Large-Signal Performance of AllInN/GaN-on-Silicon HEMTs at 94 GHz

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Considerations / Outline

- **AlInN/GaN Materials**
  - Lattice-Matching to GaN
  - Reduced Surface Depletion vs. AlGaN/GaN

- **Requirements for mm-Wave HEMTs**
  - Gate-Channel Spacing / Source-Drain Separation
  - Short-Channel Effects (SCEs)
  - Series Resistances / Ohmic Contacts (Annealed vs. Regrown)
  - Large-Signal on Silicon (W-Band)
  - PDK and W-Band Prototype on Silicon
Lattice Matching \((\text{Al}_{0.83}\text{In}_{0.17}\text{N}:\text{GaN})\)
Materials
Lattice Matching: A Reliability Enhancer (?)

Cumulative Strain (Mismatch + Piezo) Correlated to Device Degradation

G. Meneghesso et al.

Park et al. (TRIQUINT)
Materials

AllInN/GaN High Temperature Stability (1000°C)

F. Medjdoub et al., IEDM 2006

AllInN/GaN HEMTs Survive 1000°C Temperatures

(Potential for High-T Electronics)
Materials

Substrate Choices

Silicon:
1,030 cm²/Vs @ 2×10¹³/cm²
300 Ω/□ (−17% mismatch)

SiC:
1,300 cm²/Vs @ 2.4×10¹³/cm²
205 Ω/□ (−3.5% mismatch)

Excellent Mobility in 2DEG:
Dislocations are screened by the high carrier density

Materials

Surface Depletion: InP vs. GaAs HEMT Analogy

Reduced Gate-to-Channel Distance

Theoretical Advantages:

- Higher $G_M$
- Higher Current Drive, $I_{DMAX}$
- Improved Aspect Ratio $L_G/d$
- Weaker Short-Channel Effects
- Textbook Approach to High-Speed

All Recent Record GaN HEMTs:

- Thin Barriers (AlInN or AlN)
- Higher Channel Sheet Density
Requirements: Reduced S/D Spacing

The Original Studies of $R_S$ and $R_D$ Effects on GaN HEMT Bandwidth...
(Essentially, re-work Hughes/Tasker pHEMT analysis)

Transistor Delay Analysis and Effective Channel Velocity Extraction in AlGaN/GaN HFETs

1,2) C. R. Bolognesi, 1) A. C. Kwan, 2) D. W. DiSanto
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Ohmic Contacts (1)

Metallization:
- Ti / Al / Mo / Au

Yields
- $R_C \approx 0.3$ to $1 \, \Omega \cdot \text{mm}$
  (strong variability)

Requirements:
- Good Morphology
- Low Contact Resistance

Rapid Thermal Annealing
- $T \sim 850^\circ \text{C}$
Regrown Contacts \(^{(2)}\)

Regrown: 

![Diagram of regrown contacts](image)

RegrownContacts.png

Beneficial for Short \(L_{SD}\) Spacings \((R_{SD} < R_C)\)

Better Reproducibility with Respect to Annealed Ohmics

(Best Example: Shinohara et al., HRL)
Regrown Contacts (3)

Annealed

Regrown

Gain (dB)

Frequency (GHz)

\( H_{21} \)

\( f_{\text{MAX(U)}} = 230 \text{ GHz} \)

\( f_T = 128 \text{ GHz} \)

\( V_{DS} = 10 \text{ V} \)

\( V_{GS} = -1 \text{ V} \)

\( V_{DS} = 9 \text{ V} \)

\( V_{GS} = -1.1 \text{ V} \)

\( f_{\text{MAX(U)}} = 250 \text{ GHz} \)

\( f_T = 170 \text{ GHz} \)
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- Requirements for mm-Wave HEMTs
  - Gate-Channel Spacing / Source-Drain Separation
  - Short-Channel Effects (SCEs)
  - Series Resistances / Ohmic Contacts (Annealed vs. Regrown)
  - Large-Signal on Silicon (94 GHz / W-Band)
Large-Signal Operation

- Current Collapse and SCEs Limit $P_{\text{OUT}}$

$+ \text{Output Impedance Matched for max } P_{\text{OUT}}$

$+ \text{Current Collapse and SCEs Limit } P_{\text{OUT}}$
Large-Signal Operation (On Silicon)

$d = 7.5$ nm, $L_G = 50$ nm, $L_{SD} = 2$ $\mu$m on HR-Silicon.

Improved Buffer / Channel Design. Regrown Contacts.

DC Characteristics

+ $G_M > 650$ mS/mm
+ Good Transport: $\mu = 1200$ cm$^2$/Vs (300 $\Omega$/sq)
+ Adequate Pinch-Off
+ Back-Barrier not Implemented
Large-Signal Operation

d = 7.5 nm, \( L_G = 50 \) nm, \( L_{SD} = 2 \) \( \mu \)m on HR-Silicon.

Improved Back-Buffer / Channel Design. Regrown Contacts

94 GHz Initial Results

1 W/mm / PAE = 12% / \( G_p = 4 \) dB @ \( P_{IN,Del} = 16 \) dBm

(Better than 1 W/mm Result on SiC)
Large-Signal Operation @ 94 GHz on SiC

\( d = 6 \text{ nm}, \ L_G = 100 \text{ nm}, \ L_{SD} = 1 \mu \text{m on SiC.} \)

No Back-Barrier. Regrown Contacts.

Best results at 94 GHz for AlInN-based HEMTs on SiC
PDK and PA Prototype Development (1)

Large-Signal Model (Angelov) Harmonic Balance Simulation in ADS) vs. Load Pull Measurement at 94 GHz for a 2x50um AlInN/GaN on Si device.

Process Design Kit PDK

Scalable Large-Signal Model (Gate Width & Fingers)
PDK and PA Prototype Development (2)

MMIC Process based on Grounded Coplanar Waveguides

![Grounded Coplanar Waveguide Diagram]

- Ground
- Signal
- Ground
- Via
- Ground

Reflection Coefficient $S_{11}$ (dB)

Transmission Coefficient $S_{21}$ (dB)

Losses: 0.68 dB/mm @ 94 GHz

$W = 40 \mu m$, $G = 30 \mu m$, $T_{MET} = 3 \mu m$

$L = 5000 \mu m$, $H_{SUB} = 100 \mu m$
PDK and PA Prototype Development (3)

3 Stage PA Simulation
(2x50 um Devices for all Stages)

Input, Inter-Stage and Output Networks Simulated with Lumped Elements (Full Characterization and Modeling of Passives Elements are Underway)
PDK and PA Prototype Development (4)

- 3 Stage PA Simulation Results

- Additional Losses of 1 to 3 dB Expected with Lossy Interconnects in Implementation.
Conclusions

- Excellent Progress with mm-Wave AlInN/GaN HEMTs
  - Process Integration Developments (Back-Barrier / Regrown Ohmics)

- GaN-on-Silicon is mm-Wave Ready

- Impressive $P_{\text{OUT}}$ at 94 GHz on Silicon (1.3 W/mm)

- Improved Large-Signal Stability

- PDK and PA Prototype Development on Silicon
  - W-Band Gain Block Feasible: 15 dB at W-Band
  - Refinements Required