Low dislocation density and high mobility GaN layers for DHFET channels grown by high-temperature ammonia-MBE

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"Semiconductor Technologies and Equipment" Joint Stock Company

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SemiTEq GROUP PROFILE

Semiconductor Devices, JSC
www.atcsd.ru
(1991)

High power laser diodes and arrays
LD-based medical and scientific equipment
LD-related fibers and optics

SemiTEq JSC
www.semiteq.ru
(2001)

MBE Systems and components
UHV & HV Equipment for semiconductor wafer processing
Demo process technologies in Application Lab

Svetlana-Rost, JSC
www.svetlana-rost.ru
(2004)

MBE growth of III-V heterostructures;
III-V epi-wafers planar processing:
- GaAs - based MMIC
- GaN - based high power transistors

SemiTEq GmbH
(2007)

European representative, logistic service

Outlook

Brief introduction: substrates for III-N growth, III-N growth methods

MOCVD and convectional MBE : “bulk” GaN electron mobility on sapphire vs dislocation density

MBE system for high temperature (HT) III-nitrides growth (substrate T up to 1200^0C)

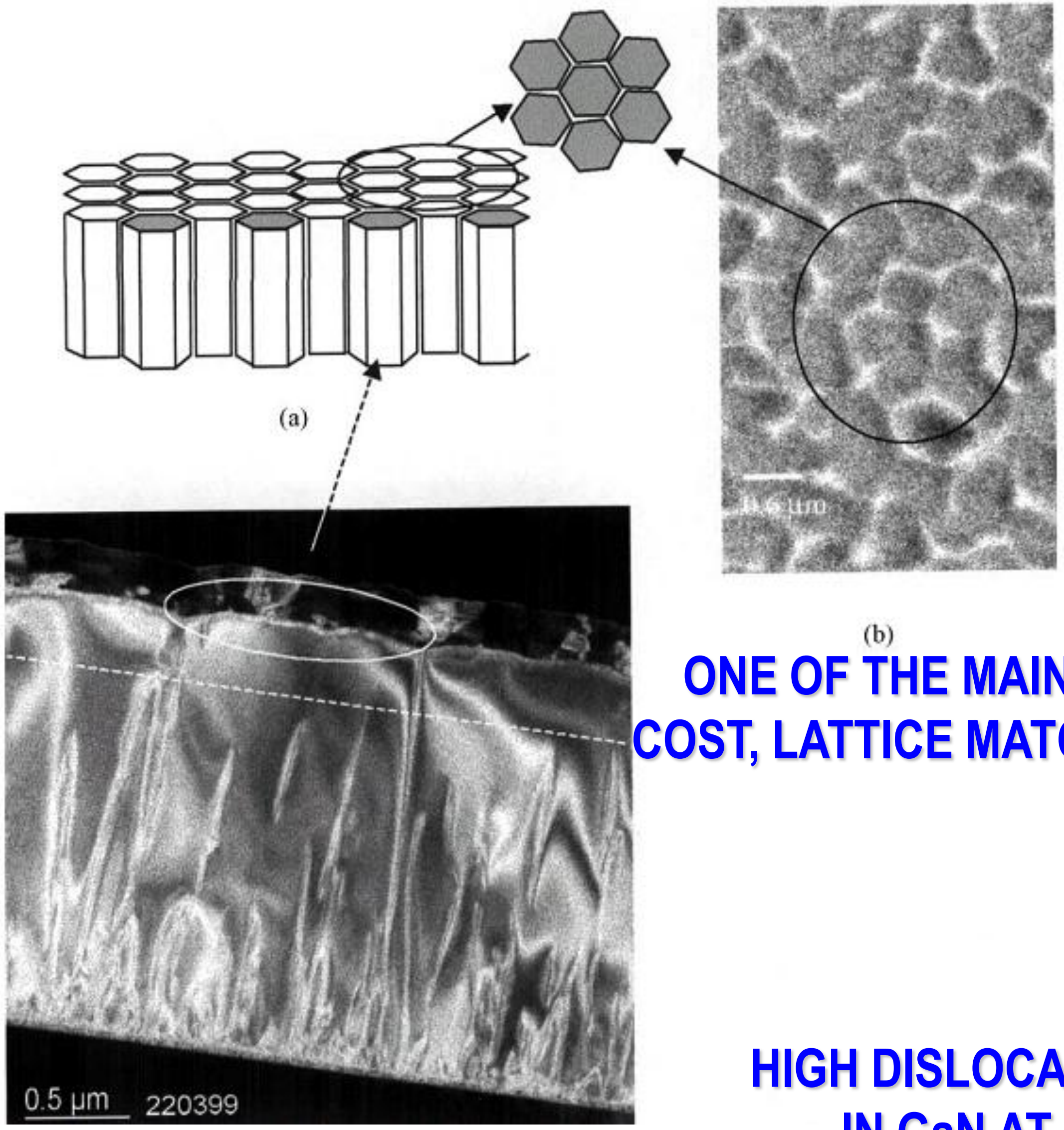
HT AlN buffer and multilayer heterostructure (MHS) AlN/SLS/AlGaN/GaN

GaN properties in MHS grown on HT AlN: “bulk” electron mobility vs dislocation density

Application of MHS for HEMT

Summary

Brief introduction: SUBSTRATES FOR III-N GROWTH



	$\Delta a/a$, %	$\alpha\Delta l/\alpha l$, %
AlN	2.4	+26
SiC	3.4	+25
Al_2O_3	13.8	-34
Si	17	+100

ONE OF THE MAIN PROBLEMS IS THE LACK OF LOW COST, LATTICE MATCHED SUBSTRATES FOR III-NITRIDES

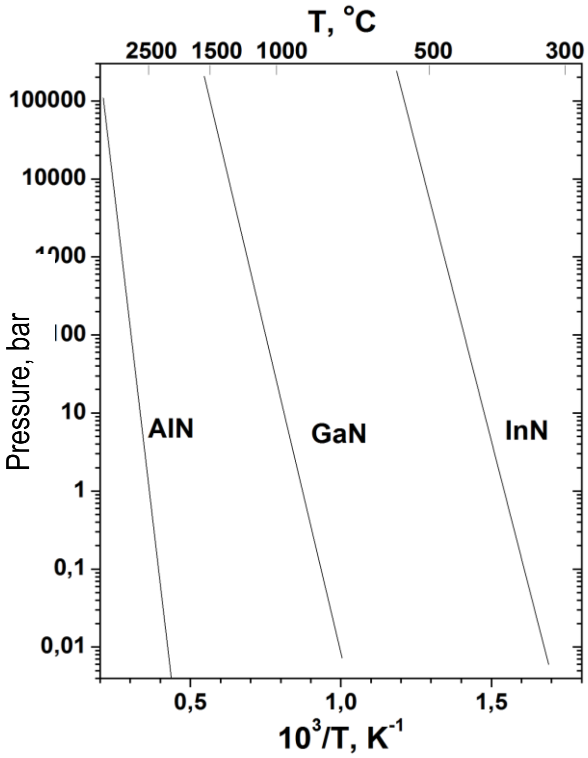
⬇

HETEROEPITAXY

⬇

HIGH DISLOCATION DENSITY $N_{DIS}=10^8$-10^{10} cm^{-2}
IN GaN AT 1-3 mkm FROM SUBSTRATE

III-N GROWTH METHODS



Nitrogen equilibrium pressure over AlN, GaN и InN

NON-EQUILIBRIUM GROWTH METHODS

HVPE – quasi-substrates growth

MAIN GROWTH METHODS:

MOCVD AND MBE

MOCVD T_{GROWTH}>1000^0C V/III>1000 $N_{DIS}=10^8$-10^9 cm^{-2}

PA-MBE T_{GROWTH}=600-800^0C V/III~1

LT growth without H_2, InN, p-doping

NH_3-MBE T_{GROWTH}=800-900^0C V/III>1

$\}$ $N_{DIS}=10^9$-10^{10} cm^{-2}

HT MBE growth

MBE advantages in comparison with MOCVD:
In-situ diagnostics (RHEED), abrupt heterointerface, high purity of growth chamber, cluster system possibility, precursors efficiency, safety

Dislocation density:
“bulk” GaN mobility on sapphire vs growth method

Growth method and conditions	Dislocation density	“Bulk” GaN mobilty
MOCVD **$T_{GROWTH}>1000^0C$** **V/III>1000**	**10^8-10^9 cm^{-2}** (ELOG **10^7 cm^{-2}**)	Typical 500-700 cm^2/V·s 900 cm^2/V·s *S.Nakamura et al*
PA-MBE T_{GROWTH}=600-800^{0}C V/III~1 **Tgr not higher than GaN decomposition (750-800^{0}C)**	**10^9-10^{10} cm^{-2}**	Typical 200-350 cm^2/V·s 1100 cm^2/V·s on MOCVD template *G. Koblmüller et al*
NH_3-MBE T_{GROWTH}=800-900^{0}C V/III>1 **Tgr higher than GaN decomposition but ammonia flow restricted by high vacuum**	**10^9-10^{10} cm^{-2}**	Typical 200-350 cm^2/V·s Comparable to MOCVD on MOCVD template 560 cm^2/V·s on AlN buffer grown by magnetron sputtering J. *Webb et al*

PROPERTIES OF GaN GROWN ON “THIN” AlN NUCLEATION LAYER (20 nm) GROWN AT 900^{0}C

№	Substrate temperature, ^{0}C	NH$_3$flow , sccm	rms , nm	Grain size, mkm	μ_{max}, cm^2/V·s	Dislocation density, cm^{-2}
1	900	30	~5	0,3-0,5	150-250	>$9\cdot10^9$
2	900	400	~5	0,5-0,7	150-250	>$9\cdot10^9$
3	960	400	~6	0,8-1	250-300	>$7\text{-}8\cdot10^9$
4	960	150	~50	0,8-1	<50	

✓ Increase of V/III ratio and substrate temperature allows to improve GaN properties

✓ For increase of substrate temperature up to values comparable with MOCVD we need to increase V/III ratio an order of magnitude:

difficult to realize in MBE

✓ Another way: to improve structural quality of III-N layers on initial growth stage – change of structure design.

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High temperature AlN and multilayer heterostructure (MHS)

TO IMPROVE GaN STRUCTURAL QUALITY IT IS NESSESARY

TO ICREASE EFFICIENCY OF NUCLEATION ISLANDS COALESCENCE

↓

TO INCREASE GROWTH TEMPERATURE ON INITIAL GROWTH STAGE

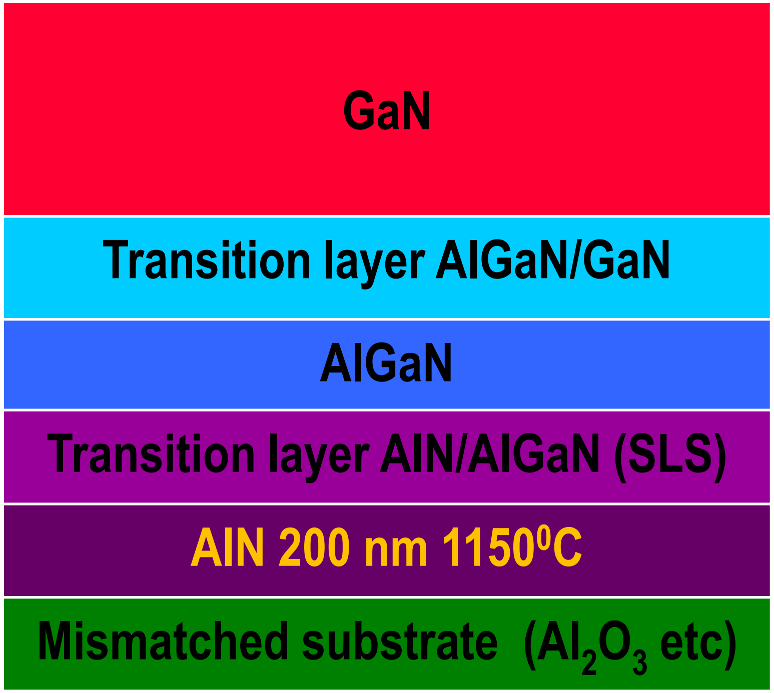
↓

AT INCREASED GROWTH TEMPERATURE GaN THERMAL DECOMPOSITION OCCURS BUT AlN DECOMPOSITION TEMPERATURE IS HIGHER

↓

GROWTH OF “THICK” AlN LAYER (>100 nm) AT ICREASED TEMPERATURE ON INITIAL GROWTH STAGE

TO LOWER STRESS DUE TO LATTICE MISMATCH



GaN

Transition layer AlGaN/GaN

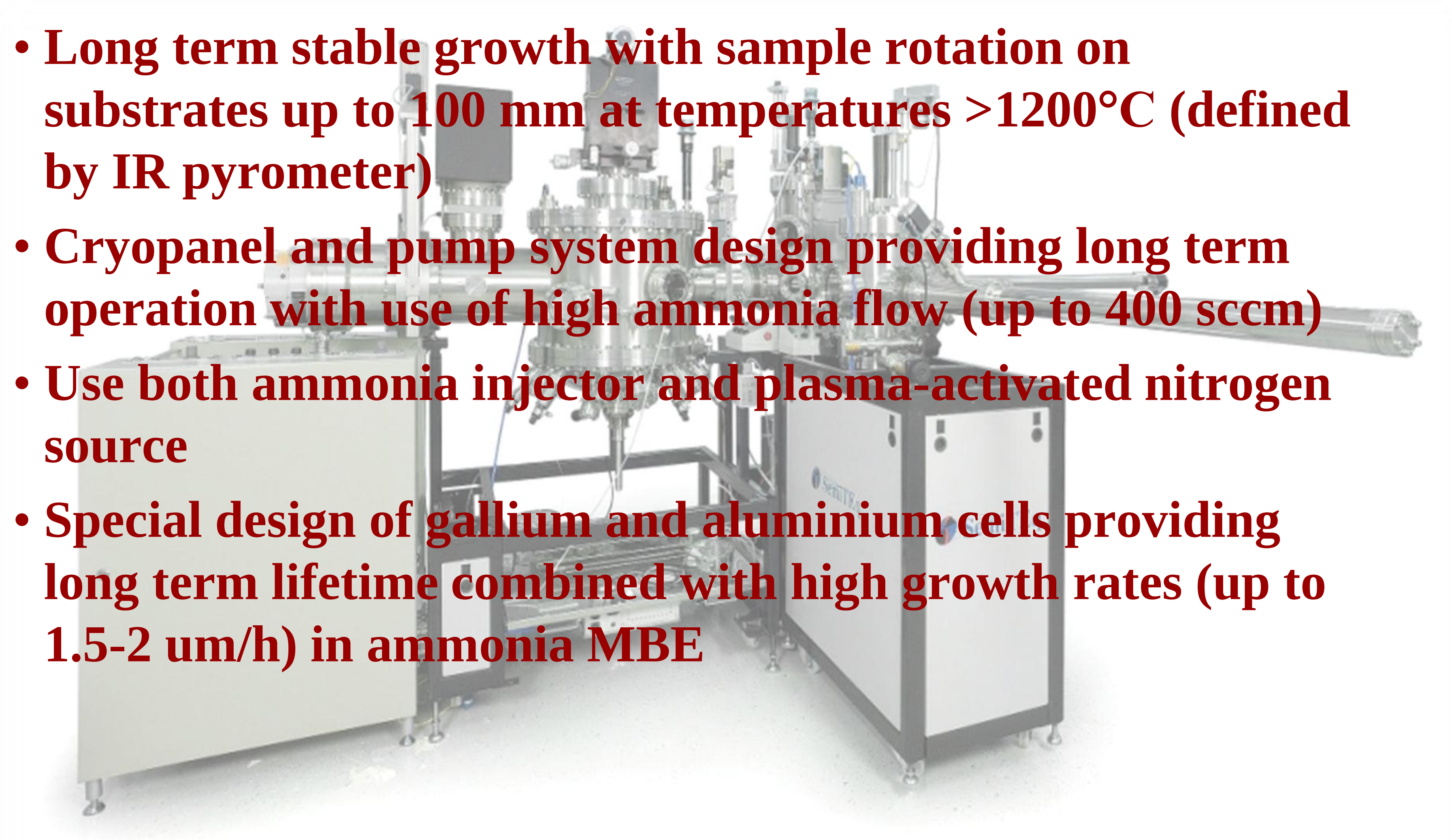
AlGaN

Transition layer AlN/AlGaN (SLS)

AlN 200 nm 1150^0C

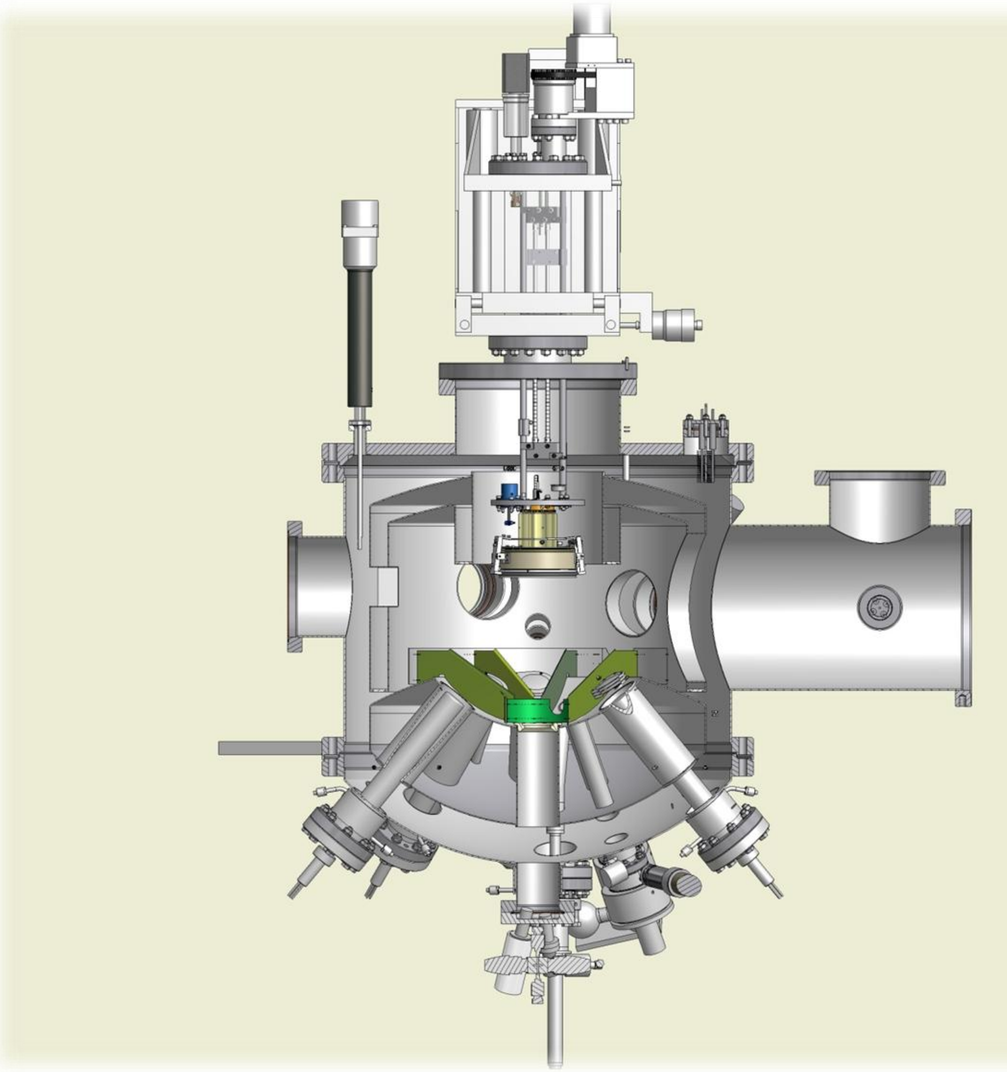
Mismatched substrate (Al_2O_3 etc)

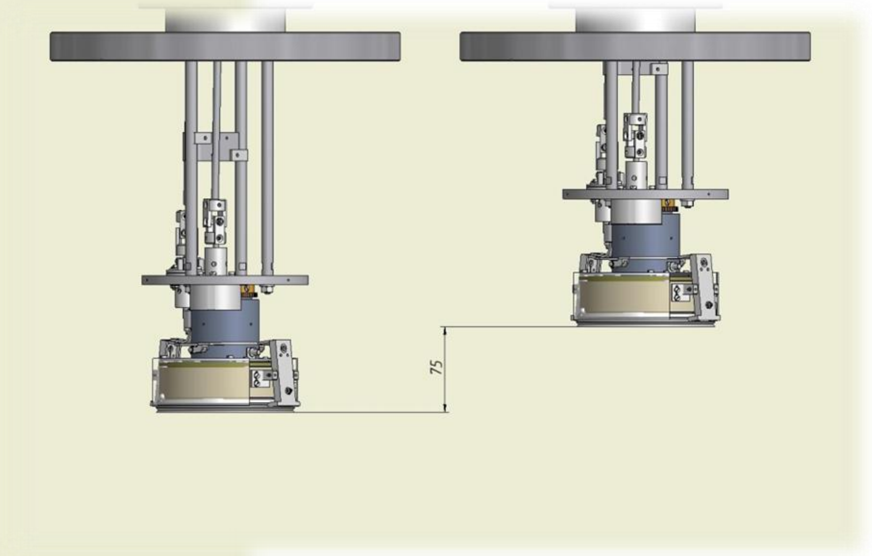
STE3N* – unique MBE system for high temperature III-nitrides growth



- Long term stable growth with sample rotation on substrates up to 100 mm at temperatures >1200°C (defined by IR pyrometer)
- Cryopanel and pump system design providing long term operation with use of high ammonia flow (up to 400 sccm)
- Use both ammonia injector and plasma-activated nitrogen source
- Special design of gallium and aluminium cells providing long term lifetime combined with high growth rates (up to 1.5-2 um/h) in ammonia MBE

STE3N MBE System – DESIGN FEATURES





Key components of MBE System containing original know-how

РОССИЙСКАЯ ФЕДЕРАЦИЯ

ПАТЕНТ

№ 61717

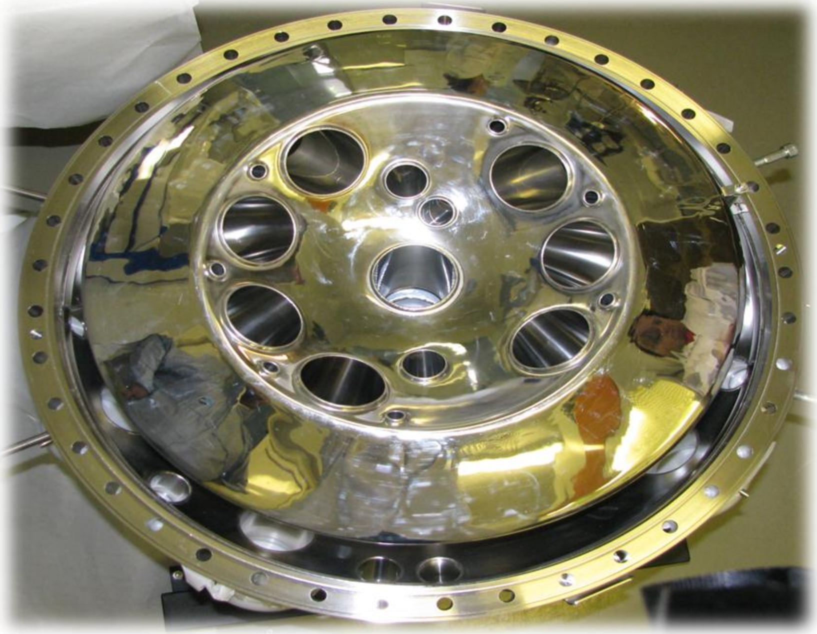
РОСТОВОЙ МАНИПУЛЯТОР ВАКУУМНОЙ КАМЕРЫ ДЛЯ ВЫРАЩИВАНИЯ ПОЛУПРОВОДНИКОВЫХ ГЕТЕРОСТРУКТУР

РОССИЙСКАЯ ФЕДЕРАЦИЯ

ПАТЕНТ

№ 61716

РОСТОВОЙ МАНИПУЛЯТОР ВАКУУМНОЙ КАМЕРЫ ДЛЯ ВЫРАЩИВАНИЯ ПОЛУПРОВОДНИКОВЫХ ГЕТЕРОСТРУКТУР



- special designed substrate holders providing high temperature uniformity
- original *flexible* growth geometry (Z-moving both the heater and wafer)
- large surface, very reliable LN2 cryopanels
- growth with high temperature stage based on PBN/PG/PBN element
- “creeping free” design of effusion cells for Al and Ga, *without water cooling*

Effusion cells specially designed for ammonia-assisted GaN-MBE

Conventional type, water cooled Al cell after 40 runs: AlN V_g<0.2 µm/h

SemiTEq patented design, after 40 runs;
full lifetime more than 300 runs: AlN V_g>0.1-1 µm/h

High temperature AlN and multilayer heterostructure (MHS)

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AT INCREASED GROWTH TEMPERATURE GaN THERMAL DECOMPOSITION OCCURS BUT AlN DECOMPOSITION TEMPERATURE IS HIGHER

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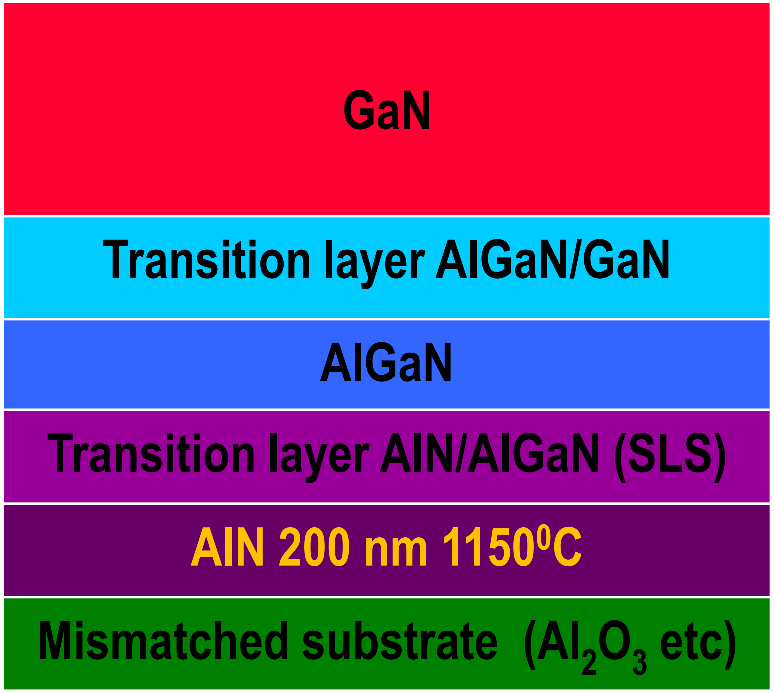


GaN

Transition layer AlGaN/GaN

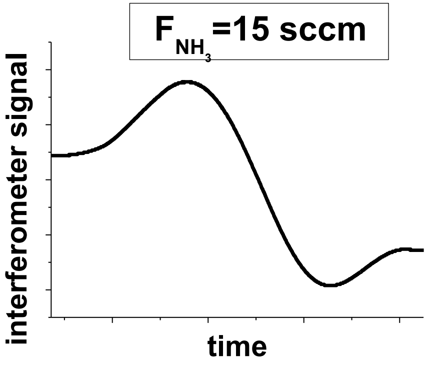
AlGaN

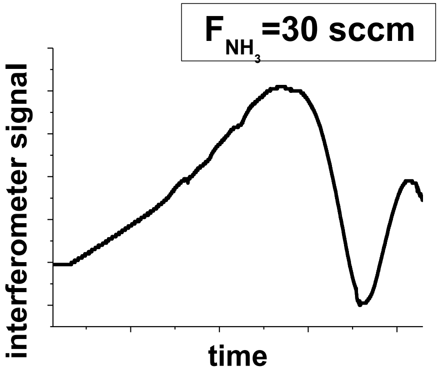
Transition layer AlN/AlGaN (SLS)

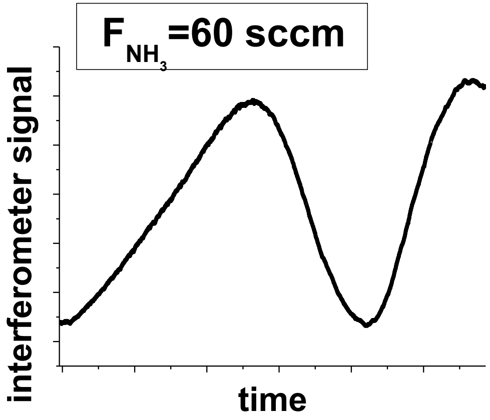
AlN 200 nm 1150^0C

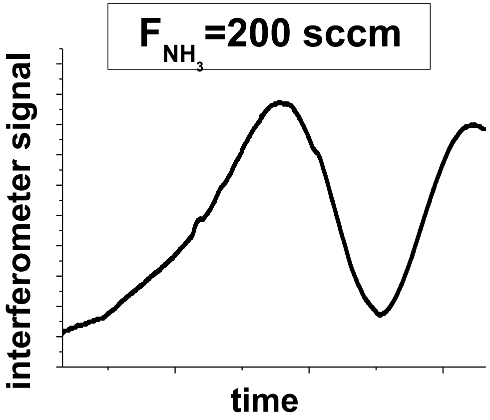
Mismatched substrate (Al_2O_3 etc)

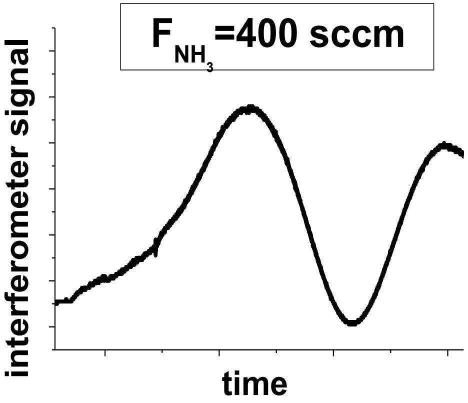
AlN growth optimum conditions



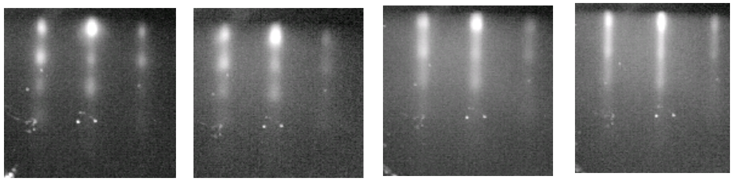






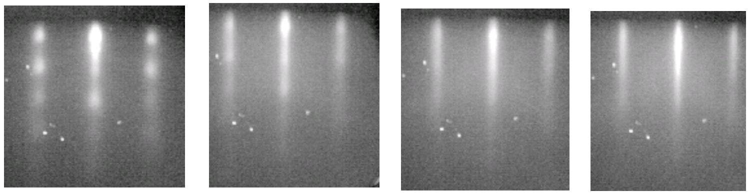


$T_{gr}=900^0C$



1 min 8 min 15 min 20 min

$T_{gr}=1150^0C$



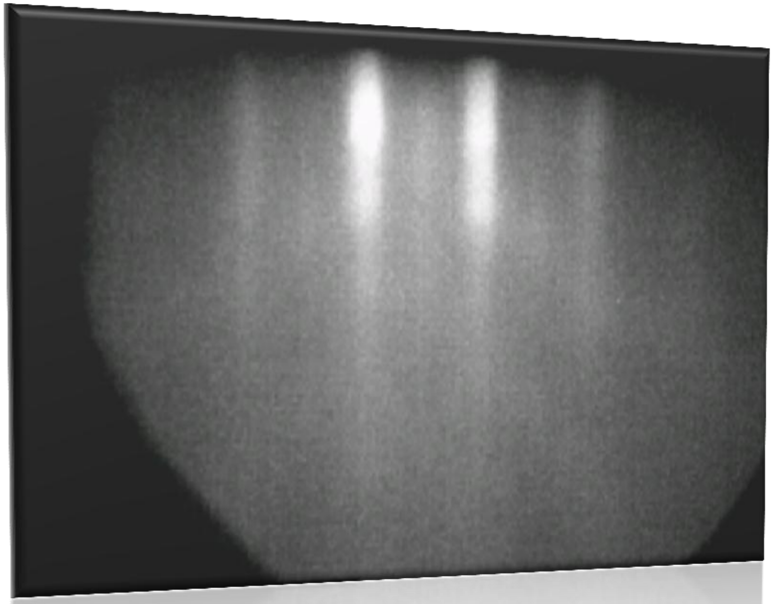
1 min **8 min** 15 min 20 min

Optimum conditions:

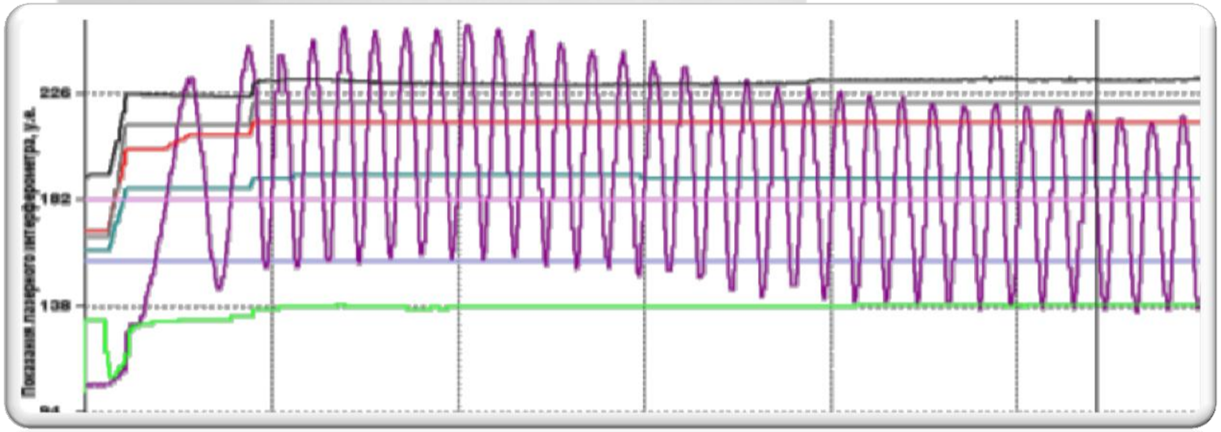
$T_{growth}=1150^0C$

ammonia flow 60 sccm

AlN Growth results



- T growth 1150°C
- Vg >0,5 µm/h
- Epilayer thickness from 0,2 to several microns



- Results in easy technology transfer on different mismatched substrates (sapphire, SiC, SiC/AlN, Si)

MULTILAYER HETEROSTRUCTURE (MHS): dislocations density

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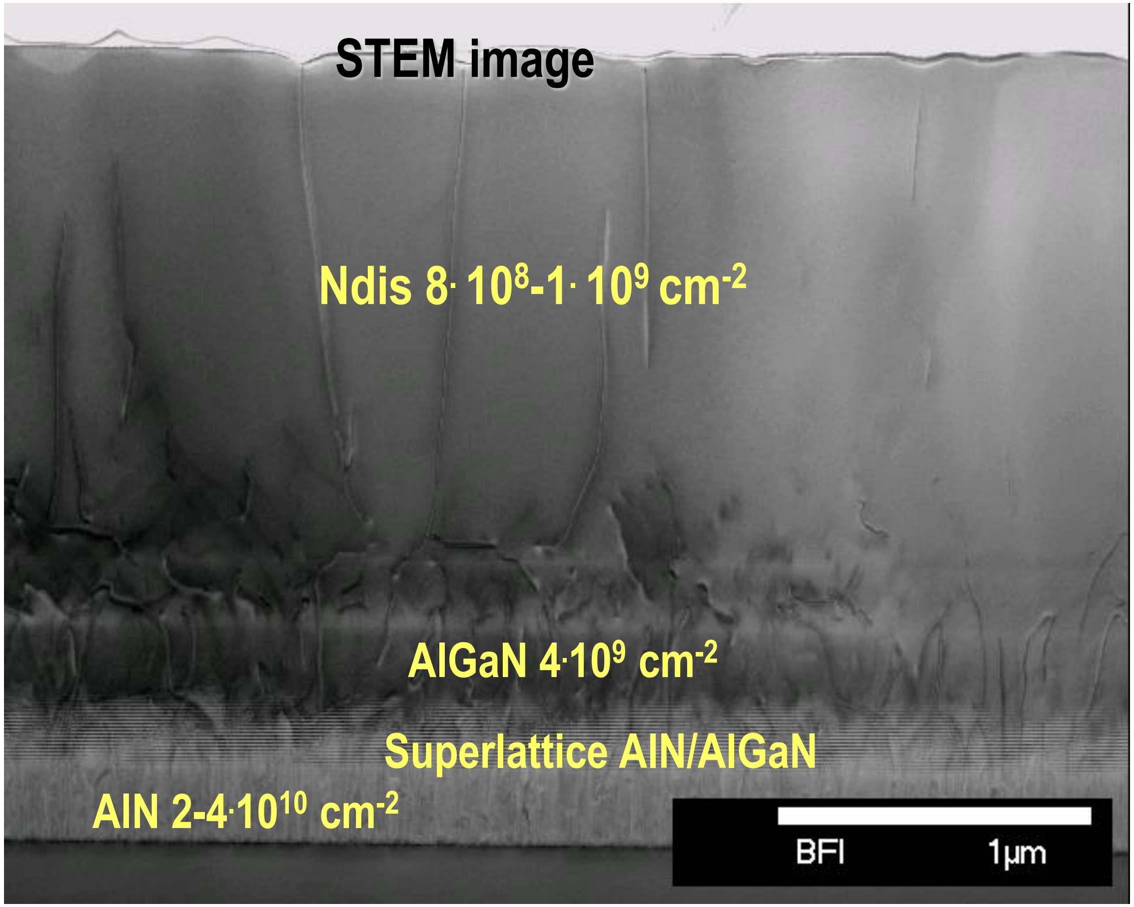
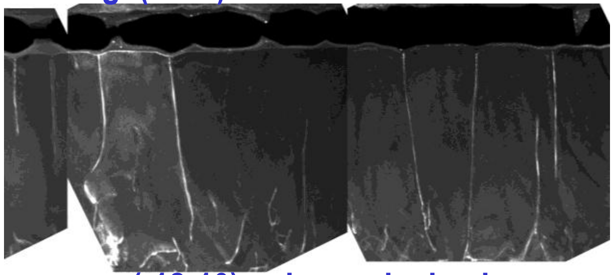
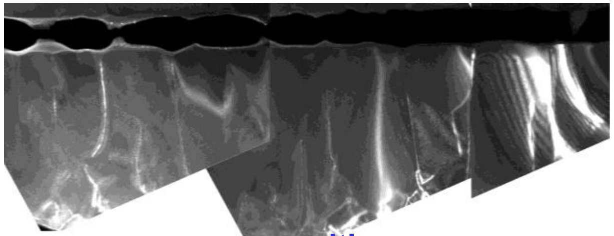


TEM images

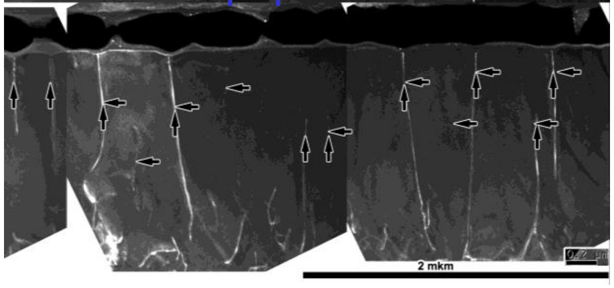
g=(0002) screw and mixed



g=(-12-10) edge and mixed



superposition



	Screw	Edge	Mixed	Total
Dislocation density ($\times 10^9$ cm^{-2})	~0.2	~0.4	~0.4	1

MULTILAYER HETEROSTRUCTURE (MHS): GaN properties

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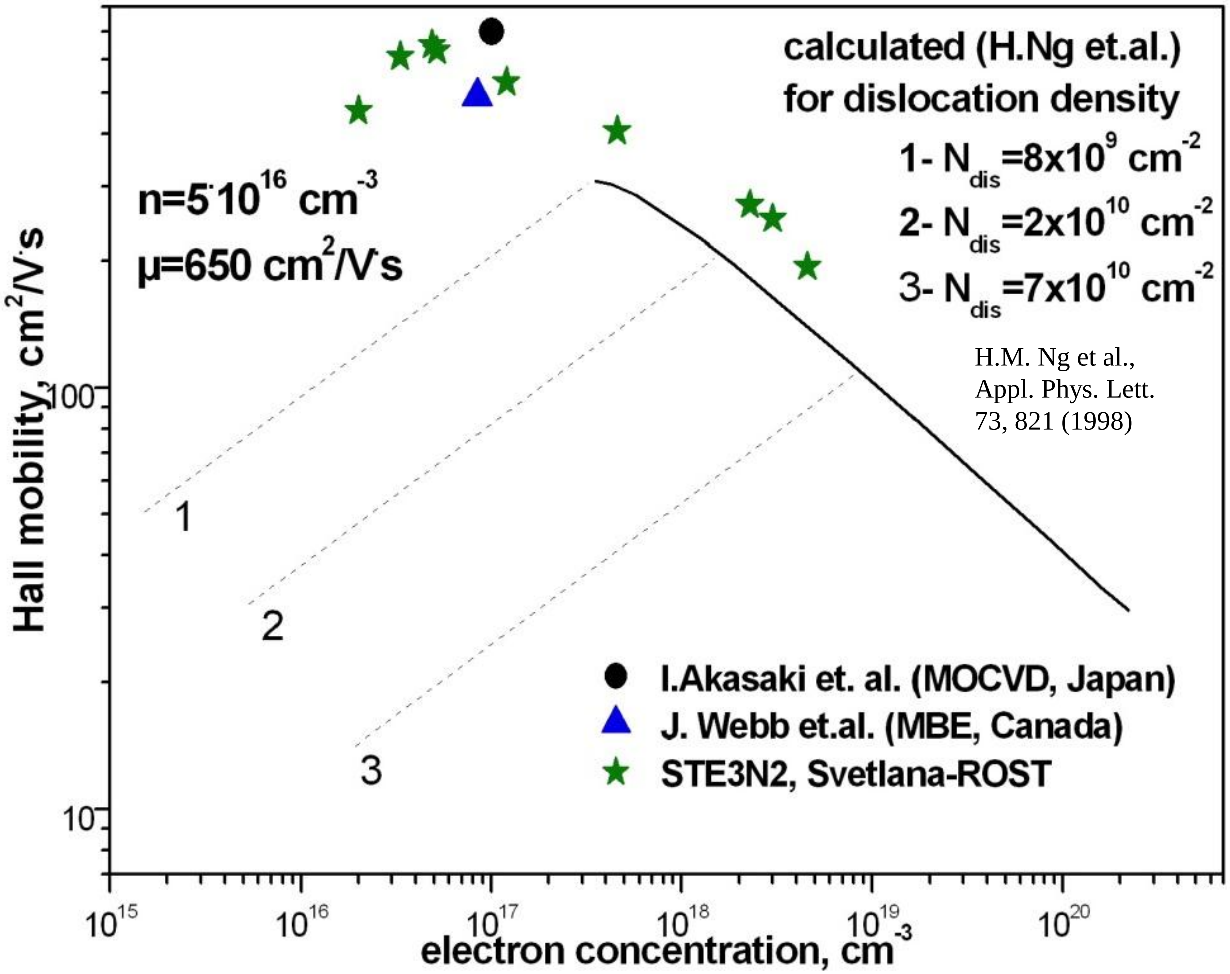

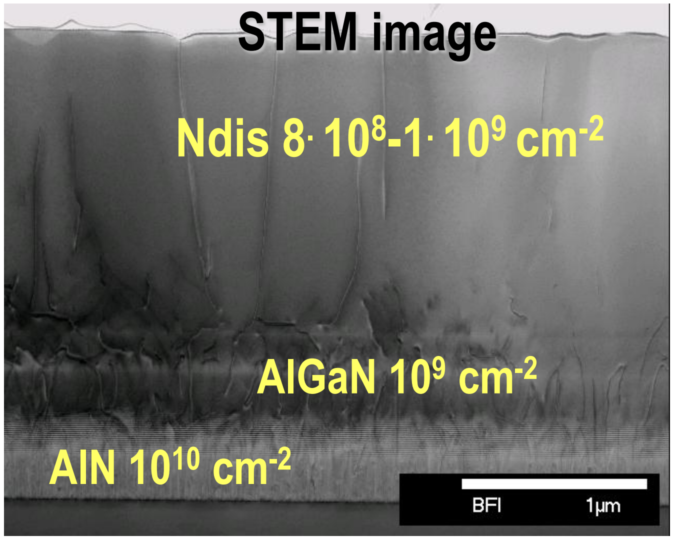

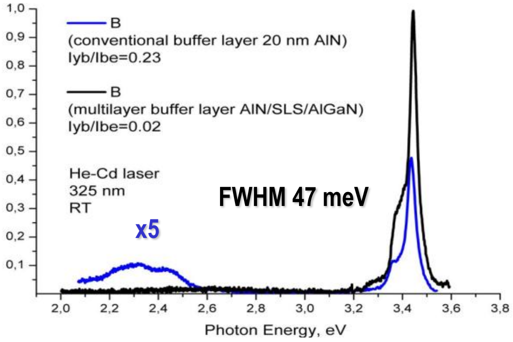

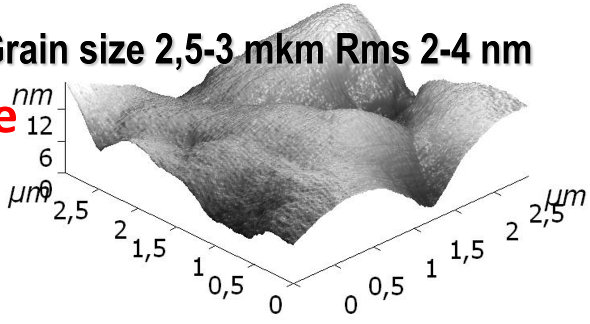

Maximum electron mobility in MBE grown GaN on sapphire (without using of MOCVD templates).

Corresponds to a good quality MOCVD GaN

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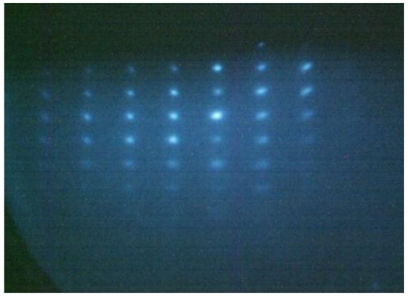
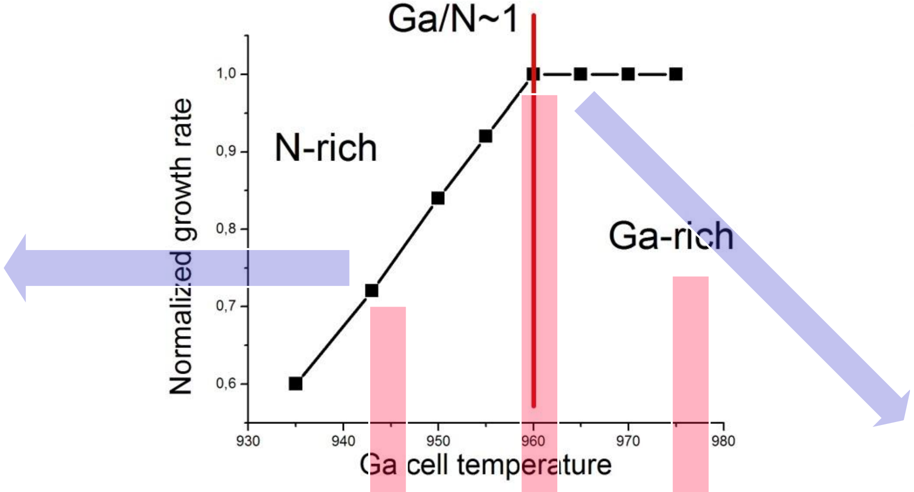
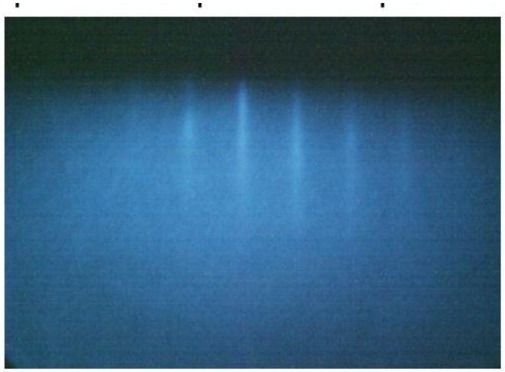
PA-MBE GaN growth mode determination

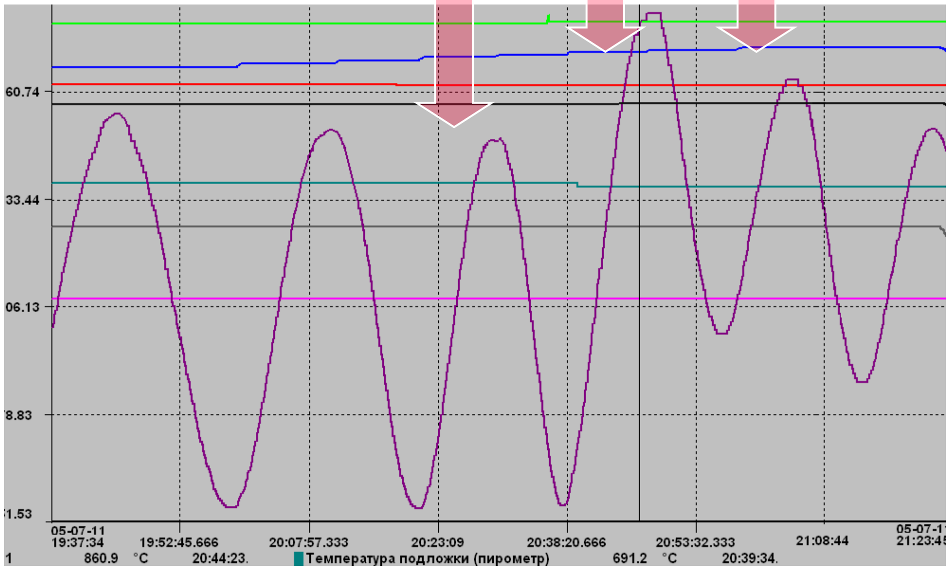


3D mode



2D mode





μ_{max} >500 $cm^2/V \cdot s$

in GaN grown by PA-MBE

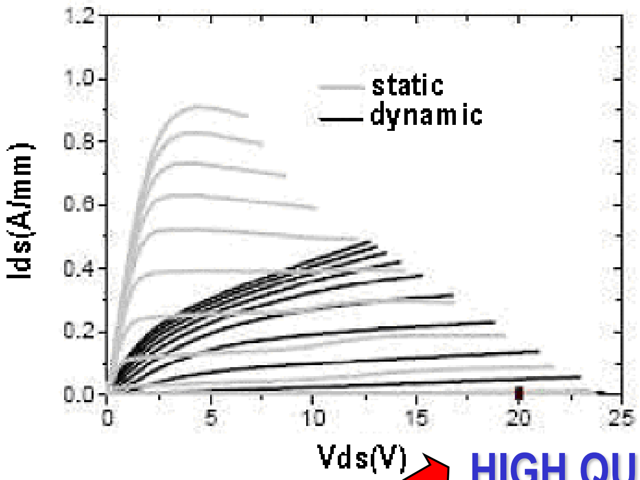
on “ammonia”

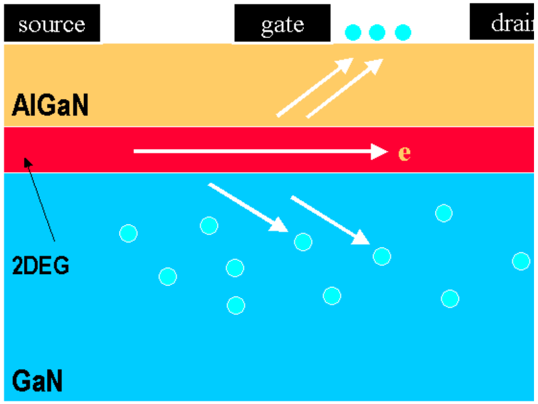
AlN/SL/AlGaN buffer

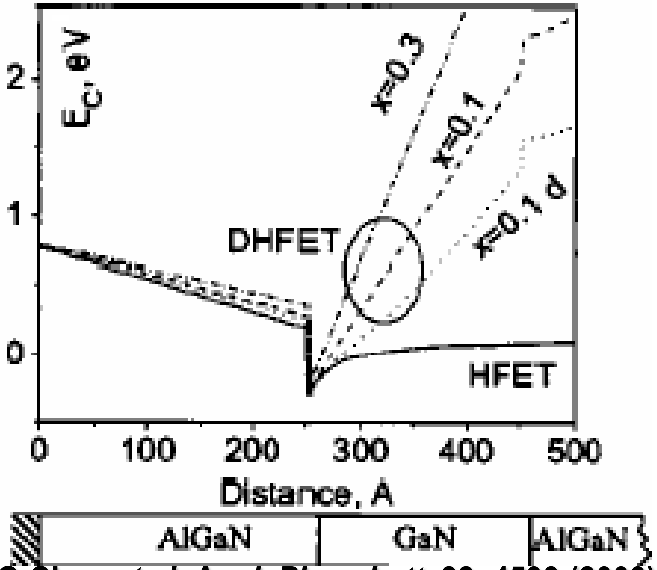
HEMT HETEROSTRUCTURE: DESIGN CHOICE

ONE OF THE PROBLEMS OF GaN HEMT PRODUCTON – RF CURRENT “COLLAPSE”

(REASON – HOT ELECTRON SPILLOVER UNDER HIGH GATE-SOURCE BIAS AND TRAPPING IN BUFFER AND UPPER BARRIER LAYERS)







C.Q.Chen *et al*, *Appl. Phys. Lett.* 82, 4593 (2003)

DECISION

- HIGH QUALITY GaN
- SURFACE PASSIVATION
- ELECTRON CONFINEMENT INCREASE

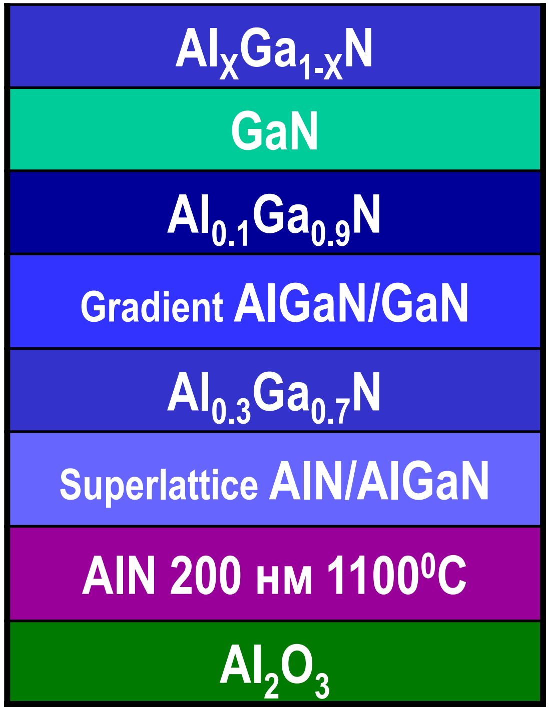
COMPENSATION DOPING OF GaN

ADDITIONAL TRAPS

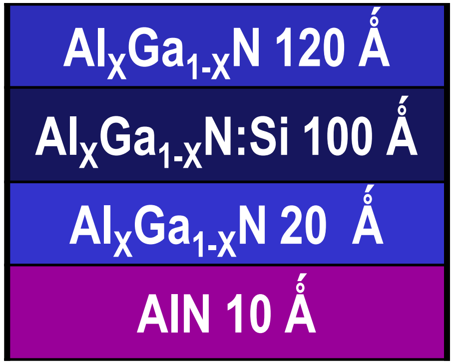
DOUBLE HETEROSTRUCTURE (DHS) AlGaN/GaN/AlGaN

x_{Al}<0.15 in buffer layer: *p*-type region is not formed, band offset is enough for quantum confinement

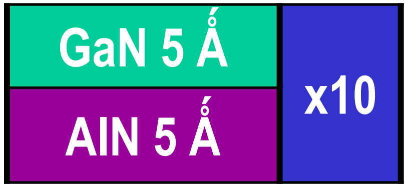
DHEMT HETEROSTRUCTURE: AlGaN BARRIER LAYER DESIGN



Modulate doped barrier layer AlGaN



Barrier layer based on superlattice AlN/GaN

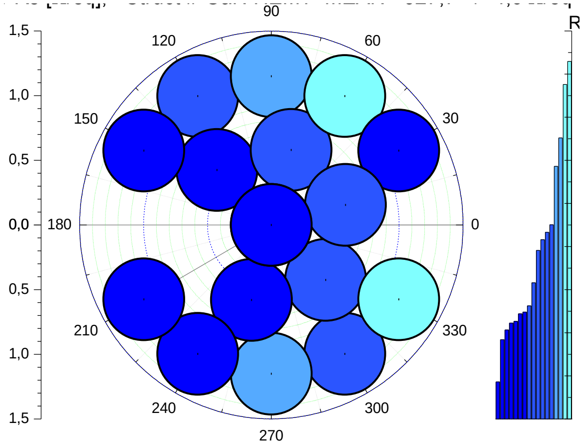


X_{Al}	n·10^{13} , cm^{-2}	μ, cm^2/B·c	Rs
0.25	1.1-1.2	1300-1400	400-420
0.3	1.5-1.6	1300-1400	290-310
0.4	1.7-1.8	1300-1400	250-270
0.5 SLS AlN/GaN	1.8-1.9	1500-1700	230-250

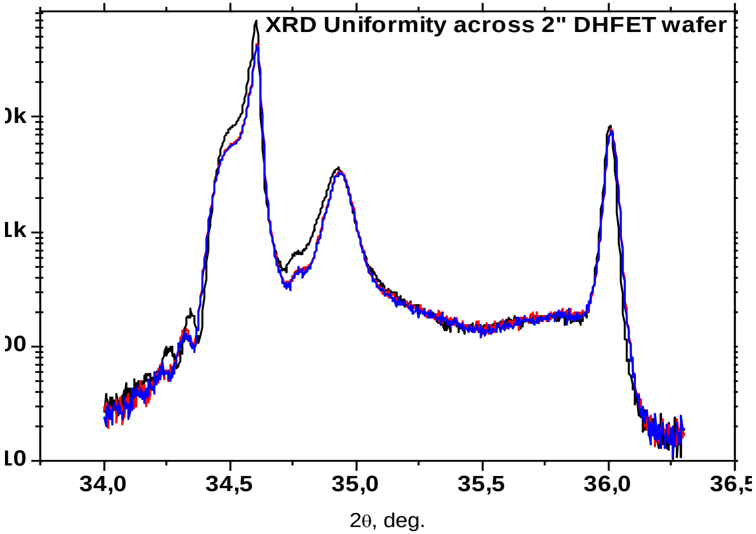
Controllable change of sheet resistance (Rs) in the range of 230-400 Ohm/sq

UNIFORMITY AND REPRODUCIBILITY

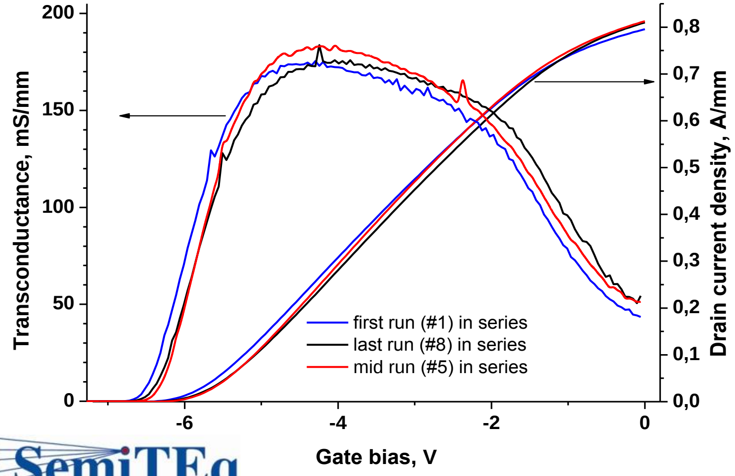
Sheet resistance uniformity 307.2 Ω/□ +/-1% (3” DHFET wafer)

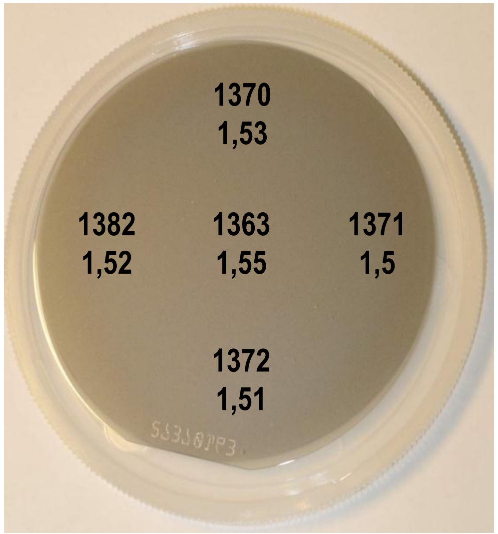


Composition uniformity +/-1%

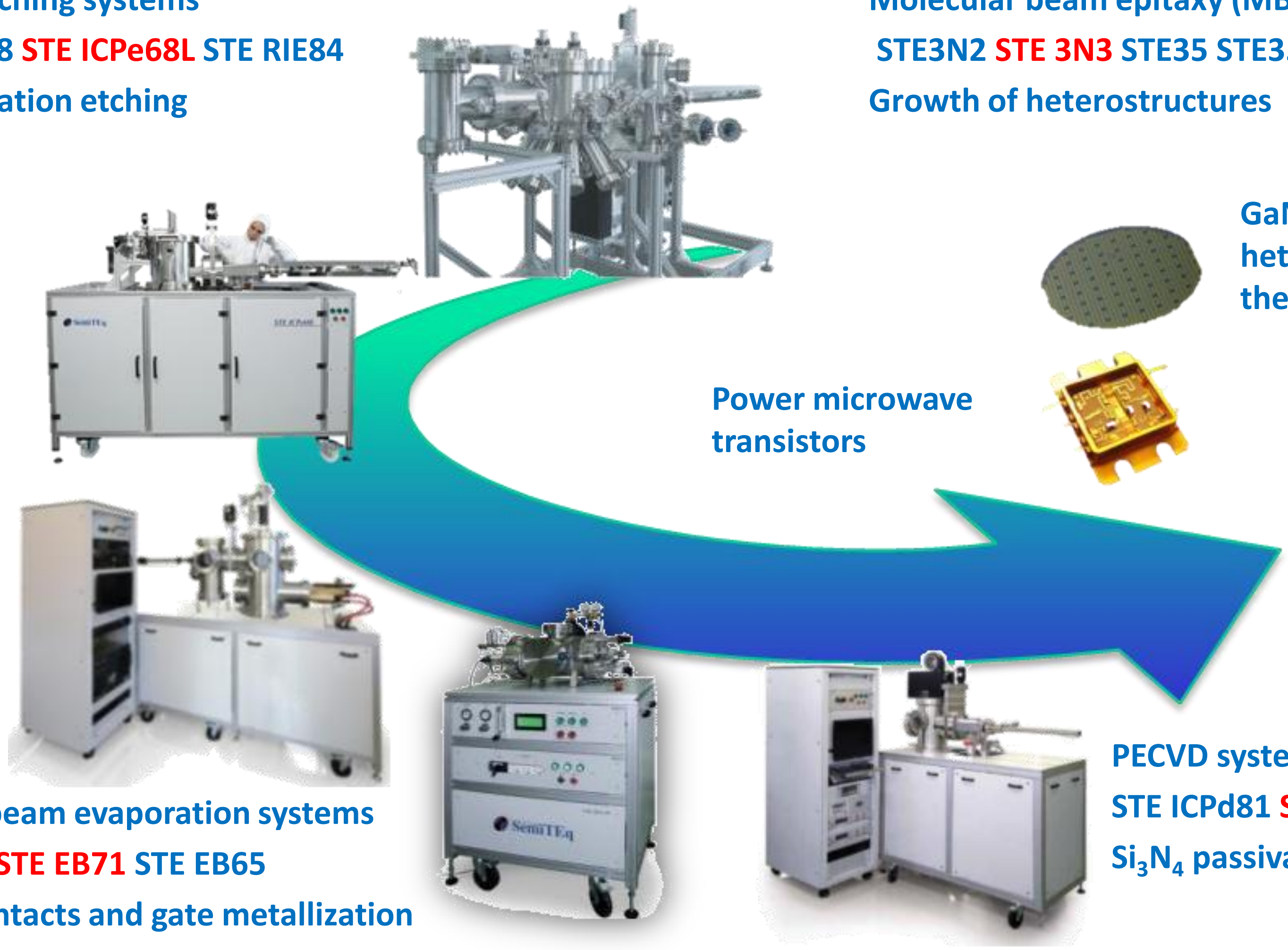


Run-to-run reproducibility of AlGaN DHFET static parameters





Set of SemiTEq Equipment optimized for III-Nitrides: power microwave transistor technology application



Plasma etching systems

STE ICPe68 STE ICPe68L STE RIE84

Mesa-isolation etching

Molecular beam epitaxy (MBE) systems

STE3N2 STE 3N3 STE35 STE3526 STE75

Growth of heterostructures

GaN based heterostructures with the formed elements

Power microwave transistors

Electron beam evaporation systems

STE EB48 STE EB71 STE EB65

Ohmic contacts and gate metallization deposition

Rapid thermal annealing systems

STE RTA70 STE RTA79

Ohmic contacts thermal activation

PECVD systems

STE ICPd81 STE ICPd81L

Si_3N_4 passivation layer deposition

Wafer processing equipment for GaN DHFET

Ohmic contacts and gate deposition in electron beam evaporation system:

STE EB71

Thermal activation of ohmic contacts in rapid thermal annealing system **STE RTA79**

*Rc<0.5 Ohm*mm*

Mesa-isolation etching in plasma etching system :

STE ICPe68L

Rmesa>50 MOhm (Ubr>150 V)

Si_3N_4 passivation layer deposition in PECVD system :

STE ICPd81L

SemiTEq

The technology of submicron gate on the GaN-DHFET using SemiTEq equipment

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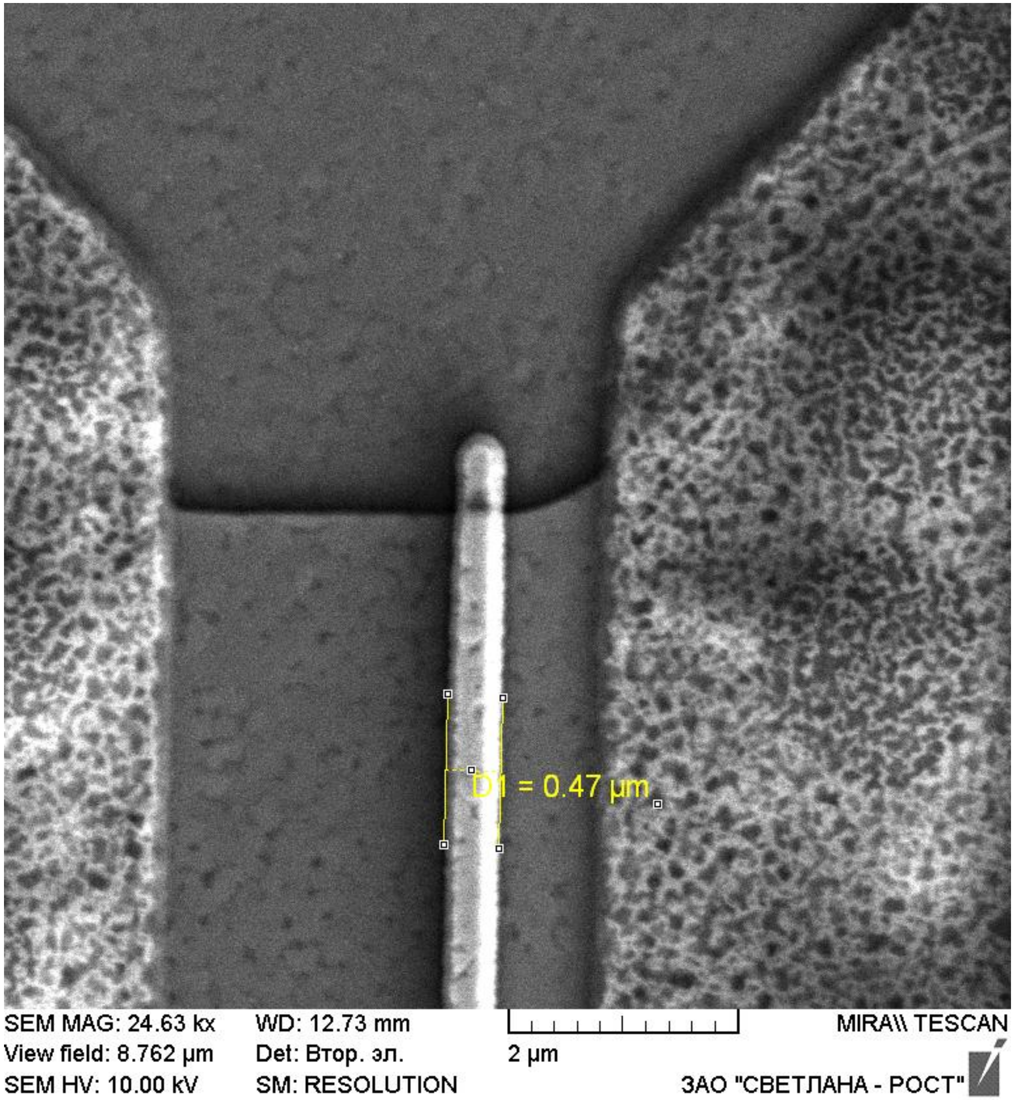

STE3N2 – growth of GaN DHFET

STE EB71 – Ti/Al/Ni/Au contacts & Ni/Au gate metallization

STE RTA79 – Thermal activation of ohmic contacts

STE ICPe68 – Mesa-isolation etching

Reverse current gate-source at Ugs= -50 V <10µA (Wg=100µm)

The complex result of the use of SemiTEq equipment in the manufacture of microwave transistors based on GaN

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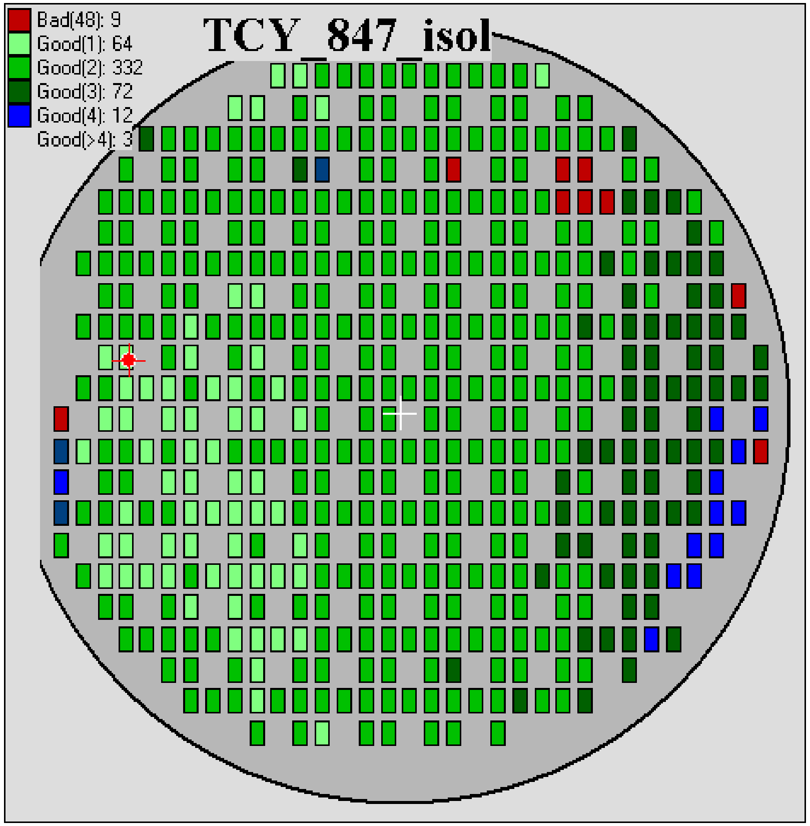
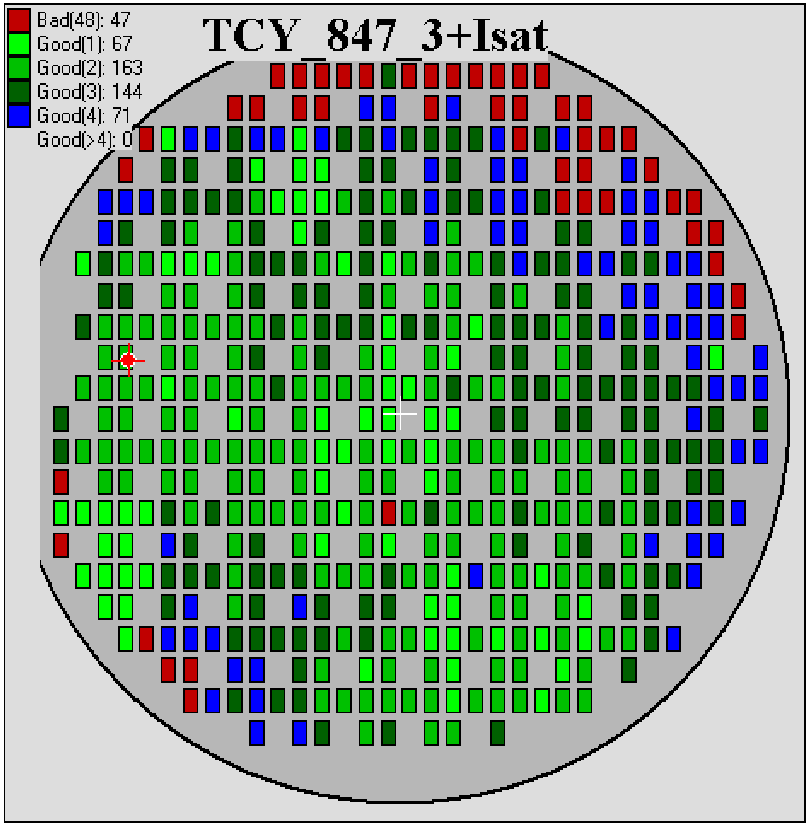
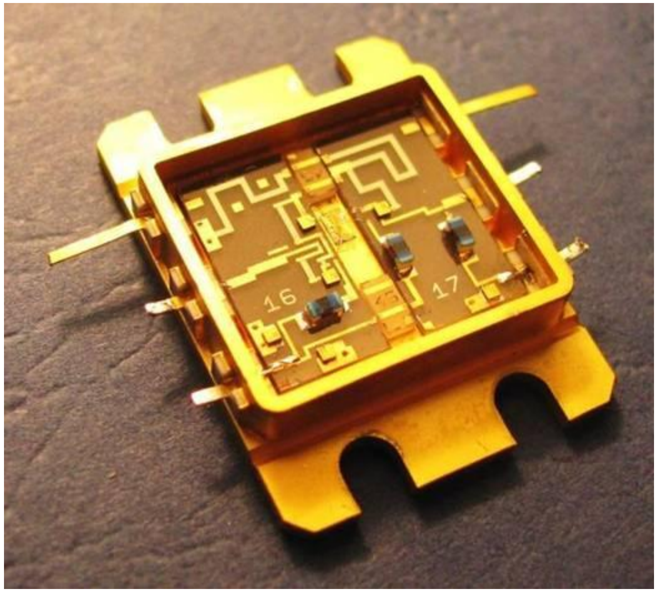


Resistance insulation mapping in three-section 900um AlGaN transistors on 2“ SiC wafer, yield is 97.3%



Saturation current mapping in three-section 900um AlGaN transistors on 2“ SiC wafer, yield is 76.1%

DEVICE REALIZATION EXAMPLE



Broadband amplifiers

30 MHz - 4,0 GHz

Gain =17-25 dB

P_{out} = 2,5 W; Efficiency = 30%

≥ 3500 hours at +85°C

device parameters confirm the high quality of the heterostructure and chosen technological and design approaches

Summary

Low-dislocation-density and high-electron-mobility GaN layers are grown on by NH_3-MBE on c-Al_2O_3 in a special STE3N system under the ultimate for MBE growth temperature using the buffer layer sequence: AlN ($T_S=1150^0C$)/SL/$Al_xGa_{1-x}N$ ($x=0.1-0.3$).

STEM showed gradual decrease of threading dislocation density: $(2-4)\times10^{10}$ cm^{-2} in AlN, $(4-6)\times10^9$ cm^{-2} in $Al_{0.1}Ga_{0.9}N$, and finally $(9-10)\times10^8$ cm^{-2} in GaN that comparable with MOCVD GaN grown on sapphire and several times lower than in conventional MBE.

Detailed study by TEM allowed separate evaluation of the density of screw ($\sim2\times10^8$ cm^{-2}), edge ($\sim4\times10^8$ cm^{-2}), and mixed ($\sim4\times10^8$ cm^{-2}) dislocations in the top GaN layer.

The improvement of structural quality resulted in increase of electron mobility in GaN (up to 600-650 cm^2/Vs at $n=(3-5)\times10^{16}$ cm^{-3}) that corresponds to a good quality MOCVD GaN.

Employing such a GaN layer in a double heterostructure (DH) with the cap $Al_xGa_{1-x}N$ barrier ($x=0.25-0.4$) allows to change the mobility and electron sheet density in 2DEG in the range of 1300-1700 $cm^2/V{\cdot}s$ and $(1.0-1.8)\times10^{13}$ cm^{-2} (sheet resistance 230-400 Ω/□).

Application of this technology and DH design for growing on SiC enabled one to manufacture a DHFET for 0.03-4.0 GHz extra-broadband power amplifiers having $P_{out}=2.5$ W, gain 17-25 dB and efficiency 30% (gate length of 0.5 μm).

These device parameters confirm the high quality of the heterostructure and chosen technological and design approaches.

Thank you for your attention!