GaN and Ultra Wide Bandgap III-Nitrides for Power Electronics

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• Current GaN Power Devices and Performance
• Technological challenges and opportunities for GaN:
  • Device Passivation
  • N-Polar vs. Ga-Polar
  • Ion Implantation
• Ultra Wide Bandgap III-Nitrides (AlGaN $\rightarrow$ AlN)
  • Device demonstrations
  • Contacts
• Making III-Nitride technology accessible at NCSU
GaN for Power

- GaN Power Device market size expected to surpass $400M by 2022
- Compared to SiC’s ~$1B market size in 2022
- **BUT** the GaN for RF market is projected to reach $1.3B by 2023
- **BUT** the GaN-based optoelectronics market is also growing >$1B

\[
BFOM = \frac{4BV^2}{R_{on\text{-ideal}}}
\]

http://www.yole.fr/iso_album/illus_power_gan_market_applications_yole_oct2017_updated.jpg
Lateral AlGaN/GaN HEMTs

- AlGaN/GaN heterojunction creates quantum well (2DEG) with high electron mobility
- 2DEG is polarization doped:
  - Spontaneous polarization
  - Piezoelectric polarization
- AlGaN/GaN HEMTs are normally-on devices
- Heteroepitaxially grown on Si, SiC or Sapphire substrates
E-Mode AlGaN/GaN HEMTs

Commercialization Gap

Research

2007
8300V Blocking Voltage AlGaN/GaN Power HFET with Thick Poly-AlN Passivation

Yasuhiro Uemoto, Daisuke Shibata, Manabu Yanagihara, Hidetoshi Ishida, Hisayoshi Matsu, Shuichi Nagai*, Nagaraj Batta*, Ming Li*, Tetsuo Ueda, Tsuyoshi Tanaka, and Daisuke Ueda

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2006
40-W/mm Double Field-plated GaN HEMTs

Y.-F. Wu, M. Moore, A. Saxler*, T. Wisleder and P. Parikh
Cree Santa Barbara Technology Center, 340 Storke Road, Goleta, CA 93117
*Cree Inc., 4600 Silicon Drive, Durham, NC 27703

Product

50-600V

6.6 W/mm
Thermal Management

IV degradation due to Self-Heating

GaN

HOTSPOT

Advanced Characterization

Gate Resistance Thermometry

Advanced

Cooling

DARPA

“ICECool”

GaN on Diamond


Del Alamo, Microelectronics Reliability, 2009

Pavlidis et al., IEEE TED, 64 (1), 78-83, 2017

Advancement in Device and System Cooling

elementsix™
a De Beers Group Company
AlGaN/GaN HEMT Passivation

- Two challenges:
  - N- bond is less stable than O-bond
    - GaO_x forms on the surface
  - Charged surface states on the surface
    - Transient effects
    - Fermi level pinning

What materials and device fabrication techniques can we use to passivate?
In-situ nitridation ensures a clean interface between AlGaN and passivation

LPCVD SiN_x process offers ex-situ nitridation and high-quality passivation

Temperature Instability due to Poor Interfaces

- Forward bias non-idealities in photolithography-processed SBDs are reduced via anneal
- Shadow-masked contacts show superior reverse leakage performance
- Acid treatment prior to metal deposition yields ideal Schottky diode behavior

N-Polar GaN

Curiosity

Non-equivalent properties

Performance

Lower contact resistance improves output power!

What about N-GaN surfaces?

- MOCVD-grown N-polar GaN on sapphire
- O$_2$-doped

<table>
<thead>
<tr>
<th>Step</th>
<th>Sample 1 (Control)</th>
<th>Sample 2 (Treated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohmic Contact</td>
<td>Shadow Mask (V/Al/Ni/Au)</td>
<td>Shadow Mask (V/Al/Ni/Au)</td>
</tr>
<tr>
<td>Schottky Contact Patterning Method</td>
<td>Shadow Mask</td>
<td>Lithography</td>
</tr>
<tr>
<td>Surface Treatment</td>
<td>---</td>
<td>Boiling HCl:H$_2$O</td>
</tr>
<tr>
<td>Schottky Metal Deposition</td>
<td>Ni</td>
<td>Ni</td>
</tr>
<tr>
<td>Lift-Off</td>
<td>---</td>
<td>NMP (at 70°C) then acetone &amp; IPA</td>
</tr>
</tbody>
</table>

I-V Comparison

Control Sample

\[ \Phi_B = 0.4 \text{ eV} \]
\[ n = 1.08 \]

Near-ideal ideality factor via shadow masking

Processed Sample

Defective surface introduces non-idealities

Experimental IV

0.3eV - Simulated

0.87eV - Simulated


We need passivation!
Ion Implantation Technology for GaN

Ar implantation for edge termination

Mg-Implantation for p-GaN

Activation anneal is critical

Ultra WBG III-Nitrides (AlGaN and AlN) offer the next frontier of power electronics, and are once again supported by optoelectronics applications (e.g., UV water purification).

Ion-Implanted AlN Channels

Si implantation n-type dopes AlN

V-based ohmic contacts outperform traditional Ti-based contacts

Ion implantation in AlN provides a pathway to higher $N_D$ than epitaxial doping

Activation anneal recipe is critical!

AlN-/AlGaN-Channel Devices

MIT/Tsukuba University (2018)

Sandia (2018)


E. A. Douglas et al., 76th Device Research Conference (DRC), Santa Barbara, CA, USA, 2018.
Passivation of $\text{Al}_x\text{Ga}_{1-x}\text{N}$

- As $E_G$ increases, things become more challenging...

Type II staggered band alignment

- $\text{Si}_3\text{N}_4$
- 0% $\rightarrow$ 2 eV
- 30% $\rightarrow$ 2.3 eV
- 40% $\rightarrow$ 2.2 eV
- 60% $\rightarrow$ 1.8 eV
- 80% $\rightarrow$ 1.4 eV
- 100% $\rightarrow$ 1.4 eV

$\Delta E_V$ 1.3 eV

Measurement Error


Band bending observed $x>0.6$
Fabrication Capabilities

E-Mode AlGaN/GaN MIS-HEMT

WBG Device Fabrication Course (& Industry Short Course?)

![Graph showing current vs. gate-source voltage](image)

**Graph Details:**
- **X-axis:** Gate-Source Voltage, $V_{GS}$ (V)
- **Y-axis:** Current, $I$ (A)
- **Legend:**
  - Blue line: Drain Current
  - Red line: Gate Current
Measurement Capabilities

On-Wafer

DC I-V

Transient
1 GHz BW

High-Power, High-Speed PIV
220V / 2A / 200 ns PW
2kV / 100A / 1 μsec PW
AlGaN/GaN HEMTs are rapidly penetrating the power device market
  • But we are leaving performance on the table (passivation, thermal and reliability)

NCSU is tackling these challenges from materials to circuits to systems
  • Example: N-polar GaN vs. Ga-polar GaN vs. mixed polar?

UWBG III-Nitrides (e.g., AlGaN and AlN) are just around the corner
  • We are developing epitaxy, bulk substrates, implantation contacts and passivation

Can we derive inspiration from III-Nitrides’ many uses?
  • Mixed optical/electrical systems for higher-speed and integration
Acknowledgements

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