III-Nitride HFETs

Topic objectives:
1. Why III-Nitride HFETs?
2. Key features of III-Nitride HFET physics
1. Why III-Nitride HFETs?

III-Nitride HFETs are advantageous for high-power, high-frequency, high-temperature, harsh environment applications.

These advantages come from

(i) fundamental GaN material properties and
(ii) unique properties of AlGaN/GaN interface
Breakdown Voltage

<table>
<thead>
<tr>
<th>Material</th>
<th>Breakdown field, MV/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1</td>
</tr>
<tr>
<td>GaAs</td>
<td>2</td>
</tr>
<tr>
<td>SiC</td>
<td>5</td>
</tr>
<tr>
<td>GaN</td>
<td>3</td>
</tr>
</tbody>
</table>
Electron velocity

![Graph showing electron velocity versus electric field for GaN and GaAs at different temperatures.](image)
# Thermal properties and bandgaps

<table>
<thead>
<tr>
<th>Material</th>
<th>Lattice constant (Angstroms) at 300 K</th>
<th>Thermal Conductivity W/cm-K at 300 K</th>
<th>Thermal expansion coefficient (10^{-6} 1/K) at 300 K</th>
<th>Bandgap (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN</td>
<td>a = 3.188 c = 5.185</td>
<td>2.0</td>
<td>3.1 (ave. 300 to 3.5 800 K)</td>
<td>3.39</td>
</tr>
<tr>
<td>AlN</td>
<td>a = 3.112 c = 4.982</td>
<td>3.2 (c-axis)</td>
<td>2.30</td>
<td>6.2</td>
</tr>
<tr>
<td>6H SiC</td>
<td>a = 3.081 c = 15.117</td>
<td>4.9 (a-axis)</td>
<td>2.9</td>
<td>3.03</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>a = 3.080 c = 10.082</td>
<td>~3.7</td>
<td>~2.8</td>
<td>3.26</td>
</tr>
<tr>
<td>Sapphire</td>
<td>a = 4.765 c = 13.001</td>
<td>0.35 (c-axis)</td>
<td>5.9</td>
<td>9.9</td>
</tr>
<tr>
<td>Si</td>
<td>a = 5.4301</td>
<td>1.56</td>
<td>2.57</td>
<td>1.1</td>
</tr>
<tr>
<td>GaAs</td>
<td>a = 5.6533</td>
<td>0.54</td>
<td>5.8</td>
<td>1.42</td>
</tr>
</tbody>
</table>
Significance of the bandgap offset in HFETs

Consider maximum electron density in the 2D channel

\[ V_T \approx \phi_b - \frac{qN_d d_i^2}{2\varepsilon_i} - \Delta E_c / q \]

\[ n_S = \left( \frac{C_1}{q} \right) \times (V_G - V_T) = \left( \frac{C_1}{q} \right) \times V_{GT} \]

Maximum electron density in the 2D channel can be achieved at \( V_G = \phi_b \), or \( V_{GT} = \phi_b - V_T \)

\[ n_{SMAX} = \frac{C_1}{q} \left( \frac{qN_d d_i^2}{2\varepsilon_i} + \frac{\Delta E_c}{q} \right) \]
Maximum 2DEG sheet density in HFETs

\[ n_{\text{SMAX}} = \frac{C_1}{q} \left( \frac{qN_d d_i^2}{2\varepsilon_i} + \frac{\Delta E_c}{q} \right) \]

Note, for charge neutrality, \( n_{\text{SMAX}} = N_d d \);

\[ n_{\text{SMAX}} = \frac{C_1 n_{\text{SMAX}} d}{2\varepsilon_i} + C_1 \frac{\Delta E_c}{q^2} \]

Note, \( C_1 = \varepsilon_i / d \), or \( C_1 \frac{d}{\varepsilon_i} = 1 \)

\[ n_{\text{SMAX}} = \frac{n_{\text{SMAX}}}{2} + C_1 \frac{\Delta E_c}{q^2} \quad \Rightarrow \quad n_{\text{SMAX}} = 2C_1 \frac{\Delta E_c}{q^2} \]
Maximum 2DEG sheet density in HFETs

Maximal \( n_S \) increases with \( \Delta E_C \):

\[
\nonumber n_{SMAX} = 2C_1 \frac{\Delta E_C}{q^2}
\]

Conduction band discontinuity:

Example:

\( \Delta E_C = 1 \text{ eV} \) (AlGaN/GaN)
\( d = 200 \text{ A} \)
\( \varepsilon_i = 10 \varepsilon_0 \)

Estimate \( n_{SMAX} \)

\( n_{SMAX} \approx 5 \times 10^{12} \text{ cm}^{-2} \)

For AlGaAs/GaAs:

\( \Delta E_C < 0.3 \text{ eV} \)

\( n_{SMAX} \approx 1.5 \times 10^{12} \text{ cm}^{-2} \)
Polarization Charges in III-N HFETs
Polarization Charges in III-N HFETs

Polarization-induced sheet charge density,

\[ \sigma_{pol}/e = \frac{(-2[e_{31} - (c_{13}/c_{33}) e_{33}](a_{\text{GaN}}/a_{\text{AlN}} - 1)x + P_{sp,z}^{\text{GaN}} - P_{sp,z}^{\text{AlGaN}})}{e} \]

Piezo-polarization

Spontaneous polarization

Using typical elastic constants and polarization coefficients for AlGaN, an approximate expression for \( \sigma_{pol} \) can be obtained:

\[ \sigma_{pol} \approx (5 - 6.5) \times 10^{13} x \text{ e/cm}^2 \]

The equivalent sheet charge density,

\[ (\sigma_{pol}/q) = (5 - 6.5) \times 10^{13} \times x, \text{ cm}^2 \]

Example: for \( x = 0.25 \) (Al\(_{0.25}\)Ga\(_{0.75}\)N barrier layer)

\[ (\sigma_{pol}/q) \approx 5 \times 10^{13} \times 0.25 = 1.25 \times 10^{13} \text{ cm}^2 \]

This density is equivalent to an additional doping of \( 1.25 \times 10^{13} \text{ cm}^2 \)
Polarization Charges under the gate in III-N HFETs

(a) Schematic diagram of the epitaxial layer structure and device geometry for an AlGaN/GaN HFET.
(b) Electrostatic charge distribution;
(c) Schematic energy-band diagram in the Schottky gate region.
Polarization Charges in III-N HFETs: free surface

Polarization charges at the AlGaN/GaN interface.
Left: actual charge distribution.

Right: simplified picture
The threshold voltage and 2D electron density in III-N HFETs

For the conventional HFET (no polarization), the voltage balance equation was

\[ V_G = \varphi_B - \frac{\Delta E_C}{q} - V_N + \frac{\Delta E_f}{q} \]

where \( V_N = \frac{qN_dd_i^2}{2\varepsilon_i} \)

To account for polarization charges, the expression for \( V_N \) should be replaced with

\[ V_{NP} = \frac{qN_dd_i^2}{2\varepsilon_i} + \frac{\sigma_p d_i}{\varepsilon_i} \]

The threshold voltage corresponds to the Fermi level close to the bottom of the conductance band (\( \Delta E_f = 0 \)). Therefore, for III-N HFET

\[ V_T \approx \varphi_b - \frac{qN_dd_i^2}{2\varepsilon_i} - \frac{\sigma_p d_i}{\varepsilon_i} - \Delta E_c / q \]
The threshold voltage and 2D electron density in III-N HFETs

\[ V_T \approx \phi_b - \frac{qN_d d_i^2}{2\varepsilon_i} - \frac{\sigma_p d_i}{\varepsilon_i} - \Delta E_c / q \]

The additional voltage shift due to polarization,

\[ \Delta V_T \approx -\frac{\sigma_p d_i}{\varepsilon_i} \]

Example:
\[ \sigma_p = 1.25 \times 10^{13} \text{ cm}^{-2} \times q = \]
\[ = 1.25 \times 10^{13} \text{ cm}^{-2} \times 1.6 \times 10^{-19} \text{ C} = 2 \times 10^{-6} \text{ C/cm}^2 \]

Let \( d_i = 200 \text{ A} = 200 \times 10^{-8} \text{ cm} \)
\[ \varepsilon_i = 10 \varepsilon_0 \]
\[ \Delta V_T = 5 \text{ V} \]

This threshold voltage can be obtained even if \( N_D = 0 \), i.e. there is no doping
Maximum 2DEG sheet density in III-N HFETs

For regular HFETs, we found

\[ n_{SMAX} = \frac{C_1}{q} \cdot \left( \frac{q N_d d_i^2}{2 \varepsilon_i} + \frac{\Delta E_c}{q} \right) \]

For III-N HFETs, the charge neutrality condition should be modified:

\[ n_{SMAX} = N_d d + \frac{\sigma_p}{q} \]

From the previous example, for \( x = 0.25 \) (Al\(_{0.25}\)Ga\(_{0.75}\)N barrier layer)

\( (\sigma_p/q) \approx 5 \times 10^{13} \times 0.25 = 1.25 \times 10^{13} \text{ cm}^{-2} \)

Therefore, even for UNDOPED barrier, the sheet carrier density in the III-N HFET channel can be as high as

\[ n_{SMAX} = 1.25 \times 10^{13} \text{ cm}^{-2} \]
Polarization Charges in III-N HFETs

Simulated dependencies of $n_s(d)$ for the AlGaN/GaN HFET
Polarization Charges in III-N HFETs

Experimental dependencies for the AlGaN/GaN HFETs with d=300 Å (dashed lines show the theoretical contributions of spontaneous and piezo polarizations)
Maximum achievable 2D concentration in III-N HFETs

Fermi level (counted from the bottom of the conduction band) versus sheet electron concentration at the Al$_{0.2}$Ga$_{0.8}$N-GaN (solid line) and Al$_{0.2}$Ga$_{0.8}$As-GaAs (dotted line) interfaces. Horizontal dashed lines show the positions of the corresponding conduction band discontinuity.

When the sheet electron density in AlGaN-GaN heterostructures exceeds the critical value, the electrons spill from the quantum well near the heterointerface and occupy the de-localized states in the channel.