***Session*:**
Millimeter-Wave PAs for 5G and Beyond

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

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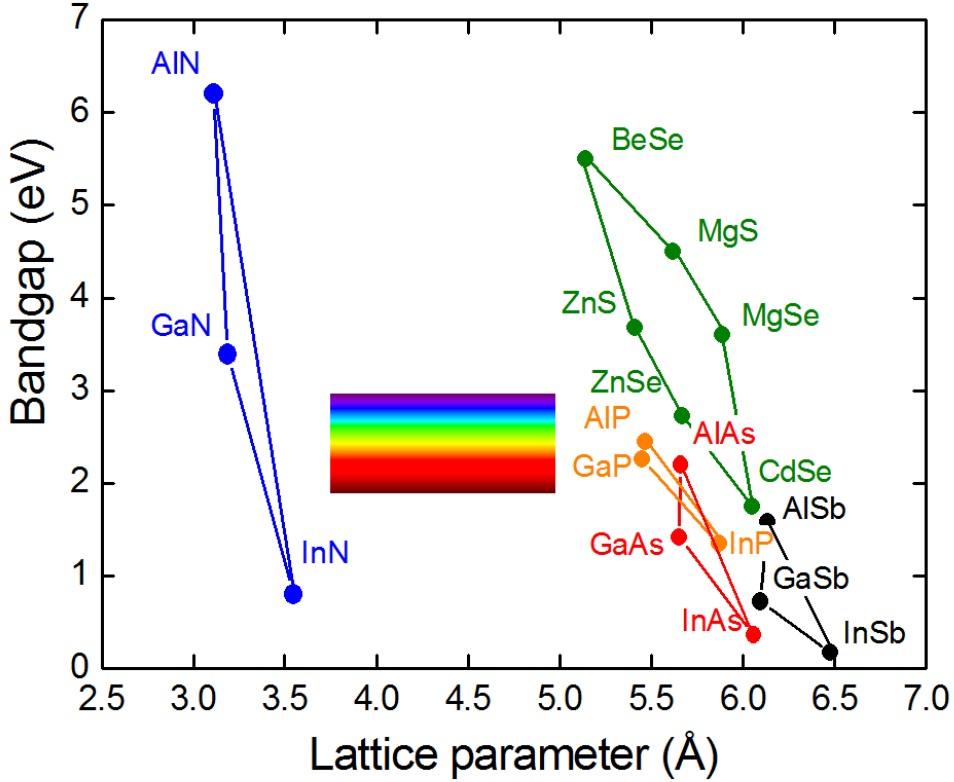
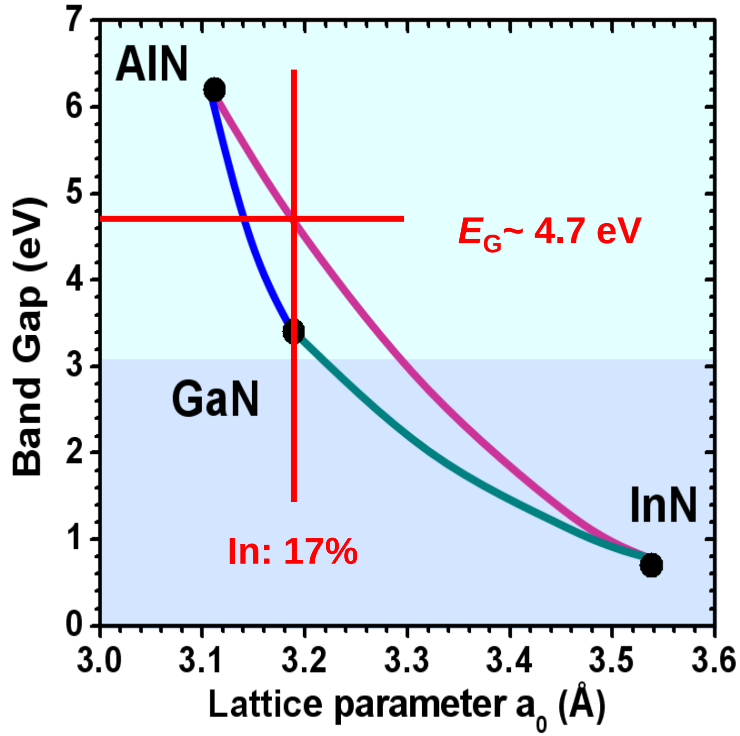
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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

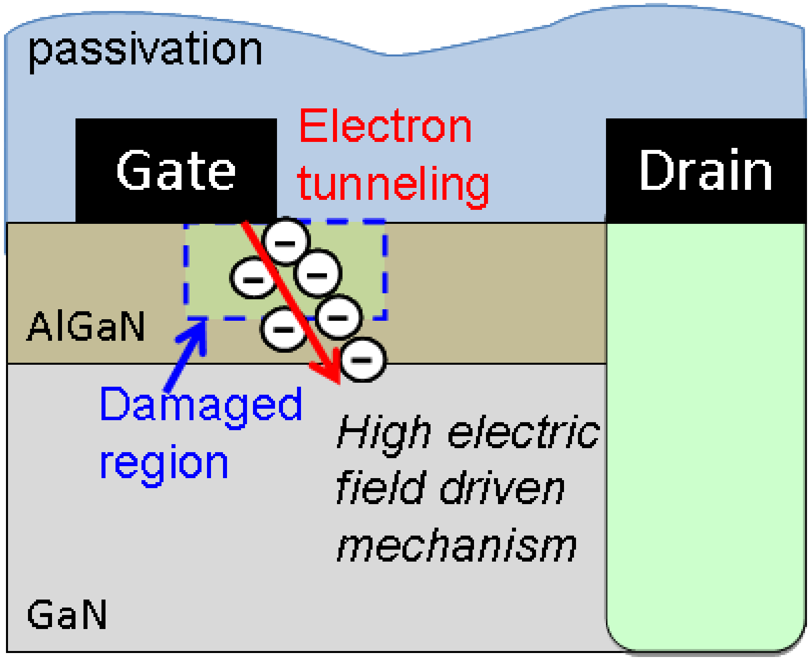
Lattice Matching ($Al_{0.83}In_{0.17}N$:GaN)



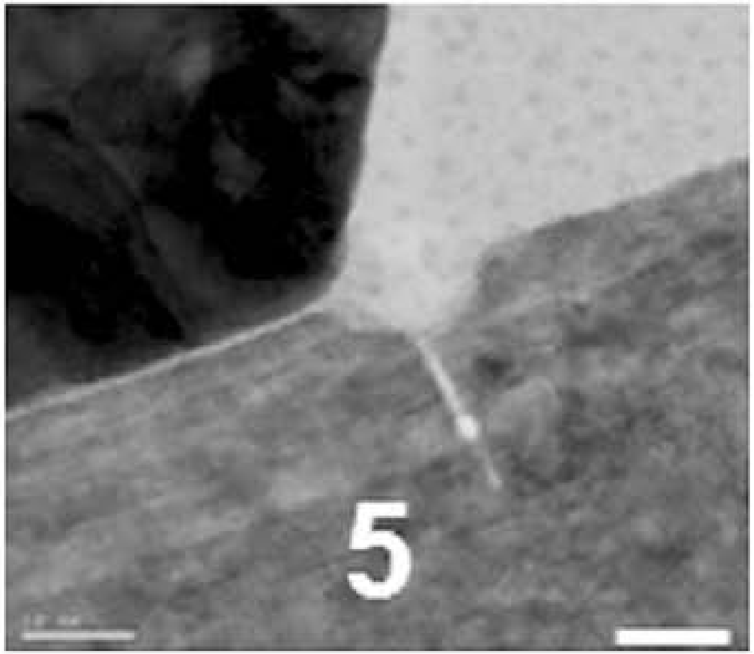


Materials

Lattice Matching: A Reliability Enhancer (?)



G. Meneghesso et al.

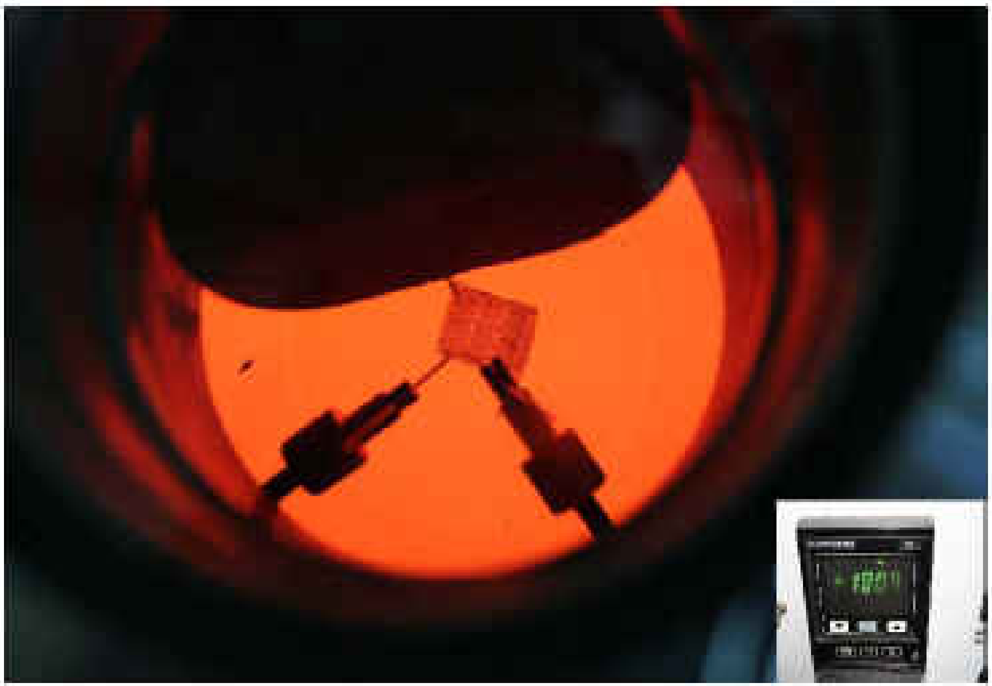


Park et al. (TRIQUINT)

Cumulative Strain (Mismatch + Piezo) Correlated to Device Degradation

Materials

AlInN/GaN High Temperature Stability (1000°C)



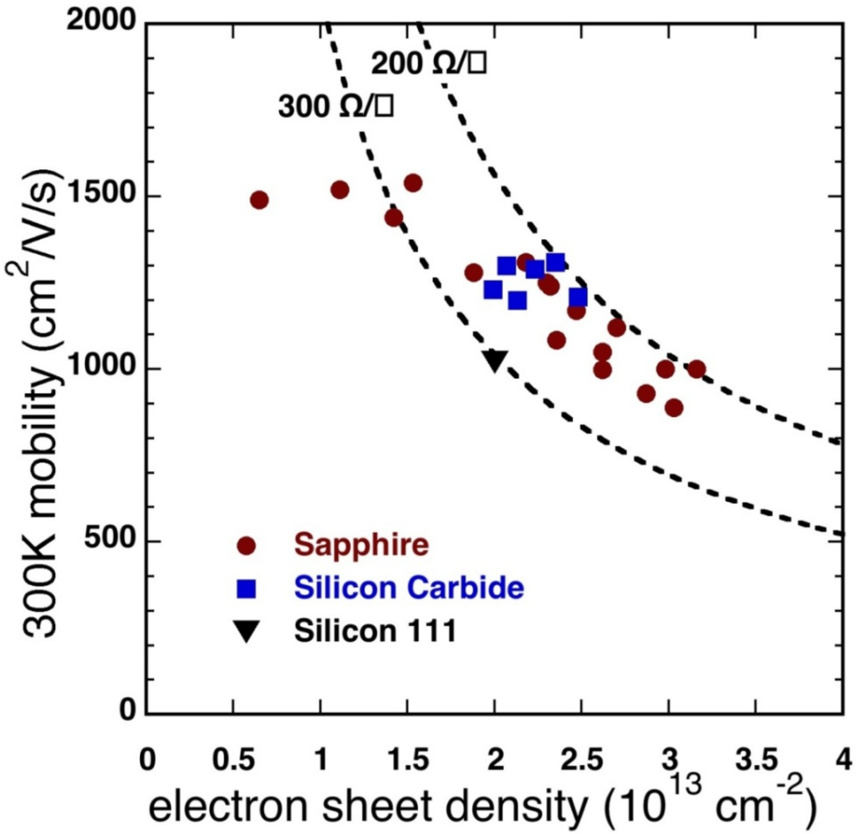
F. Medjdoub *et al*., IEDM 2006

AlInN/GaN HEMTs Survive 1000°C Temperatures

(Potential for High-T Electronics)

Materials

Substrate Choices



Silicon:
1,030 cm^2/Vs @ 2×10^{13} $/cm^2$
300 $\Omega/\square$ (–17% mismatch)

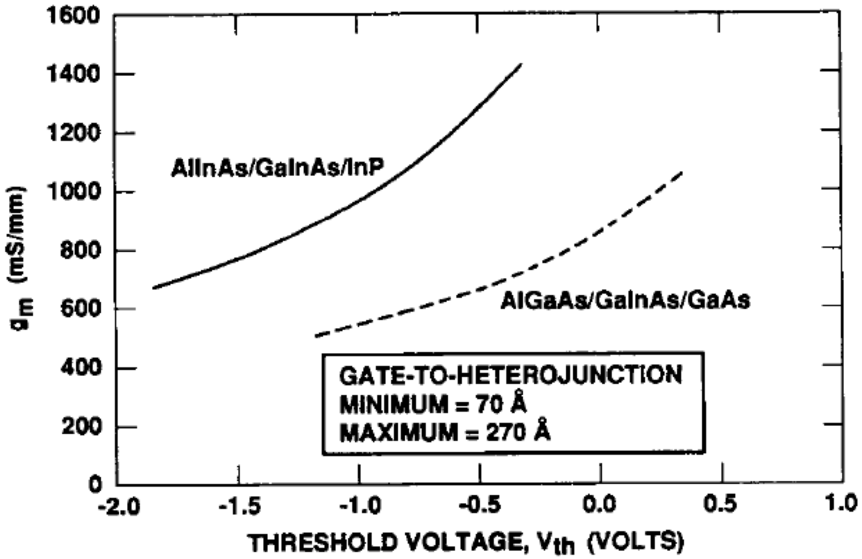
SiC:
1,300 cm^2/Vs @ 2.4×10^{13} $/cm^2$
205 $\Omega/\square$ (–3.5% mismatch)

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

Appl. Phys. Lett. ***89****, 062106 (2006)*

Materials

Surface Depletion: InP *vs*. GaAs HEMT Analogy



Ultra-High-Speed Modulation-Doped Field-Effect Transistors: A Tutorial Review

LOI D. NGUYEN, MEMBER, IEEE, LAWRENCE E. LARSON, SENIOR MEMBER, IEEE, AND UMESH K. MISHRA, SENIOR MEMBER, IEEE

Proc. IEEE, p.494 (1992)

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

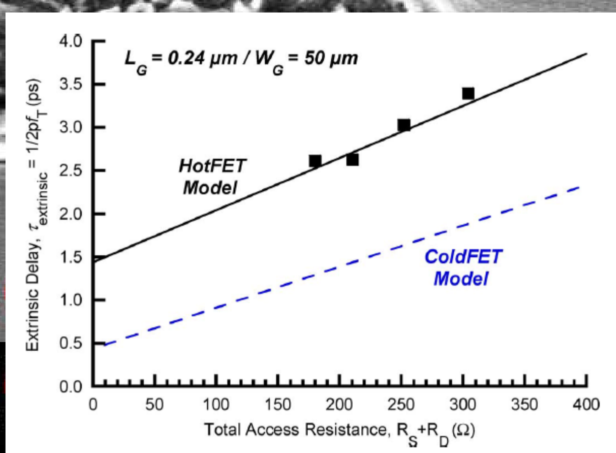
Requirements: Reduced S/D Spacing

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*



2914 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 53, NO. 12, DECEMBER 2006

At-Bias Extraction of Access Parasitic Resistances in AlGaN/GaN HEMTs: Impact on Device Linearity and Channel Electron Velocity

David W. DiSanto, *Member, IEEE*, and C. R. Bolognesi, *Senior Member, IEEE*

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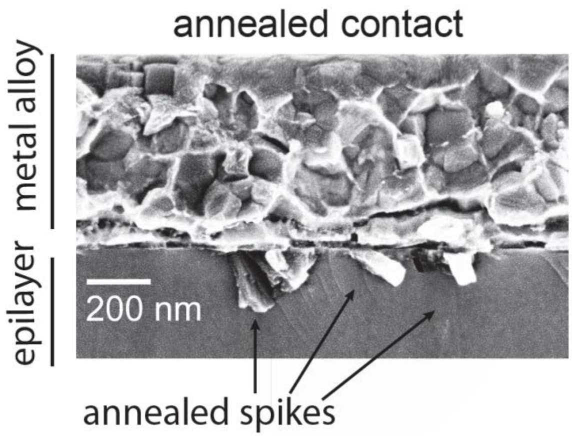
  - Large-Signal on Silicon (94 GHz)

Ohmic Contacts (1)



Metallization:

Ti / Al / Mo / Au

Yields

$R_C \approx 0.3$ to $1\ \Omega\cdot$mm

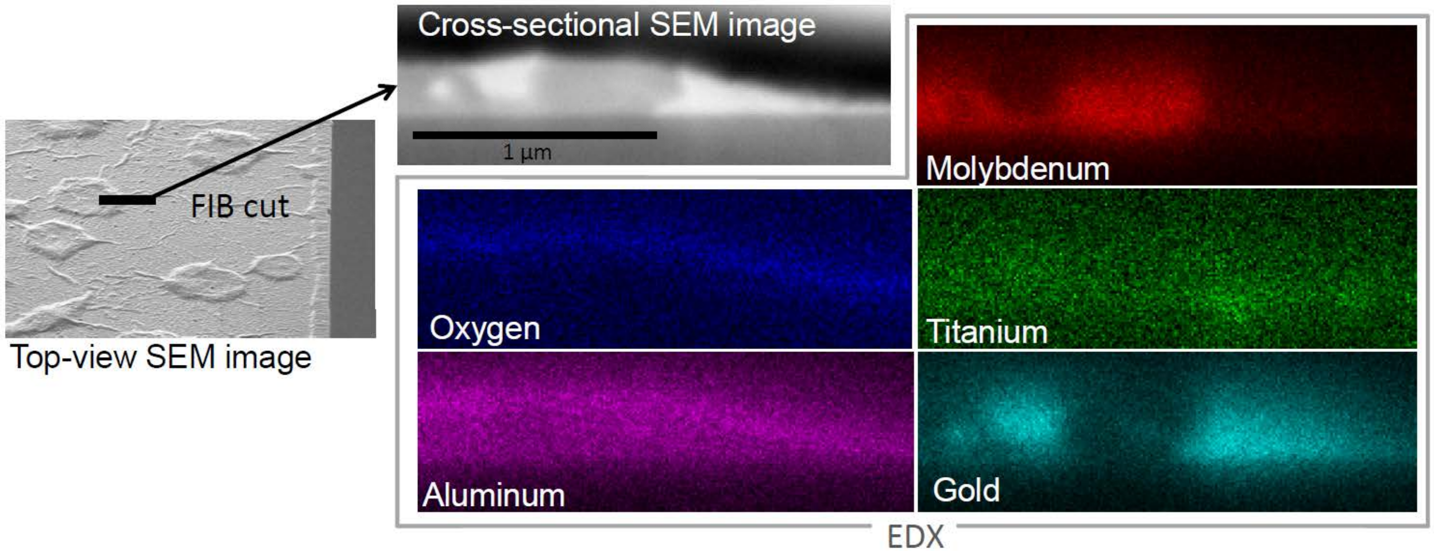
(strong variability)

Requirements:

- Good Morphology
- Low Contact Resistance

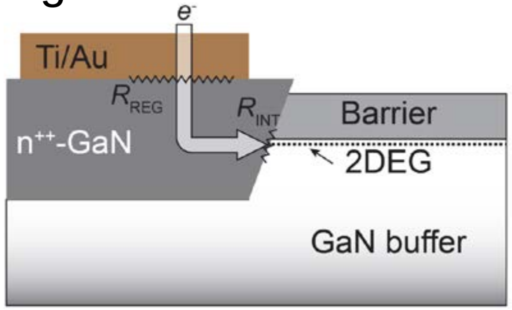
Rapid Thermal Annealing

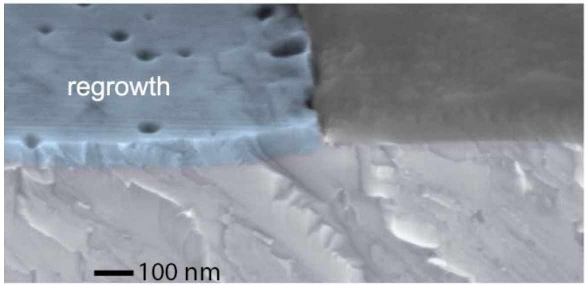
$T \sim 850$ºC

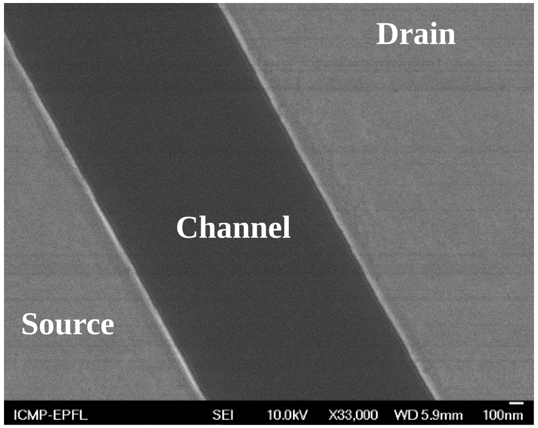


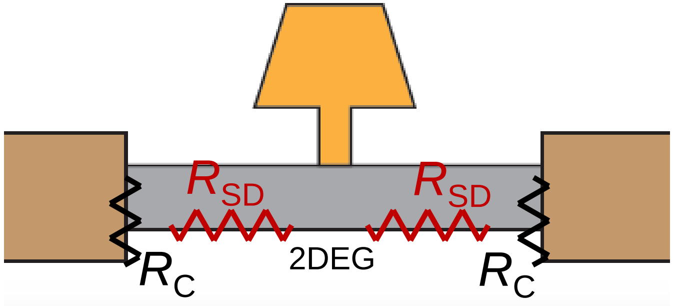
Regrown Contacts (2)

Regrown:







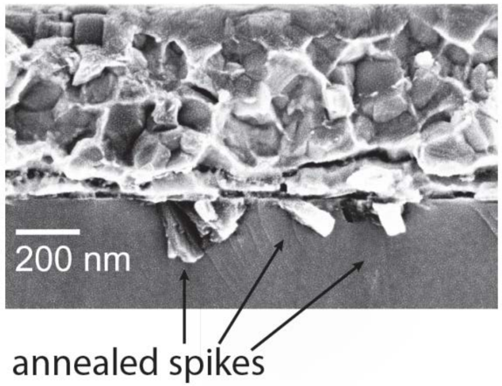


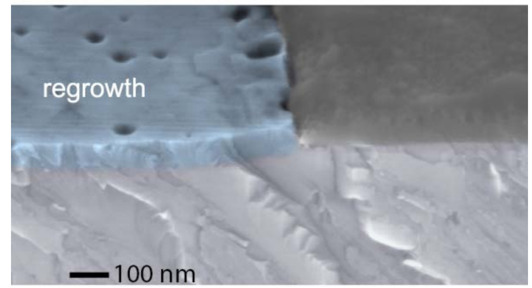
Beneficial for Short L_{SD} Spacings (R_{SD} < R_C)

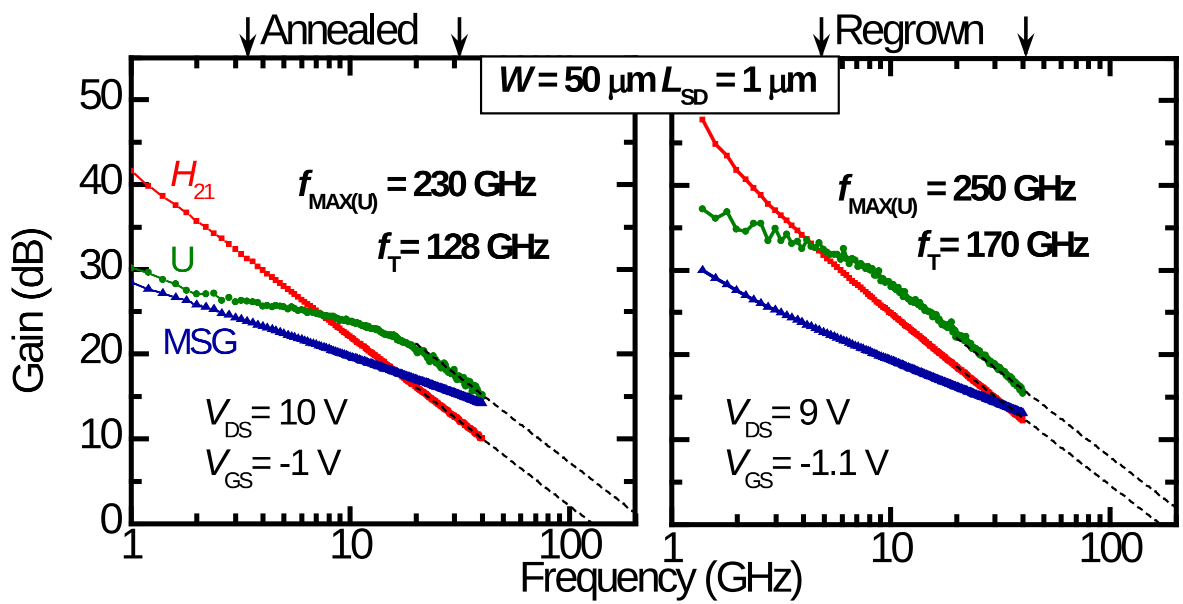
Better Reproducibility with Respect to Annealed Ohmics

(Best Example: Shinohara *et al.*, *HRL*)

Regrown Contacts (3)







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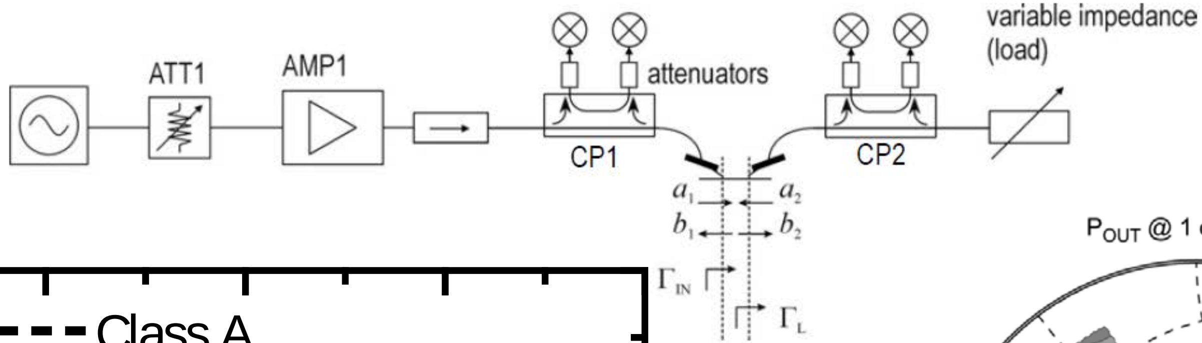
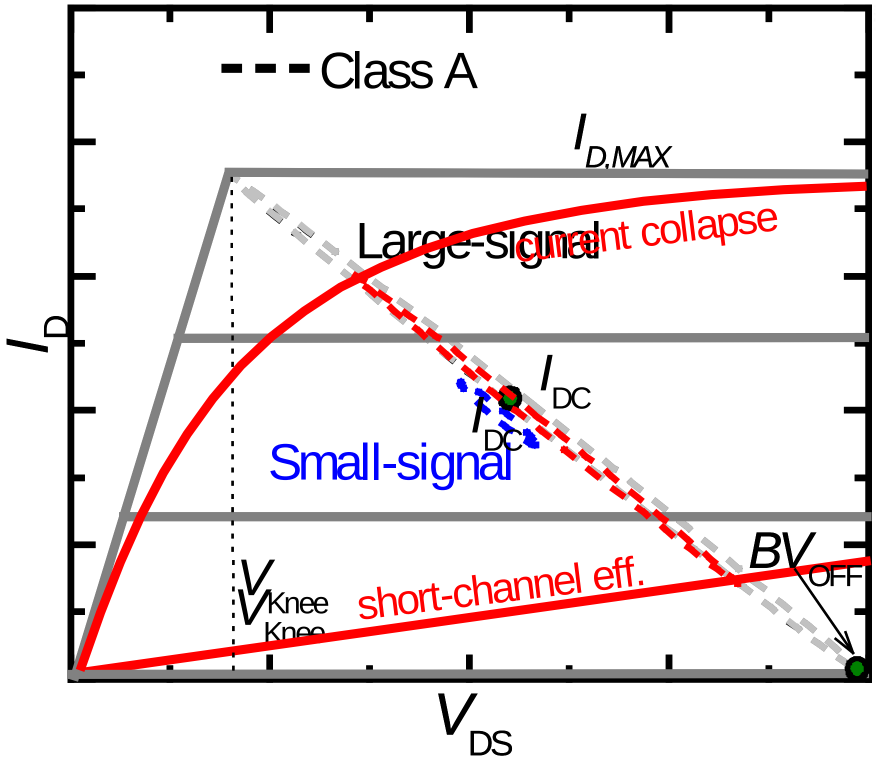
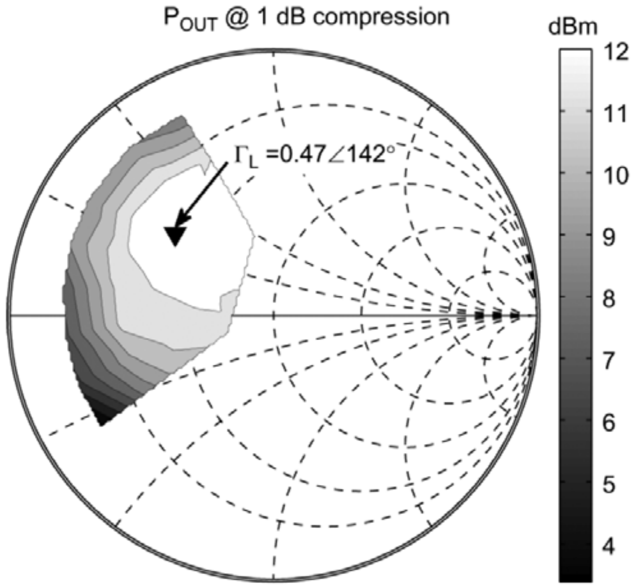
  - **Large-Signal on Silicon (94 GHz / W-Band)**

Large-Signal Operation







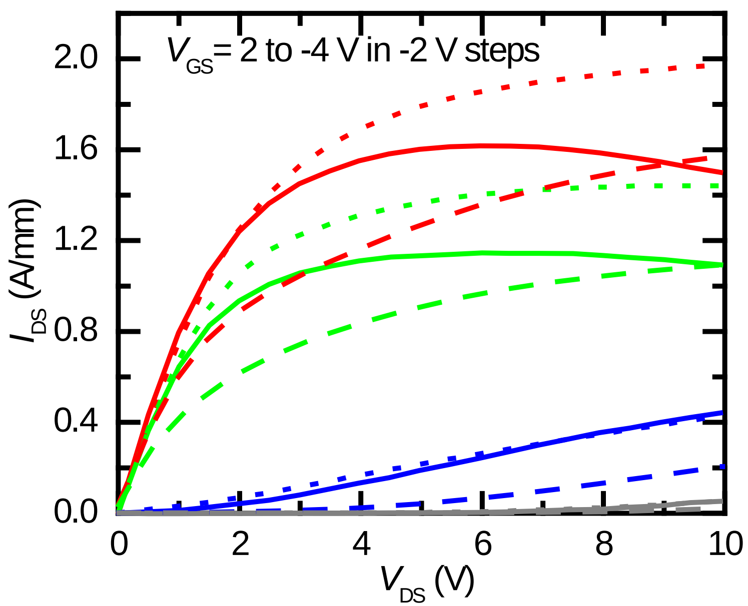
+ Output Impedance Matched for max P_{OUT}

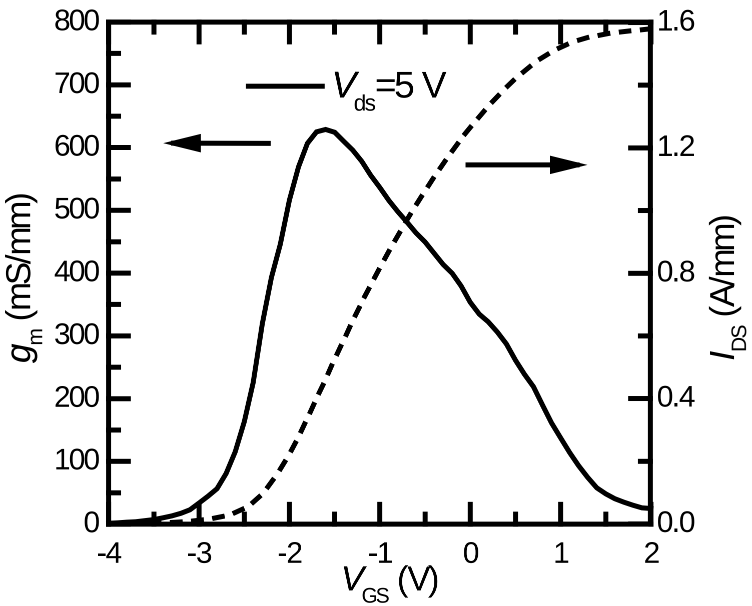
+ Current Collapse and SCEs Limit P_{OUT}

Large-Signal Operation (On Silicon)

d = 7.5 nm, L_G = 50 nm, L_{SD} = 2 µm on HR-Silicon.

Improved Buffer / Channel Design. Regrown Contacts.





DC Characteristics

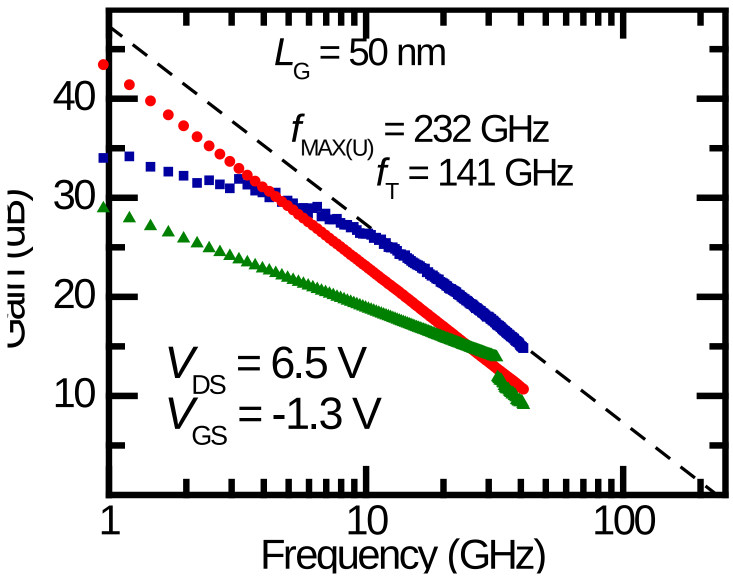
- + G_M > 650 mS/mm
- + Adequate Pinch-Off
- + Good Transport: μ = 1200 cm^2/Vs (300 Ω/sq)
- + Back-Barrier not Implemented

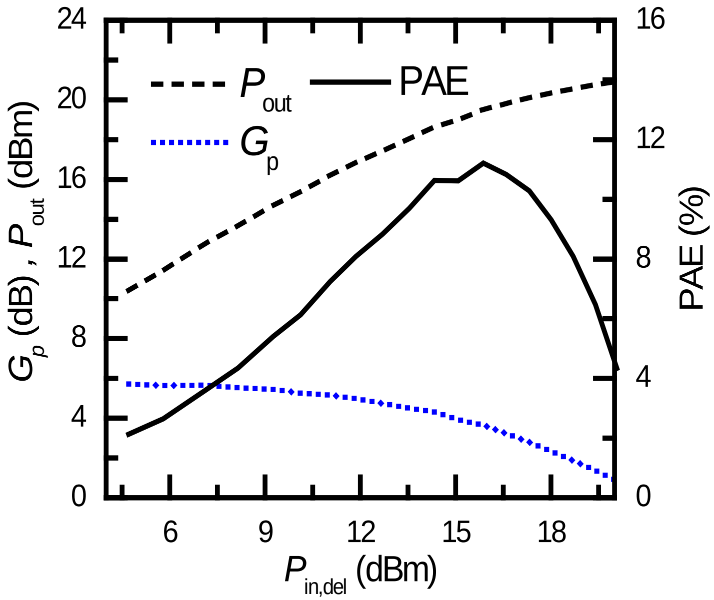
Large-Signal Operation

d = 7.5 nm, L_G = 50 nm, L_{SD} = 2 µm on HR-Silicon.

Improved Back-Buffer / Channel Design. Regrown Contacts

Power gain (Gp), output power (Pout), power added efficiency (PAE) at VGS = – 1.2 V and VDS = 9 V at 94 GHz for a 50 nm gatelength device, with source-drain spacing of 2 µm, source-gate spacing 0.5 µm and a total gate width of 100 µm





94 GHz Initial Results

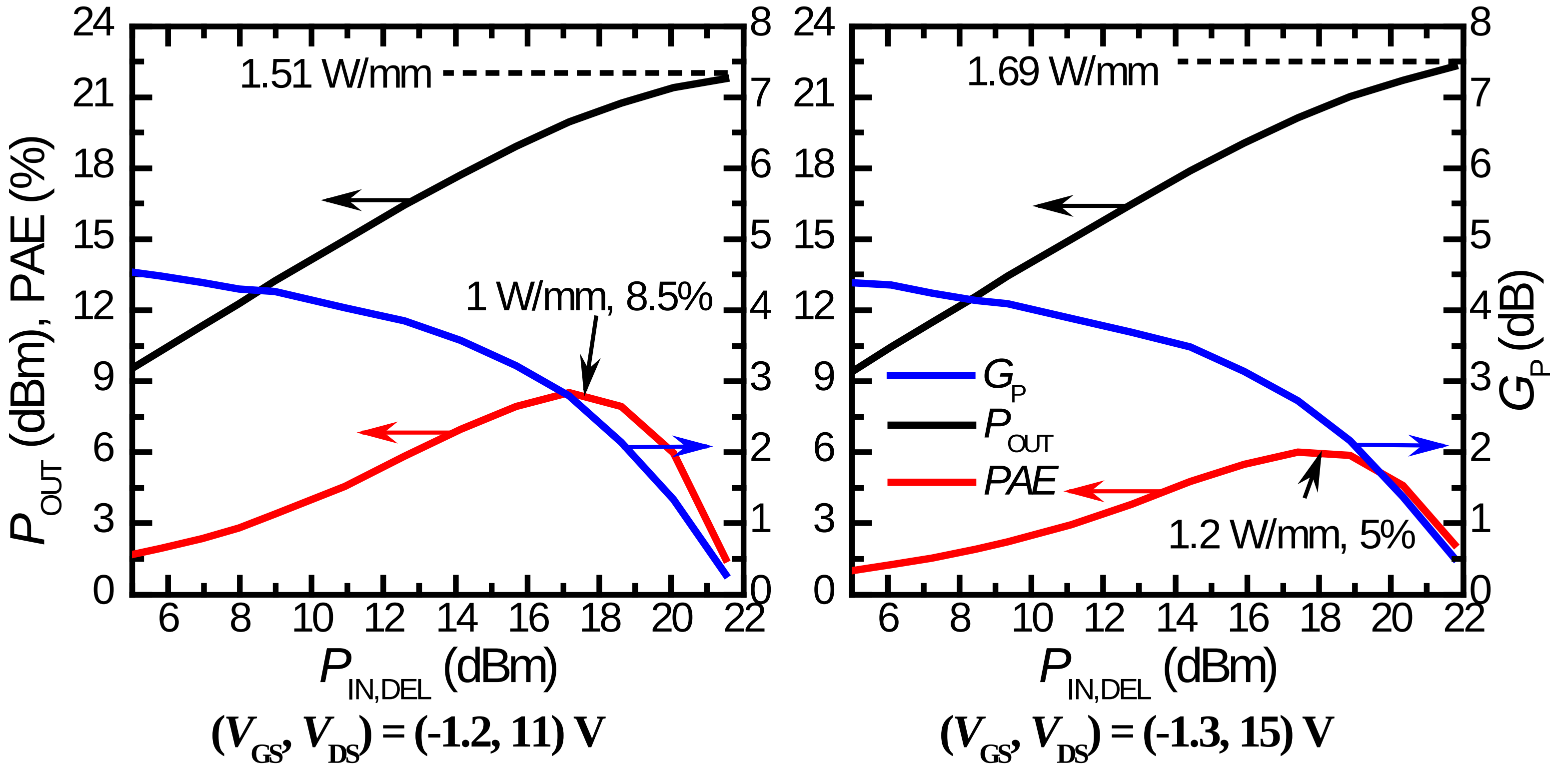
1 W/mm / PAE = 12% / G_P = 4 dB @ $P_{IN,Del}$ = 16 dBm

(Better than 1 W/mm Result on SiC)

Large-Signal Operation @ 94 GHz on SiC

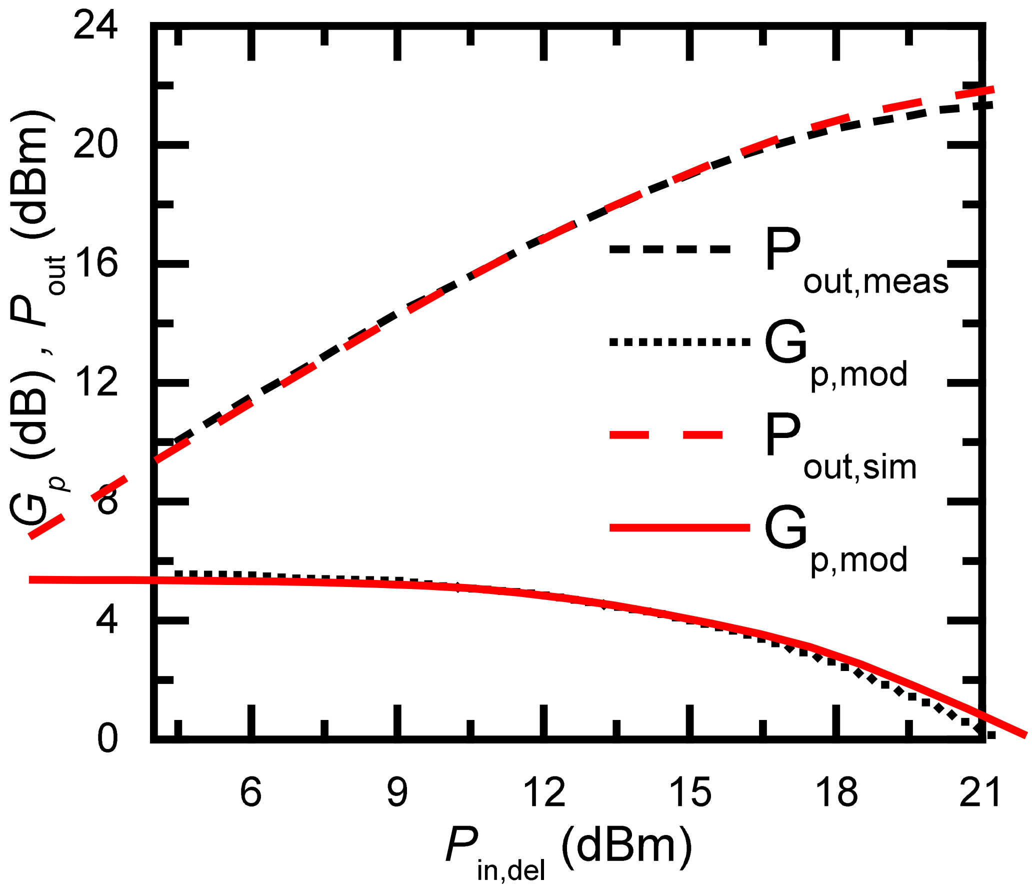
d = 6 nm, L_G = 100 nm, L_{SD} = 1 µm on SiC.

No Back-Barrier. Regrown Contacts.



Best results at 94 GHz for AlInN-based HEMTs on SiC

PDK and PA Prototype Development (1)



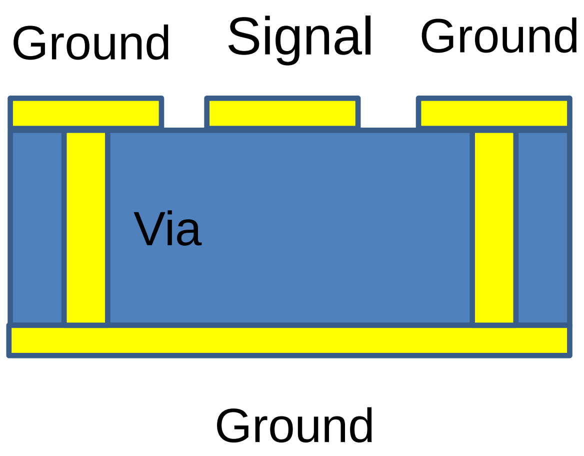
Large-Signal Model (Angelov) Harmonic Balance Simulation in ADS) vs. Load Pull Measurement at 94 GHz for a 2x50um AlInN/GaN on Si device.

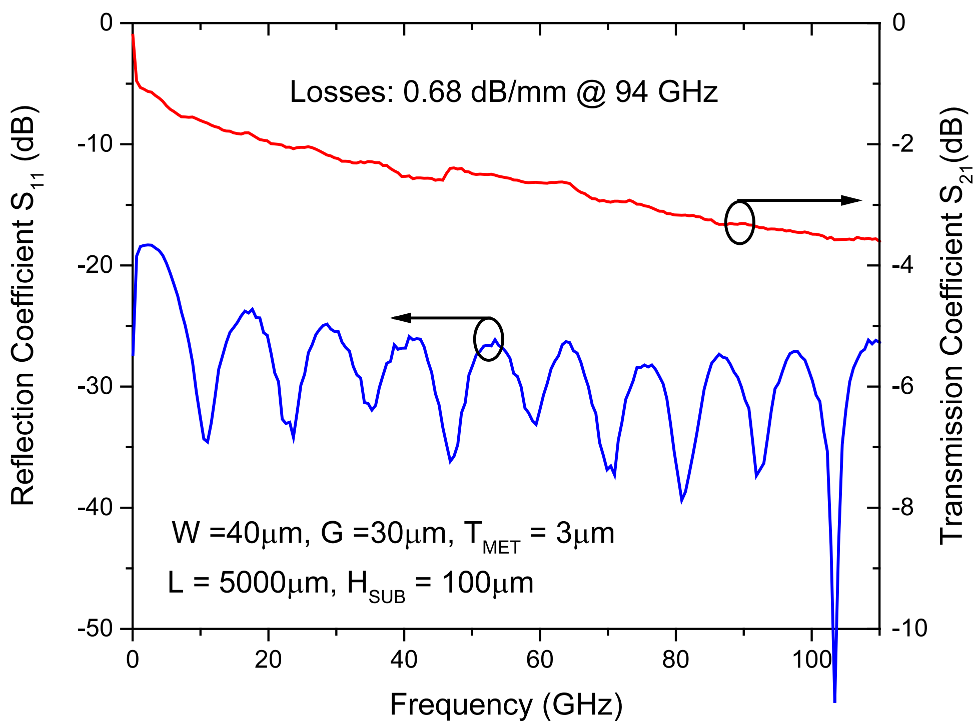
Process Design Kit PDK

Scalable Large-Signal Model (Gate Width & Fingers)

PDK and PA Prototype Development (2)

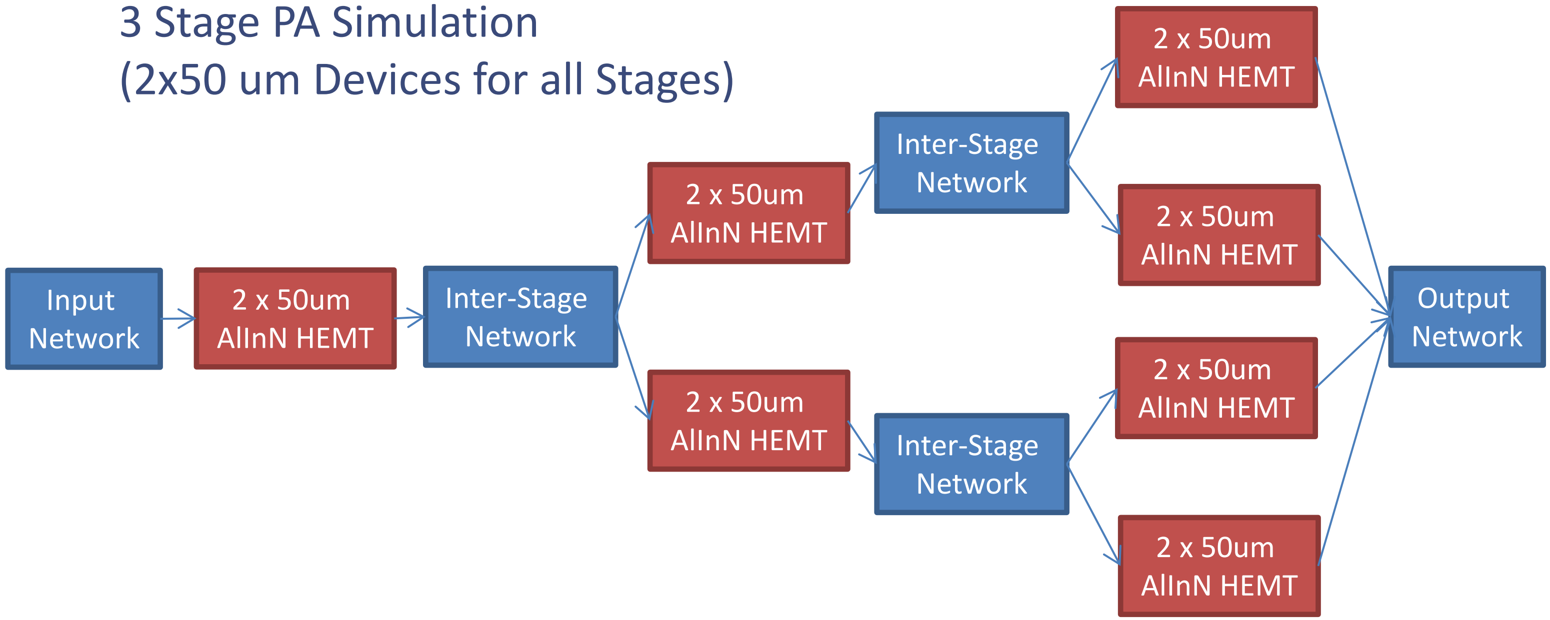
MMIC Process based on Grounded Coplanar Waveguides





PDK and PA Prototype Development (3)

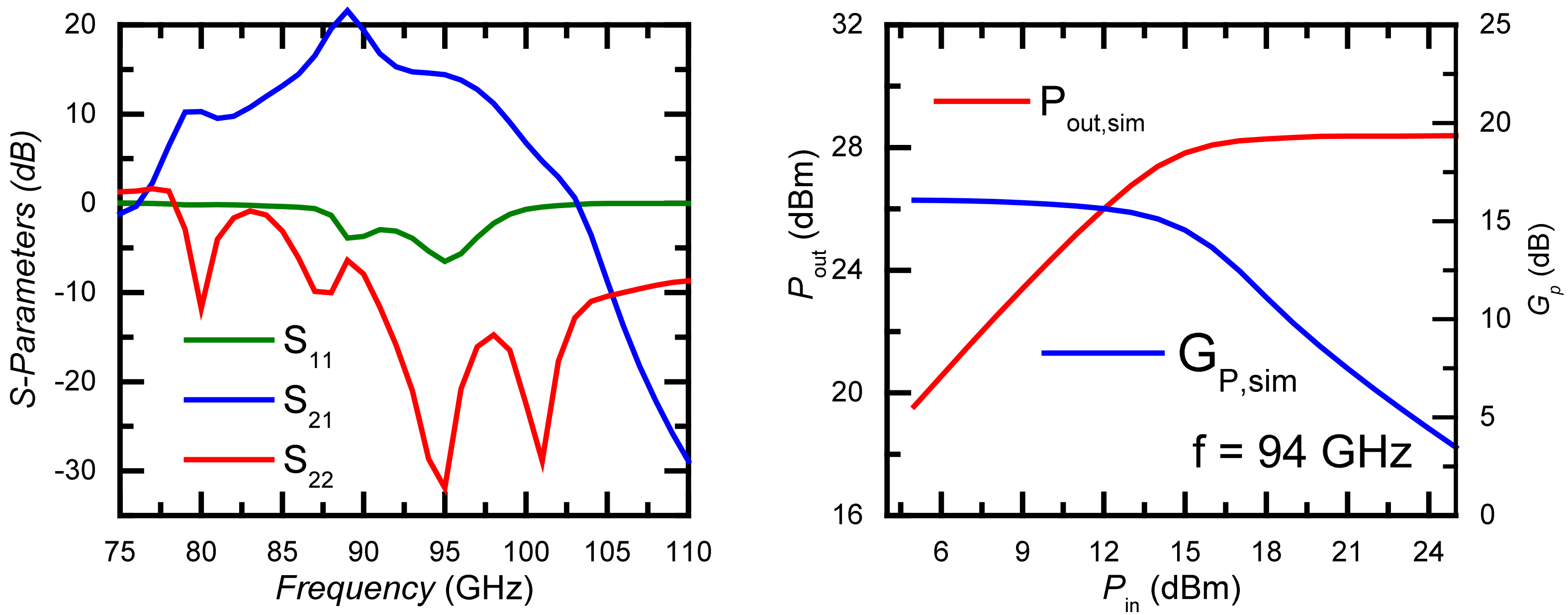
3 Stage PA Simulation
(2x50 um Devices for all Stages)



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_{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