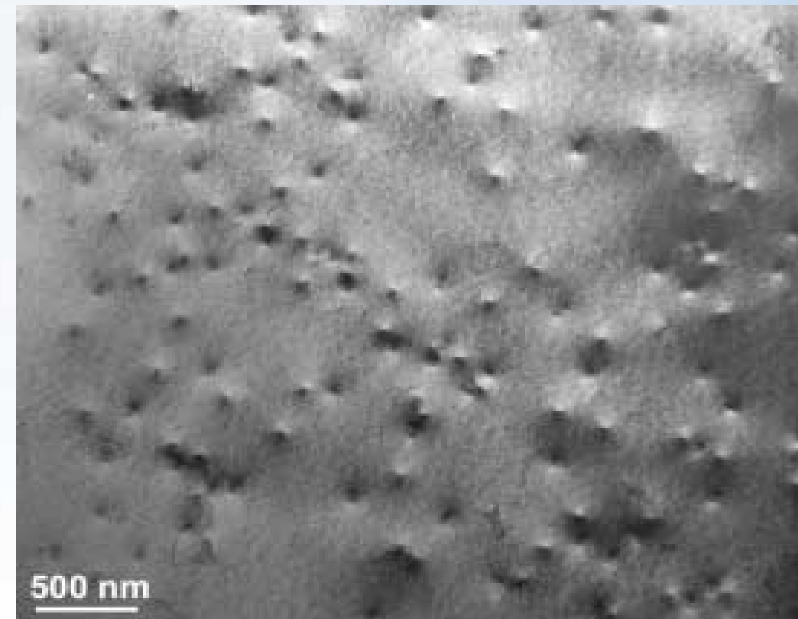


New process in 3x2" Reactor

(i.3-process)

(PV-TEM: L. Nistor, EMAT)

[dislo] ~ 2.10^{9} cm^{-2}



WP 2100 - Growth on Al_2O_3 : substrate thickness effect

- **Better results on thinner substrates:**
  - **<u>Conductive undoped GaN layers</u>**

    lower background
  - **<u>Conductive Si-doped layers</u>**

    less extended defects

    ➪ XRD (0004) peak FWHM 15% lower
  - **<u>Insulating GaN layers:</u>**

    higher resistivity

➪ **Usage of 290 or 330 µm (instead of 430 µm)**

WP 2100 - Growth on Al_2O_3 : insulating layers (1)

Highly resistive layers for HEMTs

Literature: no extensive study;
ammonia effect, C doping (MBE), growth pressure effect
(significant increase of dislocation density!)

IMEC: * Engineering the Recrystallisation time RT,
* the growth rate v_G
* the growth temperature T_G
(* and…the substrate thickness)

____Several processes identified in a phase diagram (hereafter)
Thick layers seems to keep their insulating character

The Graal : define a process compatible with low extended defect density

WP 2100 - Growth on Al_2O_3 : insulating layers (2)

R versus recrystallisation time

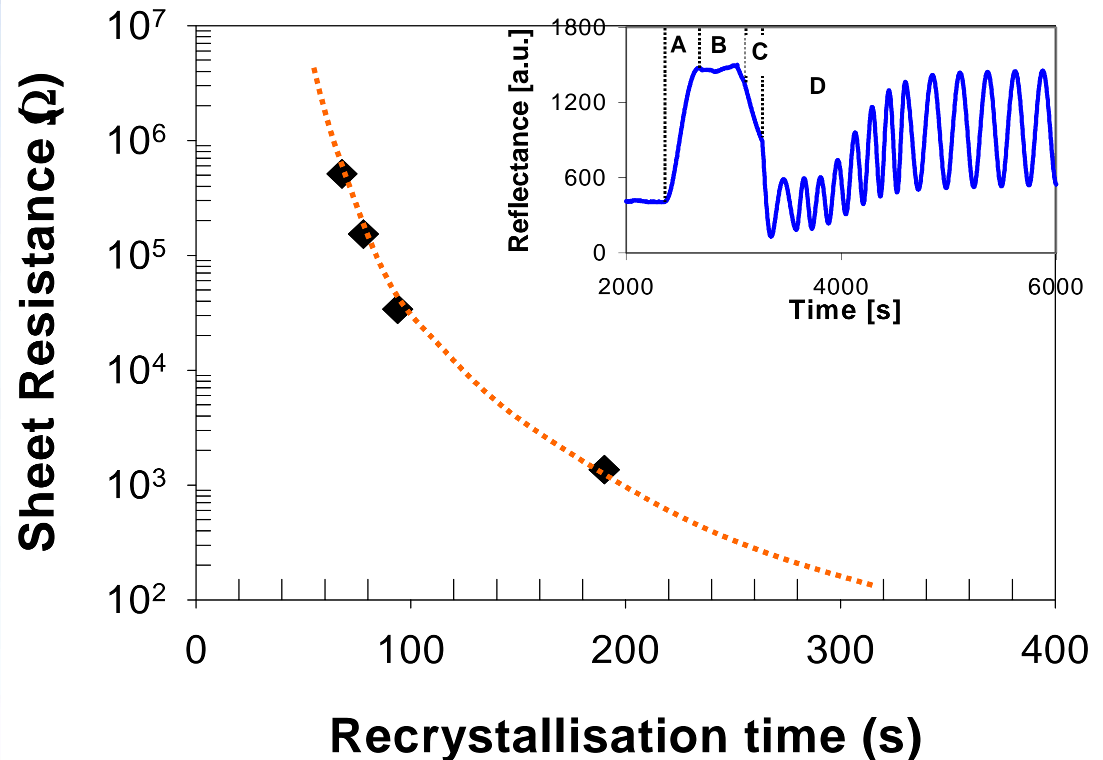
In the inset:
interferogram showing the reflectivity at the surface
of the wafer during the epitaxy

A: NL deposition

B: wafer heating

C recrystallisation

D: epilayer deposition



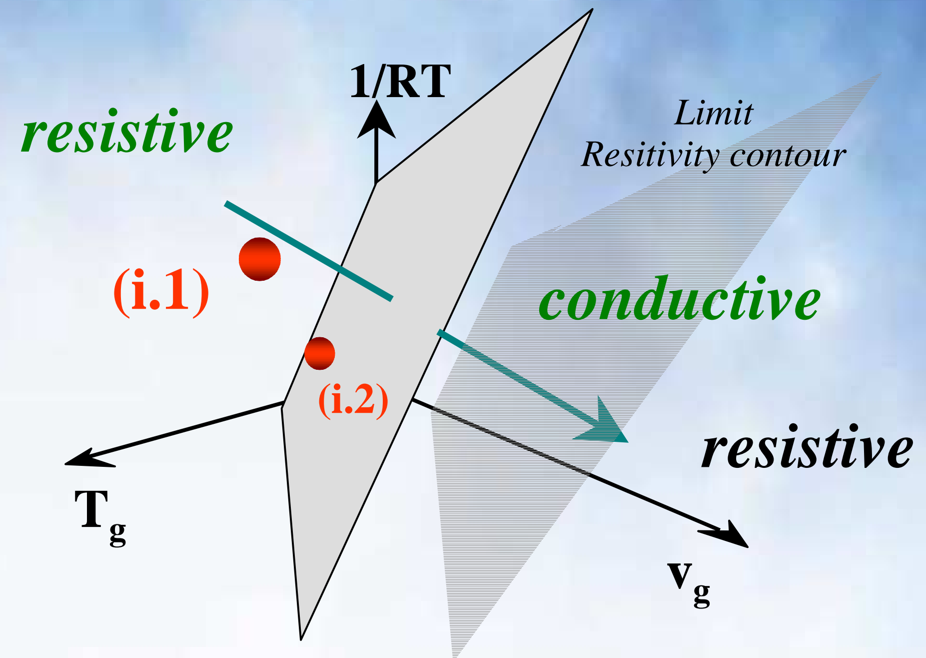
Z. Bougrioua et al, J. Crystal growth 230, 438 (2001).

WP 2100 - Growth on Al_2O_3 : insulating layers (3)

•Phenomenological diagram

- based on some experimental points
- iso-resistivity plans arbitrarily
- assumed planar

•RT = recrystallisation time



•Some processes

i.1 : LP (100 Torr), high T_G (~1070ºC),
high v_G (2.7 µm/h), small RT

i.2 : LP, low T_G (~1040ºC), medium v_G (< 1.6 µm/h), medium RT

i.3 : based on i.2 and on ***the modulation of Vg, usage of a thin NL and a very short RT, starting on the NL with at a low rate*** **(~0.5 µm/h), T_G ~1040ºC**

i.4 : i.3 + NL growth at pressure > Patm/2

WP 2100 - Growth on Al_2O_3 : insulating layers (3)

Comments on i.3

- Thin NL : *improved micro-crystalline quality*
- Small recrystallisation time

  permit an early 2D growth mode for the HT epilayer
  ...which condition the high resistivity...
- Low growth temperature:

  prevent formation of hillocks
- Low starting growth rate

  to ensure insulating character
- Increased growth rate afterwards

  permit acceptable timing while insulating character is maintained

- So ? ➪ More reproducible process than i.1 and i.2

  Less temperature dependent, faster process than i.2

  ➪ Relatively low dislocation density: $2.10^9 cm^{-2}$

WP 2100 - Growth on Al_2O_3 : insulating layers (4)

Compensation/Traps ?

Layers with sheet resistance > 10 MΩ/Sqr

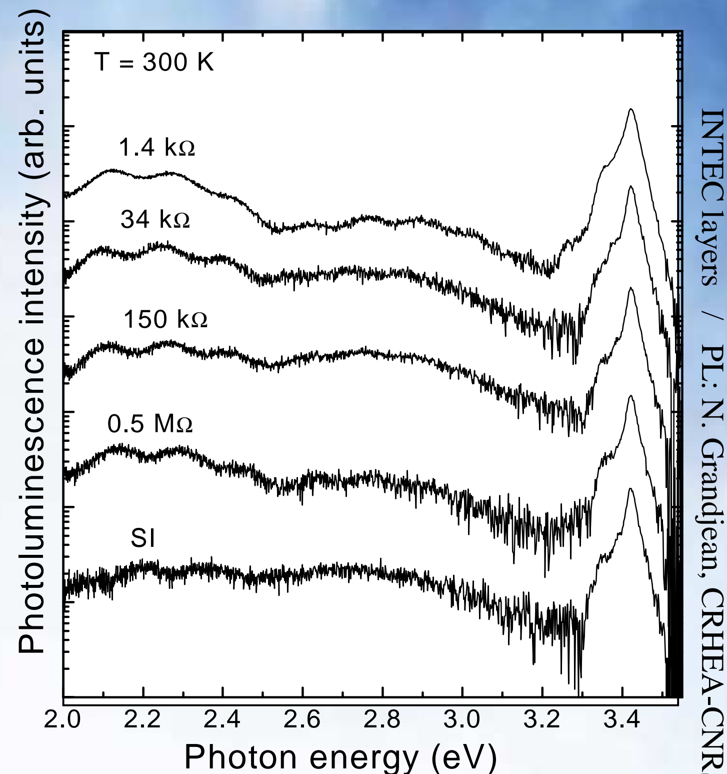
Hall, C-V, SIMS : no trend or no possible measurement

Plan View TEM : no difference in the density and in the distribution of threading dislocations between conductive undoped GaN and semi-insulating GaN.

Still Unknown**:**

% of each type of dislocation depending on growth process ? Dislocation decoration ?

PL : only a weak relation between the BE intensity and YL intensity. Etc…



1 to 2 microns GaN:nid / sapphire

Process i.1 (different RT) and i.2

Other technics ?

The NL is important: it determines strain and stochiometry in the epilayer (microanalysis/TEM, Positron annihilation spectroscopy ?)

WP 2100 - Growth on Al_2O_3 : Growth engineering

Growth engineering challenge:

Reducing together

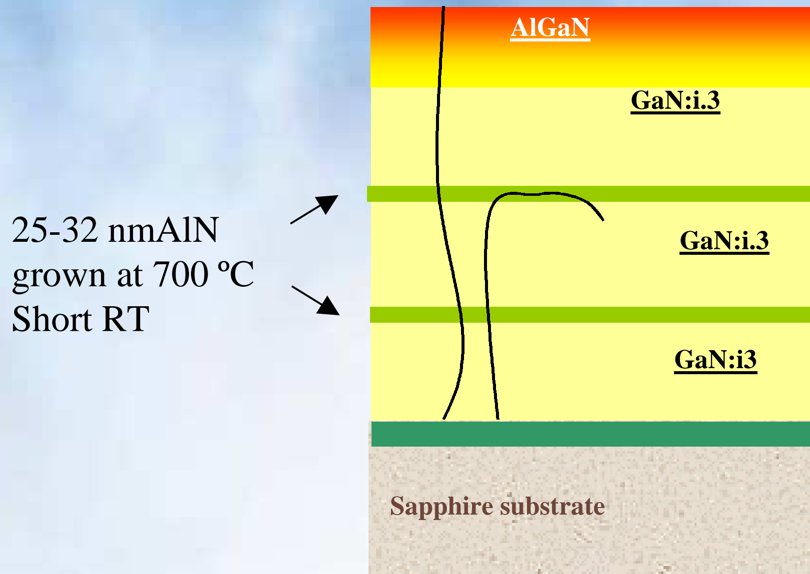
dislocations

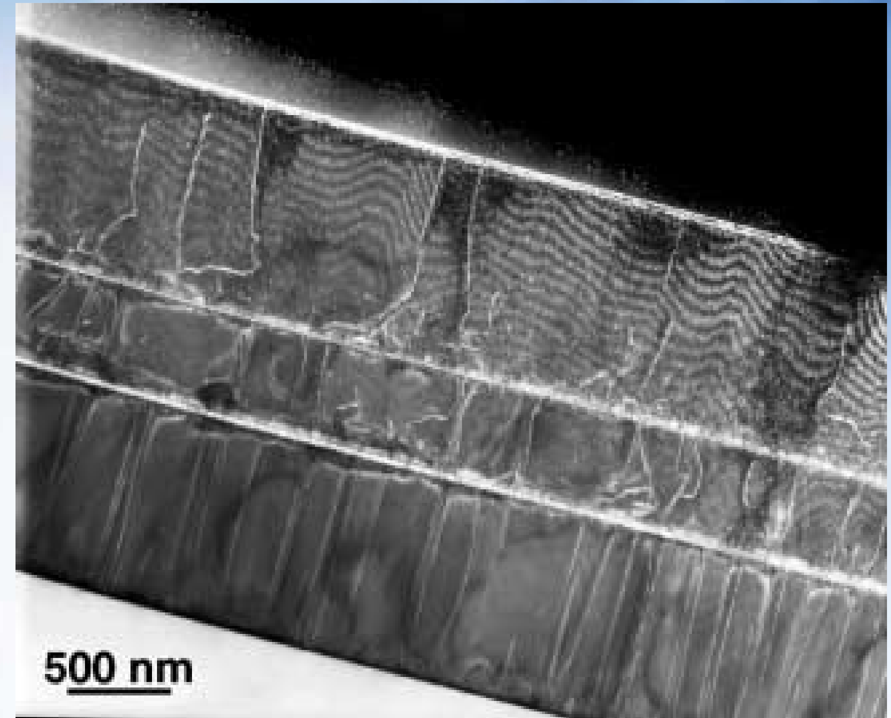
AND

conductivity

WP 2100 - Growth on Al_2O_3 : Growth engineering

Dislocation filtration: LT interlayers



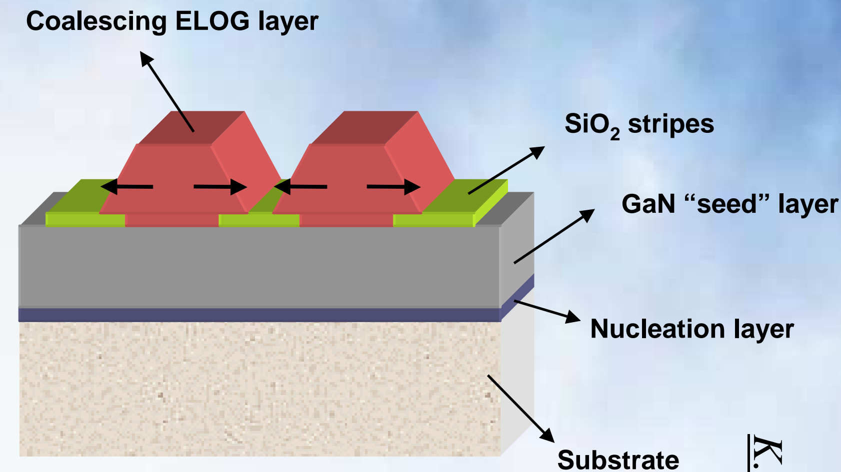


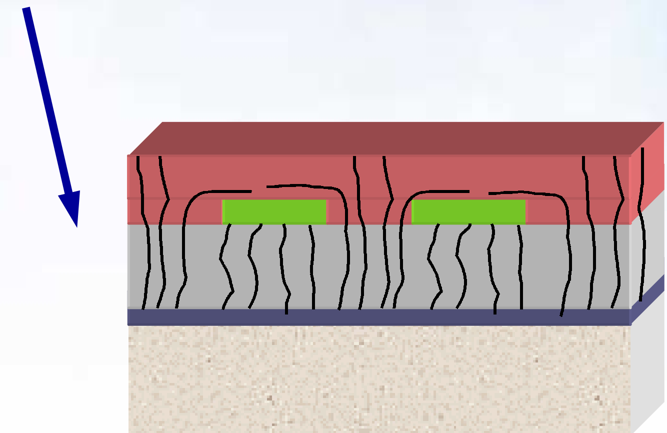
(CS-TEM: L. Nistor, EMAT)

- LT AlN interlayers Filtration works!
  One order of magnitude less dislocations
- 2-DEG structure
  ⇒ mobility 1000 -1200cm^2/Vs for n ~1,1 -1,7x10^{13} cm^{-2}
  ⇒ Acceptable insulating character!
- Successful HEMT demonstrated *(see after…)*

WP 2200 - Epitaxial Lateral Overgrowth of GaN

- **Primary goals**
  - full uniform overgrowth
  - dislocation density reduction
  - insulating overgrown material
  - smooth morphology
- **Route 1**
  - ELOG
    - **very conductive (n>3.10^{18} cm^{-3})**
    - **SIMS: huge Si, O peaks spread 1 micron around masks**



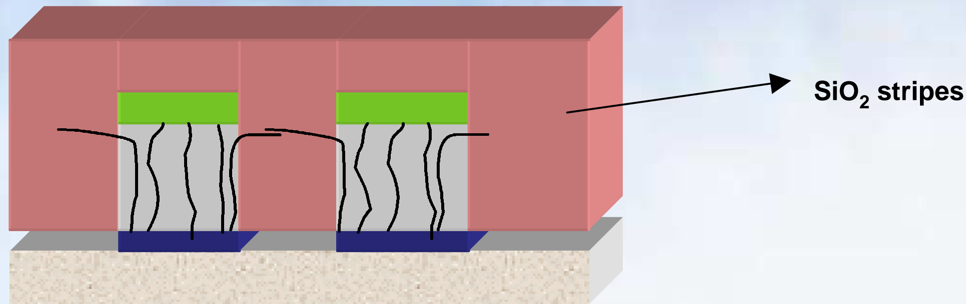


K. Jacobs, INTEC-Gent

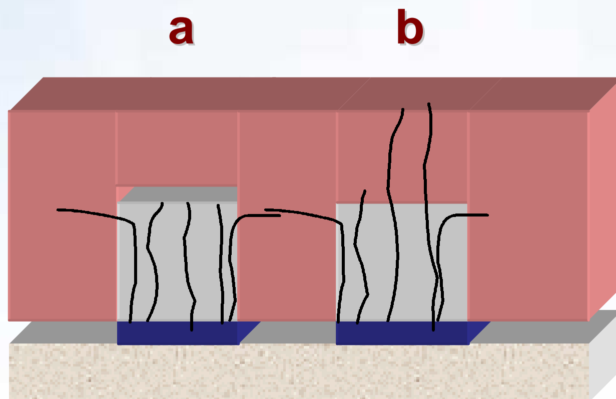
WP 2200 - Non planar growth

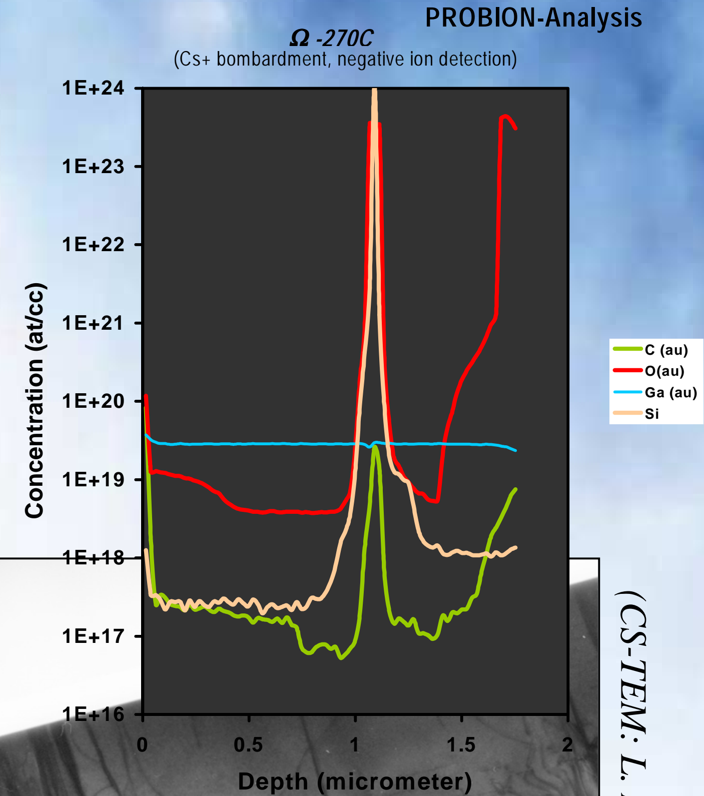
Route 2

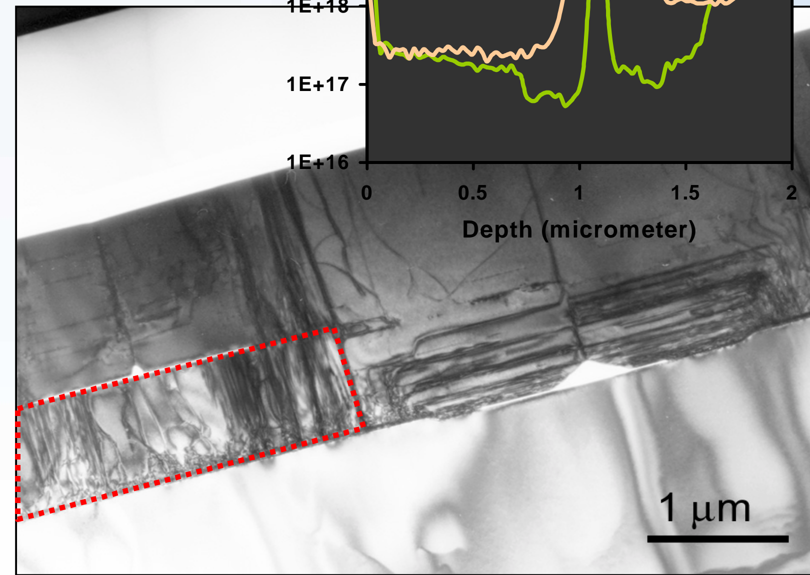
- Classical Pendeo-Epitaxy™ (PE)



- Maskless Pendeo-Epitaxy™ (MaPE)



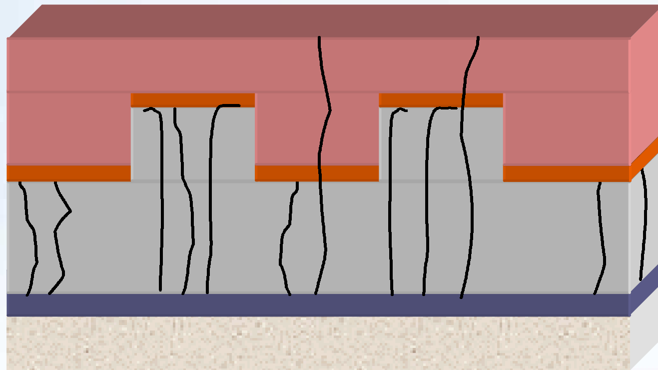




(CS-TEM: L. Nistor, EMAT)

WP 2200 - Non-planar growth

- **Route 3**
  - Grooved ELO (GrELO)
    - Growth on a textured-grooved insulating GaN template with or without a LT GaN layer



Textured template

(CS-TEM: L. Nistor, EMAT)

WP 2300 - GaN growth on new substrates

- **NGO**
  - orientations (110), (101) & (011)
  - First experiments:
    - all in N_2, BO at lower T
    - very thick NL and rough Epi could be deposited
    - no nitradation & half the usual ammonia flow
    - PL: peak of GaN and YL are visible
    - XRD: impossible
- **SiC**
  - First experiments:
    - wafers
      - CREE n-type 4H
      - **Umicore** (Sint-Petersburg) ⇒ extra polishing needed
    - thick AlN NL-layer, HEMT-like structures
    - Featureless morphology on 8° off CREE-wafers

AlGaN-GaN HEMT structures

- Si-doped or UN-doped AlGaN barrier
- undoped 2DEG channel
- *Insulating GaN buffer*

11 - 34 nm $Al_xGa_{1-x}N$ (x = 6 - 44%)

2.4 to 5 µm GaN insulating buffer

GaN:NL 20 to 70 nm

Al_2O_3 substrate

Optimisation of AlGaN growth

Composition : Al % controllable

- incorporation curve: TMAl acts somewhere between a dimer and a monomer

- more or less linear with TMG/TMA fluxes from **6% to 44 %** (Intec-XRD)

Growth rate can be tuned (important for AlGaN quality ?)

Growth pressure: growth at 50 torr => less pre-reactions

otherwise 100torr Al% ~ 20% lower

Vg ~ 30 % lower

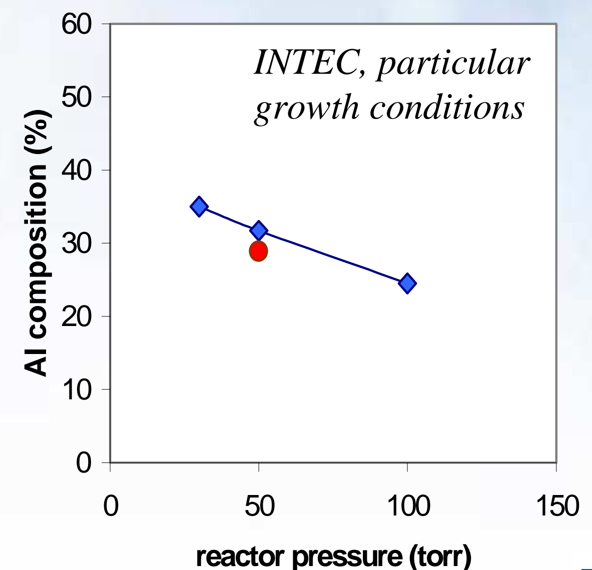
Uniformity : better than 3% stdv on Rsqr

Morphology : good**,** cracks only after some 100 nm

Interface:

flat to the atomic level,

no misfit dislocation? => ***not sure!***

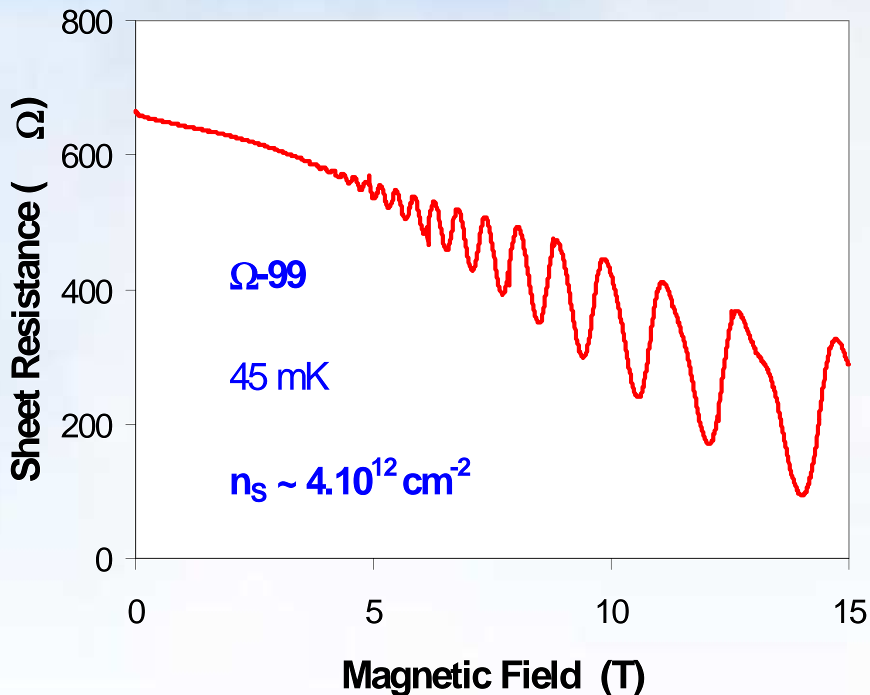


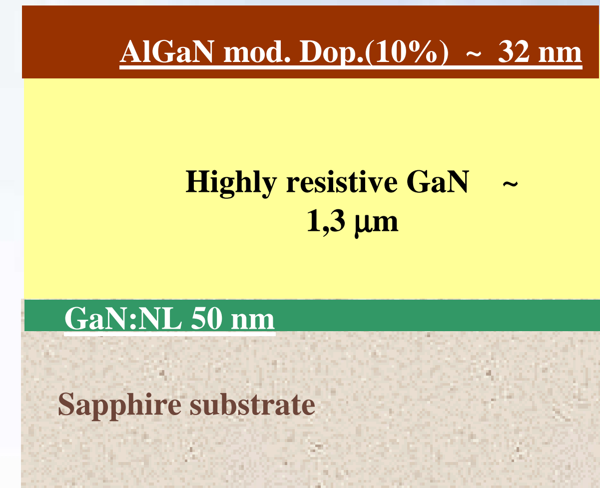
One proof of 2DEG: cryo-magnetotransport

- Example of Shubnikov de Haas effect :

Structure Ω-99

(J.J. Harris et al., University College, London)

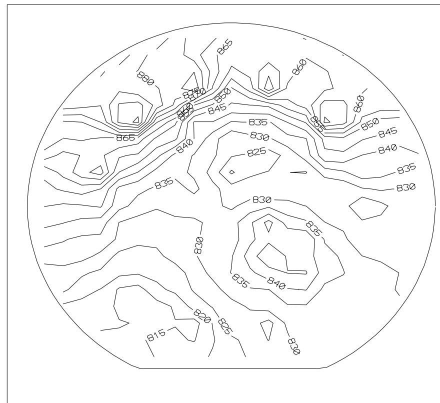


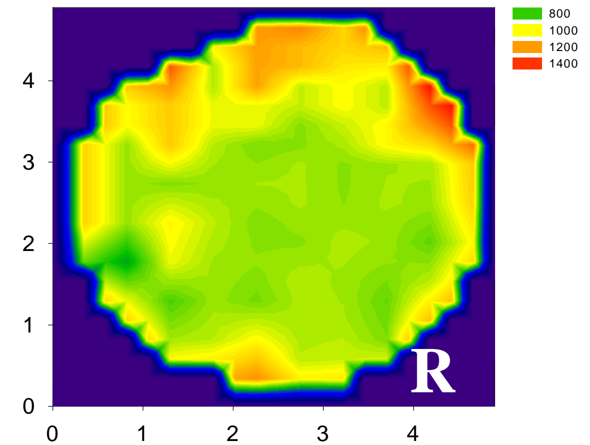


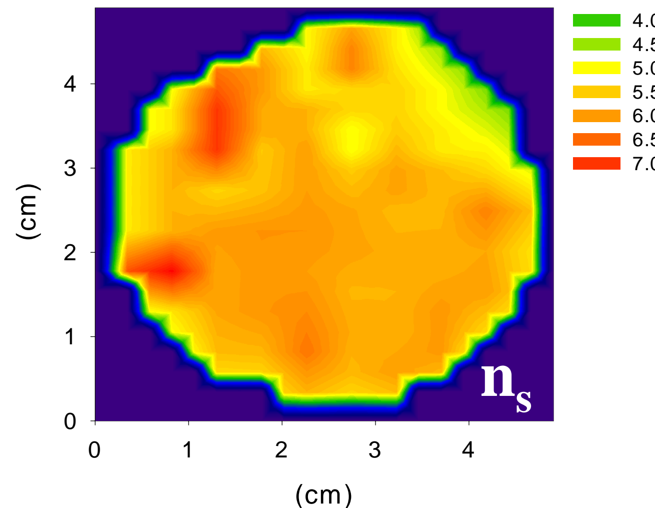
2DEG uniformity over 2" wafer

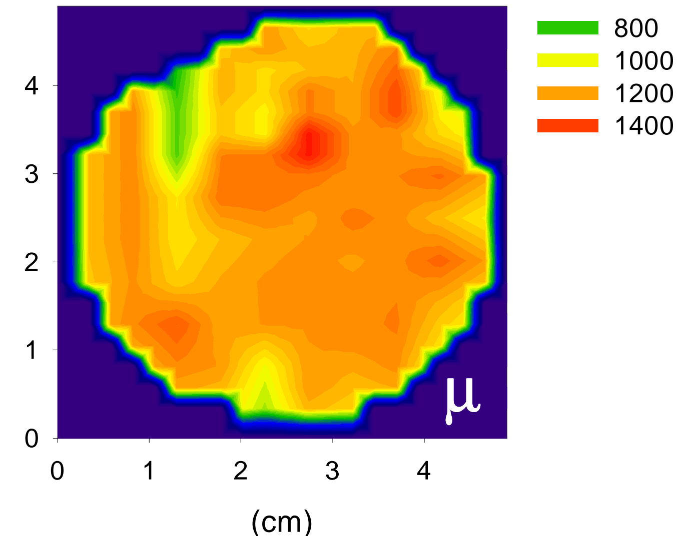
Structure Ω160 : transport properties at 300K

33nm $Al_{16\%}GaN$ - 1.1µm "i.1"GaN









Average

- R_{mapper} ~ 838 Ω
- R_{VdPauw} ~ 900 Ω
- n_S ~ $5.8.10^{12}$ cm^{-2}
- µ ~ 1190 $cm^2V^{-1}s^{-1}$

Uniformity

- R_{mapper} ➪ 2,4 %
- R_{VdPauw} ➪ 9.4 %
- n_S ➪ 8 %
- µ ➪ 9 %

Some typical heterostructures

2” Wafer	Ω-164	Ω-318	Ω-384	Ω-341	Ω-381	Ω-461
Buffer	i.2	i.3	i.3	i.3	i.3	I3+ LT IL
Thickness µm	2.3	4.5	3	4,3	3.1	3.5
AlGaN: Al%	**20 %**	**25 %**	**28%**	**32%**	**28 %**	**36 %**
Thickness	30 nm	27 nm	13 nm	21 nm	22 nm	18 nm
$N_{Hall,300K}$ (cm^{-2})	7.5×10^{12}	9.6×10^{12}	9.7×10^{12}	1.3×10^{13}	1.1×10^{13}	1.7×10^{13}
μ_{300K} ($cm^{-2}V^{-1}s^{-1}$) *average*	1300 - 1450	1220 - 1420	1440 - 1760	1220 - 1250	1300 - 1510	1100
μ_{77K} ($cm^{-2}V^{-1}s^{-1}$) *some points*	3770	~ 4000	5900 ?	~ 3340	5908 6028	~2800

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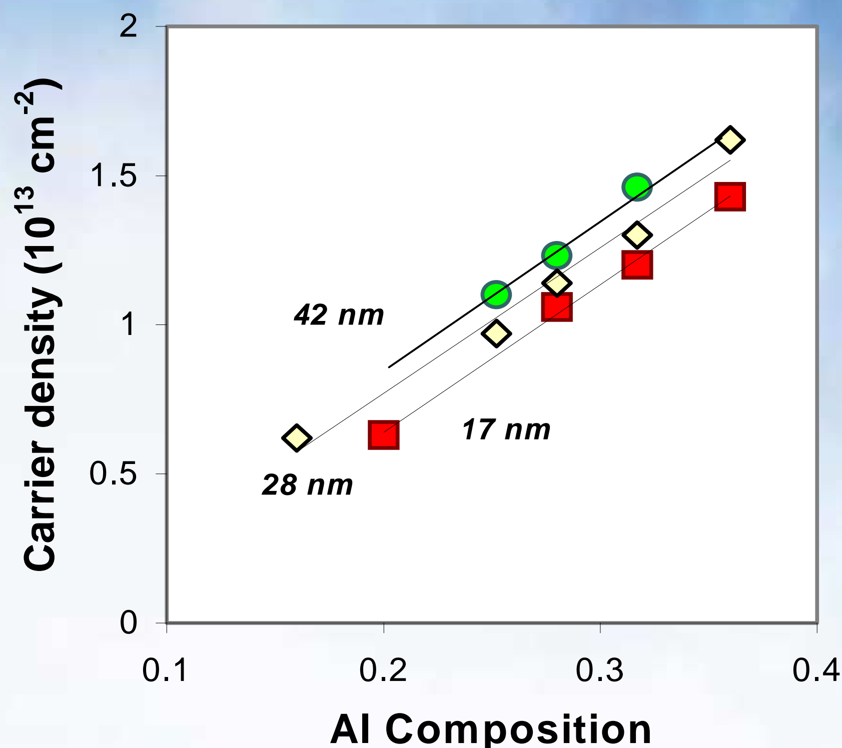
2DEGs density Vs Al composition

- Van der Pauw
  square specimens
  In contacts
- Hall measurement
  at 300 K, B ~ 0.2-0.4 T
  6% Al: no 2DEG

Behaviour consistent with carrier generation *via* Piezoelectric and Spontaneous Polarisations

$n_s = 4{,}9.10^{13}.\ X_{Al}$ - *Constant*



*Z. Bougrioua, J.-L. Farvacque, I. Moerman, F. Carosella published in Phys Stat Sol b-**228**, 625-628 (2001)*

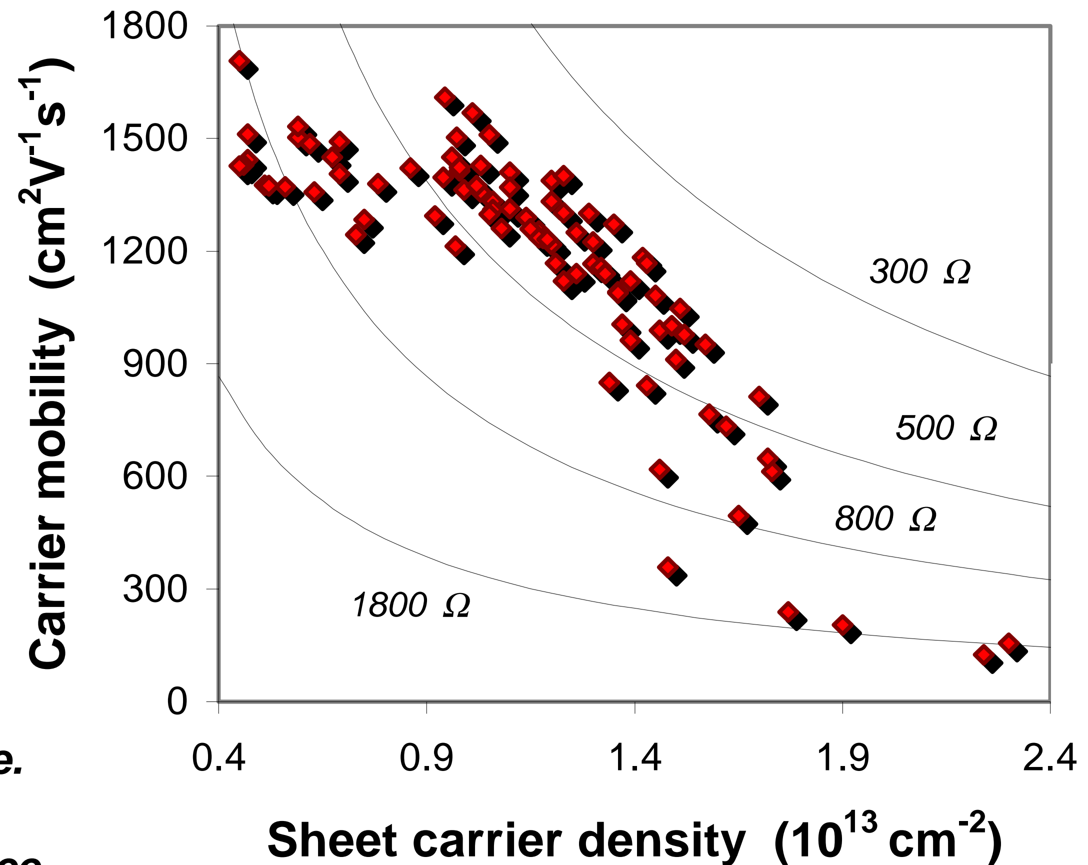
2DEG mobility Vs carrier density (1)

VdP-Hall at 300 K

Evolution corresponding to some 30 wafers, AlGaN-GaN structures.

➪ quite good properties for $n_s < 1.4 \times 10^{13}$ cm^{-2}, $\mu \sim 1000 - 1710$ cm^{2}V^{-1}s^{-1}

➪ but for $n_s > 1.4 \times 10^{13}$ cm^{-2}, the mobility drops abruptly.



Interface roughness is a critical issue. The higher the carrier density, the more sensitive they are at the interface

Possible AlGaN relaxation is under study.

2DEG mobility Vs carrier density (2)

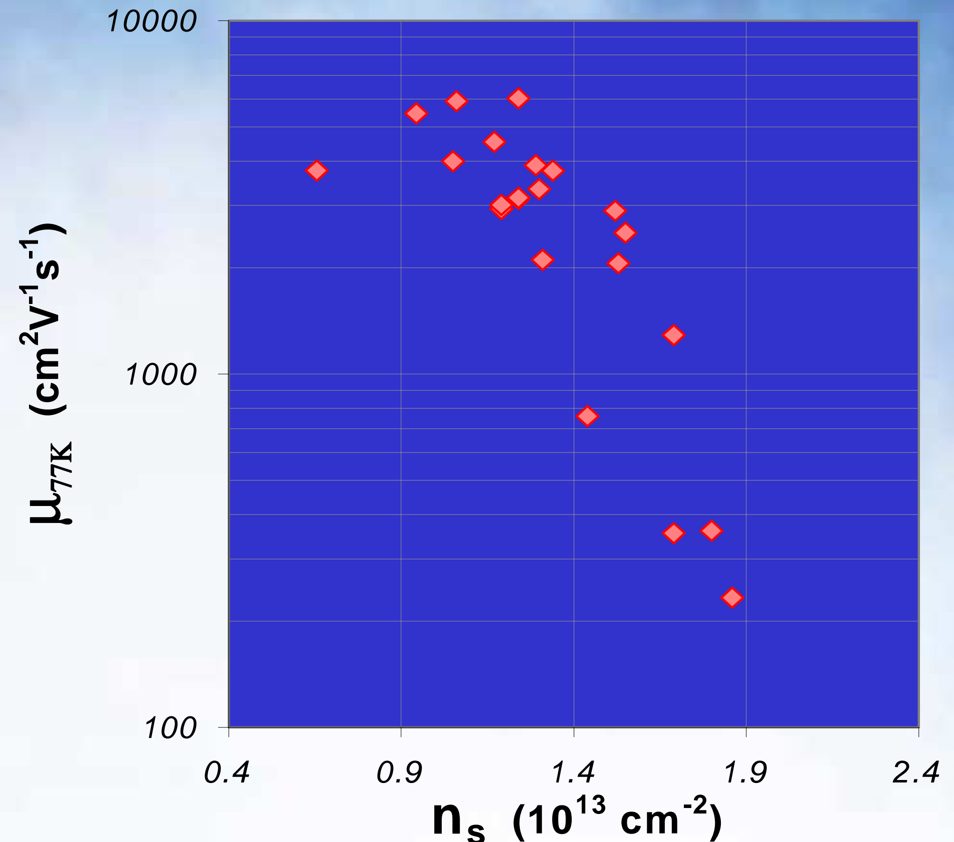
- **VdP-Hall at 77 K**

$n_s \sim 1 \times 10^{13}$ cm^{-2}:

$\mu \sim 5000 - 6000$ cm^{2}V^{-1}s^{-1}

$n_s > 1 \times 10^{13}$ cm^{-2}:

mobility quenches



- **Modelling**
  - First developments :
    Z. Bougrioua, J.-L. Farvacque,
    I. Moerman, F. Carosella
    published in Phys. Stat. Sol. (Nov. 2001).
  - Follow-up in collaboration with LSPES
    (J.-L. Farvacque)

Overview on some singular heterostructures

Process and device characterisation at

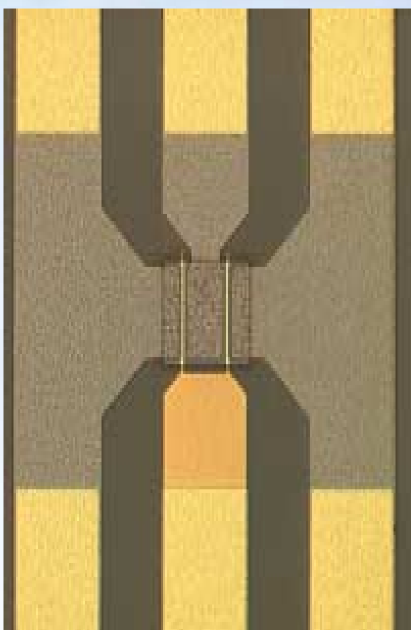
- **Marconi-Caswell, Thales-LCR Orsay**
- **Madrid Polytechnic University, lab. INTEC-Hannover, COBRA and IEMN-Lille**

Some INTEC "GaN-history"

- Ω91 : Feb. 2000 - *first 2DEG with modulation doping - Map 77K and 300K properties*
- Ω99 : Feb. 2000 - *first modulation doped working HEMTs (Marconi - Thales)*
- Ω160 : May 2000 - *pol. doped 2DEG with good mobility - Map 300K properties*
- Ω164 : May 2000 - *best undoped HEMT - **f_t ~ 40 GHz** (0,2 μm gate), **irradiation tests***
- Ω318 : Feb. 2001 - *first structure using i.3 for power device, **1 A/mm,** 2W/mm **(Marconi)***
- Ω339 : Mar. 2001 - *first 2DEG with peak mobility > 1700 cm2/Vs (Al% ~ 15%)*
- Ω340 : Mar. 2001 - *very good characteristics at UPMadrid (extrapol: 5W/mm)*
- Ω355 : Mar. 2001 - *first HEMT with LT AlN IL - good characteristics at Madrid and IEMN*
- Ω381 : May 2001 - *best mobility for high carrier density structure (UPMadrid,Thales)*
- Ω389 : May 2001 - *first HEMT with a 3nm GaN cap-layer (UPMadrid)*
- Ω461 : Aug. 2001 - excellent *HEMT with LT AlN IL => extrapolation ~1500A/mm (see after)*
  Ω462 : Aug. 2001 - *first HEMT with a 1.5nm AlN spacer layer.*
- Ω505 : Oct. 2001 - *HEMT(44% Al) with LT AlN IL*
- Ω508 : Oct. 2001 - *HEMT(32% Al) with GaN:Si^{++} caplayer*

HEMT characteristics

- **WP2400 - WP2500**
  process at Marconi - Caswell

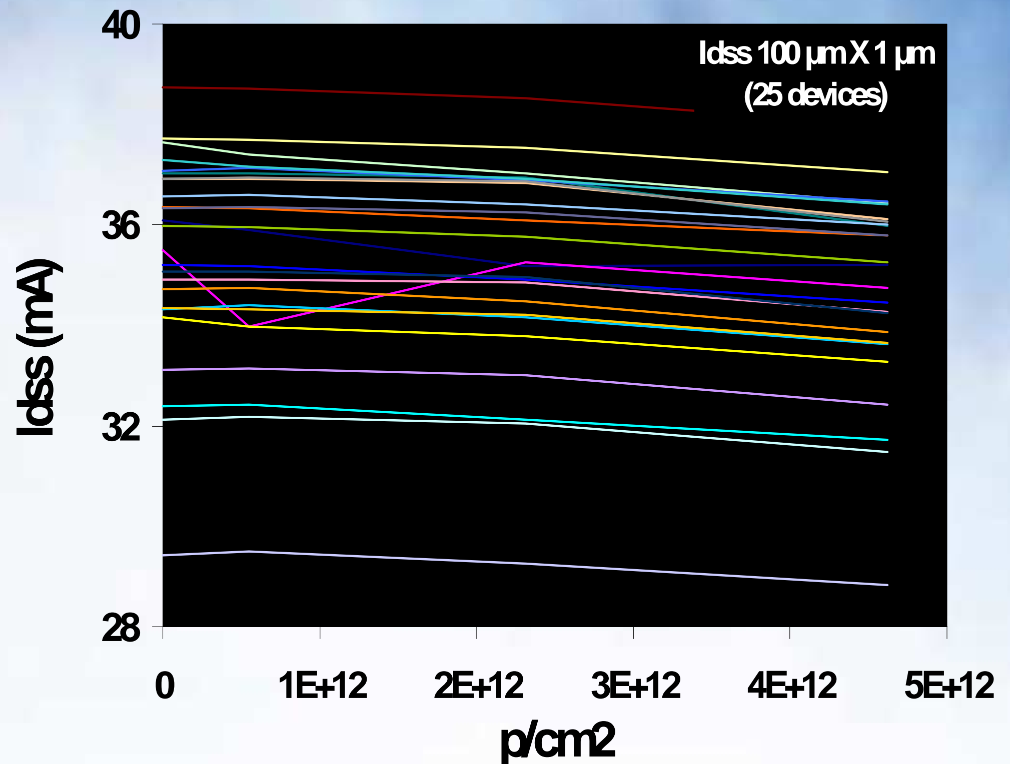


Gate length	=	**1.2 μm**
f_c	=	4-8 GHz
f_{max}	=	10-20 GHz
$I_{DS, max}$	>	0.3 - 1 A/mm

Gate length	=	**0.2 μm**
f_c	=	40 GHz
f_{max}	=	80 GHz
$V_{breakdown}$	>	100 V
Good pinch-off		

Irradiation testing on AlGaN-GaN-Sapphire

- Irradiation testing have been carried out:
  - Wafer templates from **Ω-164**
    50 devices on each template
  - Two types of devices:
    - 100 µm x 1 µm
    - 100 µm x 2 µm
  - Unbiased
  - DC characterisation
  - Under Co60 up to 5 Mrads (Si)
  - Under Protons
    60 MeV up to 4.7 10^{12} p/cm^2



No significant degradation
has been observed

**Test to be extended under bias
with RF characterisation**

esa

TOS-QCT Component Engineering - Microwave Components

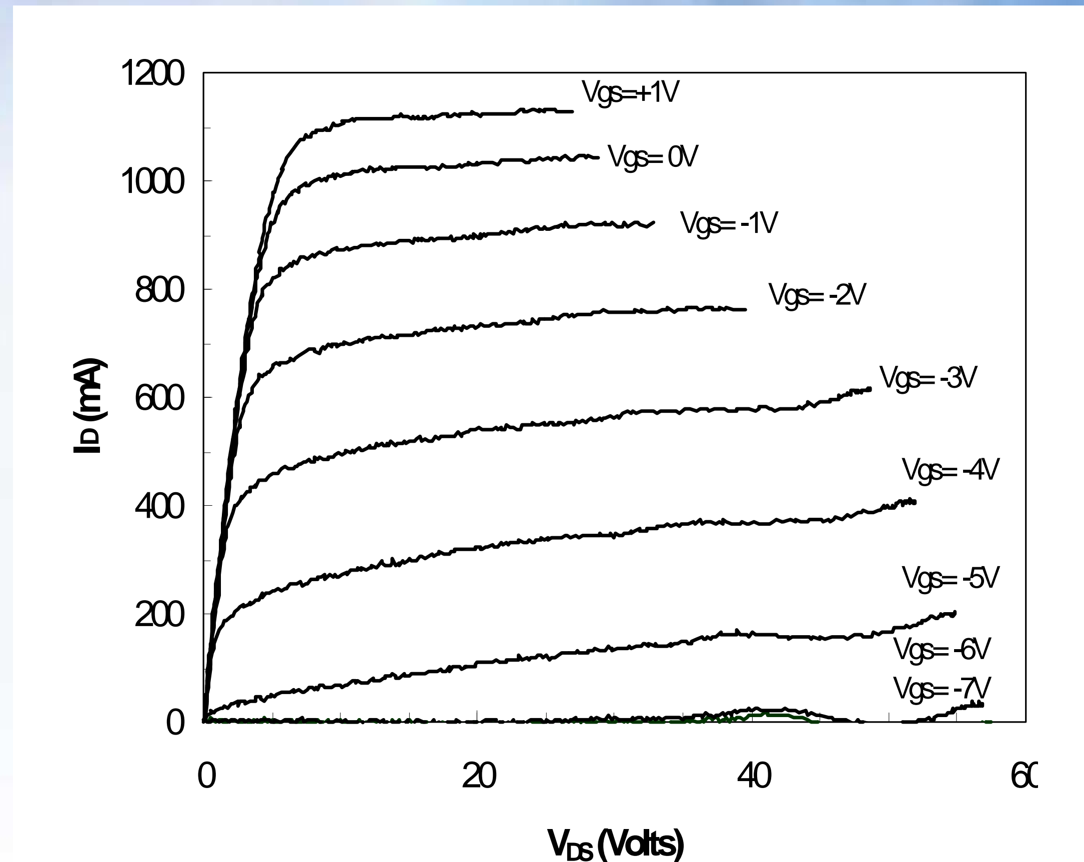
HEMT characteristics

New HEMT with high current

- processed by ***Marconi***
- => HEMT Ω318

[28 nm $Al_{25\%}GaN$ - 4.6 mm “i.1” GaN]

- Power device: transistors with gate lengths 0.2 µm * gate widths **1.2 mm** maximum oscillation **(f_{max}) and (f_T)** were **27 and 22 GHz** respectively.
  I/V characteristics of the power device is measured under pulsed conditions.
- **maximum current** of ~ **1.1A**.
- Maximum output power of **2W** for a 1.2 mm device with 0.2 µm gate length (*limited by imperfect passivation*)
- **current gain at 10GHz : 13dB**



What about using LT AlN interlayers for HEMT ? (1)

- Ω-460: reference [20 nm Al(36%)GaN]
- Ω-461 with 2LT AlN interlayers

TEM:

32 nm LTIL. Evidence of dislocation filtration

Other: still under investigation

	reference	LT AlN IL
300 K n_S (cm^{-2})	1.6×10^{13}	1.7×10^{13}
300 K μ (cm^2/Vs)	920	1100
77 K n_S (cm^{-2})	1.6×10^{13}	1.75×10^{13}
77 K μ (cm^2/Vs)	1800	2800

Transport: better properties

=> identical or higher n_S

=> higher 2DEG mobility

Reasons ??

GaN upper layer is differently strained

=> effect on polarisations, on interface roughness and …on AlGaN relaxation

(to be published)

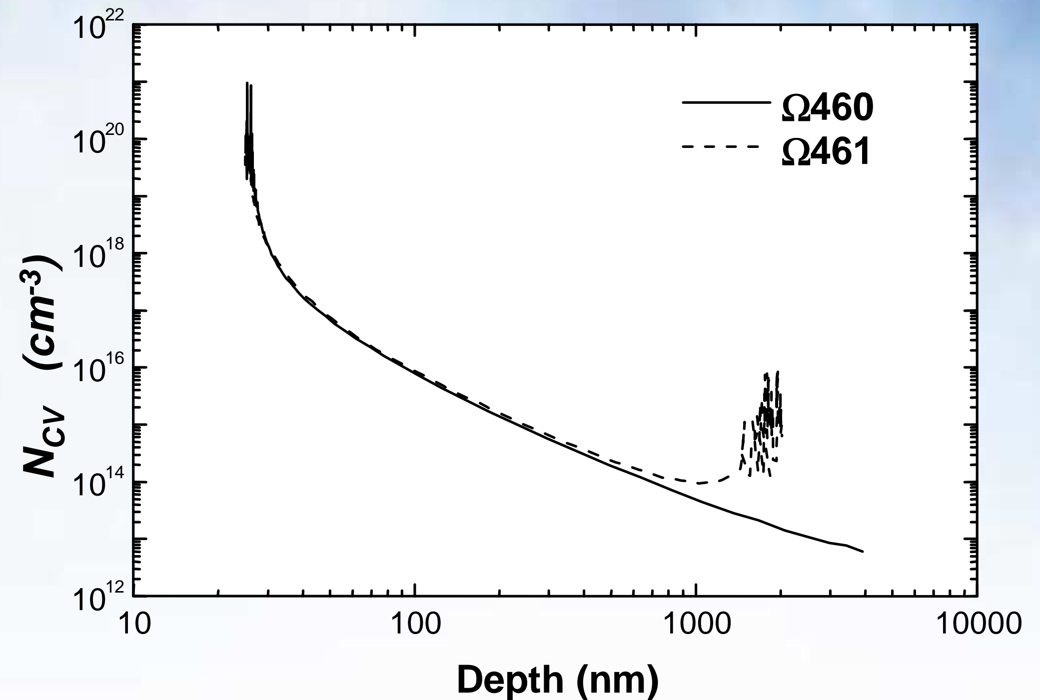
What about using LT AlN interlayers for HEMT ? (2)

- Ω-460: reference [20 nm Al(36%)GaN]
- Ω-461 with 2LT interlayers

CV:

no parasitic channel

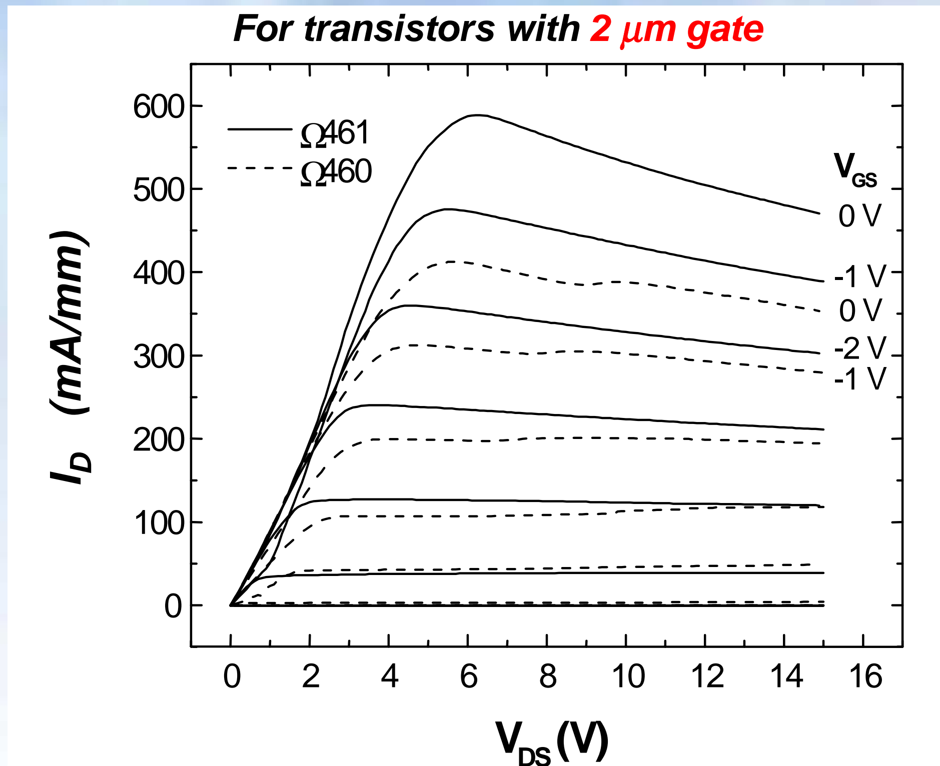
at the GaN-LTAlN interfaces



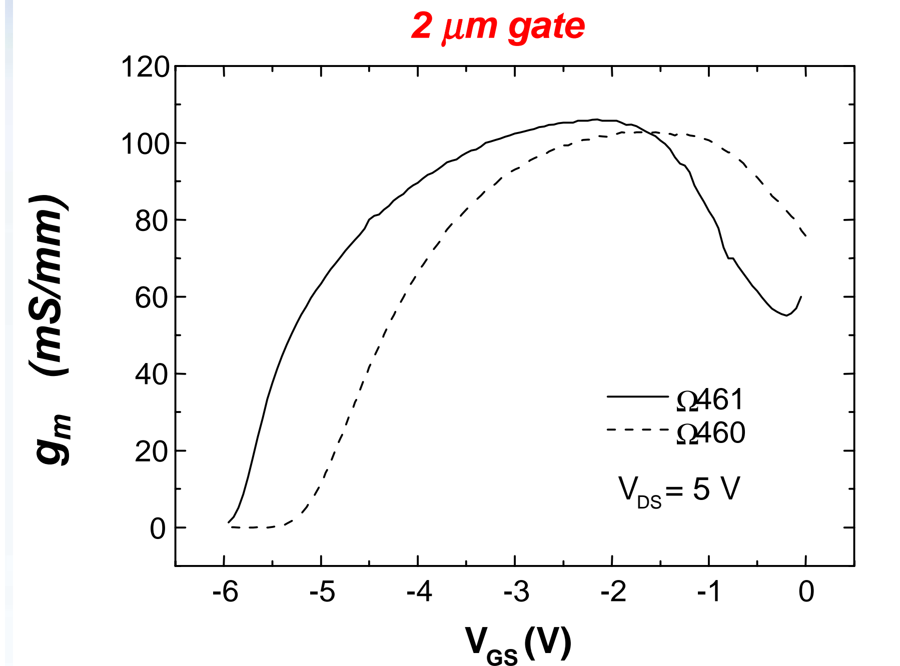
E. Monroy, Univ.Poly.Madrid

What about using LT AlN interlayers for HEMT ? (3)

- Ω-460: reference
- Ω-461 with 2LT interlayers



F. Calle et al, University Polytechnic Madrid



- **Better transistor** characteristics with the structure with LT interlayers
- Anticipated transistor performance for 0.2 μm gate: 1500 mA/mm, g > 200 mS/mm