Thrust 3: Electrical Characterization Overview/ Effect of Strain on Trap-related Reliability Mechanisms

T. Nishida and S. Thompson, Co-PIs
A. Koehler
Department of Electrical and Computer Engineering
Outline

• Motivation and review from last meeting
• Piezoresistance measurements
• Simulation of strain effects on 2DEG resistivity
• Summary
Outline

- Motivation and review from last meeting
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- Summary
Failure Mechanisms in GaN HEMTs

Influenced by stress:
- carrier mobility
- polarization and 2DEG
- trap energy levels
- Schottky barrier height
- bandgap
- generation of traps

Stress in GaN HEMT Devices

Lattice mismatch (built-in) stress:

Strained AlGaN

Inverse piezoelectric (generated) stress:

\[
\begin{pmatrix}
P_x \\
P_y \\
P_z \\
\end{pmatrix} = \begin{pmatrix}
0 & 0 & 0 & 0 & e_{15} & 0 \\
0 & 0 & 0 & e_{15} & 0 & 0 \\
e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \\
\end{pmatrix}
\]
Outline

• Motivation and review from last meeting
• **Piezoresistance measurements**
• Simulation of strain effects on 2DEG resistivity
• Summary
Piezoresistance

- Piezoresistance: Change in electrical resistance with mechanical stress

**Piezoresistance coefficient (π):**

\[ \pi = \frac{\Delta R/R}{\sigma} \]

\[ \sigma = \text{Stress} \]

**Gauge factor (GF):**

\[ GF = \frac{\Delta R/R}{\varepsilon} \]

\[ \varepsilon = \text{Strain} \]

- Stress alters semiconductor band structure impacting reliability and failure mechanisms of GaN HEMT devices

- Measure piezoresistance of GaN HEMT channel:
  - hot-carrier injection/trapping
  - impact ionization

- Experiment on two GaN HEMT samples from different manufacturers
Experimental Setup

- GaN HEMT wafer samples too small to directly bend in 4-point bending setup
- Device is wirebonded and connected to probe tip to take electrical measurements while simultaneously applying stress
- Measure total device resistance ($R_{TOT} = R_{CH} + R_S + R_D$) (extracted by 4-point measurement)
4-Point Wafer Bending Experiments

Strain Engineering to Improve Data Retention Time in Nonvolatile Memory


Piezoresistance Coefficients of (100) Silicon nMOSFETs Measured at Low and High (~1.5 GPa) Channel Stress

S. Suthram, J. C. Ziegert, T. Nishida, and S. E. Thompson

Strain-induced changes in the gate tunneling currents in p-channel metal–oxide–semiconductor field-effect transistors

X. Yang, J. Lim, G. Sun, K. Wu, T. Nishida, and S. E. Thompson

Key Differences For Process-induced Uniaxial vs. Substrate-induced Bliaxial Stressed Si and Ge Channel MOSFETs

S.E. Thompson, G. Sun, K. Wu, J. Lim, and T. Nishida

University of Florida, PO Box 116170, Gainesville FL 3261

Abstract

For both n and pMOSFETs, this paper confirms via conduction band deformation potentials for germanium

Mechanical stress altered electron gate tunneling current and extraction of conduction band deformation potentials for germanium

Youn Sung Choi, Ji-Song Lim, Toshinori Numata, Toshikazu Nishida, and Scott E. Thompson

Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611, USA

(Received 9 July 2007; accepted 14 September 2007; published online 30 November 2007)

Strain altered electron gate tunneling current is measured for germanium (Ge) metal–oxide–semiconductor devices with HIO$_2$ gate dielectric. Uniaxial mechanical stress is applied using four-point wafer bending along [100] and [110] directions to extract both dilation and shear deformation potential constants of Ge. Least-squares fit to the experimental data results in $E_x$ and $E_y$ of $-4.3$ and $16.5$ eV, respectively, which agree with theoretical calculations. The dominant mechanism for the strain altered electron gate tunneling current is a strain-induced change in the conduction band offset between Ge and HIO$_2$. Tensile stress reduces the offset and increases the gate tunneling current for Ge while the opposite occurs for Si. © 2007 American Institute of Physics. [DOI: 10.1063/1.2809374]
Strain Gauge measures strain on top surface of GaN HEMT wafer.
Bending does not permanently deform metal plate.
Strain gauge calibrated:
- optical curvature
- force sensor measurements
- 4-point bending equation
Wide Range of Published GaN HEMT GFs

<table>
<thead>
<tr>
<th>Reference</th>
<th>GF</th>
<th>ΔR/R</th>
<th>ε (%)</th>
<th>σ (MPa)</th>
<th>Method of Stressing</th>
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<tbody>
<tr>
<td>[1]</td>
<td>-4</td>
<td>0.14%</td>
<td>.03</td>
<td>95</td>
<td>3-point bending</td>
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<tr>
<td>[2]</td>
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<tr>
<td>[4]</td>
<td>-90</td>
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<td>0.167</td>
<td>525</td>
<td>Cantilever</td>
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<tr>
<td>[6]</td>
<td>-1,259</td>
<td>1.7%</td>
<td>1.35x10^-4</td>
<td>0.42</td>
<td>Cantilever</td>
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<tr>
<td>[7]</td>
<td>-38,889</td>
<td>15%</td>
<td>3.85x10^-4</td>
<td>1.2</td>
<td>Circular Membrane</td>
</tr>
</tbody>
</table>

Largest change in resistance measured is ~15%
Could result from charge trapping effects?

Charge Traps in GaN HEMTs

**Cause**
- growth-*as fabricated* traps
- post-growth process *as fabricated* traps
- hot-carrier injection *generated* traps
- inverse piezoelectric strain *generated* traps

**Effect**
- current collapse
- gate-lag
- drain-lag
- \( \Delta V_T \)
- increased \( I_G \)
- light sensitivity
- breakdown

Significance of trapping effects depend on processing conditions
Effect of Light on Device Resistance

Sample A

Microscope Light ON

15% change in $R_{TOT}$ from detrapping

Sample B (AFRL)

Microscope Light ON

0.2% change in $R_{TOT}$ from detrapping

- Microscope light detraps trapped charge decreasing $R_{TOT}$
- Sample B (AFRL) is less sensitive to light (fewer traps)
Experimental Setup – UV Illumination

**Electrical measurements under stress**
- Probe tip
- Gold wire
- Conductive epoxy
- GaN HEMT wafer under stress
- Epoxy
- Steel rods

**Elimination of charge trapping effects**
- Polystyrene heat shield
- Band-pass filter
- UV source
- High carbon steel strip
- Electrical measurements under stress
- Elimination of charge trapping effects

A 21st Century Approach to Reliability
Output of UV Light Source

- Near bandgap photons will photoionize trapped charge
- Photons with energy > $E_G(GaN)$ photogenerate e-h pairs
Effect of UV Light on $I_D-V_G$

- Photoionization of trapped charge shifts $V_T$
- Photogenerated e-h pairs increases offstate $I_D$
- AFRL sample is less sensitive to light (fewer traps)
Output of Filtered UV Light Source

- Near bandgap photons still photoionize trapped charge
- No photons with energy > $E_G$(GaN) to photogenerate e-h pairs
Effect of Filtered UV Light on $I_D-V_G$

Sample A

- Under UV
- Much Smaller Increase
- Under UV with filter
- Dark

Sample B (AFRL)

- Under UV
- Much smaller Increase
- Under UV with filter
- Dark

- BP filter eliminates photons $> E_G($GaN$)$ and does not increase offstate $I_D$
- Only parallel shift in $V_T$ is observed from charge detrapping
- AFRL sample has less sensitivity to light (fewer traps)
Light Sensitivity

- Sample B (AFRL) is less sensitive (fewer traps)
- Filtered UV used to stabilize $R_{TOT}$ measurements to obtain piezoresistance
Infrared Heating From UV Source

No heat shield

- Thermocouple placed near sample
- Infrared heating from source prevents stable resistance measurements
Device Resistance Stabilized

With heat shield

Sample A

Sample B (AFRL)

- With polystyrene shield, < 0.025% stability in measured RTOT is achieved
- Piezoresistance can be measured
Measured Piezoresistance

Sample A

GaN HEMT: ~1 %/GPa
Si nMOS: ~31 %/GPa
# GaN HEMT Piezoresistance

## Wide range of published gauge factors (GF)

<table>
<thead>
<tr>
<th>Reference</th>
<th>GF</th>
<th>$\Delta R/R$</th>
<th>$\varepsilon$ (%)</th>
<th>$\sigma$ (MPa)</th>
<th>Method of Stressing</th>
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</thead>
<tbody>
<tr>
<td>This work</td>
<td>-2.6</td>
<td>0.3%</td>
<td>0.114</td>
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<tr>
<td>[1]</td>
<td>-4</td>
<td>0.14%</td>
<td>0.03</td>
<td>95</td>
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<td>525</td>
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<tr>
<td>[5]</td>
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<td>[6]</td>
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<td>1.35x10^{-4}</td>
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**A 21st Century Approach to Reliability**
Outline

• Motivation and review from last meeting
• Piezoresistance measurements
• **Simulation of strain effects on 2DEG resistivity**
• Summary
• Future plans and goals
Determination of Band Parameters

Comparison of Threshold-Voltage Shifts for Uniaxial and Biaxial Tensile-Stressed n-MOSFETs

APPLIED PHYSICS LETTERS 89, 073509 (2006)

Measurement of conduction band deformation potential constants using gate direct tunneling current in n-type metal oxide semiconductor field effect transistors under mechanical stress

Ji-Sung Lim, Toshinori Numata, Toshikazu Nishida, and Scott E. Thompson
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611, USA
(Received 9 July 2007; accepted 14 September 2007; published online 30 November 2007)

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Extraction of Deformation Potentials

<table>
<thead>
<tr>
<th>(eV)</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Xi_d )</td>
<td>( 1.0 \pm 0.1^c, 1.1^b, 1.2^b, 1.13^b, 5^b, )</td>
</tr>
<tr>
<td>( \Xi_u )</td>
<td>( 9.6 \pm 1.0^c, 10.5^b, 8.86^b, 9.2^b, 7.3^b, 9.29^b, )</td>
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<tr>
<td>a</td>
<td>( 2.1^b, 2.46^b, 2.06^b, )</td>
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<tr>
<td>b</td>
<td>( -2.33^b, -1.5^b, -2.1^b, -2.2^b, -2.12^b, -2.35^b, -2.58^b, -2.27^b )</td>
</tr>
<tr>
<td>d</td>
<td>( -4.75^b, -3.4^b, -4.85^b, -5.3^b, -3.69^b )</td>
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<table>
<thead>
<tr>
<th>(eV)</th>
<th>Ge</th>
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</thead>
<tbody>
<tr>
<td>( \Xi_d )</td>
<td>( -4.3 \pm 0.3^a, -4.43^b, -12.3 \sim -10.5^b, -6.6^b, )</td>
</tr>
<tr>
<td>( \Xi_u )</td>
<td>( 16.5 \pm 0.5^a, 16.8^b, 11.07^b, 15.13^b, 16.2^b, 15.9 \sim 19.3^b, )</td>
</tr>
<tr>
<td>a</td>
<td>( 2.0^b, 1.24^b, 2.09^b, -12.7^b, 1.39^b )</td>
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<tr>
<td>b</td>
<td>( -2.16^b, -2.1^b, -2.2^b, -2.08^b, -2.5^b, -2.55^b, 2.86^b, -3.11^b )</td>
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<tr>
<td>d</td>
<td>( -6.06^b, -3.5^b, -4.4^b, -3.7^b, -4.5^b, -5.3^b, -4.65^b, -7.0^b )</td>
</tr>
</tbody>
</table>

\(^a\) [JAP, vol. 102, pp. 104507, 2007]  
\(^b\) [JAP, vol. 80, pp. 2234, 1996]  
\(^c\) [APL, vol. 89, pp. 073509, 2006]
Factors that Need to be Considered

Stress can affect GaN HEMT channel resistance through:

• 2DEG density caused by polarization
• Electron mobility

\[ \rho \propto \frac{1}{n_s \mu} \]
Stress on upper surface at the center of the substrate:

\[
\sigma = \frac{E \cdot t \cdot y_{x=a}}{2a \left( \frac{L}{2} - \frac{2a}{3} \right)}
\]

- \( E \) = Young’s modulus
- \( t \) = sample thickness
- \( y \) = vertical displacement
- \( a, L \) = rod spacing

\[ t = 150 \, \mu m \]

\[ 18 \, nm \]
Stress Induced Polarization Change

Spontaneous Polarization ($P_{SP}$)
- Exists if c/a ratio differs from $\sqrt{8/3}$
- Considered material parameter (independent of mechanical stress)

Piezoelectric Polarization ($P_{PE}$)
- Electric field is generated proportional to stress (lattice mismatch or mechanical)
- Will have mechanical stress dependence

As Fabricated

+1 GPa
Uniaxial Stress

Strained AlGaN

Polarization (C/cm$^2$)

0.00
0.02
0.04
0.06

Relaxed GaN

Polarization (C/cm$^2$)

0.00
0.02
0.04
0.06

$p_{PE, \text{ mech.}}$
$p_{PE, \text{ lattice}}$

$p_{SP}$
2DEG Density Calculation Procedure

**AlGaN**

- **Build in** $P_{SP} + P_{PE,\text{lattice}}$
- Additional strain from mechanical stress
- Piezoelectric Constant

**GaN**

- **Build in** $P_{SP}$
- Additional strain from mechanical stress
- Piezoelectric Constant

$$P_{total} = P_{SP}(\text{AlGaN}) + P_{PE,\text{lattice}}(\text{AlGaN}) + P_{PE,\text{mech}}(\text{AlGaN}) - P_{SP}(\text{GaN}) - P_{PE,\text{mech}}(\text{GaN})$$

2DEG Density:

$$n_s(x) = \frac{P_{total}}{e} - \left( \frac{\varepsilon_0 \varepsilon(x)}{de^2} \right) [e\varphi_b(x) + E_F(x) - \Delta E_C(x)]$$

[Ref: JAP, vol. 85, pp. 3222]
Simulation Uncertainty

Effective mass calculation error depends on:

- Piezoelectric coefficients
- Stiffness constants
- Tight-binding model and parameters (not considered)

\[ \text{sp}^3\text{d}^5 \text{ is a very accurate model (Ref. JJAP, vol.34, pp.5912)} \]

### GaN piezoelectric coefficients

<table>
<thead>
<tr>
<th>( e_{13} )</th>
<th>( e_{33} )</th>
<th>( e_{15} )</th>
<th>Ref.</th>
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<td>-0.34</td>
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<td>0.44</td>
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<td>-0.33</td>
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<td>0.65</td>
<td>J. Appl. Phys. Vol.81, pp.6332</td>
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</table>

### AlN piezoelectric coefficients

<table>
<thead>
<tr>
<th>( e_{13} )</th>
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<th>( e_{15} )</th>
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<td>-0.48</td>
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<td>1.55</td>
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</table>
## Simulation Uncertainty

### GaN stiffness constants

<table>
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<tr>
<th>$C_{11}$</th>
<th>$C_{12}$</th>
<th>$C_{13}$</th>
<th>$C_{33}$</th>
<th>$C_{44}$</th>
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<td>37.3</td>
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<td>8.0</td>
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<td>9.4</td>
<td>11.8</td>
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<td>36.5</td>
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<td>11.5</td>
<td>J. Phys. Condens. Matter 9,241</td>
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<td>37.3</td>
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<td>37.0</td>
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<td>10.6</td>
<td>39.8</td>
<td>10.5</td>
<td>12.3</td>
<td>Appl. Phys. Lett. 72,2400</td>
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<td>41.05</td>
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<td>9.89</td>
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<td>12.46</td>
<td>12.3</td>
<td>J. Am. Ceram. Soc. 76,1132</td>
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</table>
Strain-Varied 2DEG Density

\[ n_s(x) = \frac{+P^{\text{int}}(x)}{e} \left( \epsilon_0 \epsilon(x) \right) \left[ e\phi_b(x) + E_F(x) - \Delta E_C(x) \right] \]

- Assumed independent of stress:
  - \( \phi_b \) since \( \Delta P^{\text{int}} \) is small
  - \( \Delta E_C \) since only 26% Al in AlGaN
  - \( \epsilon \) and \( E_F \) since no change in Si and no papers reporting change for GaN

- Small changes observed in \( n_s \) (0.28%/GPa) since external stress creates offsetting piezoelectric polarizations
Mobility Relevant Factors

Mobility

- Effective mass
- Carrier repopulation
- Band warping
- Sub-band splitting
- Change of DOS

Scattering rate
Band Structure: GaN vs. Si

- Indirect bandgap with band minima located at the X-point
- Six equivalent conduction valleys

Mobility relevant parameters:
- Effective mass change caused by electron repopulation
- Scattering rate variation

- Direct bandgap with band minimum locates at the Γ-point
- Only one conduction valley

Mobility relevant parameters:
- Effective mass change caused by conduction band warping
Tight-binding Model

\[
H = \begin{bmatrix}
H_{11} & H_{12} & H_{13} & H_{14} \\
H_{12}' & H_{22} & H_{23} & H_{24} \\
H_{13} & H_{23}' & H_{33} & H_{34} \\
H_{14} & H_{24}' & H_{34}' & H_{44}
\end{bmatrix}
\]

sp³d⁵ model:
- s and p orbital for N atom (total 4 orbitals)
- s, p and d orbital for Ga atom (total 9 orbitals)

Resulting 26×26 H matrix

[Ref. JJAP, vol.34, pp.5912]
Under Biaxial Stress

- Hexagonal shape retained, only bond length changes, no change in bond angle
- Reciprocal lattice remains the same

\[ \text{Biaxial Stress} \]
\[ a \rightarrow a' = a(1 + \epsilon_{xx}) \]
\[ c \rightarrow c' = c(1 + \epsilon_{zz}) \]

Under Uniaxial Stress

Uniaxial Stress

\[ a_x = a(1 + \varepsilon_{xx}) \]
\[ a_y = a(1 + \varepsilon_{yy}) \]
\[ c' = c(1 + \varepsilon_{zz}) \]

- Both bond length and bond angle change
- Reciprocal lattice also changes

First theoretical study on the effect of uniaxial stress on GaN HEMT
Tight-binding Parameters

<table>
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<tr>
<th>E(s,N)</th>
<th>-12.675</th>
<th>\eta_{ss}^{(1)}</th>
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<th>\eta_{sas}^{(2)}</th>
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<td>E(s,Ga)</td>
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<td>\eta_{pad}^{(1)}</td>
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<td>\eta_{pcc}^{(2)}</td>
<td>0.332</td>
</tr>
</tbody>
</table>

Tight-binding parameters. Onsite matrix E (eV) and coefficients \eta = md^2V/\hbar^2

[Ref. JJAP, vol.34, pp.5912]
Longitudinal Effective Mass Change

Stress (GPa)

Effective Mass Change (%)

Effective Mass ($m_0$)

-0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4-0.5

0

0.5

0

0.197
0.1975
0.198
0.1985

Biaxial Stress

<11\bar{2}0> Uniaxial Stress

<10\bar{1}0> Uniaxial Stress
Transverse Effective Mass Change

![Graph showing effective mass change as a function of stress for different crystallographic orientations. The graph illustrates the impact of biaxial and uniaxial stress on the effective mass change.]
Out-of-Plane Effective Mass Change

Stress (GPa) vs. Effective Mass Change (%)

- Biaxial Stress
- <11̅20> Uniaxial Stress
- <10̅10> Uniaxial Stress

Effective Mass (m0)

Stress (GPa)

-0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4

Effective Mass Change (%)

-0.5 0 0.5

<0001> <11̅20> <10̅10>

transverse longitudinal
GaN Band Gap Change

Band Gap Change (%) vs. Stress (GPa)

- Biaxial Stress
- Biaxial Stress [Jogai]
- <1120> Uniaxial Stress
- <1010> Uniaxial Stress

Outline

• Motivation and review from last meeting
• Charge trapping effects
• Piezoresistance measurements
• Simulation of strain effects on 2DEG resistivity
• Summary
• Future plans and goals
Simulation vs. Experiment

![Graph showing simulation vs. experiment results.](attachment:image.png)
# Best Fit Parameters

## Stiffness Constants

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<th>$C_{11}$</th>
<th>$C_{12}$</th>
<th>$C_{13}$</th>
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<th>$C_{44}$</th>
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<td>11.8</td>
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<td>Appl. Phys. Lett. 72,2400</td>
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## Piezoelectric Coefficients

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<tbody>
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<td>-0.58</td>
<td>1.55</td>
<td>IEEE Trans. Sonics Ultrason. SU-32.634</td>
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</table>

*Feed-forward into reliability simulator*
Outline

• Motivation and review from last meeting
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Future plans and goals

- Continue investigation of GaN HEMT failure mechanisms influenced by stress
- Focus includes stress dependence of gate current
  - Trap energy level
  - Schottky barrier height
  - Out-of-plane effective mass
- Calibrate simulations to select ‘best-fit’ parameters
- Feed-forward into reliability simulator
Influenced by stress
- carrier mobility
- polarization and 2DEG
- trap energy levels
- Schottky barrier height
- bandgap
- generation of traps

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  - Mehmet Baykan
  - Robert Dieme
  - Ukjin Roh