GaN component technology development in Europe - current status and perspectives

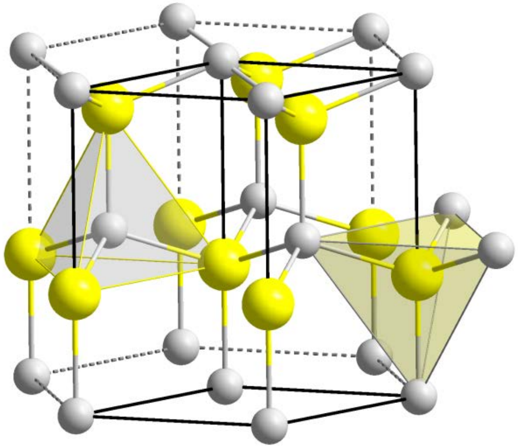
A Barnes TEC-QTC

esccon 2013
12 - 14 march 2013

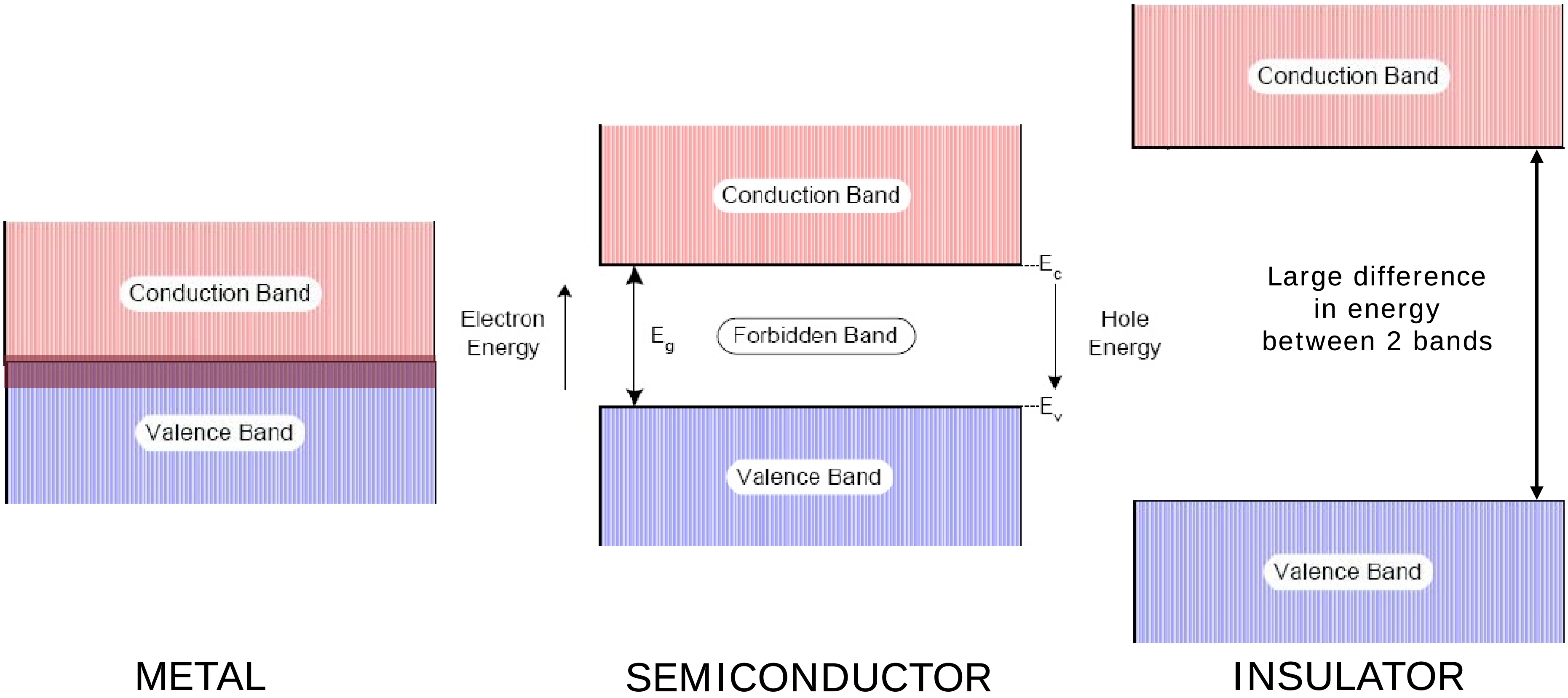
Talk outline

- Introduction to WBG semiconductors
- ESA IPC roadmap and strategy 2006-2012
- Key achievements from ongoing projects
- Conclusions
- Issues and next steps

1. Introduction to WBG semiconductors



What is a wide band gap semiconductor?



European Space Agency

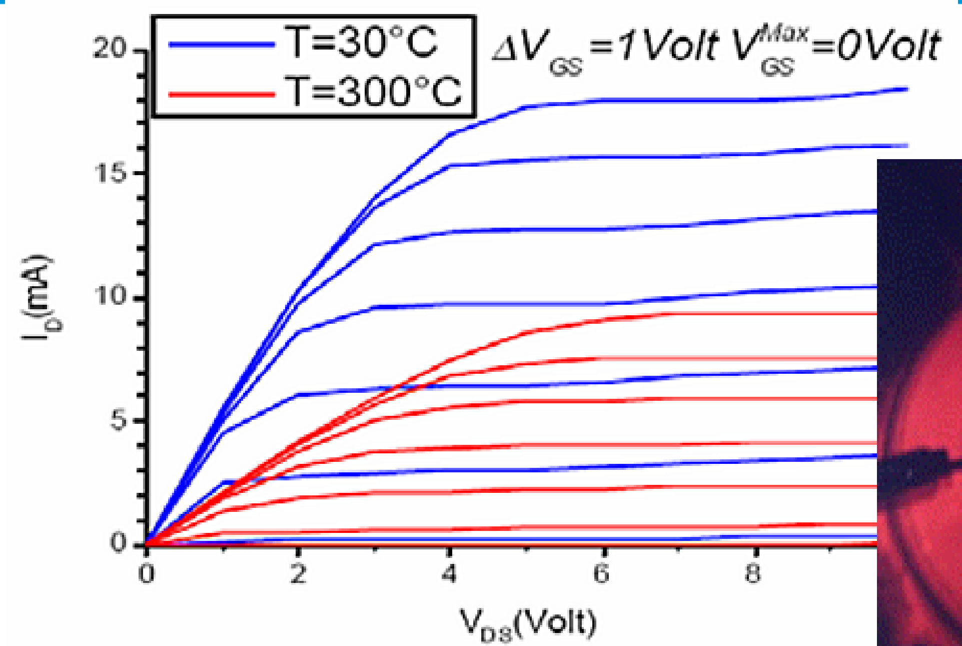
Properties of WBG semiconductors

esa

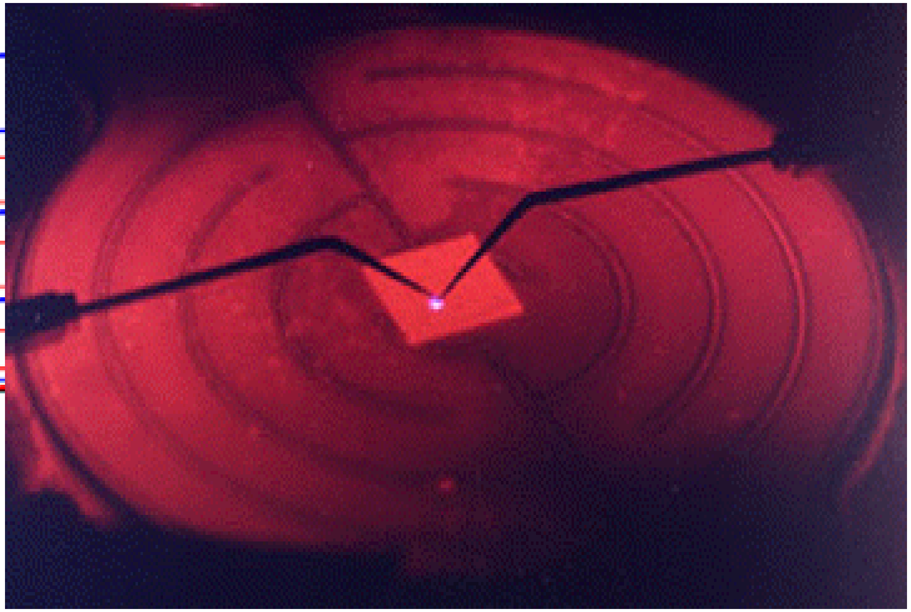
	Narrow band gap Eg<<1eV		Intermediate band gap Eg≈1eV			Wide band gap Eg>3eV	
	InSb	**InAs**	**$In_{0.53}Ga_{0.47}As$**	**Si**	**GaAs**	**SiC**	**GaN**
Electron Mobility $x10^3$ ($cm^2V^{-1}s^{-1}$)	30	16	8	0.6	4.5	0.8	1.6
Electron Velocity (10^7 cm/s)	5.0 (peak)	4.0 (peak)	2.7 (peak)	1.0 (sat.)	2.0 (sat.)	2.0 (sat.)	2.7 (sat.)
Band-gap (eV)	0.18	0.36	0.72	1.1	1.43	3.2	3.4
Breakdown field (MV/cm)	0.01	0.1	0.4	0.6	0.6	3.5	3.5
Thermal conductivity (W/cmK)	0.18	0.27	≈0.3	1.5	0.46	3.55	1.7
Heterojunctions	Yes	Yes	Yes	Yes	Yes	No	Yes

European Space Agency

Properties of WBG semiconductors



GaN HEMT DC IV characteristic
Tamb=30°C
Tamb=300°C



Photodiode (25mm^2) operating at 600°C

- High temperature operation
- Inherent radiation hardness

Why the interest in SiC and GaN?

Material properties

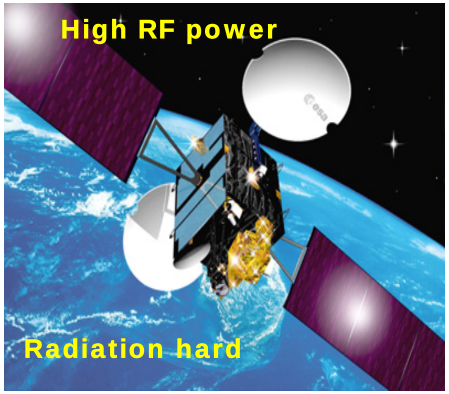
- High electron saturation velocity ≈2.5 x10^7 cm/s
- High carrier density ≈10^{13}/cm^2
- Large bandgap
  - High breakdown field
  - High temperature operation
  - Radiation robustness
- Heterostructure design (GaN)

Device performance

- High output power density, small size, easy impedance match
- High voltage operation, simplified voltage conversion
- Operation under extreme environmental conditions

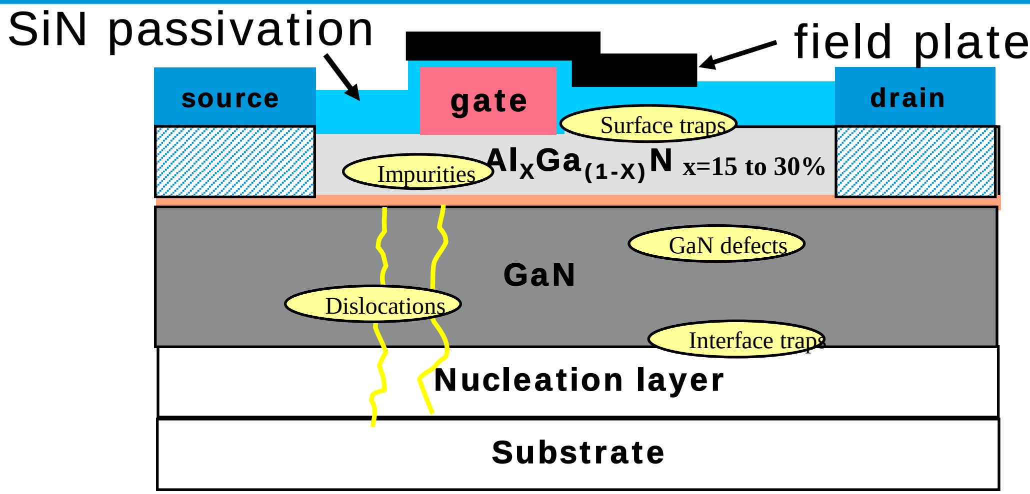
Applications

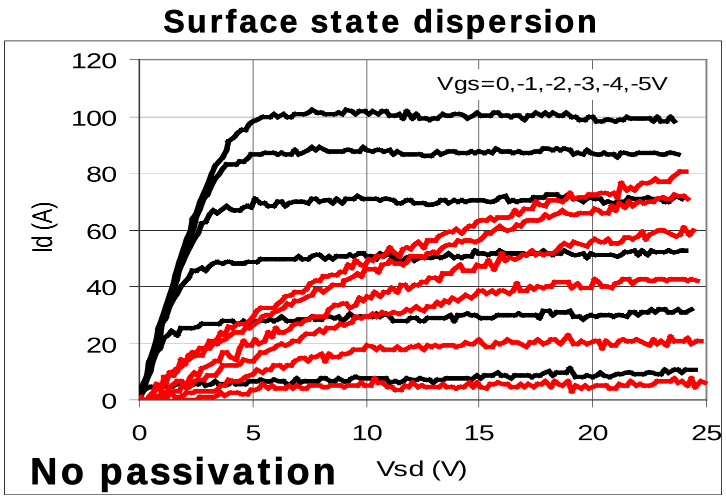
- Telecommunications
- Radars
- Novel sensors, detectors
- Power switching
- Solar cells, blocking diodes

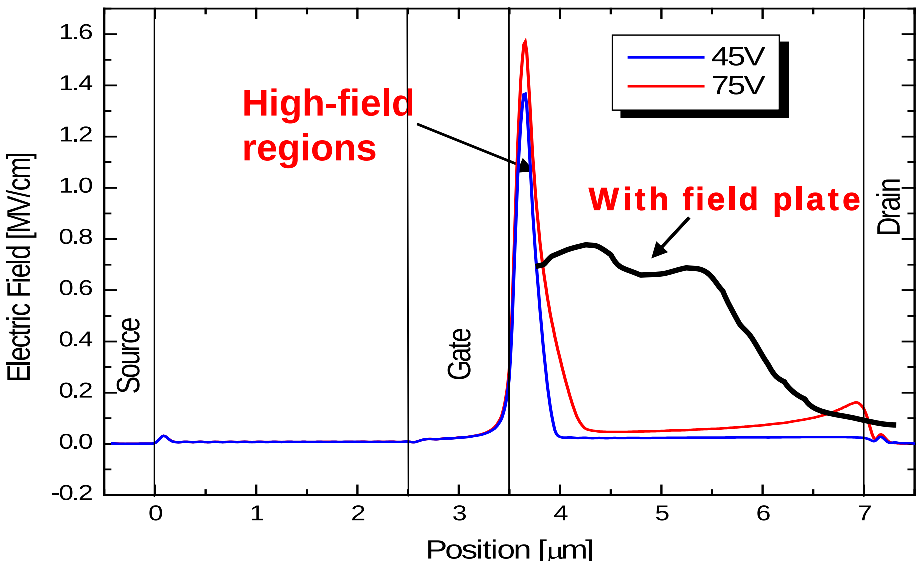


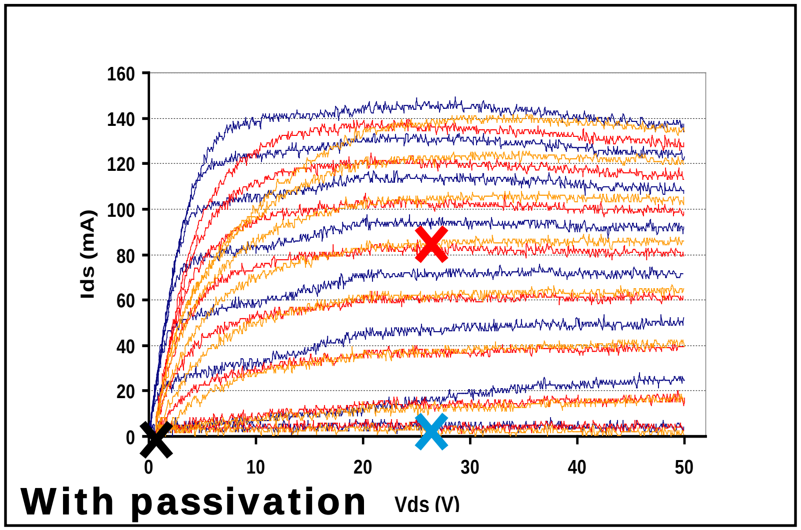
European Space Agency

AlGaN/GaN HEMT performance issues







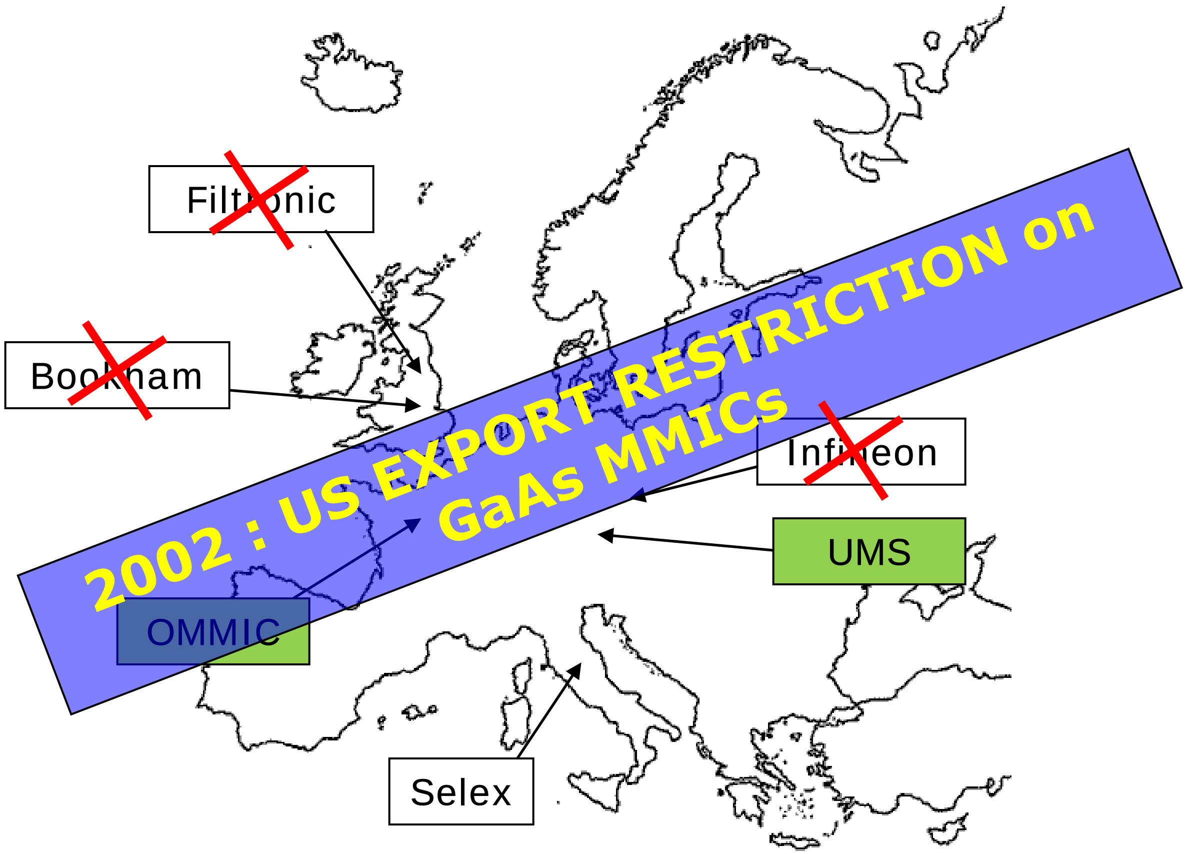


European Space Agency

2. ESA IPC roadmap and strategy 2006-2012

European Space Agency

European GaAs microwave foundry situation 2002



- 6 potential foundry sources

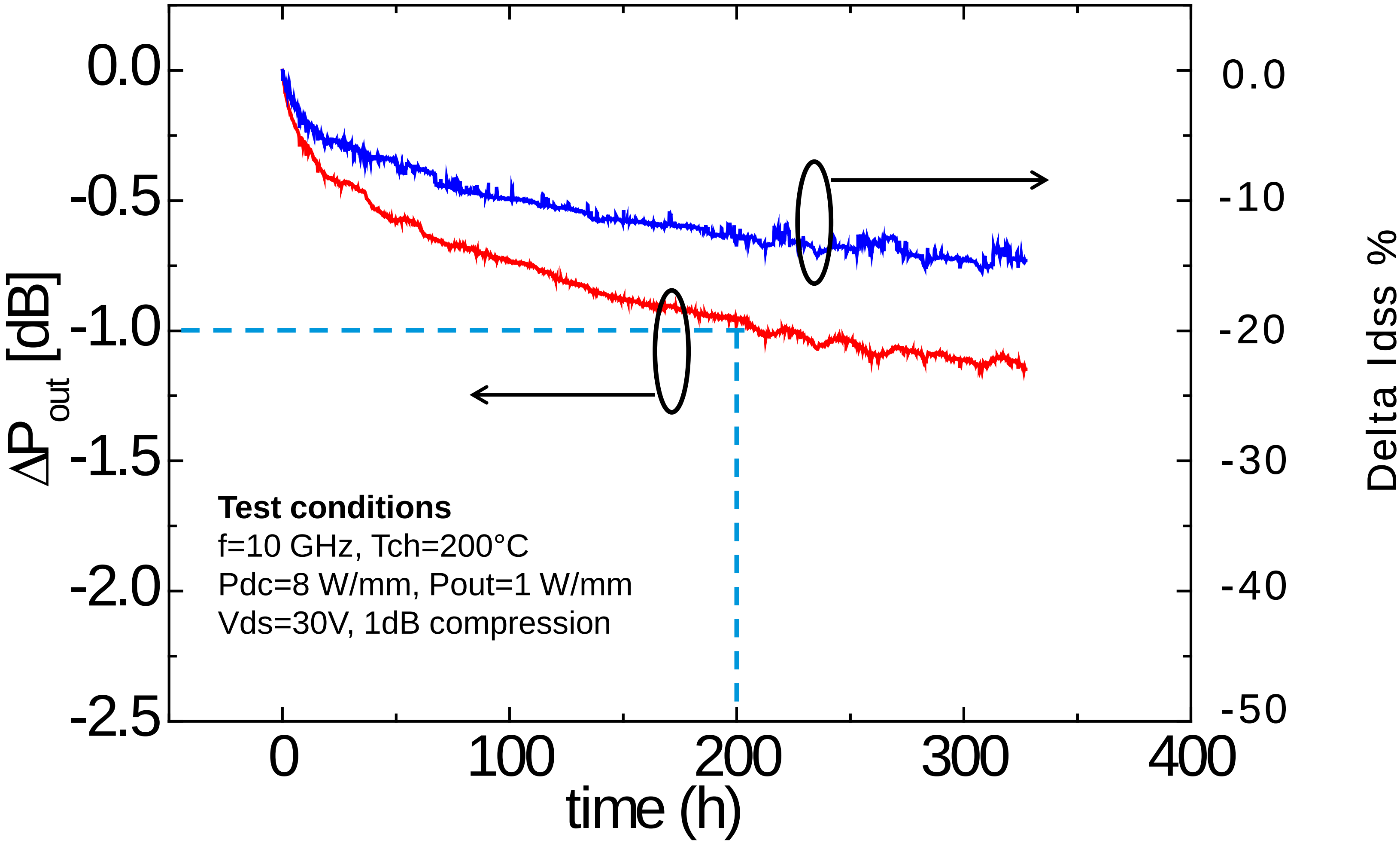
- 2 primary merchant foundry sources + Selex

- Many companies using Triquint products

European Space Agency

GaN technology development status 2006

- Rapid RF output power degradation after 10-200 hundred hours operation



ESA / IPC(2006)89 strategy paper goals

- Safeguard European access to strategic microwave components (GaN)
- Secure European non-dependence

1. Improving GaN device reliability for space
2. Establishment of an independent European supply chain that is accessible by space industry
3. Improved understanding of the disruptive benefits offered by GaN
4. Developing appropriate thermal management + packaging techniques
5. Investigation of non-RF component applications

ESA INITIAL R+D EMPHASIS

(2) MICROWAVE ELECTRONICS

Low noise, high frequency

High Power (>10 Watts)

Mobile Communications
Radar Systems
Satellite Communications
Magnetron replacement

SMALL - MEDIUM MARKET (€0.3bn by 2009)
STRONG AEROSPACE INTEREST
DIFFERENT MATERIALS REQUIREMENT TO OPTOELECTRONICS

(1) OPTOELECTRONICS

LEDs
Lasers
UV detectors
Solar cells

LARGE ESTABLISHED MARKET (€6bn by 2009)

(3) HIGH POWER + HIGH VOLTAGE ELECTRONICS

DC-DC power conversion
power switches / rectifiers

LARGE MARKET (>€3bn by 2010))
IMMATURE FIELD

Leverage materials and reliability know-how "investment" towards Power Conversion and Photonics markets

Demonstrate - space "spin-in"

Activities initiated

- 1. Improving GaN device reliability for space → GREAT^2 (GSTP); GaN HEMT reliability Physics (NPI)

- 2. Establishment of an independent European supply chain, accessible by space industry → EuSiC (FP7); Low dislocation density GaN substrates (PECS); Establishment of commercial GaN epitaxy supplier (GSTP)

- 3. Improved understanding of the disruptive benefits offered by GaN → Numerous TRP activities ….
(e.g. Single chip HPA/LNA for radar applications, GaN power stage based on European technology for Navigation SSPA…)

- 4. Developing appropriate thermal management + packaging techniques → AGAPAC (FP7)

- 5. Development of non-RF component applications → GaN device manufacture compatible with a Si production environment (GSTP)

European Space Agency

3. Key achievements and highlights

European Space Agency

GaN Reliability Enhancement and Technology Transfer Initiative (GREAT^2)

- Establishment of space compatible European GaN HEMT / MMIC foundry process
  - 0.5µm gate length GaN HEMT process
    - (UMS GH50, useable to 6GHz)
  - 0.25µm gate length GaN MMIC process
    - (IAF GaN25, UMS GH25, useable to 20GHz)
- GREAT^2 consortium
  - Leading European research institutes and manufacturing industry
  - Technology transfer
    - Planned processing throughput ≈170 wafers
  - Space operation potential validated
    - RF lifetime, radiation, ESD, H_2, vibration, shock ......
  - Independent validation at ESA
- Ready for ESA space evaluation 2014

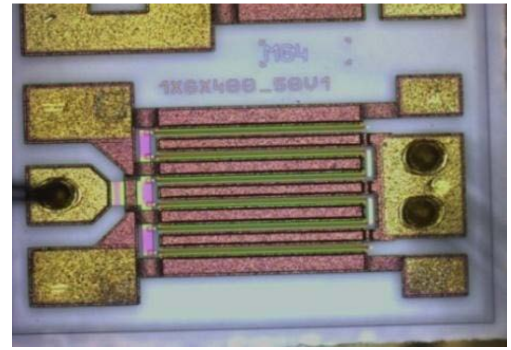
GREAT² – example L-Band milestone targets

	Milestone M3	Milestone M5	Milestone M7	
Operating frequency (GHz)	1.7	1.7	1.7	*Power density≥5 W/mm
Gate width (mm)	1.6	2.4	2.4	
Drain Bias (V)	≥50V	≥50V	≥50V	
*Output power P_{out} at max. PAE	≥37	≥37	≥37	Performance
PAE %	≥40	≥55	≥55	
Associated gain at P_{out}	≥15	≥15	≥15	
MTTF for ΔP_{xdB} ≤1dB, Tj≥230°C	**≥1 x 10^3 h**	**≥1 x 10^4 h**	**≥1 x 10^6 h**	**Reliability**
Pout variation (dB)	±1.5	±1	±0.5	
RF small signal gain uniformity (dB)	1.5	1	1	Yield
Wafer yield (%)	≥50	≥60	≥70	
Radiation sensitivity (TID, displacement, SEE)	≤15% drift (Idss, V_t, g_m)	≤15% drift (Idss, V_t, g_m)	≤15% drift (Idss, V_t, g_m)	Space Environment
Hydrogen poisoning	≤15% drift (Idss, V_t, g_m)	≤15% drift (Idss, V_t, g_m)	≤15% drift (Idss, V_t, g_m)	

Milestone M5 : Technology evaluation vehicles

esa

- L-band discrete transistor (1.7GHz)
  - Vds=50V, P_{out}≥40dBm
  - PAE>65%
  - Internal matching, 1.7GHz

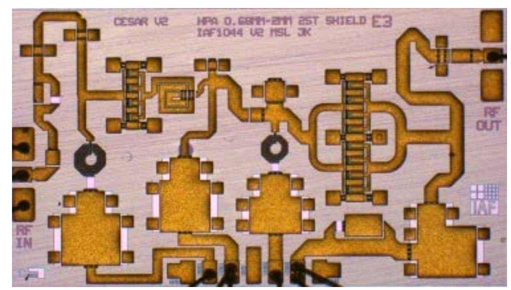


L-band

UMS GH50_10

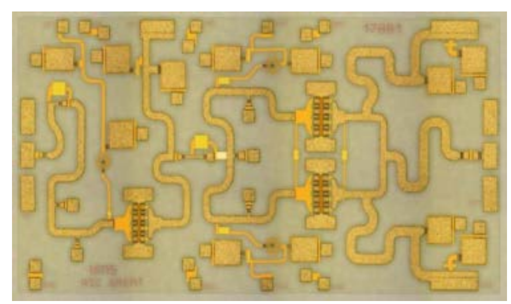
- X-band MMIC (8.5GHz)
  - Vds=30V, P_{out}=38-40dBm
  - PAE=40%

X-band



IAF GAN25

- Over 130 hermetic packaged parts at each milestone
  - 60 parts independently tested by ESA
  - DC and RF validation over stress temperature range

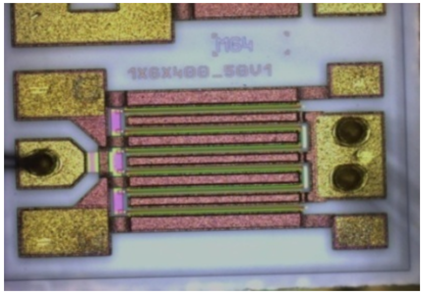


UMS GH25_10

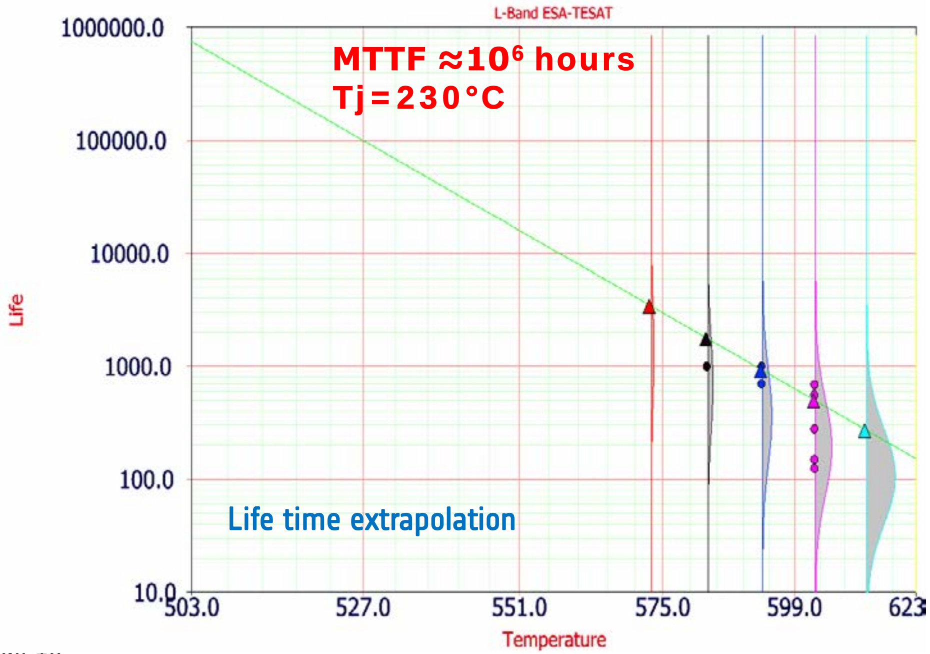
European Space Agency

GREAT² L-band RF life test results

- 3000 h accelerated RF life test
  - UMS GH50 L-band 6 x 400 µm power cell
  - 1.7 GHz CW RF operation at 50 V
  - 310 °C to 390 °C peak channel temperature
  - Pout > 10 W (initial), > 4 dB compression (at stress conditions)



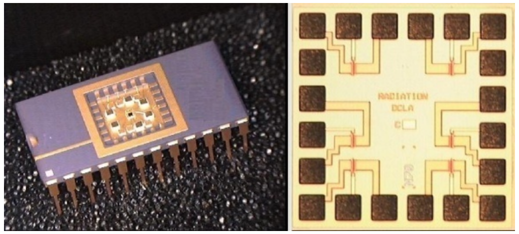
- Life time extrapolation to 230 °C peak channel temperature
  - Failure limit:
    1 dB output power degradation
  - Activation energy 2.0 eV
  - MTF > 1 x 10^6 h
    (lower limit for C.L. 60%)



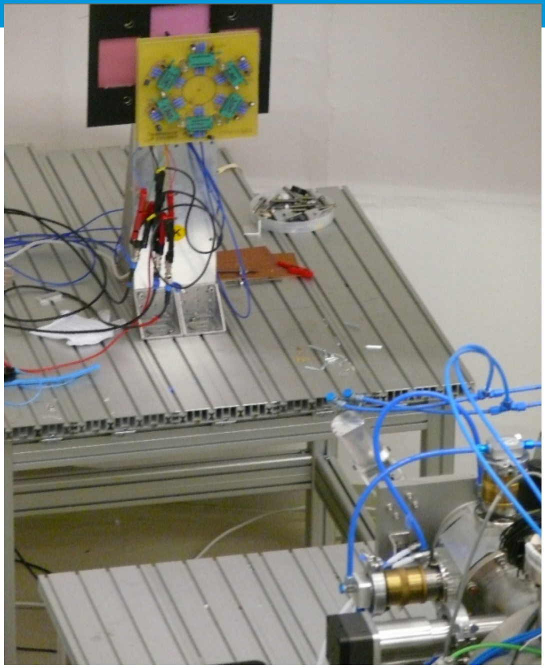
- Final 4000h RF life test ongoing as part of M7 campaign

GREAT^2 Proton and gamma irradiation

- Proton irradiation
  - Proton energy 35 MeV
  - Flux ~ 2 x 10^9 p cm^{-2} s^{-1}
  - Fluence > 2 x 10^{12} p cm^{-2}



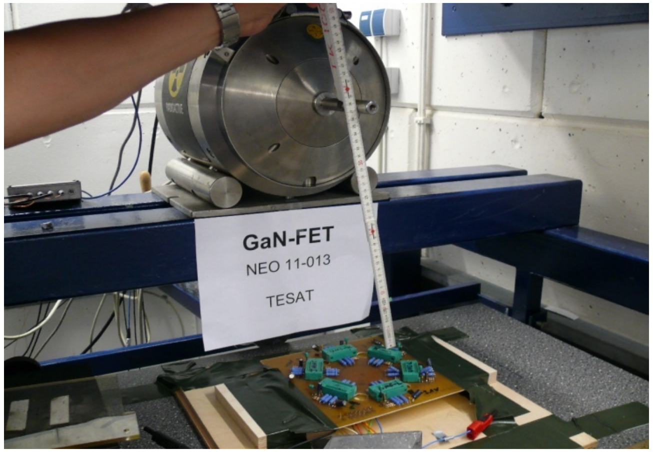
Radiation test PCM



- ^{60}Co Gamma irradiation
  - Dose rate 3.6 kRad/h
  - Up to 1 MRad (10 Gy)

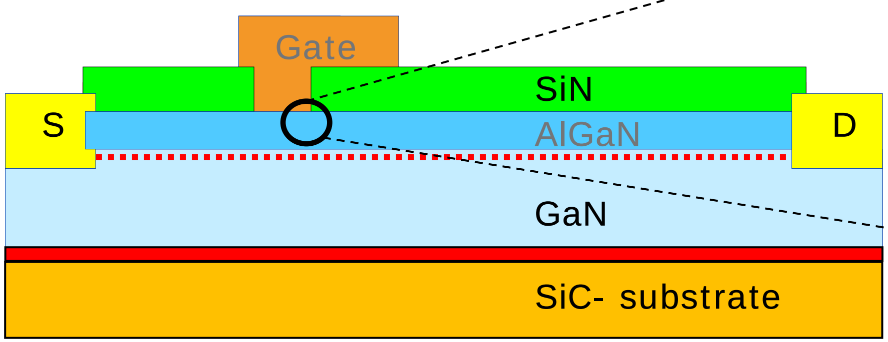
- Key parameter drift of radiation PCMs
  - UMS GH50 and GH25
  - Idss, Vth and gm << 10 %

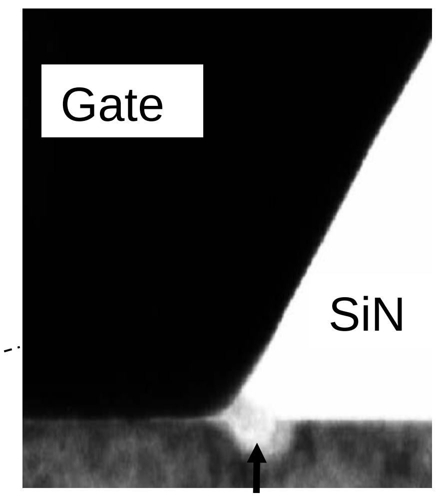
- Heavy ion tests no SEB up to Vds=125V



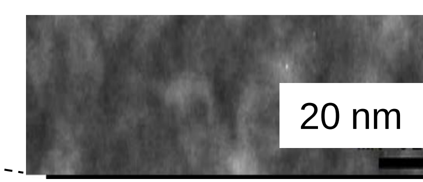
Preliminary failure mechanisms identified

- High peak temperature at the Schottky gate
  - Wide bandgap semiconductor is OK
  - But metals may be prone to diffusion and interlayer effects
- Passivation and epi layer defects
  - Trapping effects causing slow variations over time
- High field strength at drain-side gate edge
  - Pitting (chemical reaction) occurring
  - Charge and interface stress voltage and temperature dependent





Pitting after 3000 h RF life test @ Tch > 300 °C

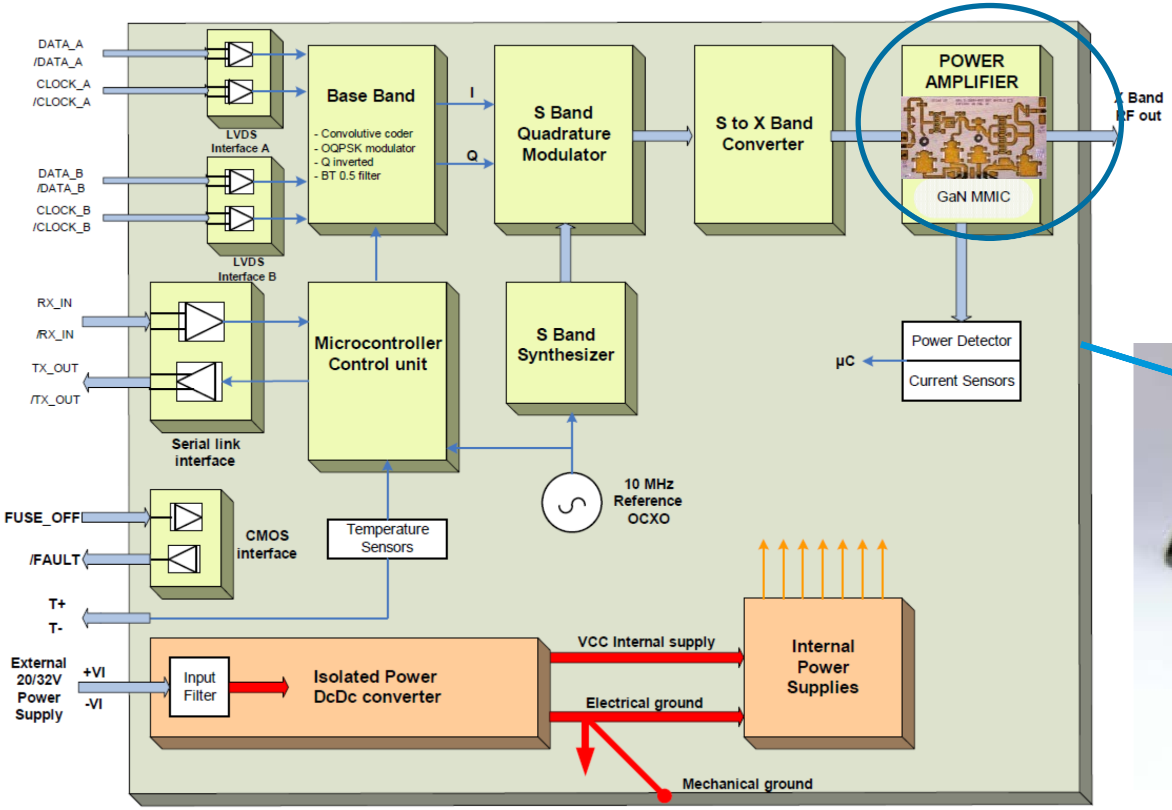


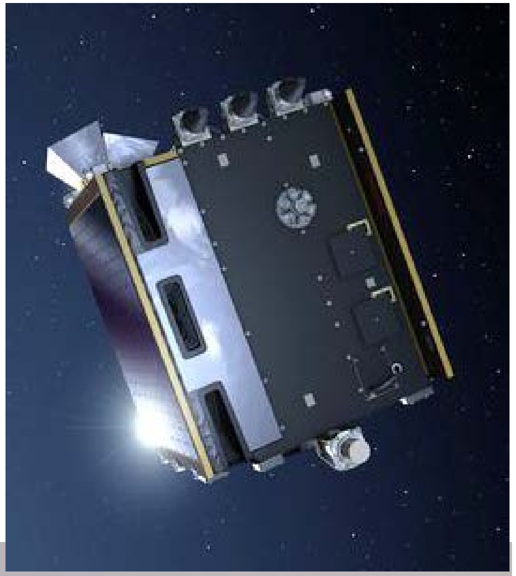
European preferred parts list

- UMS GH50_10 GaN process accepted for EPPL 2 listing November 2012
    - 2 years earlier than planned
- Space de-rated peak channel temperature ≤160°C
    - Limited to a 40W part for first release
- Additional work required to improve reliability of GH25 process
    - MIM capacitor robustness
    - Improved gate module
- Full, more extensive, space evaluation planned for GH50_20 (2013) and GH25_10 process (2014)

Early in orbit demonstration

- PROBA V 3rd telemetry transmitter using GaN X-band MMICs from GREAT[2] project
    - OQPSK modulation, 10 to 100MBps bit rate
    - >6W RF output power (power flexibility)
- First demonstration of European sourced GaN technology in space





Establishment of an independent European supply chain accessible by space industry

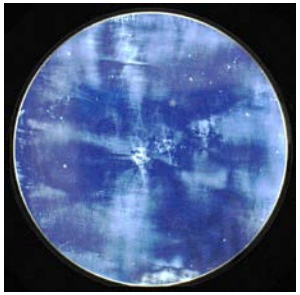
esa

~~EUROPEAN~~ RF **INDUSTRIAL** GaN SUPPLY CHAIN OPTIONS PRE 2008

S.I. SiC substrates	GaN epitaxy	GaN foundry	High thermal dissipation packages
CREE US	CREE US	CREE US SET JP	KYOCERA JP

EUROPEAN RF **INDUSTRIAL** GaN SUPPLY CHAIN OPTIONS >2012

SiCrystal AG



S.I. SiC substrates

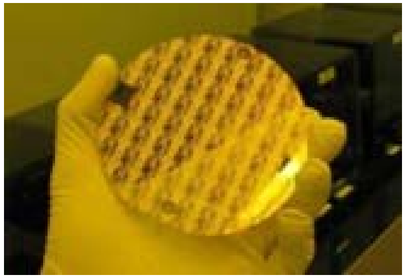
EuSiC (FP7)

EPIGAN

GaN epitaxy

ESA GSTP

united monolithic semiconductors (ums)

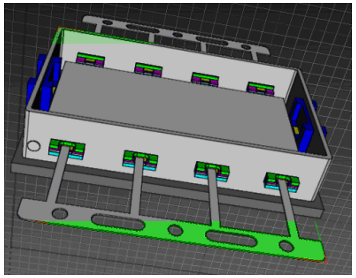


GaN foundry

ESA TRP, GSTP, ECI

ThalesAlenia Space

PLANSEE EGIDE



High thermal dissipation packages

AGAPAC Advanced GaN Packaging (FP7)

GaN HEMT for high efficiency DC-DC converters

- Lower on state resistance
- Reduced Miller capacitance
- High frequency switching

Switching frequency ↑

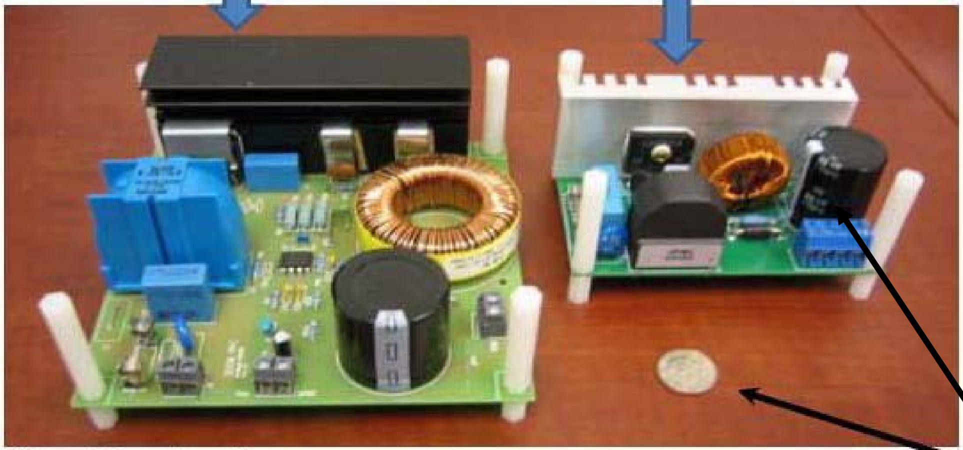
L, C values ↓

62.5 kHz

- Two stage EMI filter needed
- Large inductors needed

750 kHz

- Only need single stage EMI filter
- Less inductance for differential nois filtering
- Saves one filter stage
- ***And*** provides lower loss



US Dime

Left hand demo board
Source: Infineon

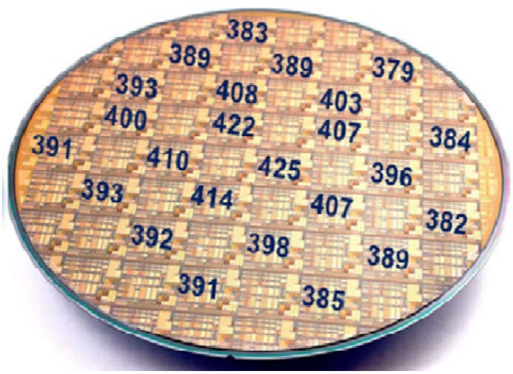
transphorm

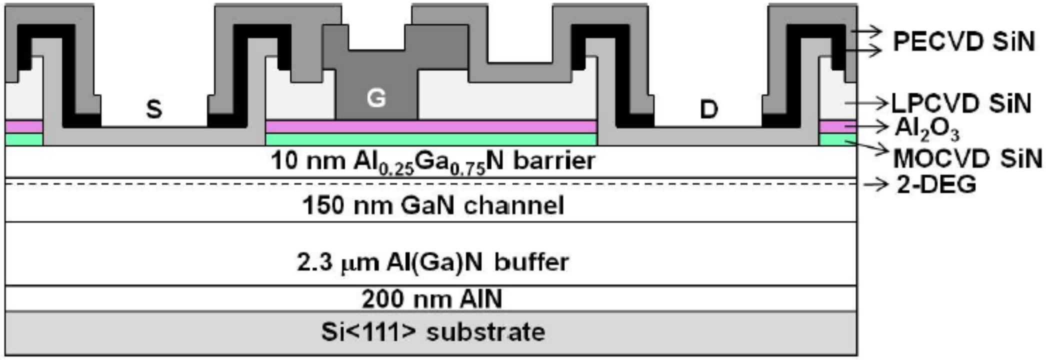
Boost DC-DC converter
GaN solution vs Si MOS

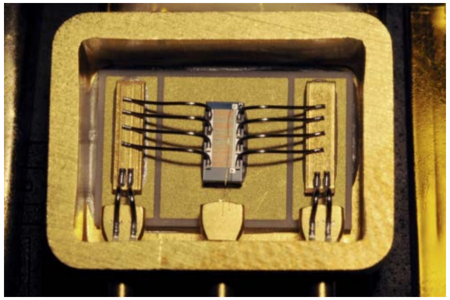
- 50% reduction in mass and volume
- 2-3% better efficiency

Development of wide band gap processing techniques compatible with a Si production environment "GaN in the line"

- ESA funded project to develop GaN on silicon power transistors using a Si CMOS compatible processing line
  - Fabrication on 150mm diameter silicon wafers for low cost
  - Novel Au free process, bi-layer insulated gate dielectric
  - Electrical performance and SEE radiation assessment

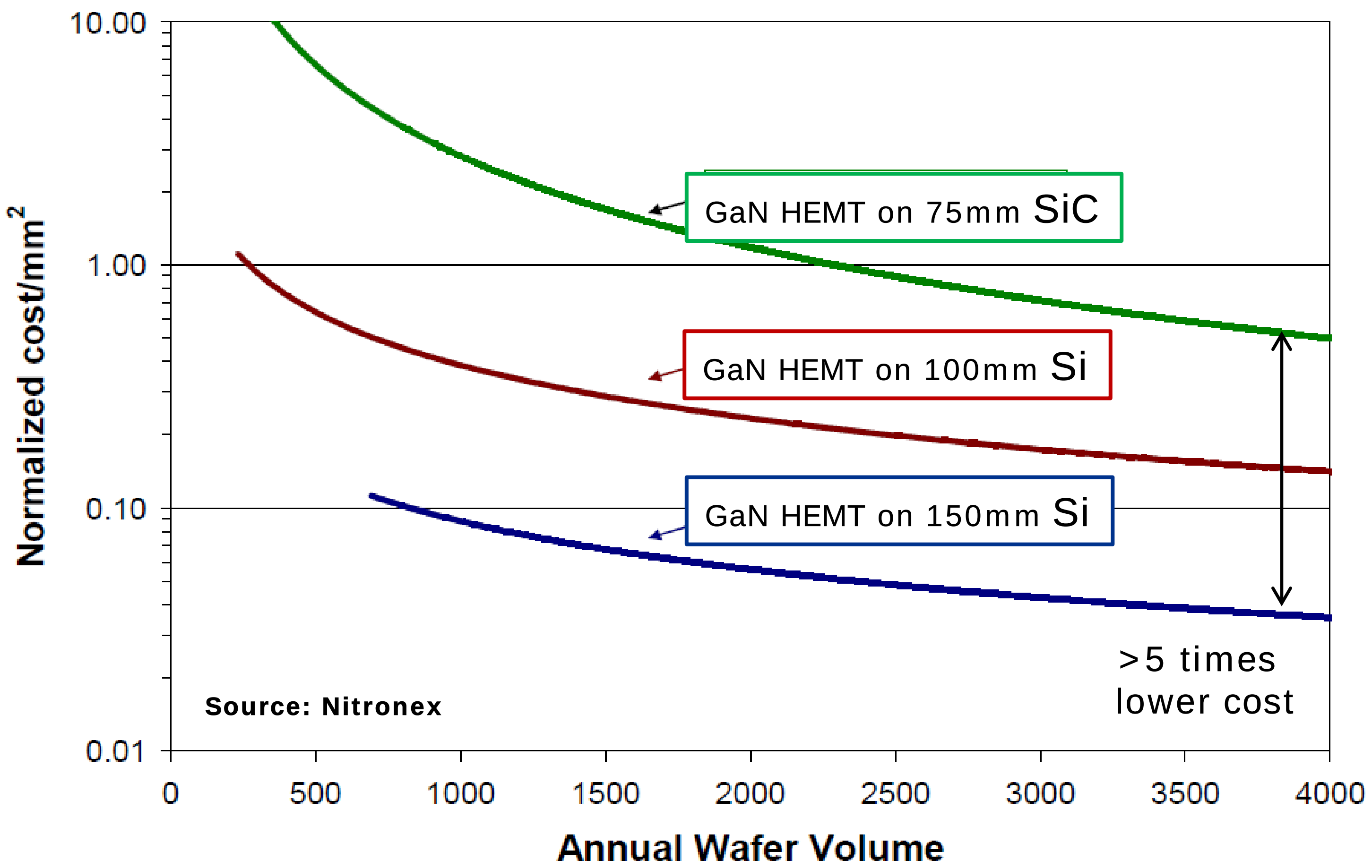






European Space Agency

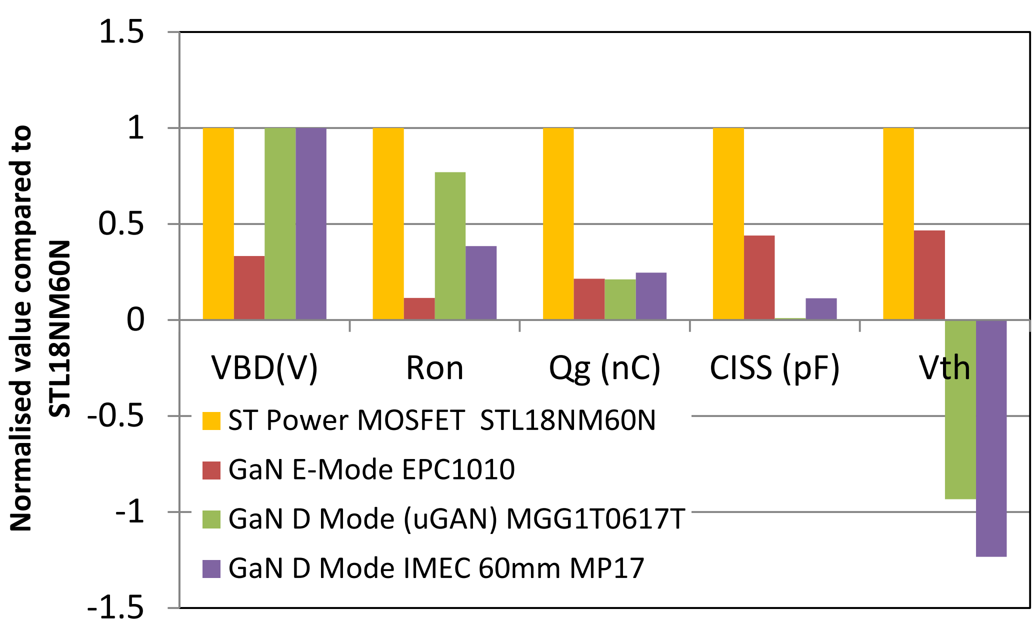
Why manufacture GaN on silicon?

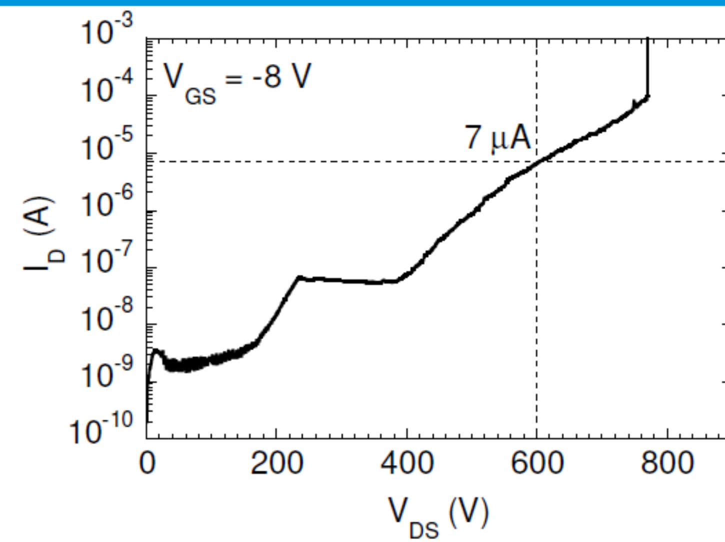


European Space Agency

“GaN in the line” key results

- Pilot manufacture through MiPlaza facility in Eindhoven (ex Philips line)
- Various transistor sizes
  - 10mm-100mm gate periphery
- Excellent yield, low leakage current
  - 7µA at 600V for 20mm (8A) device
  - Low capacitance





- State of art performance achieved in Europe
- **BUT** first devices are depletion mode
- Follow on GSTP6 program planned
  - Enhancement mode
  - Industrialisation
  - Space assessment

European Space Agency

4. Conclusions

European Space Agency

Summary of achievements

1. Major improvements made in terms of reliability
    a. Operating lifetimes from a few hundred hours to over 1 million hours
2. Major advances in establishment of European supply chain
    a. UMS GH50_10 process EPPL listed (2 years ahead of original planning)
    b. Commercial SiC substrate and epitaxy suppliers established
3. Demonstration of AgD metal matrix packages (FP7 AGAPAC) for improved thermal management
    a. 182W SSPA demonstration with 30% reduction in Tj compared to using conventional CuW baseplate material
4. First in-orbit demonstration of GaN X-band MMIC on PROBA V
5. Good progress on GaN on Si processing techniques made
6. The gap with ROW has closed from ≈10 years to around 4 years

Next steps

- Validate, stabilise and space evaluate 1st generation GaN microwave processes
  - Promote GaN technology insertion for use in future ESA missions
- Develop appropriate ESCC standards for GaN microwave components
- Development of 2nd and 3rd generation GaN HEMT processes
  - Improved efficiency transistors
  - Larger diameter SiC substrates (≥100mm)
  - Higher frequency operation (Ka, Q, V, W-band)
  - Lower loss, robust on-chip passive components
- Improved thermal management and higher Tj operation
  - Semiconductor level (60-70% of ΔT drop)
    - Device processing techniques, epitaxy and substrate optimisation
  - Package level
    - Secure European supply capability of AgD metal matrix composites for use as package baseplates
    - Qualify packaged transistor power bars
- Development of European supply chain for power switching components
  - Develop GaN HEMT enhancement mode transistors, diodes, and transfer know-how from research institutes to manufacturing industry
  - Develop CMOS compatible processes on 150mm, 200mm and 300mm silicon substrates for low cost
  - Optimise GaN epitaxy for power switching performance (125V, 600V, 1000V operation)
  - Assess performance benefits, reliability and suitability for operation in space, perform space evaluation

THANK YOU FOR YOUR ATTENTION

European Space Agency