## Doping of Wide Bandgap Semiconductors

<table>
<thead>
<tr>
<th></th>
<th>GaN</th>
<th>SiC</th>
<th>ZnO</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-type dopant</td>
<td>Si on Ga site (~ 15 meV)</td>
<td>N on C site (~ 85 meV)</td>
<td>B on Zn (~30-60 meV)</td>
<td>N (~ 1.7 eV)</td>
</tr>
<tr>
<td>p-type dopant</td>
<td>Mg on Ga site (160 meV)</td>
<td>Al on Si site (~ 200 meV)</td>
<td>N on O site (~ 170-200 meV)</td>
<td>B (~ 370 meV)</td>
</tr>
<tr>
<td>n-conductivity*</td>
<td>~ 0.002 Ωcm</td>
<td>~ 0.01 Ωcm</td>
<td>~ 0.02 Ωcm</td>
<td>&gt; 1000 Ωcm</td>
</tr>
<tr>
<td>p-conductivity*</td>
<td>0.2-2 Ωcm</td>
<td>0.5-2 Ωcm</td>
<td>0.5-40 Ωcm</td>
<td>10-100 Ωcm</td>
</tr>
</tbody>
</table>

* Experimental values

**GaAs**
- Si 6meV
- C (Be) ~ 28 meV

**Si**
- P 45meV
- B 40meV

**Diamond**
- ~ 0.001 Ωcm
Why difficult?

- Dopant binding (or activation) energy $\propto m^*$
- Maybe the ubiquitous H plays a big role?

Van Der Walle et al. Nature
Commonly Detected Deep Levels in High Quality $n$-GaN Grown by MOCVD and MBE (Steve Ringel, OSU)

Defects: dislocation, stacking fault, $V_N$, $Ga_I$, antisites, 
Impurities: C, O, H …, defect complexes: $H-V_{Ga}$, $O-V_N$, $H-Mg_{Ga}$ …

Deep Level Optical Spectroscopy (DLOS) and Deep Level Transient Spectroscopy (DLTS)

\begin{align*}
E_C - E_T & \quad E_c \\
0.25 \text{ eV} & \quad 0.60 \text{ eV} \\
0.90 \text{ eV} & \quad 1.35 \text{ eV} \\
2.40-2.80 \text{ eV} & \quad 3.04 \text{ eV} \\
3.22 \text{ eV} & \quad 3.28 \text{ eV} \\
E_v & \\
10^{13} & \quad 10^{14} \quad 10^{15} \\
\end{align*}

\begin{itemize}
\item All concentrations reflect typical distributions seen for high quality UCSB material$^{1,2}$
\item Individual concentrations can be significantly varied by growth conditions, impurities, etc.$^3$
\item SI GaN has considerably different trap spectrum$^4$
\end{itemize}

Hydrogenic model for impurities

Ionization of acceptor or donor impurities can be considered in the same fashion as the electron energy levels and radii are calculated for an isolated hydrogen atom.

The impurity levels $E_{dn}$ are given by:

$$E_c - E_{dn} = \frac{q^4 Z^2 m^*}{2n^2 (4\pi \varepsilon \hbar)^2}$$

where $n$ is a positive integer and $Z$ is the number of unit charge of the ionized donor atom, i.e. $Z = 2$, for a doubly ionized donor.

In terms of hydrogen atom ionization energies:

$$\Delta E_{dn} = E_c - E_{dn} = 13.6 \left( \frac{Z}{n\varepsilon_r} \right)^2 \left( \frac{m^*}{m} \right)$$

The orbital radii of the electrons are given by:

$$r_{dn} = 0.53 \left( \frac{n^2 \varepsilon_r}{Z} \right) \left( \frac{m}{m^*} \right) \text{ Å}$$
Doping of semiconductors I

For a semiconductor in thermal equilibrium,

\[ np = n_i^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right) \]

For flatband (charge neutral) condition,

\[ \Delta E = \frac{\rho(r)}{\varepsilon \varepsilon_0} = N_d^+ - N_a^- + p - n = 0 \]

For flatband (charge neutral) condition,

\[ \frac{N_a^-}{N_a} = \frac{1}{1 + g_a \exp\left[\left(E_a - E_f\right)/kT\right]} \]

For flatband (charge neutral) condition,

\[ \frac{N_d^+}{N_d} = \frac{1}{1 + g_d \exp\left[\left(E_f - E_d\right)/kT\right]} \]

Here \( g_a \) and \( g_d \) are the acceptor and donor degeneracy factors. For GaAs: \( g_d = 2, g_a = 4 \) (heavy and light hole bands); For Si (six minima): \( g_d = 12, g_a = 4 \); For GaN: \( g_d = 2, g_a = 4 \)
From the charge neutrality condition:

\[ \Delta E = \frac{\rho(r)}{\varepsilon \varepsilon_0} = N_d^+ - N_a^- + p - n = 0 \]

We have,

\[
\frac{N_d}{1 + g_d \exp\left[\left(E_f - E_d\right)/kT\right]} - \frac{N_a}{1 + g_a \exp\left[\left(E_a - E_f\right)/kT\right]}
\]

\[
= N_c \exp\left(\frac{E_f - E_c}{kT}\right) - N_v \exp\left(\frac{E_v - E_f}{kT}\right)
\]

The above equation is the generic equation governing the position of the Fermi level in a semiconductor at equilibrium. If the donor and acceptor concentrations and their activation energies are known, then the position of the Fermi level can be calculated. Note that if \((E_f - E_d)\) and \((E_f - E_a)\) are >> 0, then impurities are fully ionized.
p and n type doping of GaN

- N-type doping for GaN is simple and similar to other common semiconductors
  - Si has $E_a \approx 20$ meV (mobility $\sim 800 - 1000$ cm$^2$V$^{-1}$s$^{-1}$), Ge not so good for doping due to low incorporation

- P-type doping is complicated and quite different from other semiconductors
  - Mg has activation energy of $\sim 0.2$ eV (mobility few tens of cm$^2$V$^{-1}$s$^{-1}$)
  - Mg forms complexes with hydrogen which has to be broken first, for Mg to act as acceptors
  - Mg-H complexes can be broken down by
    - Annealing in nitrogen atmosphere
    - Low energy electron beam irradiation (LEEBI); $\sim 10$KeV, 60 µA
Technological impact of doping problems

- Fabrication of HBTs very difficult (poor base resistance)
- Contact resistance high for LEDs and lasers (high series resistance, bad diode characteristics)
- Other device structures involving p-type doping are not easy to fabricate
- N-type doping of AlGaN with high Al composition is also difficult (activation energy increases with bandgap)
- P-type doping for higher Al composition is even more difficult
- InN samples are usually degenerately n-type doped. It is difficult to even make a mild p-type device
GaN deposited on sapphire substrate typically shows n-type conductivity.

**SIMS of GaN film near sapphire interface:**

- Oxygen thermally etched or diffused from the sapphire substrate
- Residual impurities in precursors and gasses
  - minimize O incorporation
  - compensation via C or dislocations
**S.I. GaN… Fe doping**

Growth of GaN films grown on sapphire, first 0.3 µm Fe doped.

<table>
<thead>
<tr>
<th>Fe conc. (cm⁻³)</th>
<th>Sheet Resistance (W/sq.)</th>
<th>XRD FWHM (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3×10³</td>
<td>251/491</td>
</tr>
<tr>
<td>1.7×10¹⁸</td>
<td>2×10⁵</td>
<td>-</td>
</tr>
<tr>
<td>1.3×10¹⁹</td>
<td>7×10⁸ ( ! )</td>
<td>253/481</td>
</tr>
</tbody>
</table>

* XRD FWHM for (002) and (102) reflections

Highly insulating films of high structural quality.

*Sten Heikman et al., UCSB 2002*
Crystal growth: n-type doping

**Ga(In)N: Si** – shallow, [Si] < 10^{19} \text{ cm}^{-3} because of Si_xN_y formation and step poisoning

**Al_xGa_{1-x}N**: Si forms DX center in at x > 0.5

+ self-compensation through formation of V_{Ga} and V_{Al} = triple acceptors

**wide band gap!**

Example:

0.3 µm thick Al_xGa_{1-x}N:Si films

on Al_{0.63}Ga_{0.37}N-on-sapphire base layers

Crystal growth: p-type doping

**GaN:Mg** ~ 160 - 230 meV deep, H-passivated \((p \approx 1 \times 10^{18} \text{ cm}^{-3})\)

shallower in \(\text{In}_x\text{Ga}_{1-x}\text{N}\) (~ 80 – 160 meV)!

problem: p-type doping of AlGaN with high Al mole fractions
Modulation Doping

Polarization-enhanced Mg doping of AlGaN/GaN superlattices

Peter Kozodoy, Yulia P. Smorchkova, Monica Hansen, Hubi Xing, Steven P. DenBaas, and Umesh K. Mishra
Electrical and Computer Engineering Department and Materials Department, University of California, Santa Barbara, Santa Barbara, California 93106

A. W. Saxler, R. Perrin, and W. C. Mitchell
Air Force Research Laboratory, Materials and Manufacturing Directorate, AFFL/MLPO, Wright-Patterson AFB, Ohio 45433-7707

(Received 8 July 1999; accepted for publication 23 August 1999)

The hole-transport properties of Mg-doped AlGaN/GaN superlattices are carefully examined. Variable-temperature Hall-effect measurements indicate that the use of such superlattices enhances the average hole concentration at a temperature of 120 K by over five orders of magnitude compared to a bulk GaN film (the enhancement at room temperature is a factor of 9). An unusual modulation-doping scheme, which has been realized using molecular-beam epitaxy, has yielded high-hole-mobility superlattices and conclusively demonstrated the pivotal role of piezoelectric and spontaneous polarization in determining the band structure of the superlattices. © 1999 American Institute of Physics. 1500-3857/99/04442-31
Doping statistics

\[ p = N_v \exp \left[ -\frac{(E_f - E_v)}{kT} \right] \]

\[ N_A^- = \frac{N_A}{1 + g \exp \left( \frac{E_A - E_F}{kT} \right)} \]

\[ N_v = \frac{2(2\pi m_e^* kT)^{3/2}}{h^3} \]

\[ p + N_D = N_A^- \]

These equations are now combined yielding

\[ \frac{p(p + N_D)}{N_A - N_D - p} = \phi, \]

where we define the quantities $\phi$ and $\Delta E_A$:

\[ \phi = \frac{N_v}{g} \exp \left( -\frac{\Delta E_A}{kT} \right). \]

\[ \Delta E_A = E_A - E_V. \]

Figure 2.14 Hole concentration measured as a function of temperature on Mg-doped GaN samples. For clarity of presentation the data have been divided between two separate plots; note that the scale differs on the two plots. The solid lines represent fits to equation (2.8).

Kozodoy et al. 1999
## Ion Implantation in GaN

**Manufacturability, reproducibility, flexibility and reliability**

**But...**

<table>
<thead>
<tr>
<th>Requirements for implantation doping by activation annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Remove the implantation-produced compensation defects and the lattice disorder</td>
</tr>
<tr>
<td>- Electrically/optically activate implanted species by moving the interstitial dopants to substitutional sites via short-range diffusion.</td>
</tr>
<tr>
<td>- No considerable redistribution of dopants after post-implantation annealing.</td>
</tr>
</tbody>
</table>

- **Accurate dose control**
  - Intrinsically low temperature process
  - Impurity Concentration profile and the structural changes can be tailored
  - Insensitivity to the lattice structure and defects, and the presence of impurities
  - Not constrained by the thermodynamics
  - Simplify the device processing

- **High resistivity to annealing.**
- **Inability to epitaxially re-crystallize the implantation induced amorphous layer by annealing.**
- **Complete recovery requires 1500°C annealing (2/3 of melting point), thus high N₂ over 15Kbar N₂ overpressure, and proper capping layers.**

Haijiang Yu, UCSB 2004
Thermodynamic analysis and the thermal processing

Thermal Processing Chamber

- Processing Temperature: ~1500°C
- Pressure: 1500 psi (or ~100 bar) N₂
- 2 inch wafer accommodation

Graphite or Moly
Thermocouple in alumina sheath

RF Generator

100 bar N₂

Output power %

Sample surface temperature

Thermocouple temperature

Temperature

~1500°C

I minute

44%
GaN stability at equilibrium
- 100 bar $N_2$ ★ ~100°C
- 1500°C processing ★ >10 kbar $N_2$

1500°C annealing with 100 bar $N_2$:
- Rapid processing
- Thermally stable capping layers

(Davydov, et al., phys.stat.sol.(a) 2001)
Rapid high pressure annealing of planar GaN

- GaN protected:
  - ~1500°C
  - ~Optimized
  - sputtered AlN
  - ~100 bar N₂

Typical UCSB MOCVD GaN template
(0002)~300 arcsec  (10\bar{1}2) ~950 arcsec

Before annealing

~100nm Sputtered AlN
~2μm UID GaN
Sapphire

~1300°C annealing no AlN cap

~1500°C annealing 100 nm AlN cap
Ion implantation results

- Minimal dopant redistribution
- Very low sheet resistance: ~ 20 ohm/square, normal doping: ~ 500 ohm/square
- Contact resistance:
  - 0.07 ohm mm for non-alloyed contacts
  - 0.02 ohm mm for alloyed contacts
  - normal doping: ~ 0.2-0.5 ohm mm

Haijiang Yu et al. APL, 2004
Polarization-induced doping

Debdeep Jena, 2001
Polarization doping

Al composition $x$ increases

$\rho_{3D} = -\nabla \cdot P$

To maintain space charge neutrality, $n_s = \rho_{3D}$

• Interesting from theoretical standpoint to study such 3D charges which was found to have mobility limited by only alloy scattering at very low temperatures

Wherever high conductivity bulk material is needed – in MESFETs, JFETs, Regrown contacts, etc.

Debdeep Jena, 2001
Alternative structure: Polarization-doped FET

Advantages over conventional MESFETs
- Higher mobility: no impurity scattering
- No carrier freeze-out
- High Schottky barrier height
- High breakdown field in AlGaN

Advantages over HEMTs
- Ability to tailor $g_m$ curve for better linearity
- Different grading schemes lead to different charge profiles
PolFET: Device Characteristics

150µm x 0.7µm devices
$I_D = 850$ mA/mm
$g_m = 93$ mS/mm

$f_T = 19$ GHz
$f_{MAX} = 51$ GHz

• Output Power = $4.3$ W/mm @ 4GHz
• PAE = 63%
• Gain = 10 dB
($V_{DS} = 30$V, $I_{DS} = 40$ mA/mm)
• On sapphire

Siddharth Rajan et al. 2004
Nitride MBE (Jim Speck, UCSB)

*rf plasma MBE growth diagrams*
- Basic considerations
- Morphology control

**Bulk transport and growth**
- n-GaN
- p-GaN
  - Polarization reversal

**Alloys**
- AlGaN to AlN
  - 2DEGs (AlGaN/GaN, AlN/GaN)
- InGaN
  - Wetting layer and purity issues

Challenges:
- High In composition InGaN
- InN
- GaN, InN quantum dots

Gen 930 at ND (Albert)
Constant $N^* = 15.2 \text{ nm/min}$

Accumulation of Ga

$F_{Ga} < N^*$

RF MBE GaN Growth Diagram

Substrate Temperature (°C)

Ga-flux (nm/min)

Ga-droplet

Ga-stable

Intermediate Ga-stable

N-stable

Steady-state Ga coverage

F$_{Ga} < N^*$
Morphology: AFM

![Ga-droplet](image1)

![Intermediate](image2)

![N-stable](image3)

---

**Ga-flux (nm/min)**

**Substrate Temperature (°C)**

- A
- B
- C

- 5µm

---

AFM images showing morphological changes with varying substrate temperatures and Ga-fluxes.
Structure: Cross-Section TEM

Pits initiate at mixed and edge dislocations
Decrease in pits $\Rightarrow$ Surface kinetics $\Rightarrow$ Ga-adlayer coverage
n-GaN: Transport Structure

**Growth structure:**
- MBE-GaN film
- n-p-n+ isolation layers
- MOCVD-GaN template
- Sapphire substrate
- Hall mobility measured on 30µm x 30µm vdp patterns
- 1-2 µm thick
  \[ N_{TD} = 10^8 - 10^{10} \text{cm}^{-2} \]

**Experiments:**
1) Determine the effect of Dislocation Scattering by growing on templates with different dislocation densities.
2) Determine the effect of growth regime by changing III/V ratio.
Doped GaN: Transport Properties

Both decent n-type and p-type GaN achieved
(GaN:Mg was grown under Ga crossover regime and Hall measurement results on the right)

B. Heying et al. and I.P. Smorchkova et al.
Why MBE for Mg in GaN?

- Very sharp doping profiles

Accurate p-n junction placement is possible

**MBE**

![MBE graph showing Mg concentration vs. depth with very sharp profiles](image)

**MOCVD**

![MOCVD graph showing Mg concentration vs. depth with less sharp profiles](image)

Why MBE for Mg in GaN?

- MBE provides very sharp doping profiles, which is crucial for accurate p-n junction placement.

The diagrams illustrate the concentration of Mg and Si as a function of depth for both MBE and MOCVD processes. MBE allows for precise control over the doping profile, making it suitable for applications requiring sharp junctions.
Growth Transition Series (constant Mg flux): Morphology

Increasing Ga flux
Mg Growth Transition

Increasing Ga flux

Intermediate or N-rich growth: insulating

Optimal properties at the crossover!
Polarity Inversion: Sample Structures

Single Mg-doped layers
Ga-stable vs. N-stable

0.4 µm Mg-GaN
Mg BEP = 1x10^{-8} torr
(for Ga-rich: p = 8-9 x 10^{17})

30 nm UID MBE GaN

1 – 2 µm MOCVD GaN

Multiple Mg-doped layers
Ga-stable vs. N-stable

120 nm Mg-GaN, Mg BEP = 1.8x10^{-8} torr

120 nm UID MBE GaN

120 nm Mg-GaN, Mg BEP = 1x10^{-8} torr

120 nm UID MBE GaN

120 nm Mg-GaN, Mg BEP = 7.8x10^{-9} torr

120 nm UID MBE GaN

120 nm Mg-GaN, Mg BEP = 3.5x10^{-9} torr

30 nm UID MBE GaN

1 – 2 µm MOCVD GaN

$T_{growth} = 650^\circ C$
**N-Rich** Single Mg-Doped Layers: Complete Polarity Inversion

CBED  
X-Section TEM

MBE  
MOCVD

Scale: 0.2 µm
**Ga-Rich** Single Mg-Doped Layers: ‘Spike-Shaped’ Inversion Domains

**Plan-View**
- ID Formation
- TDs
- Isolated
- Density $\sim 10^9$ cm$^{-2}$

**Cross-Section**
- MBE
- MOCVD
Multilayer Structures: N-rich

<table>
<thead>
<tr>
<th>Layer Structure</th>
<th>Mg BEP (torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 nm Mg-GaN, Mg BEP = 1.8x10^{-8} torr</td>
<td></td>
</tr>
<tr>
<td>120 nm UID MBE GaN</td>
<td></td>
</tr>
<tr>
<td>120 nm Mg-GaN, Mg BEP = 1x10^{-8} torr</td>
<td></td>
</tr>
<tr>
<td>120 nm UID MBE GaN</td>
<td></td>
</tr>
<tr>
<td>120 nm Mg-GaN, Mg BEP = 7.8x10^{-9} torr</td>
<td></td>
</tr>
<tr>
<td>120 nm UID MBE GaN</td>
<td></td>
</tr>
<tr>
<td>120 nm Mg-GaN, Mg BEP = 3.5x10^{-9} torr</td>
<td></td>
</tr>
<tr>
<td>30 nm UID MBE GaN</td>
<td></td>
</tr>
<tr>
<td>1 – 2 µm MOCVD GaN</td>
<td></td>
</tr>
</tbody>
</table>

*MBE layers are fully inverted*
### Multilayer Structures: Ga-rich

Inversion begins at first Mg layer

<table>
<thead>
<tr>
<th>Thickness of Mg-GaN</th>
<th>Mg BEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 nm</td>
<td>$1.8 \times 10^{-8}$ torr</td>
</tr>
<tr>
<td>120 nm</td>
<td>$1 \times 10^{-8}$ torr</td>
</tr>
<tr>
<td>120 nm</td>
<td>$7.8 \times 10^{-9}$ torr</td>
</tr>
<tr>
<td>120 nm</td>
<td>$3.5 \times 10^{-9}$ torr</td>
</tr>
<tr>
<td>30 nm</td>
<td></td>
</tr>
</tbody>
</table>

1 – 2 µm MOCVD GaN
Model for Polarity Inversion: 
*Growth on Dry Surfaces*

Ga wetting layer development

- 300 Å
- 630 Å
- 1250 Å
- 2500 Å

Ga wetting layer develops gradually *(Solution: pre-wet surface!)*

GaN WL

ID nucleation on dry regions

- c+ GaN
- c- Mg-GaN
- c+ Mg-GaN
- c+ GaN (no Mg)
Alloy Growth: AlGaN

Idea:

- Composition is controlled with the group III component with the highest sticking coefficient (Al)
- Full range of Al composition available

- III/V > 1
- Al comp. = 10%
AlGaN/GaN III/V Study

All Samples: $\text{Al}_{0.12}\text{Ga}_{0.88}/\text{GaN}$

- **Ga Rich**
- **No Ga Droplets**
- **Spirals**
- **77K $\mu=11,200$ cm$^2$/Vs**

- **Ga Rich**
- **Ga Droplets**
- **Spirals**
- **77K $\mu=11,200$ cm$^2$/Vs**

- **Ga Rich**
- **No Ga Droplets**
- **AlGaN Spheres**
- **4nm x 150nm**
- **77K $\mu=8000$ cm$^2$/Vs**

- **Ga Rich**
- **No Ga Droplets**
- **AlGaN Spheres**
- **5nm x 120nm**
- **77K $\mu=3000$ cm$^2$/Vs**
Transport Properties of Al$_{0.09}$Ga$_{0.91}$N/GaN Heterostructure

Temperature Dependent Hall Properties

Shubnikov-de Haas Oscillations

$4.2 \text{ K}$

$n_{sh} = 2.2 \times 10^{12}\text{cm}^{-2}$

$\text{MBE-AlGaN}$

$\text{MBE-GaN Spacer}$

$\text{MOCVD-Template}$

$\text{ref}$
Growth of AlN under Ga wetting layer

I.P. Smorchkova et al., JAP 90, 5196 (2001)
Alloy Growth: InGaN Growth

Idea:
- Composition is controlled with the group III component with the highest sticking coefficient (Al > Ga > In)
- Full range of In composition available

Example: InGaN Growth
- III/V > 1 for optimal morphology and properties

C. Poblenz et al. 2003
In Flux Series: Morphology and Transport

12.9% In, droplets
\( \mu = 110 \text{ cm}^2/\text{Vs} \)
\( n = 1.5 \times 10^{18} \text{ cm}^{-3} \)

11% In, no droplets
\( \mu = 87 \text{ cm}^2/\text{Vs} \)
\( n = 1.56 \times 10^{18} \text{ cm}^{-3} \)

600\(^\circ\)C
1.1 \times 10^{-7} \text{ Ga BEP}
Variable In flux

5.3% In, no droplets
\( \mu = 134 \text{ cm}^2/\text{Vs} \)
\( n = 7.0 \times 10^{17} \text{ cm}^{-3} \)

Structure:
0.5 \mu m InGaN on npn isolation structure

Hall:
30 \mu m x 30 \mu m Greek Cross

All AFM: 5 \mu m x 5 \mu m
Towards 2DEGs: AlGaN/InGaN

\[
\text{Al}_{0.12}\text{Ga}_{0.88}\text{N}/\text{In}_{0.06}\text{Ga}_{0.94}\text{N}
\]
\[\mu (77K) = 500 \text{ cm}^2/\text{Vs}\]

\[
\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}/\text{GaN}
\]
\[\mu (77K) = 18,470 \text{ cm}^2/\text{Vs}\]

Low temperature freeze-out not observed in InGaN
Impurity Incorporation in MBE-In$_{0.17}$Ga$_{0.83}$N: SIMS

No Indium Desorption

Indium Desorption

B.E.P.

GaN

InGaN

GaN

MOCVD

GaN

150 nm

Oxygen

Counts per second

Indium

Boron

Depth (a.u.)
Sensitivity of Ga Wetting Layer to Excess In

Desorption of excess metal

No desorption

Ga-rich GaN growth at 600°C

Counts per second

Depth (a.u.)

GaN
GaN (In)
GaN
GaN (In)
GaN
MOCVD GaN

AlGaN markers

(In) indicates excess In present during growth

Oxygen

Aluminum

Boron

150 nm
Structure of Ga and In Wetting Layers

Ga-rich growth
Laterally contracted Ga bilayer

In-rich growth
In wetting layer

Why such high UID in InGaN?
Difference in wetting layer (Ga bilayer vs In ‘monolayer’)


Effect of Ga Flux on InGaN Composition and Growth Rate

Maximum of 17% In incorporation at 600 °C

In (BEP) = 4.05 x 10^{-7} Torr

In Droplet Regime, 600 °C

<table>
<thead>
<tr>
<th>Ga Flux (BEP)</th>
<th>%In by XRAY</th>
<th>Growth Rate (µm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.07</td>
</tr>
<tr>
<td>2.00E-08</td>
<td>0.01E+00</td>
<td>0.01</td>
</tr>
<tr>
<td>4.00E-08</td>
<td>0.02E+00</td>
<td>0.02</td>
</tr>
<tr>
<td>6.00E-08</td>
<td>0.03E+00</td>
<td>0.03</td>
</tr>
<tr>
<td>8.00E-08</td>
<td>0.04E+00</td>
<td>0.04</td>
</tr>
<tr>
<td>1.00E-07</td>
<td>0.05E+00</td>
<td>0.05</td>
</tr>
<tr>
<td>1.20E-07</td>
<td>0.06E+00</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Effect of Ga Flux on InGaN Composition and Growth Rate

\[ \text{F}_{\text{Ga}} = 0 \]

Complete In wetting layer: ‘monolayer’ structure

\[ \text{F}_{\text{Ga}} > 0 \]

Ga + In wetting layer: structure unclear

Complete Ga wetting layer: fluid-like bilayer
# Origin of Impurities

<table>
<thead>
<tr>
<th>Source</th>
<th>Impurity</th>
<th>Possibility</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outgassing of Ga, In, or N source</td>
<td>O, B</td>
<td>NO</td>
<td>SIMS</td>
</tr>
<tr>
<td>Background pressure in the system</td>
<td>O</td>
<td>NO</td>
<td>System base pressure is in mid $10^{-11}$ Torr range</td>
</tr>
<tr>
<td>Reduced growth rate in the InGaN layer</td>
<td>O, B</td>
<td>NO</td>
<td>TEM</td>
</tr>
<tr>
<td>N source gas</td>
<td>O</td>
<td>YES</td>
<td>Low cracking efficiency of plasma source</td>
</tr>
<tr>
<td>N source</td>
<td>B</td>
<td>YES</td>
<td>Plasma could sputter crucible during growth</td>
</tr>
</tbody>
</table>

**~1% N source efficiency:**

$10^{18}$ UID = 1 ppm oxygen from total N source