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SOME CHALLENGES IN DEVICES
Challenges and Opportunities in Polar Materials

- Polar Materials have large bandgaps; can create built-in electric fields
- Materials have a high piezoelectric, pyroelectric coefficient
- May have a strong ferroelectric effect.
  - Nitrides
  - Oxides
Nitrides: Wide bandgap range 0.9 to over 6 eV; Novel Heterostructure possibilities; Undoped electronics?

- High power microwave
- Lighting and display
- Energy conversion: Solar cells
- Smart devices: High polarization; piezoelectric effect

**Challenges: Physics related:** Electronic properties; Charge transport; Heterostructure physics; Polarization issues; High field transport; Radiative processes; Doping issues; Contact issues

**Challenges: Technology related:** Substrates; Dislocations; Defects; Alloy microstructures
Introduction

C-axis growth: Spontaneous and piezoelectric effects dominate

• Two-dimensional electron gas can be formed in undoped structures.
• Strong band bending is created in quantum wells used in light emitters.
• Electronic Devices: Motivation

• Transport and Scaling Issues
  -> transconductance collapse: Source-gate region physics
  -> Self-heating effects and hot phonon issues
  Carrier energies in the device

• Light Emission Devices
  Blue, green, red emission: Challenges in high injection radiative efficiency
Nitrides: Heterojunction FETs

Doping: Not needed

Applications:
• High power (up to 42V insub-micron)
• High temperature
• High frequency ($f_T = 180$GHz)
From microwave to Light emitting diodes

Issues in GaN HFETs
- Carrier transport
- Quantum well
- Contact Engineering
- Heating Issues
- Scaling Issues

Monte Carlo Program
- Poisson Solver
- Schrödinger Solver
- Thermal conduction
- Drift-Diffusion Solver
- Tunneling calculation
- K·P program

Issues in GaN LEDs
- Carrier vertical Transport
- Carrier lateral transport
- Contact Engineering
- MQWs
- MQDs
- Thermal stability
Issues in AlGaN / GaN HFETs

- Very high sheet charge: $>2 \times 10^{13} \text{cm}^{-2}$
- Non-local transport
- Self-heating & Hot phonon issues
- Velocity-Field nuances
- Transconductance collapse: Gate access resistance
- Scaling issues: Gate extension

GaN HFETs
Low-field bowing contributes to transconductance collapse

Onset of transfer to upper valleys

Low-field bowing caused by progressive increase in polar optical phonon emission scattering
Experimental Observation: AlGaN/GaN HFET

From the experimental observation, the maximum $f_T$ is 60% lower than expected theoretical prediction. Also one observes a transconductance decrease for higher drain current.
Role of velocity – field relation: Diffusive flow under the source-gate region

Non-linear source resistance ($R_s$) the reason for the decrease in $g_m$?

1. High current state: Diffusive current flow in regions from source to gate
The $g_m$ obtained by our 2D Poisson solver

Simulations show a clear decrease in $g_m$

Note:
For all $g_m$ calculations, $V_D=10V$.
For $t<20$ns, the heat has not flowed into the substrate interface. Choice of either sapphire or SiC does not influence the results for very short pulse measurement.
Study of self-heating effects and Hot phonon Issues

I-V curve obtained from 2D simulations

Due to the high power output of GaN HFETs, the self-heating effect in the channel is very serious and temperature increase in the channel can be over 200K
Scaling Issues in GaN HFETs

\[ f_T = \frac{v}{2\pi L_g} \]

The unit gain cutoff frequency should be inversely proportional to \(L_g\).

In spite of progress in AlGaN/GaN, the \(f_T\) is still lower than expected. For example, extrinsic \(f_T=153\) GHz at \(L_g=0.10\) \(\mu\)m, the extrinsic \(v\) can be extracted by

\[ v_{ex} = L_g 2\pi f_T = 9.6 \times 10^6 \text{ cm/s} \]

However, the theoretical expected \(v\) is around \(2.5 \times 10^7\) cm/s
Effective Gate Length versus Lithographic Gate Length

\[ V_G = -1V \text{ and } V_D = 5V \]

The increase of the effective gate length is proportional to the increase of the parasitic capacitances \( C_{gs} \) and \( C_{gd} \).

**Recessed gate is useful to reduce the effective gate length, however, larger gate leakage is unwanted.**
Calculations of $f_T$

\[ f_T = \frac{v_{\text{ave}}}{2\pi L_{\text{eff}}} \quad \text{\textit{L}_{\text{eff}} : effective gate length} \]

\[ v_{\text{ave}} : \text{average v in the effective gate region} \]

\[ \text{Al}_{0.35}\text{Ga}_{0.65}\text{N - GaN HFETs} \]

- Ref 1,3,4
- Ref 2
- $V_D=10\text{V}$
- $V_D=7\text{V}$ Recessed
- $V_D=10\text{V}$ Recessed

\[ f_T(\text{GHz}) \]

$V_D(\text{V})$

$\tau(\text{ps})$

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The Reduction of $L_{\text{eff}}$ with Buried Contacts

Effective Gate Length ($L_{\text{eff}}$) vs. Lithographic Gate Length ($L$)

- $N = 1 \times 10^{19} \text{ cm}^{-3}$
  $T = 100 \text{ A deep}$

- $N = 1 \times 10^{20} \text{ cm}^{-3}$
  $T = 200 \text{ A deep}$

This shows the effect of the buried contact on reducing the effective gate length $L_{\text{eff}}$.

These data are calculated for the bias $V_{gs} = -1 \text{ V}$, $V_{ds} = 10\text{ V}$. 
Electron Distribution as a Function of Energy and Position: Hot Carrier Effect
(Vd = 10V, Vg = -2V, T = 500K)

Although the peak average energy is 2.1 eV (at 0.41 um), a fraction of the electrons briefly rise to substantially higher energies.
Distribution of electrons at high energies beyond the gate

Electron concentration spreading into AlGaN beyond the gate contact

- $T = 500K$
- $V_{d} = 20$ V
- $V_{g} = 1$ V

Gate edge

Electron flow toward drain

0.10 microns
Distribution of electrons at high energies beyond the gate

Electron concentration spreading into AlGaN beyond the gate contact

T = 500K
Vd = 50 V
Vg = 1 V

Gate edge
Electron flow toward drain

T = 500K surface
0.10 microns

Gate

Relative Scale of Electron Density

5
4
3
2
1
0
Distribution of electrons at high energies beyond the gate

Electron concentration spreading into AlGaN beyond the gate contact

- $T = 500K$
- $V_{d} = 50 V$
- $V_{g} = 3 V$

$0.10$ microns

T = 500K surface

Electron flow toward drain

Gate

Gate edge

Jasprit Singh
Distribution of electrons below the channel

Electron concentration spreading into GaN below the channel

0.1 micron gate

T = 500K

Vd = 50 V

Vg = 3 V

InGaN back barrier

AlGaN

channel

GaN

source

Electron flow toward drain

Jasprit singh
POLAR MATERIALS: WHAT CAN THEY DO?

- Interface charges- fixed or tailorable as high as $10^{14}\text{cm}^{-2}$
- Unusually high piezoelectric, pyroelectric response.
- Ferroelectric response
- High dielectric constants
- Optical and magnetic effects not found in traditional semiconductors.
Smart Transistors: High gain for multiple device input signals
Introduction:

**Semiconductors**

\[ E_c \rightarrow E_F + \Delta E_F \rightarrow E_F \]

**“Smart” insulators**

\[ E_c \rightarrow \text{Bandgap states} \rightarrow E_v \]

Small change in $\Delta E_F$ produces orders of magnitude changes in conductivity.

- Very high piezoelectric effect.
- High pyroelectric effect.
- Sensitive surface potential.
- Electro-optic effect.
- Magnetic properties.

Sensitive $\Delta \sigma$+ “smart” material properties

**ROLE OF DEFECTS**

Jasprit singh
In the smart-FET devices shown above, we consider devices in which the two dimensional (2D) channel charge is modulated by stress and temperature change. An appropriate measure of the device performance is a new “transconductance” describing how the perturbation controls the channel current

\[
g_m = \frac{\Delta I_D}{\Delta V_G}
\]

\[
g_m = \frac{\Delta I_D}{\Delta P_G}
\]

\[
g_m = \frac{\Delta I_D}{\Delta T_G}
\]

where \(\Delta P\) is the appropriate perturbation.
Perturbation can alter:
charge density

$J = en \mu E = env$

$V_{DS}$

$I_{DS}$

unperturbed
perturbed
Models Needed

Developed Models

- Monte Carlo Program
- 1D-2D Drift-Diffusion Solver

Issues in Oxide Semiconductor

- 1D, 2D Poisson Schrödinger Solver
- Thermal conduction

Defect: traps, Surface states, leakage problem
Transport issues: Impurity scattering, Interface roughness scattering, p-type transport, self-heating, thermal sensor
Charge control issues: polar charge density, ferroelectric effect, band calculation, Contact properties.

8 band K·P band structure calculation

Tunneling calculation
Experimental works on gate insulator on GaAS

From private communication with David Braddock, they have made Ga$_2$O$_3$ on GaAs with very high mobility ( > 6000 cm$^2$/Vs). This increases the interest on examining the performance of GaAs MOSFETs.

The charge variation is mainly along the $z$ direction.

When the sensor FET is under stress, the piezoelectric polarization charge will change. Therefore, the induced 2D free carriers will also change as the fixed polar charges changes. The variation of induced free carriers are directly reflected in $I_{DS}$. By measuring the “$g_m$”, we can detect the stress.
Definition of sensitivity:

**Stress Sensor**

To understand and compare the sensitivity of the stress sensor-FET and other stress sensors, we define the sensitivity of the cantilever to be

\[ S = \frac{dn_{2DEG}}{n_{2DEG}} \frac{1}{dz} \]

**Thermal Sensor**

To understand and compare the sensitivity of the thermal sensor-FET, we define the sensitivity of the thermal sensor to be

\[ S = \frac{dn_{2DEG}}{n_{2DEG}} \frac{1}{dK} \]
Results of p-type BTO-SiO$_2$-Si Strain sensor

\[ \frac{dn_{2\text{DEG}}}{d\sigma_x} \approx 2.2 \times 10^7 \text{ N}^{-1} \]

The 2DEG at SiO$_2$/Si interface for BTO=50Å.

P-type BTO - SiO$_2$ - Si strain sensor

Optimal thickness

Thickness (Å)

Inversion region

\[ \varepsilon (\varepsilon_0) \]

Jaspreet Singh
Result for SiO$_2$ – MgO – ZnO strain sensor

\[ \frac{dn_{2DEG}}{d\sigma_x} \approx 2.7 \times 10^7 \text{ N}^{-1} \]

The layer thickness of MgO and SiO$_2$ shows weak influence on the sensitivity.
Comparison of stress sensitivity:

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si piezoresistivity sensor [4]</td>
<td>$2.40 \times 10^{-7}$ Å$^{-1}$</td>
</tr>
<tr>
<td>BaTiO$_3$/SiO$_2$/Si p-type sensor FET</td>
<td>$1.39 \times 10^{-5}$ Å$^{-1}$</td>
</tr>
<tr>
<td>SiO$_2$/MgO/ZnO n-type sensor FET</td>
<td>$1.70 \times 10^{-5}$ Å$^{-1}$</td>
</tr>
</tbody>
</table>

Comparison of thermal sensitivity:

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-N diode thermal sensors</td>
<td>2 mV/K.</td>
</tr>
<tr>
<td>BaTiO$_3$/SiO$_2$/Si thermal sensor FET</td>
<td>$6.2 \times 10^{-3}$ (K$^{-1}$).</td>
</tr>
</tbody>
</table>

For Example, the sheet charge density is $1e13$ cm$^{-2}$. Mobility is assumed to be $100$ cm$^2$/Vs. $V_D=1$V $L_g=10$µm. $J\sim 16$ mA/mm. So $\Delta J \sim 0.992$ mA/mm for $\Delta T=1$K.

Recent progress on thin film ferroelectrics

- Drezner et al., APL 2005: 3nm BaTiO$_3$ $d_{31}$$\sim$$-1.8$ pC/N.
- Zhang et al. APL 2002: 0.5μm 0.5Pb [Yb$_{1/2}$Nb$_{1/2}$]O$_3$ - 0.5PbTiO$_3$ $P_s$$=$$0.3$C/m$^2$, $e_{31}$$=$$-4.8$C/m$^2$, $\varepsilon_r$$=$$1025$.
- Stachiotti et. al. APL 2004. 2.4nm $P_s$$=$$-0.05$C/m$^2$
- Fong et al. Science 2004: PbTiO$_3$ Ferroelectric is observed at 1.2nm thickness.
- Choi et al. Science 2004: 100-200nm strained BaTiO$_3$ have $T_c$$=$$500$C and $P_s$$\sim$$0.70$ C/m$^2$.

Lists of potential materials for future work

**Table III: Material Parameters for Related Piezoelectric Materials**

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$P_{sp}$ (C/m$^2$)</td>
<td>-0.26</td>
<td>-0.71</td>
<td>-0.50</td>
<td>-0.057</td>
</tr>
<tr>
<td>$\varepsilon_{33}$ ($\varepsilon_0$)</td>
<td>48</td>
<td>28.6</td>
<td>43.7</td>
<td>9.9</td>
</tr>
<tr>
<td>$\varepsilon_{11}$ ($\varepsilon_0$)</td>
<td>1600</td>
<td>82.9</td>
<td>52.6</td>
<td></td>
</tr>
<tr>
<td>$E_0$ (eV)</td>
<td>3.1</td>
<td>4.0</td>
<td>4.6</td>
<td>3.3</td>
</tr>
<tr>
<td>$p$ (μC/m$^2$K)</td>
<td>238[28]</td>
<td>230[29]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e_{13}$ (C/m$^2$)</td>
<td>-3.88</td>
<td>0.332</td>
<td>-0.143</td>
<td>-0.534</td>
</tr>
<tr>
<td>$e_{33}$ (C/m$^2$)</td>
<td>5.48</td>
<td>1.896</td>
<td>1.804</td>
<td>1.200</td>
</tr>
<tr>
<td>$e_{15}$ (C/m$^2$)</td>
<td>32.6</td>
<td>3.631</td>
<td>2.609</td>
<td>-0.48 [7]</td>
</tr>
<tr>
<td>$e_{22}$ (C/m$^2$)</td>
<td>2.394</td>
<td>1.818</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

General Outcomes

• The use of oxide/semiconductor heterojunctions appears to have great promise for use in: force sensors, pyro-sensors, ferroelectric memories, magnetic sensors. The most promising devices are force and pyro-sensors and memory devices based on hysteresis effects in ferroelectric oxides.

• Defects present can greatly hamper the performance of devices especially when band lineups create heterojunctions with small band offsets.

• The nitrides provide a good semiconductor system on which smart oxide devices can be integrated.

• There is a need to experimentally obtain the band offsets for a number of oxide-semiconductor junctions.
New Materials: Where will They Lead?
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New Materials: Where will They Lead?

Graphene:
Very high mobility;
zero bandgap which may be tunable,
...