Advances in Plasma Processing for WBG Power Electronics

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Oxford Instruments Plasma Technology
Leading provider of nanotechnology solutions with a globally recognised brand

- FY18 Revenue: £296.9m
- 1576 Employees
- Years: 50+
- R&D spend 8.4% sales

**EBIT margin**
- 15.7%

**Cash**
- £33.4m (68.8% conversion)

Net debt: EBITDA leverage at 0.3 times

**FY18 Group Revenue %**
- Asia 40%
- North America 31%
- Europe 27%
- ROW 2%

- 28 offices globally
- Close to main tech hubs
Global Technology Trends

- Lab
  - Academic research
- Lab to Fab
  - Atomic scale processing
  - MEMS
  - Industry research
  - AR/VR
- Nano
  - CNT
  - Graphene
  - 2D materials
  - Bio sensors
  - LIB
- Discretes
  - EV
  - Wireless Charging
  - Lidar
  - Datacenters
  - RF /5G
  - Renewable energy
- Optoelectronic
  - 3D sensors
  - Lidar
  - CE: AR/VR
  - IoT
  - Datacom
  - Emerging displays
Introduction

• OIPT currently provides **production process solutions** for D-mode GaN devices

• Key challenges for E-mode GaN HEMTs
  • Recess gate etch
  • Device passivation/isolation

• OIPT’s process solutions for E-mode GaN devices
  • Atomic Layer Etching
  • Atomic Layer Deposition
E-mode for Power Supply Applications

- Power supply applications have fail safe requirements
- Fail safe operation can be achieved using:
  - Normally on GaN HEMT in cascode configuration
  - Normally off GaN HEMT
- Cascode produces enhanced performance compared to Si SJ MOSFET
- Cascode performance is limited by Si based gate driver
- E-mode devices are preferred for simpler circuitry and better performance at low voltage and high frequency
GaN HEMT Manufacturing

**GaN HEMT**

- **Epitaxy**
- **Ohmic contact**
- **Gate recess and isolation**
  - ALE + ALD
- **Passivation**
  - PECVD / ICP
  - CVD + ICP RIE
- **Mesa isolation**
  - PECVD + ICP RIE
- **Gate deposition**
- **Bond pads**

**Layers**
- Source
- Gate
- Drain
- AlGaN
- GaN
- Buffer
- Substrate
What is Atomic Layer Etching?

- Cyclical ALE process enables precise control and low damage etching
- Plasma can be on throughout cycle (or be switched on/off)

Chlorinating dose gas, e.g. Cl₂

Oxidation is self-limiting

Ar etch gas removes the chlorinated layer

AlGaN
ALE of GaN HEMT

• ALE required to form recessed gate for E-mode device
  • Required controlled etch of AlGaN to GaN surface without 2DEG damage

High mobility through 2D electron gas (2DEG) at AlGaN/GaN interface

Selective etch by ALE through AlGaN to form recessed gate
ALE of AlGaN

AlGaN/GaN ALE results: Ar/Cl₂

- Etch rate 1.5-3.0 Å/cycle
  - up to 18 Å/min
- Uniformity <±5% over 200mm
- Added roughness <<1nm

AlGaN etching rate per cycle

AlGaN surface roughness 200 cycles:
Before etching (top)
After etching (bottom)
From D-mode to E-mode HEMT

- Recess etched in GaN HEMT at OIPT
- Device fabrication at University of Glasgow
- $V_{th}$ shifts from -5 to +0.15V by recess etching

![Graph showing the shift in $V_{th}$ before and after recess etch]

- Before recess etch
  - Normally ON (D-mode)
- After recess etch
  - Normally OFF (E-mode)
PEALD for Production

- Fast cycle times enable high throughput with low damage remote PEALD
- Plasma pre-treatment improves GaN surface and device performance
- Remote PEALD offers excellent film properties with low substrate damage
- Throughput of 10,000 WPM of PEALD 20 nm $\text{Al}_2\text{O}_3$ with low CoO
ALD for GaN HEMT

- Plasma pre-treatment required to remove native oxide and restore GaN surface
- ALD required for deposition of conformal layer to passivate surface and electrically isolate GaN from gate

Plasma surface pre-treatment to improve interface

Passivation by ALD for low leakage
PEALD Al₂O₃ for GaN HEMT Passivation

- OIPT ALD systems used in production: 25 wafer cassettes; 24/7
- Meeting power semiconductor requirements of 20 nm Al₂O₃ with throughput of 10,000 WPM
- High-quality PEALD Al₂O₃ films deposited at low CoO

![Thickness Uniformity Diagram]

<table>
<thead>
<tr>
<th>Material</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precursor</td>
<td>TMA (Al(CH₃)₃)</td>
</tr>
<tr>
<td>Co-reactant</td>
<td>O₂ plasma</td>
</tr>
<tr>
<td>Deposition temperature</td>
<td>50-400 °C</td>
</tr>
<tr>
<td>Thickness uniformity (150 mm)</td>
<td>&lt; ±0.5%</td>
</tr>
<tr>
<td>Thickness uniformity (200 mm)</td>
<td>&lt; ±1.0%</td>
</tr>
<tr>
<td>Refractive Index @ 632.8nm</td>
<td>&gt;1.63</td>
</tr>
</tbody>
</table>
Nitride interlayer as GaN pre-treatment

- Use plasma treatments to form high-quality nitride interlayer

Strong reduction of Ga-O bonds with plasma pre-treatment

- Small sub-threshold swing: 64 mV/dec
- Low hysteresis: 0.09 V
- Low Dit: $1-6 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$

Yang et al., *IEEE Electron Device Lett.* 34, 1497 (2013)
Epitaxial AlN for GaN transistor

- Epitaxial growth of AlN by PEALD
- ALD Al$_2$O$_3$ gate dielectric
- Low subthreshold swing
  - $\sim$85 mV/decade
- Low-field mobility
  - $\sim$27 cm$^2$/V·s)


Epitaxial 4 nm AlN on GaN
O IPT’s ALD Experience with GaN devices

- Global install base of ALD systems for GaN device processing
  - Production customers
  - R&D customers

- Key collaboration with University of Glasgow and Kelvin Nanotechnology for GaN HEMT fabrication and characterisation
Conclusions

• ALE required for accurate AlGaN etching to form recessed gate for E-mode devices

• Plasma ALD provides a process solution for reliable manufacturing of E-mode devices

• Proven ALD process solutions and worldwide install base
  • Ease of process transfer from R&D to HVM for GaN HEMT customers

OIPT delivers Atomic Precision on a Production Scale
Thank you

For further information please contact plasma-experts@oxinst.com