Next Generation Device Architectures for Gallium Nitride and their Applications in Power and RF

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Compound Semiconductor Centre

Home of enabling technologies

Presentation Outline

- CSC and the South Wales Compound Semiconductor Cluster.
- Regional GaN research activities – Power, RF and Sensing.
- Epitaxy design for improved reliability and performance.
- Power HEMTS – progress and challenges (Dynamic Ron)
- Other applications of GaN 2DEGs (RF and Sensing).
- Progress in Vertical Power devices.
- Summary and Q&A

South Wales Semiconductor Cluster: RD & Innovation

THE COMPOUND SEMICONDUCTOR CENTRE

>£42M Investment in a JV between IQE and Cardiff University
Focus on materials and device innovation translation
Secured >£80M research funds since 2016

Cardiff University Prifysgol Caerdydd
Institute for Compound Semiconductors
Sefydliad Lled-ddargludyddion Cyfansawdd
CS Hub

>£100M investment by Cardiff University in 8" fab
Focus on research to pilot production: RF and Photonics
New facility opens 18th May 2022

CATAPULT
Compound Semiconductor Applications

>£50M investment by UK Government: 2018-2023
RTO: Focus on CS chip design, packaging and test
100 staff co-located in IQE MegaFoundry, Newport

CISM
Centre for Integrative Semiconductor Materials
Swansea University Prifysgol Abertawe

>£90M investment £40M capex/ £50M revenue
Focus on process development and integration
New facility opens in Swansea in Q2 2023

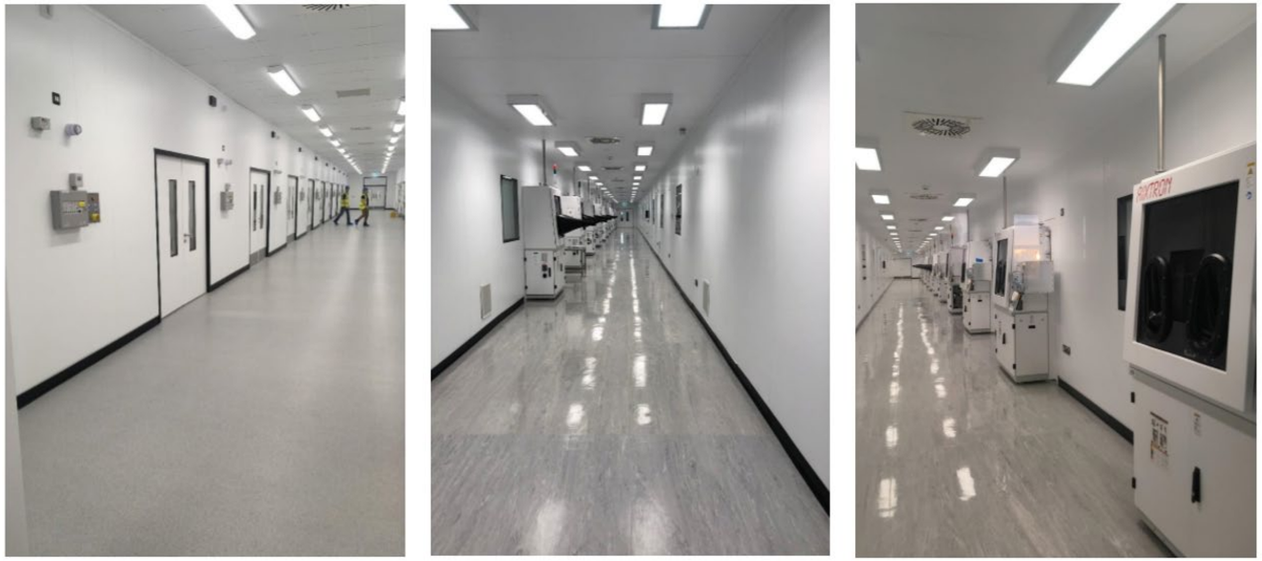
South Wales Semiconductor Cluster: Manufacturing

>£39M Investment from public sector to establish Mega-Foundry
Space for up to 100 epitaxy materials manufacturing tools
Estimate >£100M executed since 2018: >£375M to full capacity

Primary manufacturer of fab capital equipment
SPTS acquired by KLA in 2019 for $3.4B (Orbotech)
2-3x expansion with new HQ under construction.

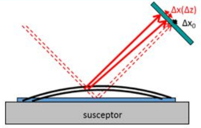
Focus on chip packaging
Microsemi acquired by Microchip for $10B in 2018
<£5M capex expansion to create power package line

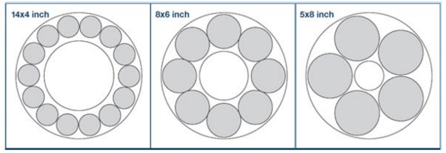
IQE Epitaxy Foundry - Installed base of Aixtron Reactors plus characterisation



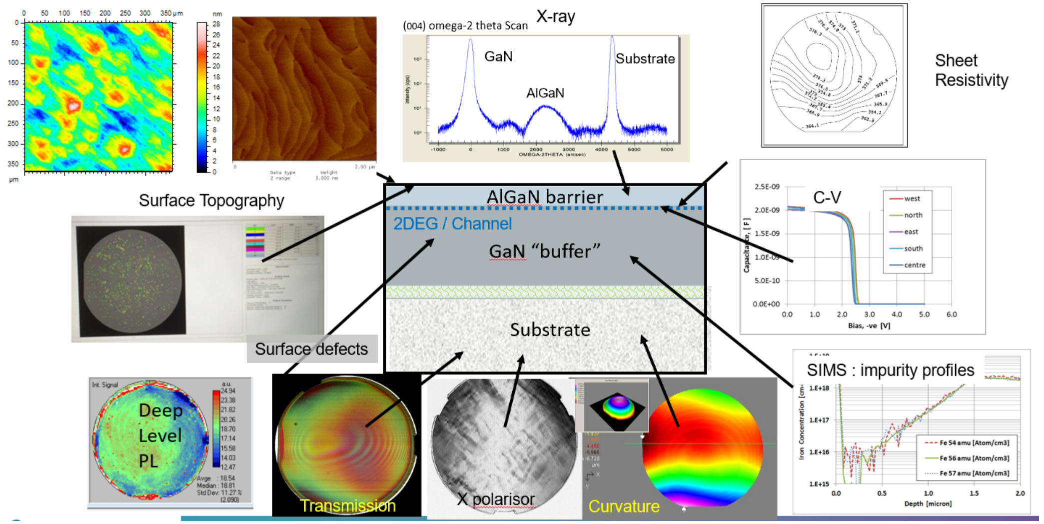
Aixtron G5+ Capacity


AIX G5+ Reactor 5 x 200 mm



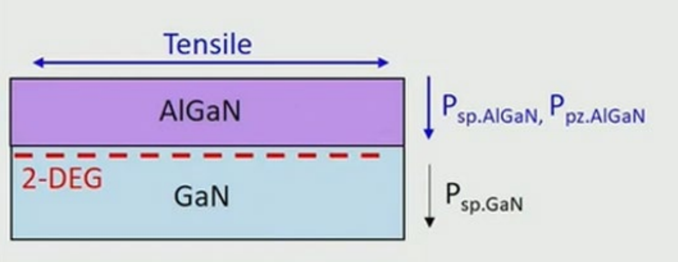


Post Epitaxy Characterisation

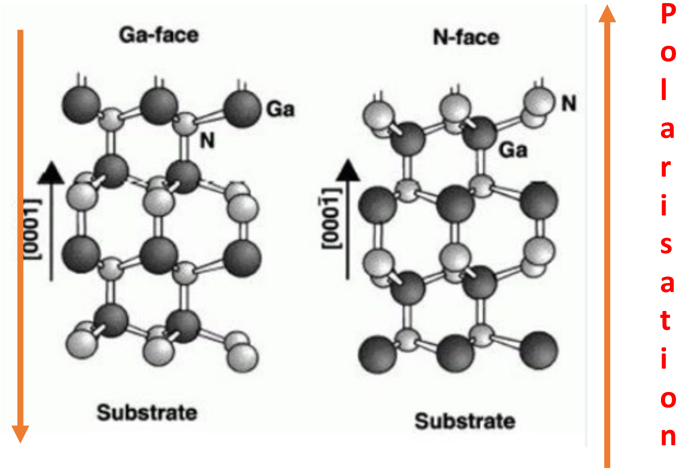


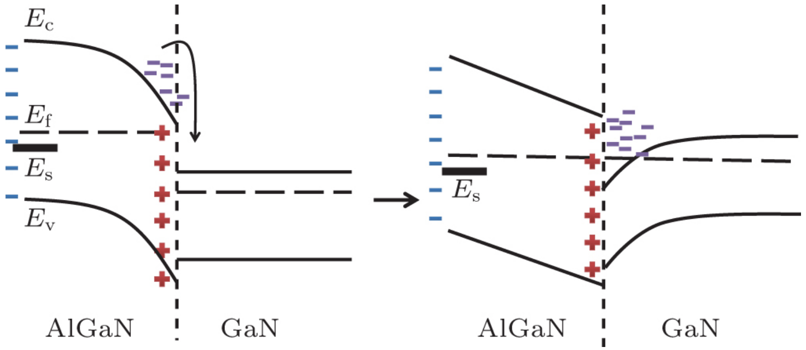
GaN Crystal Structure and 2DEG formation

- Ga–face is typically used for power electronics.
- Strong spontaneous polarisation effects exist in the GaN layer due to its asymmetrical Wurtzite structure and differences in electronegativities between Ga and N.
- AlGaN grown on GaN induces tensile strain and piezoelectric polarisation.
- Polarisation discontinuity at the AlGaN/GaN interface leads to a 2 Dimensional Electron Gas at the surface of the GaN.
- High sheet carrier density – can be tailored by increasing Al composition and thickness of AlGaN barrier.
- For 25% Al and 20nm typical Ns = 7.7E12 cm-2.



(Lattice constant: GaN > AlGaN)



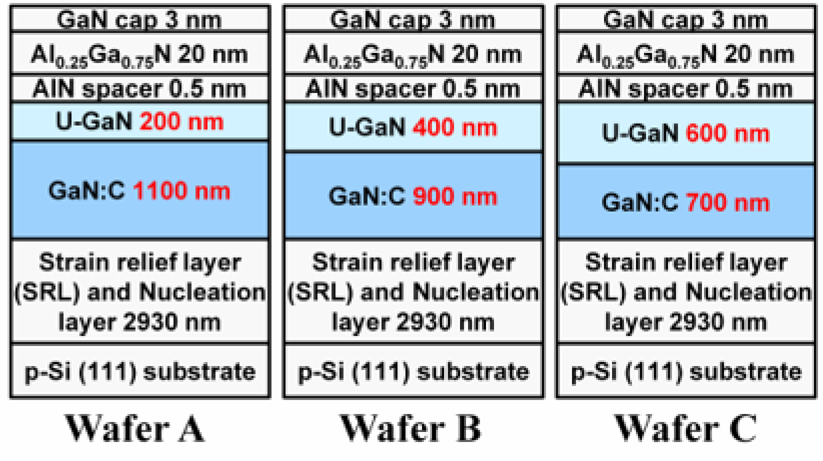


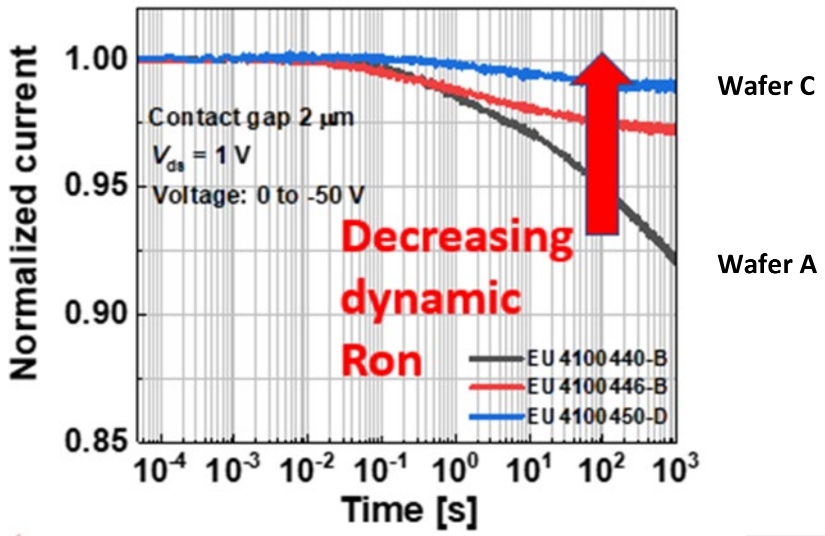
When AlGaN contacts a GaN layer, electrons will flow into the GaN side, accumulate at the surface of the GaN and form a 2DEG

Optimisation of GaN Power Epi Design

- Commercially available GaN products exhibit dynamic on resistance issues (current collapse) which limits the device performance.
- This manifests as an undesirable increase in device resistance during switching operation.
- The major cause of dynamic Rds.on in current GaN power devices is related to the charge trapping in the buffer, rather than surface effects which can be controlled using field plates.
- Optimization of epi design in AlGaN/GaN power devices is essential for control of buffer charge and improving their dynamic on-resistance (R_{ON}).
- Innovative buffer back-biasing methods have been developed at Bristol University to implement new electrical techniques which establish the vulnerability of the buffer to current collapse and undesirable parasitic leakage/breakdown.
- Recent work at CTDR and CSC on 650V GaN on Si designs shows that current collapse can largely be mitigated with the correct epitaxial layer design.

Schematic cross sections of 3 different epi designs investigated

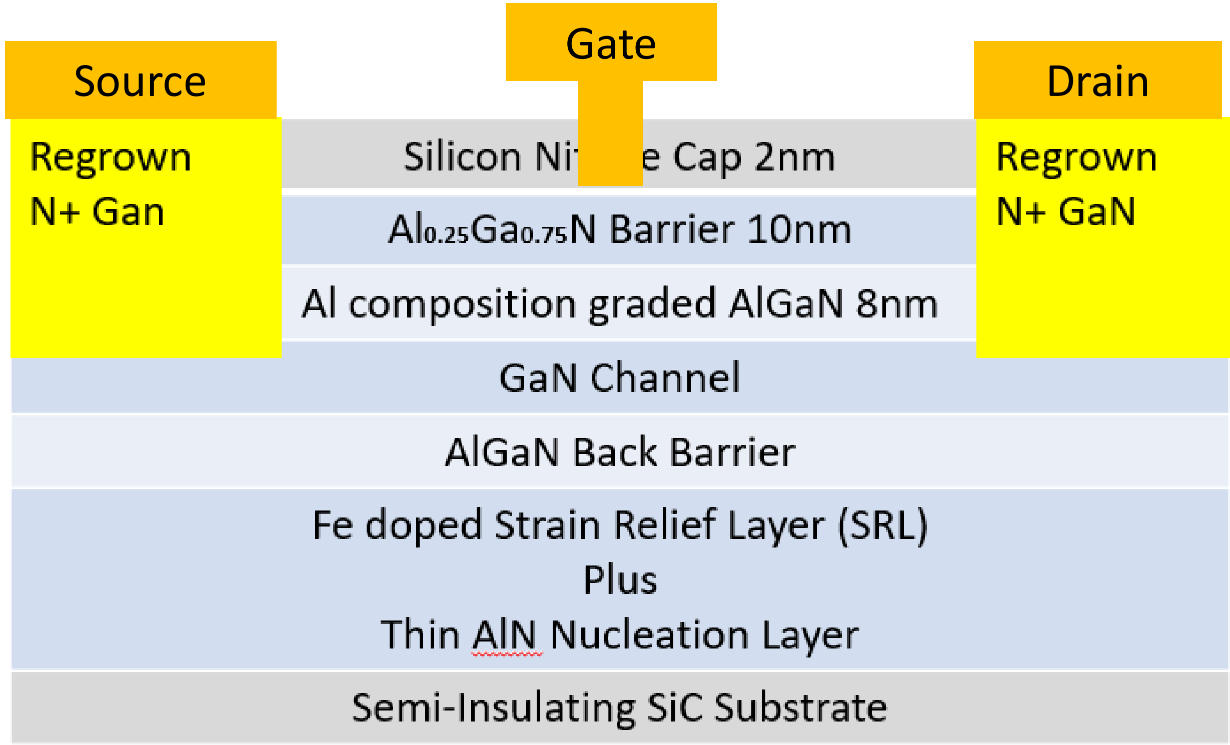




Evolution of GaN RF Epi Design.

- GaN on SiC provides a combination of wide bandwidth and higher power density.
- The use of SiC substrates results in significant improvement to the epi layer quality as well as thermal management.
- For 5G and 6G RAN applications there’s a push to increase PA output levels, efficiency, and linearity.
- Graded AlGaN barriers have demonstrated best in class linearity.
- Current collapse under pulsed and high-frequency operation is also reduced.
- Epitaxial regrowth in the source and drain contacts can also be used to reduce ohmic contact resistances.
- **Device improvements are epi – enabled.**

Graded Channel Epi Design



Source

Gate

Drain

Regrown
N+ Gan

Silicon Nit e Cap 2nm

$Al_{0.25}Ga_{0.75}N$ Barrier 10nm

Al composition graded AlGaN 8nm

Regrown
N+ GaN

GaN Channel

AlGaN Back Barrier

Fe doped Strain Relief Layer (SRL)
Plus
Thin AlN Nucleation Layer

Semi-Insulating SiC Substrate

GaN HEMTs for Sensing Applications

The Hall voltage $V_H = K_H . B . I$

The sensitivity (K_H) of the sensor is given by $K_H = 1/t.n.e$.

Where t = thickness, n = electron concentration and e = electron charge.

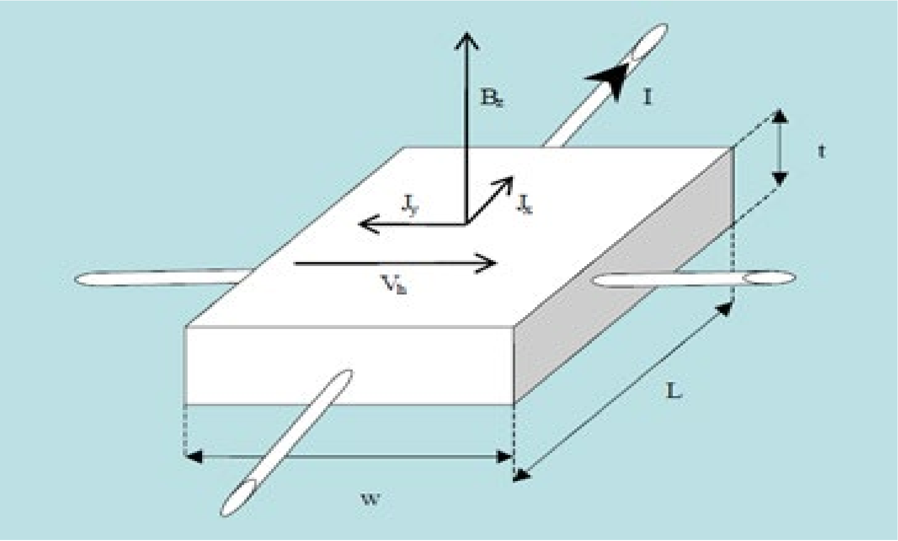
2DEGs are orders of magnitude thinner than silicon CMOS Hall effect devices and have higher carrier concentrations.

Radiation hardness and temperature tolerance of GaN makes such devices suitable for very high-performance remote sensing and control in automotive, aerospace, industrial, nuclear and satellite applications.

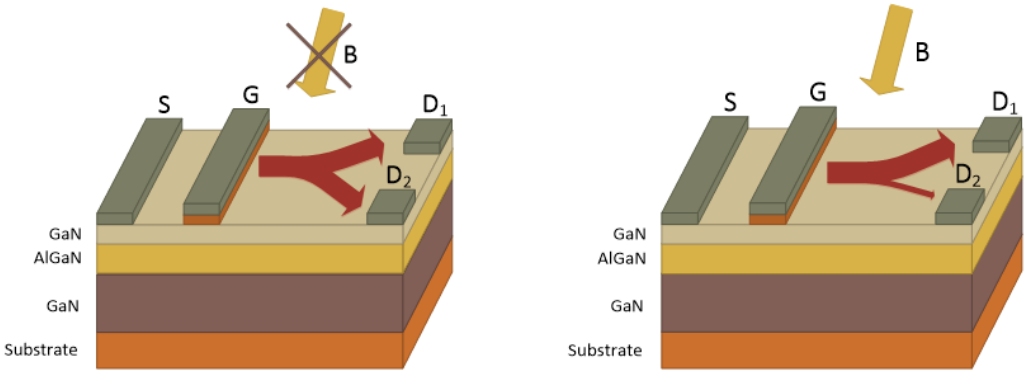
Initial device development of GaN QWHE sensors by CSC and Swansea University produced excellent device characteristics up to 400 °C.

Our next collaboration is focused on co-integration of the RF capability.

The Hall Effect



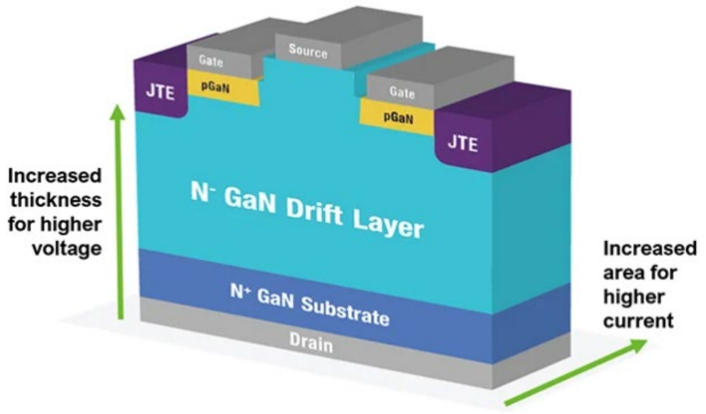
Split Drain Sensor Design



Recent commercial development of vertical GaN Devices

- NexGen – first commercially available vertical GaN devices – GaN-on-GaN JFETs – 240W low voltage power supplies for computing.
- Odyssey Semiconductor – achieved 1200V rating on a vertical GaN power device targeting automotive applications (September 2022).
- Bosch – investing heavily in vertical GaN research, presented GaN-on-Si MOSFETs at WiPDA Europe 2022.
- Toyoda Gosei – demonstrated 100A/1.2kV vertical GaN MOSFET employing a current distribution layer to reduce peak electric fields (ISPSD, 2019).
- Panasonic – published 2019 Progress Review of GaN power devices including in-house research and development of vertical GaN.

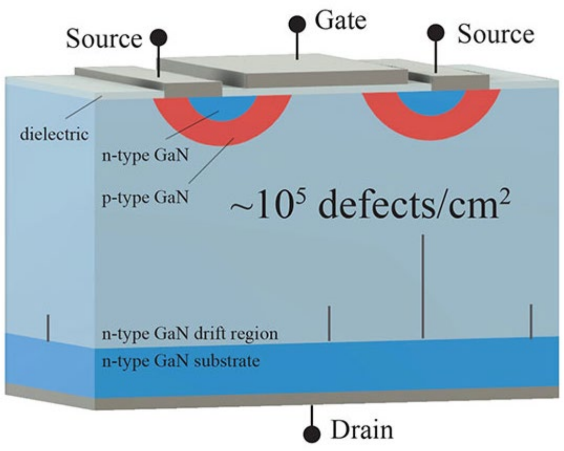
NexGen e-mode Vertical GaN JFET



Increased thickness for higher voltage

Increased area for higher current

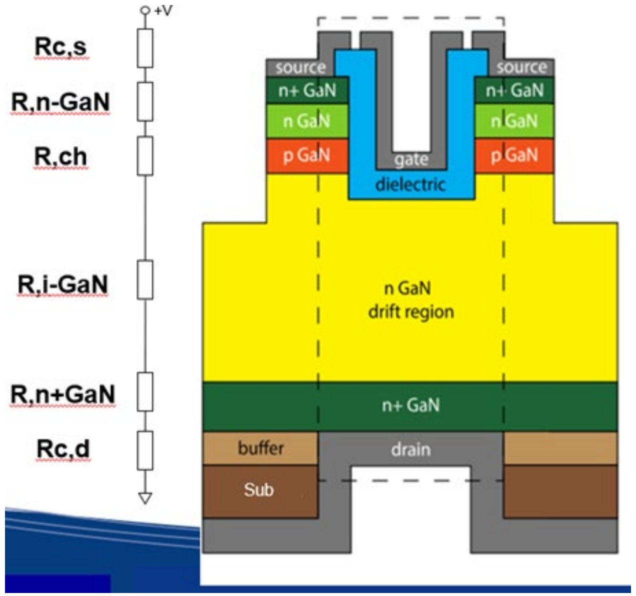
Odyssey – e-mode vertical GaN FET



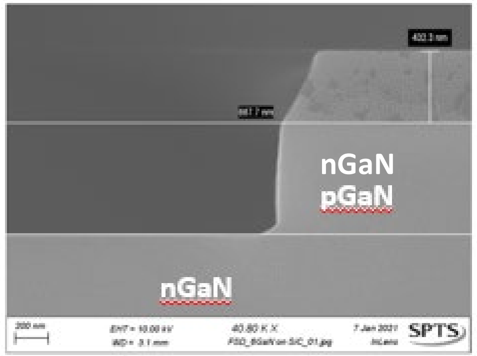
Vertical GaN Power Progress

- Live project developing novel GaN trench FET device architectures and processes.
- Improved power density and cost over lateral GaN HEMT devices.
- Scale voltage without increasing chip area.
- Development of thick epitaxial GaN layers with complex in-situ doping.
- Development of GaN trench etch with vertical sidewall and rounded corners.
- Swansea University team have produced working quasi-vertical devices.
- Now migrating to fully vertical architecture.

Trench FET Cross-section

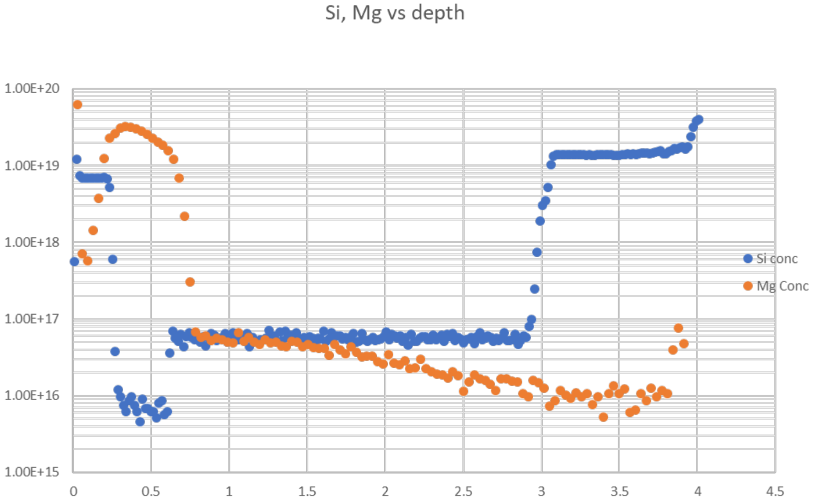


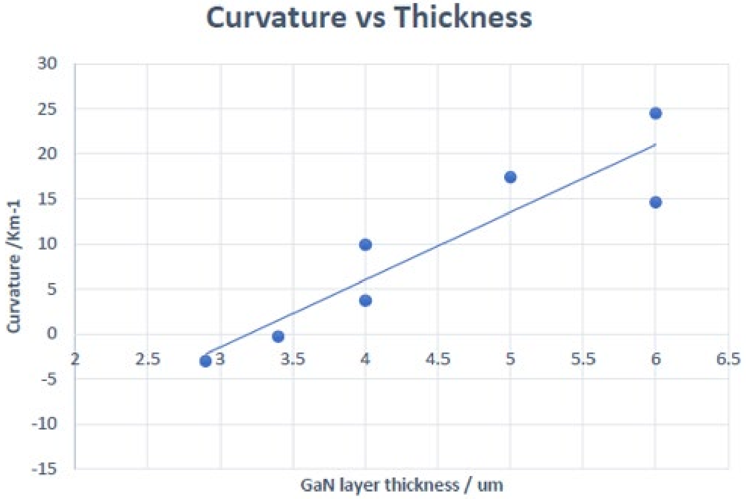
Trench Etch Profile - SPTS



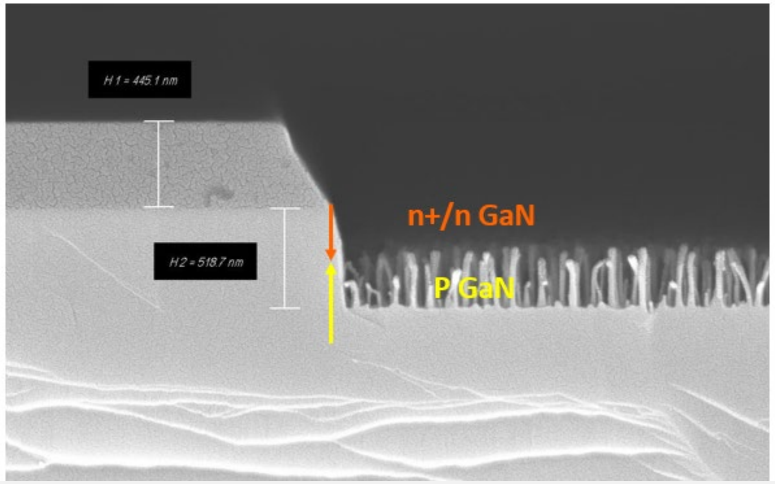
Some of the Process Challenges

- Multiple substrate types evaluated.
- Complex epi doping profile required.
- Control of bow for thick GaN layers.
- In-situ doping control was not possible using Si.
- Trench etch challenges included control of sidewall roughness, corner rounding and selectivity to p-type GaN.

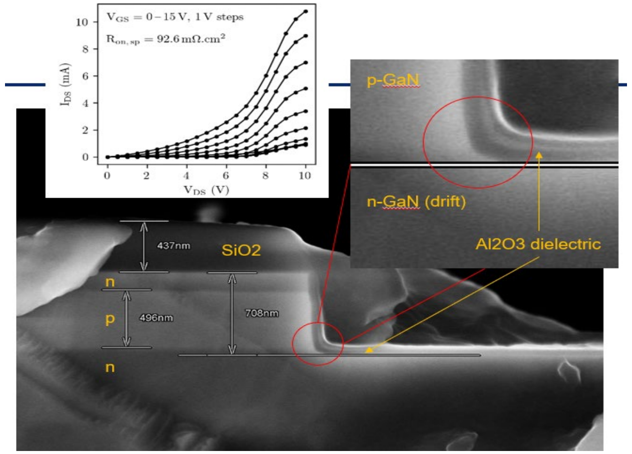

Si, Mg vs depth


Curvature vs Thickness

Residual pGaN pillars



MVD dielectric dep



Summary and Takeaways

- GaN is an amazingly versatile material suitable for a wide range of photonic and electronic devices.
- The combination of 2DEG and WBG provides significant performance advantages.
- It’s behind SiC for power but the recent availability of bulk GaN substrates could be a game-changer.
- Like SiC – everything needs epitaxy.
- New epitaxial growth structures are key enablers in Power, RF and Sensing.

Thanks For Your Attention