From MOSFETs to MISHEMTs - an evolution

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Organization

• How do we get high speed in circuits?
• MOSFETs
  – How do we get higher speed?
  – Limitations
• GaAs MESFETs
  – Advantages and limitations
• HEMTs
  – Why HEMTs?
  – AlGaAs/GaAs vs pseudomorphic vs GaN
  – Technology
  – Modeling
How do we get high speed?

\[ \Delta Q = C \Delta V = I t_d \Rightarrow t_d = \frac{C \Delta V}{I} \]

\( t_d \Rightarrow \text{Delay} \)

- To decrease delay
  - Decrease \( C \) \( \Rightarrow \) reduce device dimensions
  - Decrease \( \Delta V \) \( \Rightarrow \) reduce power supply voltage
  - Increase \( I \) \( \Rightarrow \) For a smaller \( \Delta V \), we expect higher \( I \) 
    \( \Rightarrow \) increase device conductance
MOSFETs – how do we get high speed?

\[ C = C_{ox} WL = \frac{\varepsilon_{ox}}{t_{ox}} WL \]
\[ I_{D_{sat}} = \frac{W}{2L} \mu_n C_{ox} (V_{GS} - V_{th})^2 \]
\[ g_m = \frac{\partial I_{D_{sat}}}{\partial V_{GS}} = \frac{W}{L} \mu_n C_{ox} (V_{GS} - V_{th}) \]

\[ t_d = \frac{C \Delta V}{I} = \frac{2L^2}{\mu_n (V_{GS} - V_{th})} = \frac{2C}{g_m} \]

- To reduce \( t_d \)
  - Reduce \( L \) ⇒ Use the smallest gate length possible
  - Increase \( \mu_n \) ⇒ Use a material with high carrier mobility
    - Not completely true: \( \mu_n \) degrades at high lateral electric field
    - Also need high \( v_{sat} \)
  - Increase \( (V_{GS} - V_{th}) \) ⇒ Higher power dissipation
    - Not completely true: \( \mu_n \) degrades at high \( (V_{GS} - V_{th}) \)
- \( W \) and \( t_{ox} \) has no effect on \( t_d \) !!
MOSFETs – for analog applications

\[ A_I = \frac{g_m}{j \omega C_{GS}} \Rightarrow f_T = \frac{g_m}{2\pi C_{GS}} = \frac{3\mu_n (V_{GS} - V_{th})}{4\pi L^2} \]

\[ A_V = \frac{g_m}{g_d + g_L} = \frac{W\mu_n C_{ox} (V_{GS} - V_{th})}{L(g_d + g_L)} \]

• We need high transconductance \((g_m)\)

• For high \(g_m\)
  – \(C_{ox}\) should be high \(\Rightarrow t_{ox}\) should be low
    • Gate should be as close as possible to the channel
    • More charges for same change in input voltage
  – \(\mu_n\) (and \(v_{sat}\) for small geometry devices) should be high
    • Charges travel faster for same drain field resulting in higher current
MOSFETs – present generation

• For any technology node
  – Channel length is as small as possible
  – Power supply voltage and oxide thickness dictated by scaling laws
  – Channel width is adjustable
  – $I_{D\text{max}}/W$ is an important figure of merit (captures mobility degradation at high fields)

• 14 nm node
  – FinFET technology
  – Gate length = 20 nm
  – Equivalent oxide thickness (EOT) = 0.9 nm
    • Almost reached its limit
  – $V_{DD} = 0.7$ V
  – $I_{D\text{max}}/W \approx 1\text{mA}/\mu\text{m} = 1\text{A/mm}$

• To improve performance, need to go for other materials with higher carrier mobility
  – Germanium?
  – GaAs?
GaAs vs Silicon

- **Advantages**
  - Electron mobility is more than 5 times than in silicon
    - Saturation velocity almost same as silicon
  - Higher bandgap (1.42 eV compared to 1.1 eV)
    - Higher temperature of operation
    - Possibility of semi-insulating substrate

- **Disadvantages**
  - No native oxide
  - High interface states
    - Cannot make MOSFET

- Suitable for MESFET (Metal-Semiconductor FET)
  - Use a Schottky metal-semiconductor junction as gate
• Normally ON device
• Uses a Schottky barrier gate to control current
  – conducts when gate voltage is positive
• As $V_{GS}$ is made more negative, depletion layer width in n-GaAs increases to switch off device
Schottky Metal-Semiconductor Junction

- Rectifying in nature
- p-n junction like I-V characteristics
- The depletion region in n-region increases with increasing reverse bias

\[ W = \sqrt{\frac{2\varepsilon(V_{bi} + V_R)}{qN_D}} \]
Ohmic Metal-Semiconductor Junction

\[ \phi_m < \phi_s \]

- No potential barrier
- Conducts almost equally for both forward and reverse bias
- Depending on the work-function of the metal, the metal-semiconductor junction will be either ohmic or Schottky type
- A junction between metal and heavily doped semiconductor is usually ohmic
MESFET characteristics

- For high drain current/transconductance
  - Electron concentration in channel must be high
    - $N_D$ must be high
  - Electron mobility ($\mu_n$) must be high
    - $\mu_n$ degrades at high $N_D$ due to ionized impurity scattering
      \[ \Rightarrow \text{limits maximum possible } N_D \]
- Physical separation of electrons and ionized donors preferred
  - Can be achieved with heterojunction

\[ I_D = A(x) q n v_d(x) \]
\[ = \left[ a - W_d(x) \right] W q N_D \nu_d(x) \]
Band diagram for AlGaAs/GaAs heterojunctions

\[ \Delta E_g = \Delta E_C + \Delta E_V \]

\[ \Delta E_C = \chi_2 - \chi_1 \]
A heterojunction (AlGaAs/GaAs) is the heart of the device

- The n<sup>+</sup> AlGaAs layer is depleted
- The channel is created in a thin layer at the undoped GaAs surface
  - The high concentration of electrons in the thin layer is referred to as 2-Dimensional Electron Gas (2-DEG)
- The electrons in 2-DEG have very high mobility as ionized impurity scattering is eliminated
- Hence these transistors are referred to as High Electron Mobility Transistor (HEMT)
MOSFET -> MESFET -> HEMT

MOSFET
MOSFET -> MESFET -> HEMT

MESFET

Drain

n^+

n^+

Si-Substrate

Source

Gate

Depletion region

E_F

E_C

V_G

qV_G

E_F

E_C
HEMT

MOSFET -> MESFET -> HEMT
Similarities between HEMT and MOSFET

- Charges formed in a quantum well in conduction band at interface between narrow bandgap and wide bandgap material.
Al$_x$Ga$_{1-x}$As/GaAs heterojunction

- Lattice matched for all values of Aluminium mole fraction ($x$)
  - Usually limited to $x < 0.3$ due to introduction of defects resulting in DX centres in the bandgap
- Bandgap of Al$_x$Ga$_{1-x}$As: $1.424 + 1.247x$ eV
- Type 1 band alignment with $\Delta E_C = 0.79x$ eV
Variation of sheet charge concentration with gate bias

- The maximum value of \( n_s \) for Al\(_{0.3}\)Ga\(_{0.7}\)As/GaAs
  - limited to \( 1.4 \times 10^{12} / \text{cm}^2 \)
  - depends on \( \Delta E_C \)
- Why not use other heterojunctions to get higher \( \Delta E_C \)?
Pseudomorphic HEMT

- It is possible to grow good quality heterostructures from materials with different lattice constants, provided the thickness of the grown layer does not exceed a certain critical value $t_c$.
- If the grown layer is thinner than $t_c$, its crystalline structure accommodates to that of the substrate material. → A lattice deformation in the grown layer (pseudomorphic layer)
- Pseudomorphic AlGaAs/InGaAs/GaAs heterostructures with In contents in the range of 15-25% were successfully grown on GaAs substrates and used in pseudomorphic HEMTs.
**AlGaAs/InGaAs/GaAs Pseudomorphic HEMT**

- **Compared to AlGaAs/GaAs HEMT**
  - Larger $\Delta E_C \Rightarrow$ larger $n_s \Rightarrow$ larger $g_m$
  - Larger $\mu_n \Rightarrow$ larger $g_m$
### Properties of different heterojunctions

<table>
<thead>
<tr>
<th>Heterojunction type</th>
<th>$\Delta E_G$, eV</th>
<th>$\Delta E_C$, eV</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}<em>{0.3}\text{Ga}</em>{0.7}\text{As}/\text{GaAs}$ (lm)*</td>
<td>0.38</td>
<td>0.22</td>
<td>GaAs</td>
</tr>
<tr>
<td>$\text{Al}<em>{0.3}\text{Ga}</em>{0.7}\text{As}/\text{In}<em>{0.2}\text{Ga}</em>{0.8}\text{As}$ (pm)</td>
<td>0.582</td>
<td>0.407</td>
<td>GaAs</td>
</tr>
<tr>
<td>$\text{In}<em>{0.52}\text{Al}</em>{0.48}\text{As}/\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}$ (lm)</td>
<td>0.714</td>
<td>0.52</td>
<td>InP</td>
</tr>
<tr>
<td>$\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}/\text{InP}$ (lm)</td>
<td>0.616</td>
<td>0.271</td>
<td>InP</td>
</tr>
<tr>
<td>$\text{In}<em>{0.52}\text{Al}</em>{0.48}\text{As}/\text{In}<em>{0.65}\text{Ga}</em>{0.35}\text{As}$ (pm)</td>
<td>0.768</td>
<td>0.660</td>
<td>InP</td>
</tr>
</tbody>
</table>

* Lattice matched and pseudomorphic heterojunctions are denoted lm and pm, respectively.

### 2DEG mobilities and electron sheet concentrations in HEMTs

<table>
<thead>
<tr>
<th>Heterojunction type</th>
<th>$\mu_0$, cm²/Vs</th>
<th>$n_s$, cm⁻²</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}<em>{0.3}\text{Ga}</em>{0.7}\text{As}/\text{GaAs}$ (lm)</td>
<td>5400</td>
<td>$1.4 \times 10^{12}$</td>
<td>GaAs</td>
</tr>
<tr>
<td>$\text{Al}<em>{0.25}\text{Ga}</em>{0.75}\text{As}/\text{In}<em>{0.15}\text{Ga}</em>{0.85}\text{As}$ (pm)</td>
<td>6400</td>
<td>$2.2 \times 10^{12}$</td>
<td>GaAs</td>
</tr>
<tr>
<td>$\text{Al}<em>{0.25}\text{Ga}</em>{0.75}\text{As}/\text{In}<em>{0.22}\text{Ga}</em>{0.78}\text{As}$ (pm)</td>
<td>5300</td>
<td>$3.5 \times 10^{12}$</td>
<td>GaAs</td>
</tr>
<tr>
<td>$\text{In}<em>{0.52}\text{Al}</em>{0.58}\text{As}/\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}$ (lm)</td>
<td>10000</td>
<td>$3.0 \times 10^{12}$</td>
<td>InP</td>
</tr>
<tr>
<td>$\text{In}<em>{0.52}\text{Al}</em>{0.48}\text{As}/\text{In}<em>{0.8}\text{Ga}</em>{0.2}\text{As}$ (pm)</td>
<td>12700</td>
<td>$3.6 \times 10^{12}$</td>
<td>InP</td>
</tr>
<tr>
<td>$\text{In}<em>{0.35}\text{Al}</em>{0.65}\text{As}/\text{In}<em>{0.65}\text{Ga}</em>{0.35}\text{As}$ (pm)</td>
<td>15000</td>
<td>$4.6 \times 10^{12}$</td>
<td>InP</td>
</tr>
</tbody>
</table>
Advantages of GaN over GaAs

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>4H-SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ (eV)</td>
<td>1.1</td>
<td>1.42</td>
<td>3.26</td>
<td>3.4</td>
</tr>
<tr>
<td>$E_{br}$ (MV/cm)</td>
<td>0.3</td>
<td>0.4</td>
<td>3.0</td>
<td>3.3</td>
</tr>
<tr>
<td>$\mu_n$ (cm$^2$/V s)</td>
<td>1350</td>
<td>8500</td>
<td>700</td>
<td>2000</td>
</tr>
<tr>
<td>$V_{sat}$ ($10^7$ cm/s)</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

- Higher $E_g$ ⇒ operation at higher temperature
- Higher $E_{br}$ ⇒ Higher breakdown voltage
- Higher $\mu_n$ ⇒ Higher saturation currents
- AlGaN/GaN system ⇒ attractive for HEMT devices
- For Al$_{0.3}$Ga$_{0.7}$N/GaN
  - $\Delta E_G \approx 0.84$ eV compared to 0.37 eV for Al$_{0.3}$Ga$_{0.7}$As/GaAs
  - $\Delta E_C \approx 0.42$ eV compared to 0.22 eV for Al$_{0.3}$Ga$_{0.7}$As/GaAs
GaN based devices! Why?

Adapted from Ph.D thesis of Behat Tridel, Technischen Universität Berlin, 2012.
GaN based devices! Why?

Adapted from Dr. Palacios, Associate Professor, Dept. of Electrical Engg. and Comp. Sci., MIT.
GaN based HEMTs: status

- AlGaN/GaN based HEMTs replacing Si-based devices for power amplifier and power switching applications
  - wide signal bandwidth, multiband power amplifier, higher efficiency, higher breakdown voltage, low $R_{on}$, reduced size and weight

- GaN-based multiband power amplifiers in production for both commercial and defense purpose
  Leading players: Cree, Analog devices, Infineon, RFMD

- High efficiency GaN-based power devices (600 V) are already commercially available
  Leading players: Panasonic, Infineon, Transphorm

- Besides AlGaN/GaN, AlInN/GaN and AlN/GaN based HEMTs are also emerging
  - thinner barrier layer, higher 2DEG, stable contacts, higher reliability
Polarization effect in GaN

Ideal Tetrahedron

Tetrahedron in GaN Wurtzite structure

GaN

P_{sp}

AlGaN

P_{PE}
Polarization effect in AlGaN/GaN HEMT

\[ q\sigma = (P_{SP} + P_{PE})_{AlGaN} - (P_{SP})_{GaN} \]

\[ \sigma \approx 1 - 1.5 \times 10^{13} \text{ cm}^{-2} \]

\[ n_s \approx 7 - 8 \times 10^{12} \text{ cm}^{-2} \]

\[ E = \frac{q(\sigma - n_s)}{\varepsilon} \]

\[ E \approx \begin{cases} 1 \text{ MV/cm at } V_G = 0 \text{ V} \\ 2.5 \text{ MV/cm at } V_G = V_{Th} \end{cases} \]
HEMT operation

$V_{Th}$ can be extracted from $(I_D)^{0.5}$ vs. $V_{GS}$ curve
AlGaN/GaN HEMT devices

- High Polarization induced 2DEG – High Current Density
- High Breakdown Electric Field – High Drain Bias
- High Peak Electron Velocity – High Speed/Frequency Operation
- Output Power Density $P_{out} > 10W/mm$ (in C – Band)*
- Current Gain Cutoff Frequency, $f_t > 100$ GHz#

AlGaN/GaN HEMTs have proven its high frequency and high power operation capability


Negative voltage applied to turn-off the device increases the electric field across the barrier.

Increased electric field increases the tensile strain in the barrier → structural breakdown.

Al$_{0.83}$In$_{0.17}$N/GaN HEMT devices

- Al$_{0.83}$In$_{0.17}$N is lattice matched to GaN – Stress free barrier layer
- Band gap about 4.6 eV for 83% Al mole fraction
- Difference in spontaneous polarization is close to 2-3 times higher than that for AlGaN with 30% Al mole fraction
- Higher conduction band offset (1 eV)

*F. Medjdoub et al., The open electrical and electronic journal., vol. 2, pp. 1–7, 2008.*
## Comparison with AlGaN/GaN HEMTs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\text{Al}<em>{0.3}\text{Ga}</em>{0.7}\text{N}/\text{GaN}$ (30nm)</th>
<th>$\text{Al}<em>{0.83}\text{In}</em>{0.17}\text{N}/\text{GaN}$ (10 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2DEG concentration (cm$^{-2}$)</td>
<td>$\sim 1.5 \times 10^{13}$</td>
<td>$2.5 \times 10^{13}$</td>
</tr>
<tr>
<td>2DEG mobility (cm$^2$V$^{-1}$s$^{-1}$)</td>
<td>$\sim 2000$</td>
<td>$\sim 1200$</td>
</tr>
<tr>
<td>Conduction band offset (eV)</td>
<td>0.42</td>
<td>1</td>
</tr>
<tr>
<td>Barrier band-gap (eV)</td>
<td>4.03</td>
<td>4.6</td>
</tr>
<tr>
<td>Surface potential (eV)</td>
<td>$\sim 1.5$</td>
<td>$\sim 0.5$</td>
</tr>
</tbody>
</table>

- Lower surface potential $\Rightarrow$ Thinner barrier $\Rightarrow$ Higher $g_m$
- (Little) Additional tensile strain
  - $\Rightarrow$ Enhanced carrier concentration
- Demonstrated excellent thermal stability
**Al$_{0.83}$In$_{0.17}$N/GaN AlN/GaN: Why?**

a) Al$_{0.83}$In$_{0.17}$N is lattice matched to GaN
   - stress free barrier layer
   - No/less inverse piezoelectric effect

b) Stable ohmic contact up to 900°C
   - higher temperature operation

AlInN/GaN and AlN/GaN also enjoys:

c) Higher spontaneous polarization than conventional AlGaN
   - higher 2DEG density (>10$^{13}$ cm$^{-3}$)

d) Thinner barrier layer
   - better gate control
   - higher $I_d$, $g_m$, $f_T$

e) Higher conduction band offset
   - better 2DEG confinement
\textbf{Al}_{0.83}\text{In}_{0.17}N/GaN AlN/GaN HEMTs: Gate leakage issues}

Schottky barrier gate in HEMTs

- High gate leakage
- Increased off-power dissipation
- Limited positive gate voltage swing
- Low current drive

These issues are more severe in AlInN and AlN compared to AlGaN

- Due to higher polarization charge hence, higher electric field
- Higher gate leakage current due to FN tunneling


\textbf{Solution: MIS-HEMTs}
GaN based MIS-HEMTs

- Gate dielectrics tried: Al$_2$O$_3$, HfO$_2$, TiO$_2$, SiO$_2$, SiN$_x$
- Al$_2$O$_3$ found to be very promising
  - techniques: ALD, MOCVD, thermal oxidation of Al
- MIS-HEMT characteristics:
  - significant decrease in gate leakage
  - higher gate over-drive
  - negative shift in $V_{Th}$ compared to HEMT
- This negative shift is not only due to reduced gate capacitance, but due to large positive charge density ($>10^{13}$ cm$^{-2}$) at oxide/AlGaN interface*
- Ga-O or Al-O bond at the interface is reported to be responsible for this positive interface charge*

Enhancement mode devices – Why?

- simplifies circuit design - only positive power supply required
- no/insignificant off-state leakage current ⇒ reduced power loss ⇒ increased efficiency ⇒ smaller heat sink (compact size, reduced cost)
- fail safe operation (device remains in OFF state, even if gate supply fails)
- complementary FET based logic applications

Earlier attempts

F-ion implantation, gate recessing, p-(Al)GaN cap layer have several reliability and process related issues:

- stability of $V_{Th}$ (over temperature, time, $V_G$ swing)
- control of positive interface charge or donor states – more negative $V_{Th}$
- limited positive $V_{Th}$
MIS-HEMTs using RIS-Al$_2$O$_3$

Reactive-Ion-Sputtered (RIS) Al$_2$O$_3$ has been reported to have stable negative fixed oxide charge in it ➔ may be useful for reducing interfacial positive charge

• Room temperature deposited oxide is self-aligned with gate metal
• Ohmic contact resistance 1.1 Ω. mm (Ti/Al/Ni/Au 780°C) *Feb. 2014
• L$_g$ = 4 µm, L$_{sd}$ = 30 µm, L$_{gd}$ = 20 µm (Gen-1 devices) *Feb. 2014
MIS-HEMTs using RIS-\(\text{Al}_2\text{O}_3\)

**Deposited RIS-\(\text{Al}_2\text{O}_3\)**

- XPS analysis confirms the formation of \(\text{Al}_2\text{O}_3\)
- Slow deposition rate (\(~1\) nm/min) better \(t_{\text{ox}}\) control
- Room temp. deposition
  1. Self-alignment of insulator and gate metal
  2. More useful for recessed-gate MIS-HEMT

**Comparison of gate leakage:**

Significant reduction of leakage current with 7 nm of \(\text{Al}_2\text{O}_3\)

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Transfer characteristics

- **HEMT** \( V_{\text{Th}} = -7 \text{ V} \)
- **MIS-HEMT** \( V_{\text{Th}} = -5.5 \text{ V} \)
  - positive shift in \( V_{\text{Th}} \)
- same \( I_D \) for same \( (V_{\text{GS}}-V_{\text{Th}}) \)
- low \( I_D-V_{\text{GS}} \) hysteresis – less trapping
- \( I_{\text{on}}/I_{\text{off}} \) ratio improves by \( \sim 10^2 \) times
- increase in \( g_m \) for MIS-HEMT
  - due to increase in channel mobility

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Reason for positive shift in $V_{Th}$

1st level modelling of $V_{Th}$:

$$V_{Th_{-HMT}} = \phi_b - \frac{Q_{p1}}{C_{AllnN}}$$

$$V_{Th_{-MIS-HMT}} = \phi_b - \frac{Q_f - Q_{sp2}}{C_{ox}} - \frac{Q_{p1}}{C_{AllnN}}$$

$$\Delta V_{Th} = \frac{Q_{sp2} - Q_f}{C_{ox}}$$

$Q_f < Q_{sp2}$ will result positive shift in $V_{Th}$

Present case, $Q_f = 1.2 \times 10^{13}$ cm$^{-2}$ and $Q_{sp2} = 2.1 \times 10^{13}$ cm$^{-2}$

- net negative interface charge ($\sim 9 \times 10^{12}$ cm$^{-2}$) results in positive shift in $V_{Th}$
Prospect for Enhancement mode device

Thicker oxide

Threshold voltage can be adjusted by controlling oxide and barrier layer thicknesses

Possibility of achieving normally-off (E-mode) devices using thicker oxide / thinner barrier layer
AlGaN/GaN and AlInN/GaN MIS-HEMTs

Non-recessed MIS-HEMTs

Recessed gate MIS-HEMTs

Device dimensions: $L_g = 1.5 \ \mu m$, $L_{sd} = 6 \ \mu m$ and $L_{gd} = 3 \ \mu m$ (Gen-2)

Contact resistance: AlInN/GaN $\rightarrow$ 0.4 - 0.5 $\Omega$. mm
AlGaN/GaN $\rightarrow$ 0.5 – 0.6 $\Omega$. mm
Non-Recessed MIS-HEMTs

Recessed gate MIS-HEMTs

- AlInN/GaN MIS-HEMTs showed greater positive shift in $V_{Th}$
- Quasi normally-off AlInN/GaN MIS-HEMT with RIS-$\text{Al}_2\text{O}_3$
- Possibility of E-mode with optimized layer thicknesses
MIS-HEMT output characteristics

Maximum $I_D$ of 800 mA/mm achieved: Comparable to best in literature for devices of similar geometry

Enhancement mode MIS-HEMT realized!

Enhancement mode devices achieved for the first time using RIS-Al₂O₃

Evolution of models for HEMTs from MOSFET models
QM effect in MOSFETs – Why & What?

- **Scaling of device dimensions**
  - Lower oxide thickness (< 2 nm)
  - Higher doping conc. (> $10^{18}$/cm$^3$)
  - Higher electric field

- **Carriers are confined in a short distance from the Si/SiO$_2$ interface (2-Dimensional Electron Gas or 2-DEG)**
  - Creation of sub-bands

- **Classical theory no longer sufficient for modelling**
What is the result of QM effect?

- QM effects result in
  - Increased effective bandgap
  - Reduced inversion layer charge density
  - Modified inversion layer charge profile
  - Increased effective oxide thickness
  - Reduced gate capacitance
  - Modified surface potential
  - Increased threshold voltage
  - Modified carrier mobility
  - Lower drain current
  - Modified gate current
Due to QM effects, peak carrier concentration occurs away from Si/SiO$_2$ interface

- The depth is more for holes than electrons


Calculation of inversion charge

• Consider formation of sub-bands
• Solve Schrödinger and Poisson equations self-consistently
  – computationally very intensive
  – not suitable for compact models
  – benchmark for simpler models

Self Consistent Poisson-Schrödinger equation solution

- Poisson equation (polysilicon, oxide and silicon region)
  - Boundary condition: \( \phi(z) = V_G \) at the gate contact \( \phi(z) = 0 \) and at the bulk
    \[
    \frac{d}{dz} \left[ \varepsilon(z) \frac{d\phi(z)}{dz} \right] = q \left[ N_D^+(z) - N_A^-(z) - n(z) + p(z) \right]
    \]

- Schrodinger equation (dielectric and silicon regions)
  - Boundary condition: \( \psi_{ij} = 0 \) at the gate dielectric interface
    \[
    \left[ -\frac{\hbar^2}{2} \frac{d}{dz} \frac{1}{m^*_d} \frac{d}{dz} + V(z) \right] \psi_{ij}(z) = E_{ij} \psi_{ij}(z)
    \]

- Electron concentration
  \[
  n(z) = \frac{k_B T}{\pi \hbar^2} \sum_i g_i m^*_d \sum_j \ln \left[ 1 + \exp \left( \frac{E_F - E_{ij}}{k_B T} \right) \right] |\psi_{ij}|^2
  \]
Flowchart for self-consistent solution

Start

Initial guess for the electrostatic potential

Solve the Schrodinger equation in the confinement direction for subband profiles and waveforms

Calculate the charge density

Solve the 2-D Poisson equation to update the electrostatic potential

No

The Poisson solver converge?

Yes

No

The outer loop converge?

Yes

End
Triangular potential well approximation

- Constant electric field
  \[ \psi(y) = -\mathcal{E}_s y \]
  \[ \mathcal{E}_s = \frac{q(n_{inv} + N_{dep})}{\varepsilon_{si}} \]

- Standard form of solution of Schrödinger equation involving Airy functions

- Simplifies self-consistent solution, although iteration is not avoided

- Very good match obtained with exact solution

Drain current model of intrinsic HEMT

• First step
  – Derive expression for electron density in channel ($n_s$) vs Gate voltage ($V_g$)
  – Result of self-consistent solution of Poisson and Schrodinger equations
  – Expression too complicated and not integrable
  – However, $n_s$ for a particular $V_g$ can be easily calculated

\[
\begin{align*}
n_s^{at} & = \frac{C_g V_{gm1} V_{gm1} + V_{th} \left[ 1 - \ln(\beta V_{go1}) \right] - \alpha_1 \frac{V_{go1}}{3} }{q} \\
I_D & = \frac{W \mu_n}{L} \int_{V_S}^{V_D} Q_n(y) dV_{CB}(y) \\
Q_n & = q n_s
\end{align*}
\]

Core Drain current model of intrinsic HEMT

Based on charge linearization

\[ J_n = -nq\mu \frac{dV}{dy} + qD_n \frac{dn}{dy} \]

\[ I_D = - \int J_n dx dz \]

\[ I_D = -Q_nW\mu_n \frac{dV_y}{dy} + WV_{th}\mu_n \frac{dQ_n}{dy} \]

\[ \frac{dV}{dy} = \frac{dQ_n(y)/dy}{dQ_n(y)/dV} \]

\[ I_D = \frac{W}{L} \mu_n \left[ Q_{ns}^2 - Q_{nd}^2 \frac{2\alpha_m}{2\alpha_m} - V_{th}(Q_{ns} - Q_{nd}) \right] \]

\[ Q_n|_{V_y} = Q_n|_{V_m} + \alpha_m(V_y - V_m) \]

\[ \alpha_m = \frac{dQ_n}{dV_y} \bigg|_{V_m} \]

\[ V_m = (V_S + V_D)/2 \]

Add secondary effects

- Field dependent mobility
  - Effect of both lateral and transverse field
- Velocity saturation of electrons
- Parasitic conduction in barrier layer
- Channel length modulation (CLM)
- Drain Induced barrier lowering (DIBL)
- Self-heating
- Capacitances
  - for small signal and transient simulations
Modeling Access regions

- Access regions modeled as HEMTs
  - Unlike resistors in most models
- Experimental results show that access regions have HEMT like characteristics
  - Current saturates due to velocity saturation of electrons
Model validation

- **Device Structure:**
  - **15 nm:** 
    - $\text{Al}_{0.83}\text{In}_{0.17}\text{N}$
    - GaN
    - Sapphire
  - **25 nm:** 
    - $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$
    - GaN
    - Sapphire

- **Channel Dimensions:**
  - Source (S): 15 nm
  - Gate (G): 1.5 μm
  - Drain (D): 3 μm
  - Source (S): 1.5 μm
  - Gate (G): 1 μm
  - Source (S): 1 μm
  - Drain (D): 1 μm

- **Drain Current vs. Bias Graphs:**
  - Model and Experimental Data
  - Bias Levels: $V_{GS} = 1, 0, -1, -2, -3$
Model validation

![Diagram showing two different transistor structures with their channel lengths and material layers: Al$_{0.5}$Ga$_{0.5}$N on Sapphire and Al$_{0.15}$GaN on SiC. Each structure has a gate (G), source (S), and drain (D) with specified channel lengths: 18 nm, 1 µm, 0.7 µm, 1 µm, 30 nm, 1 µm, 0.35 µm, 3 µm. The graphs on the right show the drain current (A/mm) as a function of drain-source bias (V) for different gate voltages (V$_G$).]
Summary & Conclusions

- HEMTs have evolved from MOSFETs for high frequency (HF) operation
  - Pseudomorphic HEMTs provide best HF performance
- GaN based HEMTs are best suited for high frequency power amplifiers and power switches
  - Depletion mode operation due to Schottky gate
- MIS-HEMTs can provide
  - Lower gate leakage
  - Higher gate swing as gate voltage can be positive
- Enhancement mode AlInN/GaN MIS-HEMTs with RIS-Al₂O₃ demonstrated
- Model for GaN based HEMT developed
- Further need for model and technology development
- Lots of scope for research
THANK YOU