AIGaN/GaN HEMTs

Tomás Palacios

Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology
Outline

• Introduction
  – Main material properties
  – Optoelectronic devices
  – Why do we need a new kind of transistor?
• Basic structure of AlGaN/GaN HEMTs
  – Main differences with other technologies
  – Nitride technology
• Polarization
  – Origin of polarization
  – Ga-face vs N-face
  – Calculation of charge density
  – Other applications of polarization
• Dispersion and current collapse
• State of the art in GaN HEMTs
• Challenges for nitride electronics
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Nitride semiconductors

Original research in 1990’s focused on optoelectronics (blue and white LEDs, lasers…)

Their excellent electrical and mechanical properties allow many other devices…

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Silicon</th>
<th>AlGaAs/InGaAs</th>
<th>InAlAs/InGaAs</th>
<th>SiC</th>
<th>AlGaN/GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic</td>
<td>Unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandgap</td>
<td>eV</td>
<td>1.1</td>
<td>1.42</td>
<td>1.35</td>
<td>3.26</td>
</tr>
<tr>
<td>Electron mobility</td>
<td>cm²/Vs</td>
<td>1500</td>
<td>8500</td>
<td>5400</td>
<td>700</td>
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<tr>
<td>at 300 K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated (peak)</td>
<td>X10⁷cm/s</td>
<td>1.0 (1.0)</td>
<td>1.3 (2.1)</td>
<td>1.0 (2.3)</td>
<td>2.0 (2.0)</td>
</tr>
<tr>
<td>electron velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Critical breakdown</td>
<td>MV/cm</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>3.0</td>
</tr>
<tr>
<td>field</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
GaN: The most complete semiconductor?

**Nitrides:**
- Large $E_g$ span
- Direct bandgap
- Polarization
- Piezoelectricity
- Ferromagnetism?
- Biocompatible
- Chemical and thermal stability

**Applications of GaN devices**

- Wireless Base Stations: RF Power Transistors
- Wireline Broadband Access: High Frequency MMICs
- Automotive Electronics: High Temperature Electronics
- Power Conditioning: Mixed Signal GaN/Si Integration
- Flame Sensors: UV Detectors
- DVD Information Storage: Blue Laser Diodes
- Heat Sensors: Pyro-Electric Detectors
- Pressure Sensors: MEMS
- Solid-State White Lighting: Blue/UV LEDs

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**Graph:**

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Tomás Palacios (tpalacios@mit.edu)
GaN for Power Amplifiers

Can GaN devices be used instead of TWT amps?

GaN: excellent candidate for power amplification at mm-wave frequencies

BFOM ➔ Baliga’s Figure of Merit for Power Transistor Performance at low frequencies

\[ BFOM = \varepsilon \mu E_c^2 \]

JFM ➔ Johnson’s figure of merit for Power Transistor Performance at high frequencies

\[ JFM = E_c v_s / 2\pi \]
Main requirements for power amplifiers

<table>
<thead>
<tr>
<th>Need</th>
<th>Enabling Feature</th>
<th>Performance Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Power/Unit Width</td>
<td>Wide Bandgap, High Field</td>
<td>Compact, Ease of Matching</td>
</tr>
<tr>
<td>High Voltage Operation</td>
<td>High Breakdown Field</td>
<td>Eliminate/Reduce Step Down</td>
</tr>
<tr>
<td>High Linearity</td>
<td>HEMT Topology</td>
<td>Optimum Band Allocation</td>
</tr>
<tr>
<td>High Frequency</td>
<td>High Electron Velocity</td>
<td>Bandwidth, μ-Wave/mm-Wave</td>
</tr>
<tr>
<td>High Efficiency</td>
<td>High Operating Voltage</td>
<td>Power Saving, Reduced Cooling</td>
</tr>
<tr>
<td>Low Noise</td>
<td>High gain, high velocity</td>
<td>High dynamic range receivers</td>
</tr>
<tr>
<td>High Temperature</td>
<td>Wide Bandgap</td>
<td>Rugged, Reliable, Reduced Cooling</td>
</tr>
<tr>
<td>Operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Management</td>
<td>SiC Substrate</td>
<td>High power devices with reduced cooling needs</td>
</tr>
<tr>
<td>Technology Leverage</td>
<td>Direct Bandgap:</td>
<td>Driving Force for Technology:</td>
</tr>
<tr>
<td></td>
<td>Enabler for Lighting</td>
<td>Low Cost</td>
</tr>
</tbody>
</table>
Requirements for Power amplifiers

Main requirements for high output power:

- High breakdown voltage
- High Current density
- High frequency response

\[ \text{Linear Power} = \frac{(V_B - V_{Dsat}) \cdot I_m}{8} \]

\[ \text{Saturated Power} = \frac{16}{\pi^2} \cdot P_{linear} \]
Main requirements for high output power:

- High breakdown voltage
- High Current density
- High frequency response

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<th>Indium phosphide (InAlAs/InGaAs)</th>
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<td>Critical breakdown field</td>
<td>MV/cm</td>
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<td>0.4</td>
<td>0.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>
In AlGaN/GaN HEMTs, the very high carrier density and mobility allow record current levels…

Main requirements for high output power:
- High breakdown voltage
- High Current density
- High frequency response

Fig. 2 80 µs and 200 ns pulsed i–V for passivated 2 × 75 µm device with $L_g=0.7 \mu m$ and $L_{gd}=1 \mu m$
From top to bottom $V_{GS}=4 \ V \rightarrow -8 \ V$, $\Delta V_{GS}=2 \ V$. After SiN passivation device characteristics are no longer affected by dispersion

Chini et al., Elect. Letts. 39, 625 (2003)  Tomás Palacios (tpalacios@mit.edu)
Electron velocity in GaN

From steady-state Monte Carlo simulations,

Even compared to other compound semiconductors, AlGaN/GaN is attractive:

**Main requirements for high output power:**
- High breakdown voltage
- High Current density
- High frequency response

**Steady state**
\[ v_{e, \text{GaN}} > 2.5 \quad v_{e, \text{Si}} \]

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<tr>
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<th>Silicon</th>
<th>Gallium arsenide (AlGaAs/InGaAs)</th>
<th>Indium phosphide (InAlAs/InGaAs)</th>
<th>Silicon carbide</th>
<th>Gallium nitride (AlGaN/GaN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated (peak) electron velocity</td>
<td>( \times 10^7 ) cm/s</td>
<td>1.0 (1.0)</td>
<td>1.3 (2.1)</td>
<td>1.0 (2.3)</td>
<td>2.0 (2.0)</td>
<td>1.3 (2.1)</td>
</tr>
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Tomás Palacios (tpalacios@mit.edu)
Even higher electron velocities have been measured in the ballistic transport regime:

**GaN**

\[ v_e = 7 \times 10^7 \text{ cm/s} \]

**InN**

\[ v_e = 2 \times 10^8 \text{ cm/s} \]

FIG. 2. Transient electron velocity obtained by solving Eq. (1) numerically for \( v_e \) using the experimental \( \Delta \bar{T}(t)/\Delta \bar{T}(\infty) \) data from Fig. 1 as an input. Wraback et. al., APL 79, 1303 (2001)

FIG. 1. A typical nonequilibrium electron distribution for an InN film grown on GaN. (The electric-field intensity has been estimated from a way similar to Ref. 2.) The photoexcited electron-hole pair density is \( n = 5 \times 10^{11} \text{ cm}^{-3} \). The excitation laser has a pulse width of \( \approx 0.6 \text{ ps} \). The excitation photon energy is \( h\omega_c = 1.92 \text{ eV} \). The cut-off electron velocity is around \( 2 \times 10^8 \text{ cm/s} \).

Tsen et. al., APL 86, 222103 (2005)

Very promising results for mm-wave frequencies and beyond
And at high temperatures?

Materials for High Temperature Electronics Devices

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{\text{maximum}}$ (°C)</th>
<th>$f_c$ (cut-off frequency) (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>300</td>
<td>2</td>
</tr>
<tr>
<td>GaAs</td>
<td>460</td>
<td>8</td>
</tr>
<tr>
<td>GaN</td>
<td>600</td>
<td>8</td>
</tr>
<tr>
<td>AlGaN/GaN</td>
<td>700</td>
<td>20</td>
</tr>
<tr>
<td>SiC</td>
<td>900</td>
<td>10</td>
</tr>
<tr>
<td>Diamond</td>
<td>1100</td>
<td>N/A</td>
</tr>
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* A. Khan, GaN Topical Workshop on GaN, Nagoya 1995

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  – Other applications of polarization

• Dispersion and current collapse

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• Challenges for nitride electronics
Basic Structure of AlGaN/GaN HEMTs

**SiN** | **Gate** | **SiN**
---|---|---
10-30 nm AlGaN barrier (10-40% Al)

1-2 μm GaN buffer

**Nucleation layer**

**Substrate** (SiC, sapphire, Si)

Main differences with GaAs devices...

- **Heteroepitaxy** (no cheap GaN bulk substrate)
- **No doping** needed: electrons induced by *polarization*
- Typical charge densities: $1-2 \times 10^{13}$ cm$^{-2}$ (> 3x higher than in GaAs)
- **Single heterojunction** device (in GaAs: quantum well HEMT)
- Larger conduction band discontinuities
Nitride Technology

Main steps in the fabrication of GaN HEMTs...

- Nitride layers grown by MBE or MOCVD at very high temperatures (800-1050°C)
- Ohmic contacts: Ti/Al/Ni/Au + RTA @ 870°C
- Dry etching with Cl₂ for device isolation (no reliable wet etching in nitrides)
  - Schottky gate contact: Ni, Pt or Au
- Passivation with SiₓNᵧ deposited by PECVD

More complex technologies also exist:

Gate recess, deep-submicron gates (20 nm), implantation for un-annealed ohmics, contact recess and regrowth, Fluorine surface treatment, dielectric sidewall, etc.
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Crystalline structure of GaN

Nitrides: Wurtzite structure

(almost) top view (c-axis) of wurtzite structure

(almost) horizontal view (a-axis) of wurtzite structure

Ga

N

Tomás Palacios (tpalacios@mit.edu)
Crystalline structure of GaN

2 different faces with different properties

Ga-face

N-face

C-Plane {0001}

M-Plane {1100}

A-Plane {1120}

Tomás Palacios (tpalacios@mit.edu)
**Piezoelectric vs Spontaneous polarization**

- High electronegativity of N
- Non centro-symmetric unit cell

Spontaneous and piezoelectric polarization

**Spontaneous polarization**: Intrinsic polarization of relaxed material

**Piezoelectric polarization**: When the material is grown pseudomorphically, the lattice mismatch induces strain in the lattice which deforms the position of the atoms/dipoles changing the total polarization

---

Tomás Palacios (tpalacios@mit.edu)
In a HEMT:

Polarization discontinuities @ interfaces $\rightarrow$ fixed charge densities $\rightarrow$ build-in electric fields $\rightarrow$ 2DEG
Fig. 1. Orientation of the spontaneous and piezoelectric polarization in pseudomorphic grown wurtzite AlGaN/GaN, InGaN/GaN and AlInN/GaN heterostructures with Ga- or N-face polarity. If the polarization induced charge $\sigma$ is positive, a 2DEG can be confined in the layer with the smaller bandgap close to the interface.
Charge control in AlGaN/GaN HEMTs

\[ e\Phi_s(x) - E \times t_b - \Delta E_c(x) + E_0 + (E_F - E_0) = 0 \]

where \( E = e(\sigma_{\pi}(x) - n_{2d})/(\epsilon_0\epsilon(x)) \)

from Gauss' law, and

\[ E_F - E_0 = \frac{\pi \hbar^2}{m^*} n_{2d} \]

\[ E_0(n_s) \approx \left( \frac{9\pi \hbar e^2 n_{2d}}{8\epsilon_0 \epsilon_b(x) \sqrt{8m^*}} \right)^{2/3} \]

from a basic quantum mechanical analysis of the energy levels in a triangular quantum well.

\( \sigma_n(x) \) is the fixed charged due to the polarization of GaN and AlGaN (piezoelectric and spontaneous)
**Fixed Polarization charge**

\[
\sigma_\pi (x) = P_{sp,AlGaN} (x) - P_{sp,GaN} + P_{pe,AlGaN} (x) = \\
= \Delta P_{sp} (x) + 2 \left( e_{31} (x) - e_{33} (x) \frac{c_{13} (x)}{c_{33} (x)} \right) \times \left( \frac{a(x) - a_{GaN}}{a_{GaN}} \right)
\]

Fig. 2. Piezoelectric, \( \sigma/e(P_{PE}) \), dashed lines and total polarization induced sheet charge, \( \sigma/e(P_{SP} + P_{PE}) \), (solid lines) bound at the interfaces of Ga-face AlGaN/GaN, InGaN/GaN and AlInN/GaN heterostructures, versus alloy composition of the top layer. A positive sheet charge and a formation of a 2DEG is predicted for Ga-face AlGaN/GaN and AlInN/GaN \( (x > 0.7) \) heterostructures.

Tomás Palacios (tpalacios@mit.edu)
2DEG density in AlGaN/GaN HEMTs

\[ n_s(V_G) = \frac{Q_{\pi} (\text{net}) \cdot d_{\text{AlGaN}} + \epsilon [V_G - (\phi_b - \Delta E_c/e)]}{eD} \]

In AlGaN/GaN HEMTs, the electron density in the channel is controlled by changing the AlGaN composition and thickness...

Debdeep Jena, PhD
Thesis, UC Santa Barbara

Prof. Jasprit Singh www.eecs.umich.edu/~singh

Tomás Palacios (tpalacios@mit.edu)
Origin of critical thickness

Surface Donors

\[ \Delta P_{SP} + P_{PE} \]

E Field

2DEG

Al\(_x\)Ga\(_{1-x}\)N

GaN

\[ \Delta E_c / \Delta E_g = 85\% \]

\[ \sigma_{pe+sp} = 1.5 \times 10^{13} \text{ e/cm}^2 \]

\[ T = 13 \text{ K} \]

\[ \phi_s = 1.4 \text{ eV} \]

\[ N_s (\text{cm}^{-2}) \]

Al\(_x\)Ga\(_{1-x}\)N

GaN

\[ \Delta E_s \]

\[ E_f \]

\[ \bar{E}_{Ps} \]
Ga- and N-face

In-plane and bulk properties remain the same:
*Polarization* reverses direction with respect to the surface

Top figure taken from M. J. Murphy et al, MRS Internet J. Nitride Semicond. Res. 4S1, G8A(1999)
Ga- and N-face (or polarity)

Many new device structures can be demonstrated by playing with the polarity of GaN
Polarization is a very powerful tool in device engineering...

**Dipole Engineering**

(Use of polarization to arbitrarily change the band diagram by introducing conduction-band discontinuities)
Dipole Engineering

In a \textit{GaN-ultrathin AlN-GaN} structure, the polarization-based electric field in the AlN layer induces a discontinuity (upwards) in the conduction band…

\begin{itemize}
\item \textit{d\textsubscript{AlN} extremely thin:} \( d\textsubscript{AlN} \leq 1 \text{ nm} \)
\item \textit{GaN \ AIN \ GaN}
\item \( \Delta E\textsubscript{c} \)
\item \( \Delta E\textsubscript{p} \)
\item \( \approx \)
\item \( E\textsubscript{p} = 1 \text{ eV in 10 Å of AlN} \)
\end{itemize}

In a similar way, in a \textit{GaN-ultrathin InGaN-GaN} structure…

\begin{itemize}
\item \textit{d\textsubscript{InGaN} extremely thin:} \( d\textsubscript{InGaN} = 1 \text{ nm} \)
\item \textit{GaN \ InGaN \ GaN}
\item \( \Delta E\textsubscript{c} \)
\item \( \Delta E\textsubscript{p} \)
\item \( \approx \)
\item \( E\textsubscript{p} = 0.32 \text{ eV in 10 Å of 20\% InGaN} \)
\end{itemize}

\textit{T. Palacios, et al., Invited talk, 208th Meeting of the Electroc. Soc.}
Dipole Engineering

3 atomic monolayers!!!

20 nm GaN
1 nm AlN
S.I. GaN

20 nm GaN
1 nm InGaN 20%
S.I. GaN

GaN

ΔE_p

E_p = 1 eV in 10 Å of AlN

GaN

ΔE_p

E_p = 0.32 eV in 10 Å of 20% InGaN

New degree of freedom in the device design

Tomás Palacios (tpalacios@mit.edu)
Ultra-thin InGaN layers to increase the electron confinement in GaN HEMTs

In a GaN-ultrathin InGaN-GaN structure, the polarization-based electric field in the InGaN layer induces a discontinuity (downwards) in the conduction band...

\[
\begin{align*}
\text{GaN} & \quad \text{InGaN} & \quad \text{GaN} \\
\Delta E_c & \uparrow & \Delta E_p & \downarrow \\
\Delta E_c & \downarrow & \Delta E_p & \uparrow \\
\end{align*}
\]

\[\Delta E_p = 0.17 \text{ eV in 10 Å of 10\% InGaN} \]
\[0.32 \text{ eV in 10 Å of 20\% InGaN} \]

When we apply this idea to an AlGaN/GaN HEMT...

T. Palacios et al., Electron Dev. Letts. Vol. 27, 13
Std. HEMT vs InGaN back-barrier: *Improvement in the pinch-off*

**InGaN back-barrier → Better 2DEG confinement → Excellent pinch-off**
(even at $V_{DS}>50$ V and $L_G < 200$ nm)
AlGaN/AlN/GaN HEMTs

L. Shen' PhD Thesis, UCSB
Another application of Polarization: PolFETs…

A **2DEG** is formed to screen the positive sheet charge at the AlGaN/GaN interface.

A **bulk electron gas** is formed to screen the positive polarization charge in the graded AlGaN layer.

Another application of Polarization: PolFETs…

PolFET
CV Profiling:
Charge \(\sim 1.6\times10^{18} \text{ cm}^{-3}\)
Hall Measurements:
Mobility=800 cm\(^2\)/V.s

The mobility is higher than an impurity-doped channel with similar channel charge.

Limited mainly by optical phonon and alloy scattering at room temperature.

Experiment: CV Profiling
Simulation: BandEng\(^1\)

\(^1\) Michael Grundmann, BandEng Alpha Version
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Current collapse in nitride HEMTs

Under pulsed conditions:
- Maximum current decreases
- Knee voltage increases

RF power << Expected power
Origin of Current collapse

-During pinch-off (diagram 1) some electrons move from the gate to surface traps in the drain access region.

-When the channel is open (diagram 2), the electrons slowly move back to the gate → some surface traps are still negatively charged.

-The negatively charged surface traps are the origin of a "virtual gate extension" which reduces the charge in the channel and increases the resistance, reducing maximum current and increasing knee voltage.

-Given enough time (diagram 3, or DC measurement), the traps discharge and the transistor shows its intrinsic performance.

Tomás Palacios (tpalacios@mit.edu)
Solutions to current collapse…

Solution 1: *SiN passivation*

SiN by PECVD or sputtering can eliminate current collapse / dispersion

Actual mechanism still unclear.

Solution 2: *Improved sample structure*

*Original problem:* charged surface traps deplete electrons in 2DEG channel

*Solution:* Increase the distance between the surface traps (i.e. surface) and the channel to reduce their effect on the 2DEG

---

**Diagram:**

- Source: SiN
- Gate: 10-30 nm AlGaN barrier (10-40% Al)
- Drain: 1-2 μm GaN buffer
- Nucleation layer
- Substrate (SiC, sapphire, Si)

**Graph:**

- **X-axis:** Thickness of GaN cap (nm)
- **Y-axis:** Pinch-off Voltage (V)

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Output Power vs Year

Field-plated

<table>
<thead>
<tr>
<th>Field-plated</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early work</td>
<td>1996</td>
</tr>
<tr>
<td>UCSB MOCVD</td>
<td>1998</td>
</tr>
<tr>
<td>UCSB MBE</td>
<td>2000</td>
</tr>
<tr>
<td>Cree</td>
<td>2002</td>
</tr>
<tr>
<td>Cornell</td>
<td>2004</td>
</tr>
<tr>
<td></td>
<td>2006</td>
</tr>
</tbody>
</table>
Figure 10.18: Record power densities have been achieved by employing field plates in Al-GaN/GaN technology. Shown here are power measurements taken at 4 GHz of a 246 μm wide device biased at $V_{DS} = 120$ V. The maximum output power density $P_{out} = 32.2$ W/mm with a PAE of 54.8%. Figure courtesy of Y.-F. Wu, Cree Inc.
GaN HEMTs at mm-wave frequencies

Record performance in deep-submicron HEMTs: ($L_g = 90$ nm)

- $f_T = 163$ GHz
- $f_{\text{max}} = 185$ GHz

While keeping:
- $I_{\text{DS}} = 1.3$ A/mm
- $V_{\text{bk}} > 60$ V

T. Palacios et al., Proc. IEDM 2005. Late news.

Tomás Palacios (tpalacios@mit.edu)
Power measurements @ 40 GHz

High $f_T$ and $f_{\text{max}}$
- $I_{ds} = 1.3$ A/mm
- $V_{bk} > 60$ V
- No dispersion

Very high output power

\[ P_{\text{out}} > 10.5 \text{ W/mm with 33\% PAE and Gain } = 6 \text{ dB } @ 40 \text{ GHz} \]

In Ge-spacer technology (lower $C_{GD}$) … Gain = 9.5 dB @ 40 GHz

T. Palacios et al, Electron Dev. Letts. vol 26, 781

Tomás Palacios (tpalacios@mit.edu)
High Frequency Performance

Previous devices: $f_{\text{max}} = 150-185$ GHz

*In unpassivated samples, we can get even higher $f_{\text{max}}$ performance…*

If $L_g = 100$ nm:

$f_T = 153$ GHz

$f_{\text{max}} = 230$ GHz

Unpassivated devices

Gain (dB)

Frequency (GHz)

Gain (dB)

Frequency (GHz)

T. Palacios et al., Electron Dev. Letts. vol. 27, 13
We need to develop high voltage switches to allow compact energy-efficient electric systems.

Two main requirements:
- Very high breakdown voltage
- Ultra low resistances

AlGaN/GaN HEMTs are an excellent option for power devices.
High power devices

Tomás Palacios (tpalacios@mit.edu)
Main problem: Breakdown voltage due to high peak electric field
Solution: To spread out the electric field by using field plate technology
NOTE: Field plates in conventional (non power) GaN HEMTs have significantly improved the performance of these devices by also reducing dispersion.
Figure 5.9: The breakdown voltage versus $L_{gd}$ measured with and without Fluorinert at various process steps. $L_{sg}=1\mu m$; $L_g=1\mu m$; $W_g=200\mu m$. 
Outline

• Introduction
  – Main material properties
  – Optoelectronic devices
  – Why do we need a new kind of transistor?
• Basic structure of AlGaN/GaN HEMTs
  – Main differences with other technologies
  – Nitride technology
• Polarization
  – Origin of polarization
  – Ga-face vs N-face
  – Calculation of charge density
  – Other applications of polarization
• Dispersion and current collapse
• State of the art in GaN HEMTs
• Challenges for nitride electronics
Although GaN reliability is still a very important issue, some companies (i.e CREE and Eudyna) are already selling these transistors with excellent initial results.
Other important challenges...

- P-type channel
- Access resistances
- Higher frequencies
- Vertical power devices
- Wafer size / price
- New applications:
  - High temperature electronics
  - Transistor-based sensors
Summary: Nitride transistors

Unique properties + Advanced Technology + Unprecedented flexibility = NEW REVOLUTIONARY DEVICES

Very exciting future where new materials and devices solve problems in high frequency, energy and bio-electronics