New Faces of GaN:
Growth, Doping and Devices

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LEO of a-GaN from circular opening
GaN-based CAR

- GaN-based H₂ Generator
- Gas Station
- GaN-based Display
- GaN-based Electronic Device
- GaN-based Head Lamp
- GaN-based Air Cleaner
- GaN-based Stop Lamp and Winker Lamp

酸化チタンなどの光触媒に対する光源として用いるUV-LED
## Personnel

### MOCVD
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- Arpan Chakraborty (now Cree)
- Bilge Imer
- John Kaeding - poster
- KC Kim - poster
- Don Lee
- Matt Schmidt

### HVPE
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- Asako Hirai - poster
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### MBE
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- ManHoi Wong

### TEM
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### $$$
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- UCSB SSLDC
- AFOSR
- ONR
Wurtzite Nitrides Crystal Symmetry

Reversed direction of polarization

Bulk GaN in vacuum

Ga-terminated surface

N-terminated surface

P_{SP}
Motivation – Polarization Effects

Spontaneous and piezoelectric polarization cause:
1. band bending
2. charge separation in QW

- Emission red shift
- Low recombination efficiency
- High threshold current

Growth on non-polar, semi-polar GaN will solve these problems
Total Polarization Discontinuity

In$_x$Ga$_{1-x}$N/GaN

Al$_y$Ga$_{1-y}$N/GaN

Calculated total polarization change
In$_x$Ga$_{1-x}$N coherently strained to GaN
Al$_y$Ga$_{1-y}$N coherently strained to GaN

Polarization discontinuity
Spontaneous
Piezoelectric

GaN Crystal Structure

Non-Polar Planes

C-Plane \{0001\}
M-Plane \{1\bar{1}00\}
A-Plane \{1\bar{1}20\}

Semi-Polar Planes

a1 [1000]
a2 [0100]
a3 [0010]
c [0001]
Non-Polar Growth - Summary

Systems
• $a$-GaN / $r$-$\text{Al}_2\text{O}_3$ (MOCVD, HVPE and MBE)
• $a$-GaN / $a$-$\text{SiC}$ (MOCVD, MBE, MBE $\rightarrow$ HVPE)
• $m$-GaN / $m$-$\text{SiC}$ (MOCVD and MBE, MBE $\rightarrow$ HVPE)
• $m$-GaN / (001) LiAlO$_2$ (HCPE, MBE $\rightarrow$ HVPE)

Exchange of MBE, MOCVD and HVPE material
‘Mix and match’
(e.g., MBE $m$-GaN/LiAlO$_2$ templates for HVPE $\rightarrow$ MOCVD)

Research Topics
• Growth mode and growth mechanisms
• Morphology
• Defect generation and structure
• Optical properties
• Doping
• Heterostructures
• Devices
a-GaN Growth: … the idea …

- \(a\)-plane surfaces encountered in the lateral overgrowth of \(c\)-plane GaN

![Cross-section SEM](image)

\(P_{\text{reactor}} = 76\) Torr

Increasing ammonia:
- 3.6 slm
- 1.8 slm
- 0.9 slm

Increasing TMGa flow:
- 60 \(\mu\)mol/min
- 120 \(\mu\)mol/min
- 240 \(\mu\)mol/min
Nonpolar $a$-GaN on $r$-plane Sapphire

**a-GaN grown on $r$-sapphire via MOCVD**
- Previous efforts produced faceted films
- Planar films attained using two-step growth

![Diagram of a-plane and r-plane orientations](image)

**GaN Nucleation Layer**
- V/III: 2500
- $T_g$: ~600°C
- $t$: ~20 nm

**GaN Epitaxial Film**
- V/III: 300 – 1300
- $T_g$: ~1120°C
- g.r.: 2 – 9 Å/s
- P: ≤ 100 Torr

...compare to c-GaN Epitaxy...
- V/III: 2000 – 3500
- $T_g$: ~1090°C
- P: 76-760 Torr

(1120) $a$-plane GaN

(1102) $r$-plane sapphire
- 2.6 x 10^{10} \text{ cm}^{-2} \text{ threading dislocation (TD) density}
  - Common [11\overline{2}0] TD line direction
- 3.8 x 10^5 \text{ cm}^{-1} \text{ basal plane stacking fault density}
  - Faults aligned perpendicular to the c-axis [0001]
Lateral Epitaxial Overgrowth

- Lateral overgrowth techniques effectively reduce threading dislocation densities in $c$-plane GaN

- **The LEO Process…**
  - Initial MOCVD Growth
    - GaN template layer
  - Dielectric Mask Pattern
    - 200 nm PECVD SiO$_2$
  - MOCVD LEO Regrowth
    - Same conditions as planar $a$-GaN growth
Polarity Effects

GaN polarity strongly affects lateral growth rate

- Ga-face sidewall grows ~10x faster than N-face sidewall
Dislocation Reduction

- overgrown regions of [1100] stripes relatively TD free
- dislocations bend into overgrowth from [0001] stripes
LEO: Circular Mask Openings

- Stable GaN facets under ‘a-plane’ MOCVD growth conditions

Scale bar = 3 μm
LEDs on Planar m-GaN Substrates

Fig. 1. $I-V$ characteristic of nonpolar $m$-plane LED lamp.

Fig. 2. Emission spectra of LED lamp under pulsed operation.

Fig. 3. (a) DC output power versus drive current before and after packaging. (b) Variation in external quantum efficiency with drive current for LED lamp.
Semi-Polar Orientations

(a) (10\overline{1})l, (b) and (c)(10\overline{1}3) , (d) (1\overline{1}22) templates

Summary and Prospects

• Routes to non-polar and semi-polar GaN – well demonstrated
  Major challenge: high TD density and SF density

• Defect reduction via LEO, 2S-LEO, SLEO, in situ SiN_x

• Record p-type doping in MBE GaN on m-plane SiC

• ~1 mW, unoptimized, LEDs on m-plane GaN; semi-polar GaN

• Demonstration of polarized light emission in EL from
  • m-plane LEDs
  • Semi-polar LEDs

• N-face GaN
  • New promise for advanced electronic devices
MOCVD a-GaN LEO: Evidence for $m$-Facet Stability

*a-GaN LEO with <0001> stripes*

- a and m-facets
- Increasing reactor pressure: loss of a-facets, only m-facets

- **<0001>**
  - 45 Torr
  - 60 Torr
  - 100 Torr
  - 150 Torr

*a-GaN LEO with <1100> stripes*

- Vertical Ga-face and N-face facets
- Increasing reactor pressure: favors vertical growth

- **<1100>**
  - 45 Torr
  - 60 Torr
  - 100 Torr
  - 150 Torr
Planar HVPE m-GaN on LiAlO₂

- Surfaces characterized by long-range textures, peak to valley < 200 nm.
- Near complete elimination of bulk, crystallographic defects.
LED on planar $m$-GaN

LED structure grown by MOCVD on ~250 µm thick HVPE free-standing $m$-GaN

MQW parameters:
4 nm InGaN well, 16 nm GaN:Si barrier

$n$-GaN: 2.2 µm ($3 \times 10^{18}$ cm$^{-3}$)
$p$-GaN: 0.3 µm ($6 \times 10^{17}$ cm$^{-3}$)

$n$-contact: Al/Au (30/200 nm)
$p$-contact: Pd/Au (20/200 nm)
FIG. 4. Electroluminescence efficiency of the $m$ plane InGaN LED as a function of current density, with a wire-grid polarizer placed between the sample and the photodetector selecting the polarization of the luminescence. $E//[0001]$ indicates that the polarization is parallel to the $c$ axis while $E \perp [0001]$ indicates that the polarization is perpendicular to the $c$ axis. The inset shows the electroluminescence spectrum at 500 A/cm$^2$ (both polarizations of light are included).

FIG. 5. Polarization ratio of the $m$ plane InGaN LED photoluminescence as temperature is increased from room temperature to 300 °C. The polarization ratio is defined relative to the $c$ axis. The inset shows the data plotted in an Arrhenius relationship with a fitted activation energy of 49 meV.
Advantages of N-face GaN for HEMTs

- Low gate leakage [1,2,3]
- Low contact resistance [1,2,3]
- Enhancement mode operation [1,2,3]
- Enhanced back barrier confinement [1,2,3]
- InN channel [4]

Advantages of N-Face GaN for HEMTs

Ga-face

N-face

Courtesy: S. Rajan
Outline

Background on GaN symmetry and properties
   Crystal symmetry
   Physical properties: heterostructures

A-plane and M-plane growth
   Common Microstructure
   Defect reduction
   Doping
   Devices

Semi-polar GaN
   New orientations and possibilities

N-face GaN
   Turning the crystal and devices upside down …
Epitaxial Relationship

- $a$-GaN (11\overline{2}0) growth surface
- GaN $c$-axis aligns with sapphire $c$-axis projection
  - Convergent beam electron diffraction (CBED) determined polarity
Research accomplishments – Non-polar GaN

- 2001: 1st MOCVD a-GaN
- 2002: 1st MOCVD a-GaN LEO
- 2003: Planar HVPE a-GaN LEO
- 2004: 1st HVPE m-GaN LEO
- 2005: Highly p-doped MBE m-GaN
- 2006: 1st LED on m-GaN, Advanced a-GaN LEO, Blue LED on HVPE a-GaN

MBE a-GaN growth diagram
AlGaN/GaN Heterostructures

- N-face HEMT demonstrated promising performance
  - 2DEG in excess of $10^{13}$ cm$^{-2}$ with mobility of 1300 cm$^2$/Vs [1]
  - $f_t$ and $f_{\text{max}}$ of 12 GHz and 26 GHz respectively [2]

Non-Polar – Common Microstructure

**Systems**

- $a$-GaN / $r$-$\text{Al}_2\text{O}_3$ (MOCVD, HVPE and MBE)
- $a$-GaN / $a$-$\text{SiC}$ (MOCVD, MBE, MBE → HVPE)
- $m$-GaN / $m$-$\text{SiC}$ (MOCVD and MBE, MBE → HVPE)
- $m$-GaN / (001) $\text{LiAlO}_2$ (HCPE, MBE → HVPE)

TD density (total): $\sim 1 \times 10^{10}$ cm$^{-2}$
SF density (total): $> 1 \times 10^5$ cm$^{-1}$

SFs associated with exposed N face (000-1) during early growth

**Solutions**

- In situ/ex situ nanomasking
- Lateral Epitaxial Overgrowth (LEO)
- Two-step Lateral Epitaxial Overgrowth
- Sidewall LEO (SLEO)
- ‘Bulk’ GaN
• Under the current LEO growth conditions…
  – [0001] symmetric stripe – mixture of vertical and inclined $m$-planes
  – [1102] asymmetric stripe – vertical and inclined sidewalls
  – [1100] **rectangular** x-sections with vertical $c$-plane sidewalls

*Inclined-view SEM*

Scale bar = 5 $\mu$m (window width)
Cathodoluminescence (CL)

- uniform luminescence from overgrowth of [1100] stripes
- ‘mottling’ extends across width of [0001] stripes

Scale bar = 5 µm (window width)
**a-plane GaN/AlGaN MQWs**

10-period GaN / Al\(_x\)Ga\(_{1-x}\)N MQWs regrown on a-GaN (and c-GaN) templates via MOCVD

- Regrowth conditions modeled after HT epitaxial growth conditions
  - \(T_{\text{growth}} \sim 1120^\circ\text{C}\)
  - \(P_{\text{reactor}} = 76\) Torr
**a-plane vs. c-plane MQWs**

- **a- and c-plane MQWs** *simultaneously* grown with varying well width

**a-plane**
- 69Å GaN / 96Å Al$_{0.16}$GaN

**c-plane**
- 72Å GaN / 98Å Al$_{0.16}$GaN

- **a- and c-MQW dimensions and $x_{Al}$ agree within 7%**
- **inferior a-MQW interface quality**
PL Emission vs. Well Width

• MQW emission red-shifts with increasing GaN well width
  – a-plane: redshifts up to the GaN band edge
  – c-plane: redshifts beyond the GaN band edge
MQW Emission Energy

- **a-MQW** emission modeled using square well SCPS calculations
  - exciton binding energy accounts for model overestimation
  - ‘Nonpolar’ MQWs NOT Affected by Internal Electric Fields
$m$-GaN on $m$-SiC: MBE
m-GaN MBE: [Mg] vs. III-V Ratio

Substrate Temp ~ 530 °C on T.C.

<table>
<thead>
<tr>
<th>REGIME</th>
<th>Ga BEP [Torr]</th>
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<tbody>
<tr>
<td>Ga-rich</td>
<td>3.3E-7</td>
</tr>
<tr>
<td>Intermediate</td>
<td>2.4E-7</td>
</tr>
<tr>
<td>III/V = 1</td>
<td>~2.26e-7</td>
</tr>
<tr>
<td>N-rich</td>
<td>1.54E-7</td>
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Doped Layers ~100 nm thick
AlGaN marker layers ~10 nm thick.
300K Transport Results

- **Hole Conc.**
- **Mobility**
- **Conductivity**

**Carrier concentration:** Hall bars // \(a\) and \(c\)

**Conductivity:** via TLM patterns // \(a\) and \(c\)

\[1 \times 10^{18} < p < 7 \times 10^{18} \text{ cm}^{-3}\]

\(\mu \cdot p\) ↑ as \(p\) ↑ to \(p = 7 \times 10^{18} \text{ cm}^{-3}\)

**Anisotropy in hole mobility:** expected from anisotropic hole masses
Luminescence intensity is proportional to excess minority carrier concentration.

GaN: Minority carrier diffusion length: ~ 100 nm (common)
TDs are a limiting factor in non-polar LED performance

Nitride semiconductors free of electrostatic fields for efficient white light-emitting diodes

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Compact solid-state lamps based on light-emitting diodes (LEDs) are of current technological interest as an alternative to conventional light bulbs. The brightest LEDs available so far emit red light and exhibit higher luminous efficiency than fluorescent lamps. If this luminous efficiency could be transferred to white LEDs, power consumption would be dramatically reduced, with great economic and ecological consequences. But the luminous efficiency of existing white LEDs is still very low, owing to the presence of electrostatic fields within the active layers. These fields are generated by the spontaneous and piezoelectric polarization along the [0001] axis of hexagonal group-III nitrides—the commonly used materials for light generation. Unfortunately, this crystallographic orientation corresponds to the natural growth direction of these materials deposited on currently available substrates. Here we demonstrate that the epitaxial growth of GaN/(AlGaN) on tetragonal LiAlO₂ in a non-polar direction allows the fabrication of structures free of electrostatic fields, resulting in improved quantum efficiency. We expect that this approach will pave the way towards highly efficient white LEDs.

Figure 1 Calculated band profiles in (5 nm) GaN/(10 nm) AlN/GaN quantum wells. These profiles were obtained by full-consistent effective mass Schrödinger–Poisson calculations. The transition energies given take into account both strain and Coulomb interaction. a, The very large electrostatic fields in the [0001] orientation (polarization charges) were taken from ref. 4 and result in a quantum confined Stark effect and poor electron–hole overlap. b, The [1100] orientation is free of electrostatic fields, thus true flat-band conditions are established.
Reactor Pressure - MOCVD

- Reactor Pressure: important growth variable

Reactor pressures ~76 Torr required for planar film growth

76 Torr 300 Torr 600 Torr

Reactor pressures ~76 Torr required for planar film growth
Crystal Mosaic – a-GaN on r-Al₂O₃

- a-GaN on r-sapphire: orientation-dependent crystal tilt mosaic

\[ \text{c-mosaic} = 0.28^\circ \ (\Delta c/c \sim 1.1\%) \]
\[ \text{m-mosaic} = 0.62^\circ \ (\Delta a/a \sim 13.8\%) \]
LEO Orientation Analysis

- LEO stripe morphology dependent on stripe orientation
  - Analyzed using ‘wagon wheel’ mask
  - Three primary orientations: [0001], [\(\bar{1}102\)], [\(\bar{1}100\)] (0°, 45°, 90°)
Dislocation Reduction – AFM

- characteristic surface pits in window regions
- “pit-free” overgrowth

- AFM pits decorate TD terminations
- One-to-one pit-to-TD correspondence (AFM and TEM)
Planar HVPE a-GaN

- Planar Surface decorated with high pit density.
- Faint ~1 nm steps oriented normal to <0001>.
- RMS roughness ~1 nm.

TDD: ~ 1 x 10^{10} cm^{-2}
SFD: ~ 4 x 10^{5} cm^{-1}
Partial TDs: 7x10^{9} cm^{-2}
HVPE LEO a-GaN

- $<1100>$ stripes have vertical c-plane sidewalls.
- Ga-face (0001) lateral growth rate $\sim$6x N-face (0001) growth rate.
  - Coalescence front offset towards windows (large defect-free wing area results)
• Typical stripe patterns: 2 µm windows/8 µm wings (2/8), 5/5, and 5/15.
• Asymmetrical {0001} wing growth rates
• TDD of $< 3 \times 10^{-6}$ cm$^{-2}$ and SFD of $< 10^{-3}$ cm$^{-1}$ in wings; no measurable wing tilt.
• Four-fold increase in cathodoluminescence intensity in wings versus windows.
a-GaN on a-SiC: Morphology & Orientation

- smooth a-GaN surface morphology

  - a-AlN and a-GaN orientations match the a-SiC

![AFM Image](image1.png)

![XRD 2θ-ω Image](image2.png)

[AFM]  

1 μm

[11\overline{2}0]_GaN

[0001]_GaN

[0001]_SiC

XRD 2θ–ω
- Minimal tilt mosaic orientation dependence
  - c-mosaic greater than m-mosaic

\[
\text{c-mosaic} = 0.30^\circ \ (\Delta c/c \sim -2.8\%)
\]
\[
\text{m-mosaic} = 0.27^\circ \ (\Delta a/a \sim -3.4\%)
\]
**a-GaN on a-SiC: Morphology**

- *m*-Axis rows of coalesced GaN islands coalesce slowly along the *c*-axis
- Coalesced GaN surfaces feature:
  - Undulations along the *m*-axis
  - Low density of submicron pits
  - Crystallographic terraces perpendicular to *c*-axis
a-GaN on a-SiC: N-face Surfaces

SEM – 100 nm GaN

• Exposed N-face facets responsible for basal plane faulting
Planar m-GaN (cont.)

- Threading dislocation density $\sim 4 \times 10^9 \text{ cm}^{-2}$.
- Basal plane stacking fault density $\sim 1 \times 10^5 \text{ cm}^{-1}$.
- Possible inhomogeneous distribution of TDs and SFs may explain surface morphology variations.
• **Planar direct-growth films:**
  - Lattice mismatch, island coalescence ⇒ threading dislocations.
  - Exposed (0001) planes in island/3D growth ⇒ basal plane stacking faults

• **Lateral epitaxial overgrowth:**
  - Mask geometry affects growth direction.
  - Natural growth habit: growth on \( m \)-planes preferred.
  - \( <11\bar{2}0> \)-oriented stripes (\( a \)-direction) ⇒ Growth on (0001) and (0001) planes (vertical sidewalls)
HVPE LEO of m-GaN (cont.)

AFM

- Direct growth:
  - Slate morphology most prevalent.
  - Ridge density $\sim 10^5$ cm$^{-1}$
  - Inhomogeneous distribution of ridges and pits.

- LEO, <0001> Stripes:
  - Ridges remain, no pits.
  - Roughness: 0.6 nm
  - Wings TD-free.
  - SFs persist throughout wings.

- LEO, <1120> Stripes:
  - Ga-face wing TD and SF free.
  - Ridges eliminated, clear step edges on surface.
  - Roughness: ~0.5 nm
**n-Type Doping of a-GaN**

- **a-GaN on a-SiC:**

  - Undoped GaN is resistive
  - \( n \) increases with Si/Ga ratio for \( n > 1 \times 10^{18} \, \text{cm}^{-3} \)
  - Residual acceptor concentration on the order of \( 1 \times 10^{18} \, \text{cm}^{-3} \)
    - Acceptors related to dislocations, stacking faults, and point defects
  - \( \mu \) increases with \( n \) (screening of defects)
    - at \( n = 1.5 \times 10^{19} \, \text{cm}^{-3} \), \( \mu = 109 \, \text{cm}^2/\text{V} \cdot \text{s} \)
p-Type Doping of a-GaN

- a-GaN on r-sapphire:

<table>
<thead>
<tr>
<th>Mg Flow (sccm)</th>
<th>p (cm⁻³)</th>
<th>μ (cm²/V-s)</th>
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<tbody>
<tr>
<td>87</td>
<td>3.6E17</td>
<td>3.0</td>
</tr>
<tr>
<td>130</td>
<td>5.1E17</td>
<td>3.2</td>
</tr>
<tr>
<td>152</td>
<td>6.8E17</td>
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<tr>
<td>174</td>
<td>6.1E17</td>
<td>3.3</td>
</tr>
<tr>
<td>232</td>
<td>5.7E17</td>
<td>1.0</td>
</tr>
<tr>
<td>290</td>
<td>2.5E17</td>
<td>1.8</td>
</tr>
</tbody>
</table>

- [Mg] tracks Cp₂Mg effective flow
- Reduction in hole concentration:
  - Incorporation of Mg in electrically inactive form (e.g. precipitates)
  - Formation of Mg-induced compensating defects
LED on HVPE LEO a-GaN

- Template: LEO HVPE a-GaN with 2\,\mu m windows, 8 \,\mu m wings, \langle1100\rangle direction

$n$-GaN: 2.2\,\mu m (3 \times 10^{18} \text{ cm}^{-3})

$p$-GaN: 0.3\,\mu m (6 \times 10^{17} \text{ cm}^{-3})

$n$-contact: Al/Au (30/200 nm)

$p$-contact: Pd/Au (3/200 nm)

On-chip measurement:
1.5 mW at 200 mA (unsaturated)
- Electroluminescence vs. current: no shift in peak position, little peak linewidth broadening

No quantum-confined Stark Effect present
LED on planar \textit{m}-GaN (cont.)

- MOCVD 5-QW LED on 250 \textmu m free-standing \textit{planar} HVPE \textit{m}-GaN

- Turn-on voltage: 3-4 V
- Low on series resistance: 16 \textOmega
- Ideality factor \textasciitilde 4
- EL emission at 450 nm
- Peak shift observed at low current densities due to band filling
**Unpackaged m-GaN LED Results**

- **cw on-wafer output power at 300 mA**: 2.95 mW (0.24 mW @ 20 mA)
- **Max EQE of 0.43% at 30 mA drive current**
- **Saturation in output power not observed for higher cw drive currents**

- **Pulsed on-wafer output power at 1 A for 5% duty cycle**: 8.5 mW
Packaged \textit{m}-GaN LED Results

- \textbf{Unoptimized} chip packaged in standard T05 package
- Integrated optical power measured in integrating sphere
- Approx. 6 mW at 200 mA
- Same slight emission peak shift vs. current, as for on-wafer testing