GaN MMIC PAs for MMW Applicaitons

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Motivation for High Frequency Power sources
60 GHz – 110 GHz Frequency Spectrum

High Data Rate Wireless Links (10 Gbits/s)

Commercial Bands (E-band radio)

71 GHz – 76 GHz, 81 GHz – 86 GHz, 92 GHz – 95 GHz

Inter-Satellite

59.3 GHz – 64 GHz

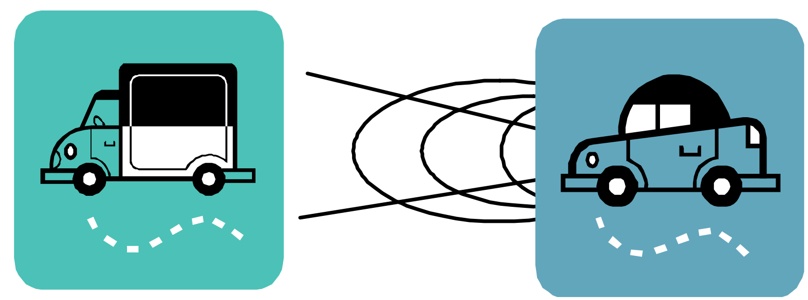
Active Millimeter-Wave Imaging

94 GHz SAR, Phase Array Radar

(Space based W-band radar for earth studies.)

RF Sources for THz Multiplier Diodes

Fundamental Power for THz Space Array Spectroscopy

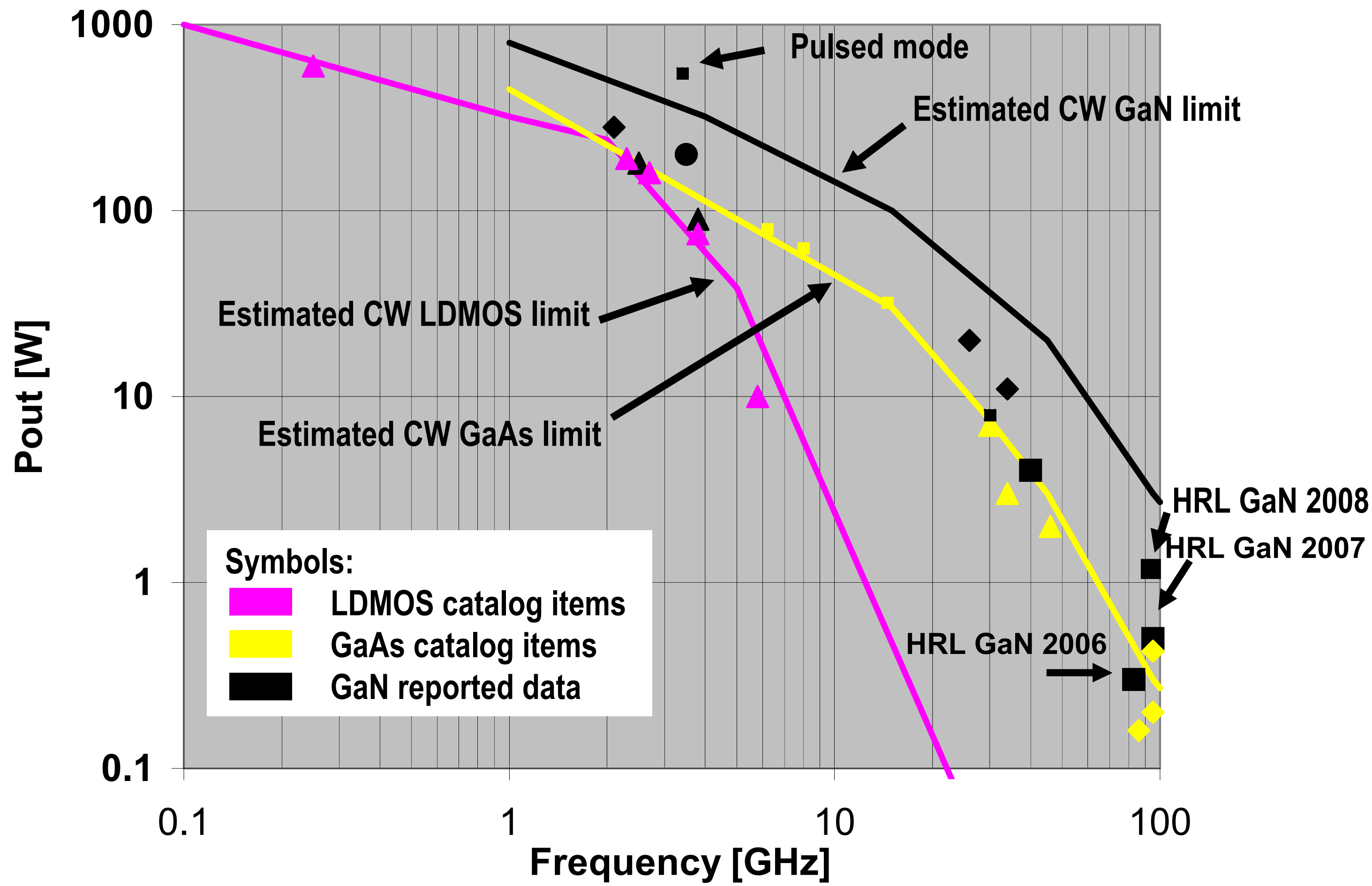


Power Required ≈ Watts

Available Sources < 200 mW

GaN MMIC ≈ 3 W at 95 GHz

Microwave and Millimeter-wave Solid State Sources



Output power per single die.

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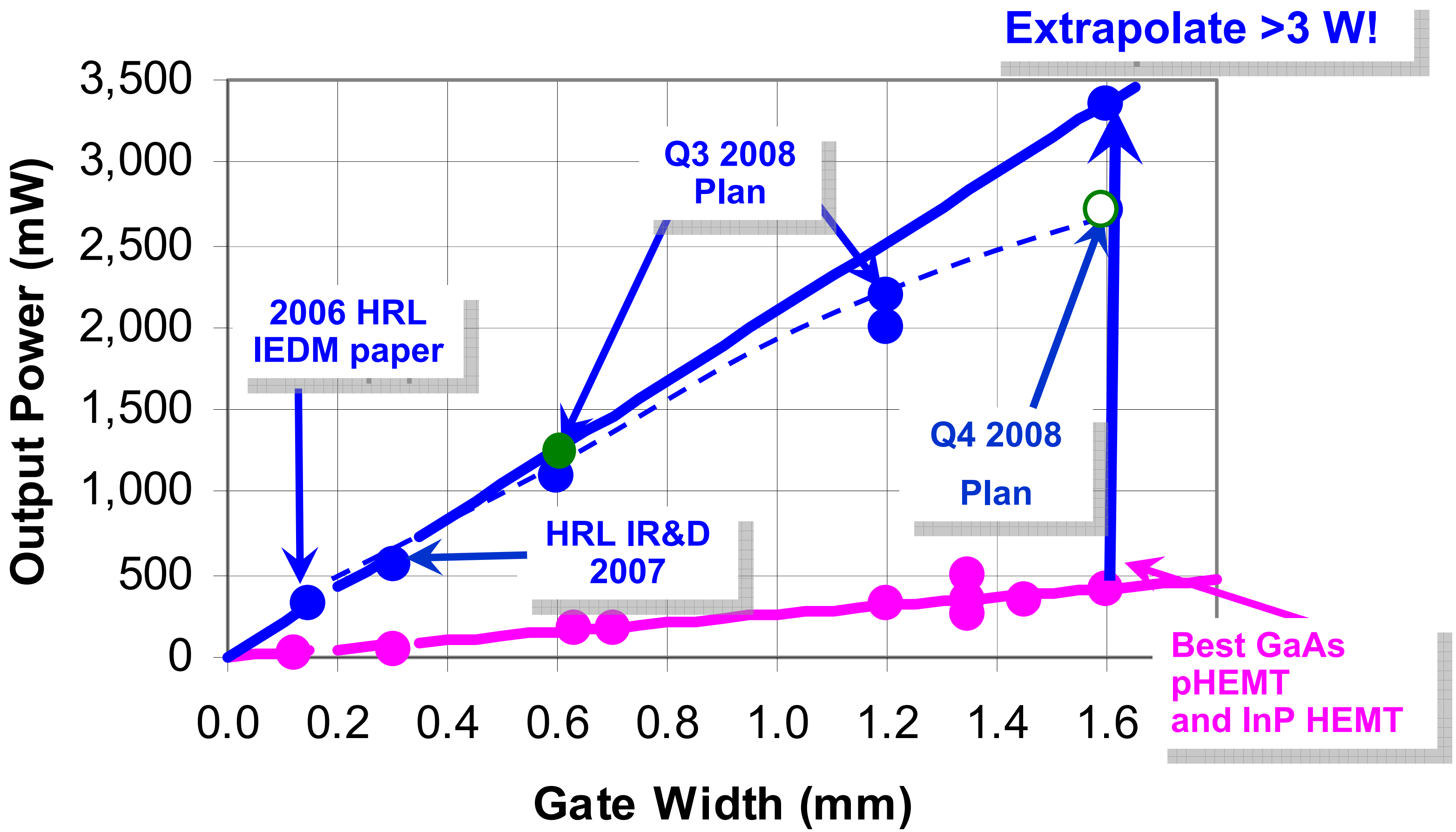
HRL W-band GaN Roadmap



Disruptive W-band GaN Power MMICs

8X higher power density than mmW GaAs pHEMT

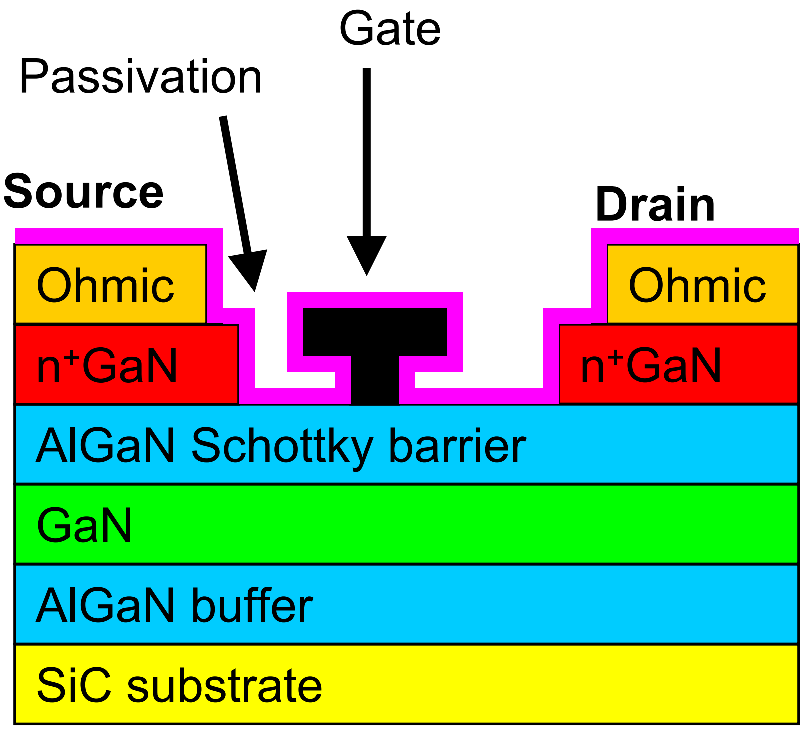
Cost trade-off estimate for 3 Watt W-band SSPA

	GaAs pHEMT SSPA	GaN SSPA
8-way waveguide combining	8-way splitter and 8 way combiner required	Power combining not required
Number of WR-10 power modules	8	1
Number of MMIC's per module	3 (Attenuator, Phase Shifter, Power Amplifier)	1 (Power Amplifier only)
Hand-tuning to obtain phase and amplitude match for combining	Combiner arms tuned manually	No tuning

3 Watt 95 GHz GaN SSPA is Cost Effective

W-band GaN MMIC Device

T-gate device Lg = 0.12 μm



N+ layer facilitates fabrication of ohmic contacts. Double Heterojunction Structure

Low ohmic contact resistance < 0.2 Ω/mm.

Comparable to GaAs pHEMT's and InP HEMT's.

Smooth ohmic metal edges.

Recessed gate

Bi-layer e-beam gate litho

Lg = 0.12 μm for Ka-band

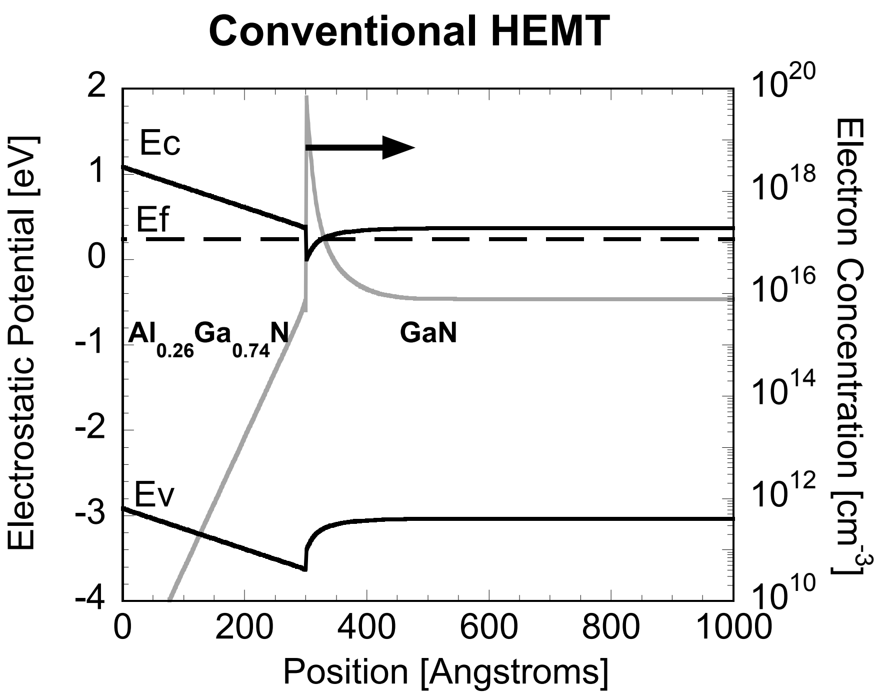
SiN passivation and capacitor dielectric

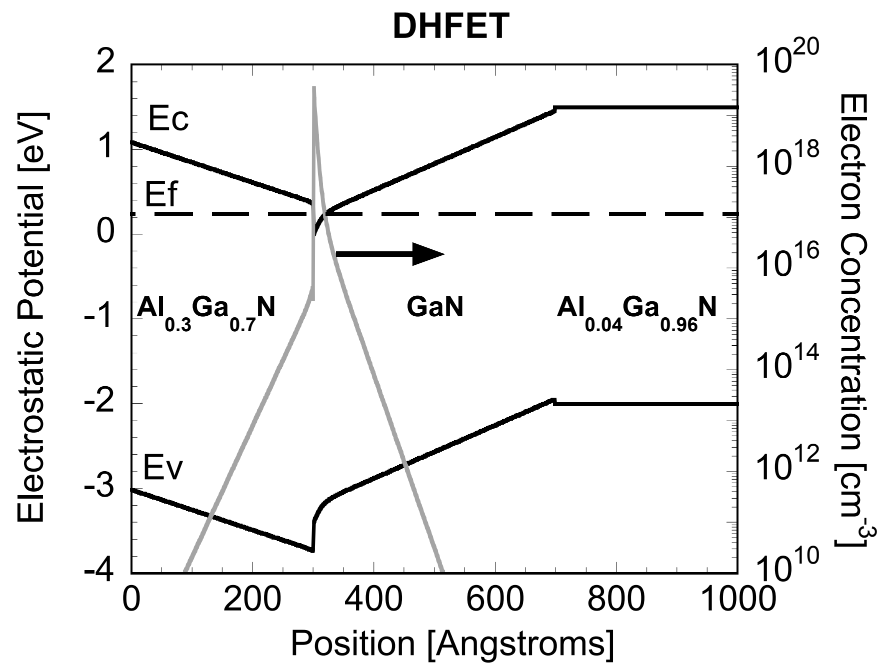
2 μm Source-Drain separation

TaN 50 Ω/Square resistor

Epi resistors

Short Channel Effects - Buffer Isolation





Techniques used to improve backside confinement and buffer isolation

Doping

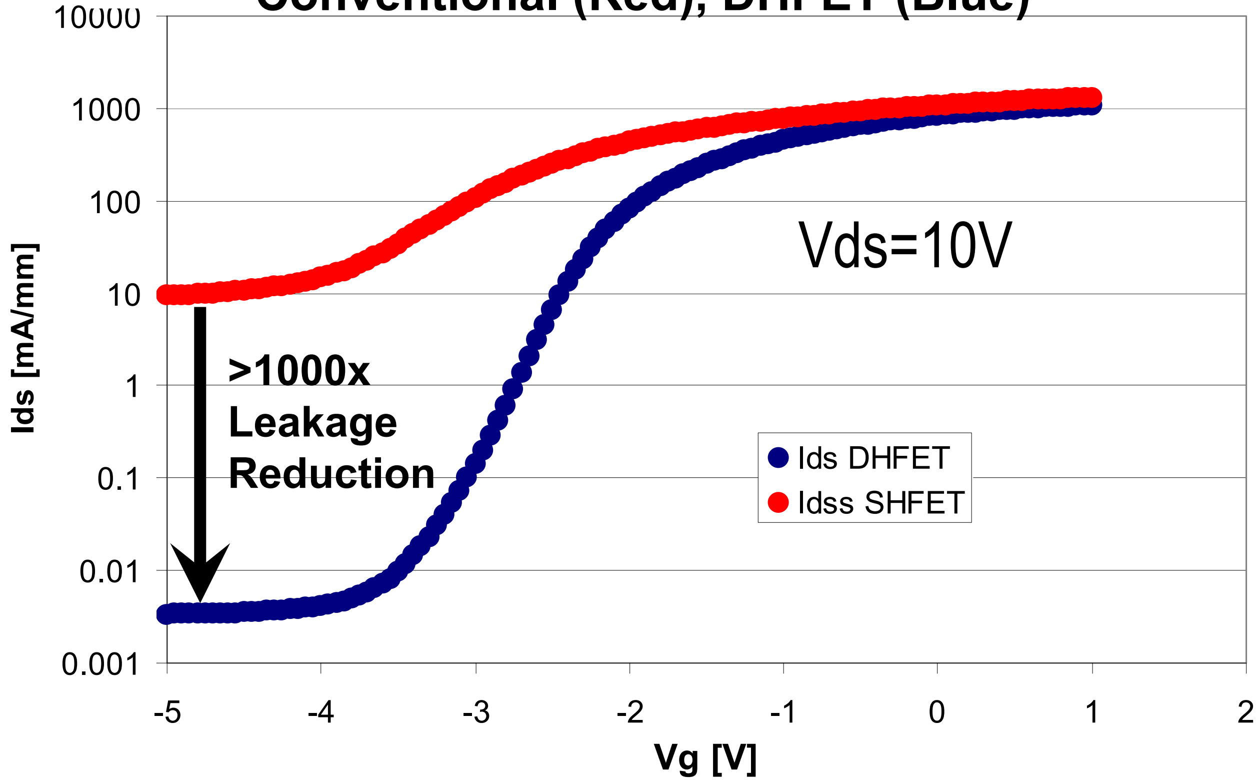
- **Fe doped buffer layer; Y.-F. Wu et al., El. Dev. Lett., Vol. 25, pp 117-119**
- **C doped buffer layer; S. Rajan et al., El. Dev. Lett., Vol. 25, pp 247-249**

Polarization Engineering

- **GaN DHFET structure; M. Micovic et al., IEDM 2004 Digest, pp 807-810**
- **InGaN back barrier; T. Palacios et al., El. Dev. Lett., Vol. 27, pp 13-15**

Short Channel Effects - Buffer Isolation

Transfer curves of Lg = 0.12 μm GaN HEMTs
Conventional (Red), DHFET (Blue)

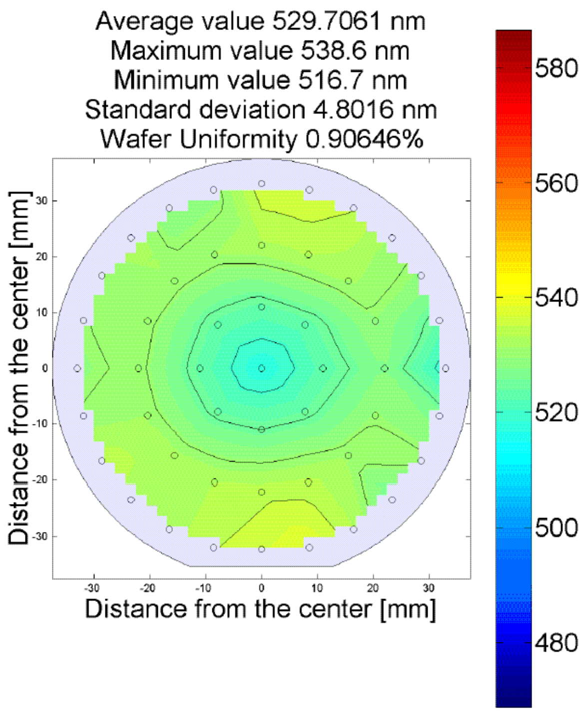


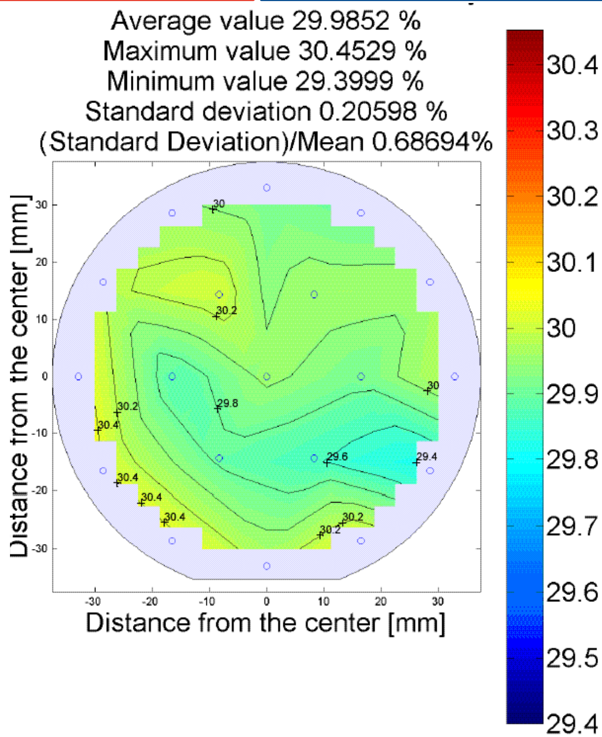
DHFET Structure:

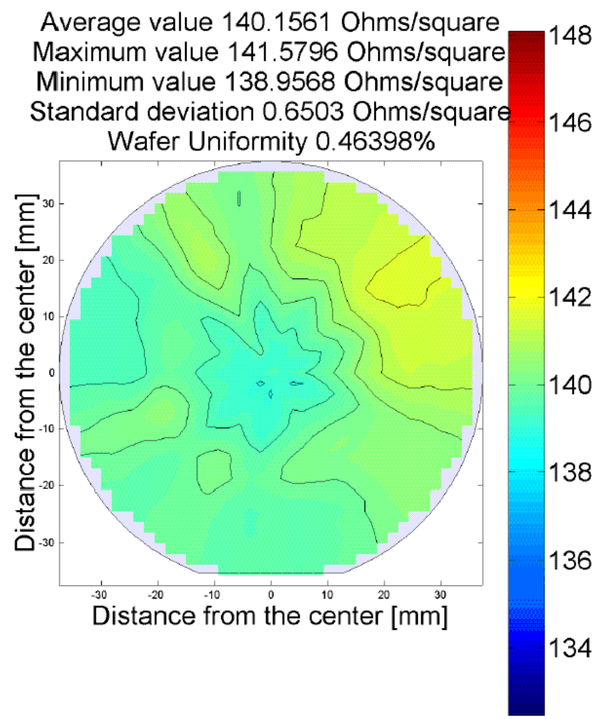
-Improved Back-Channel Confinement,

-Reduced sub-threshold drain leakage current.

Uniformity Better than 1% over 3” Wafer





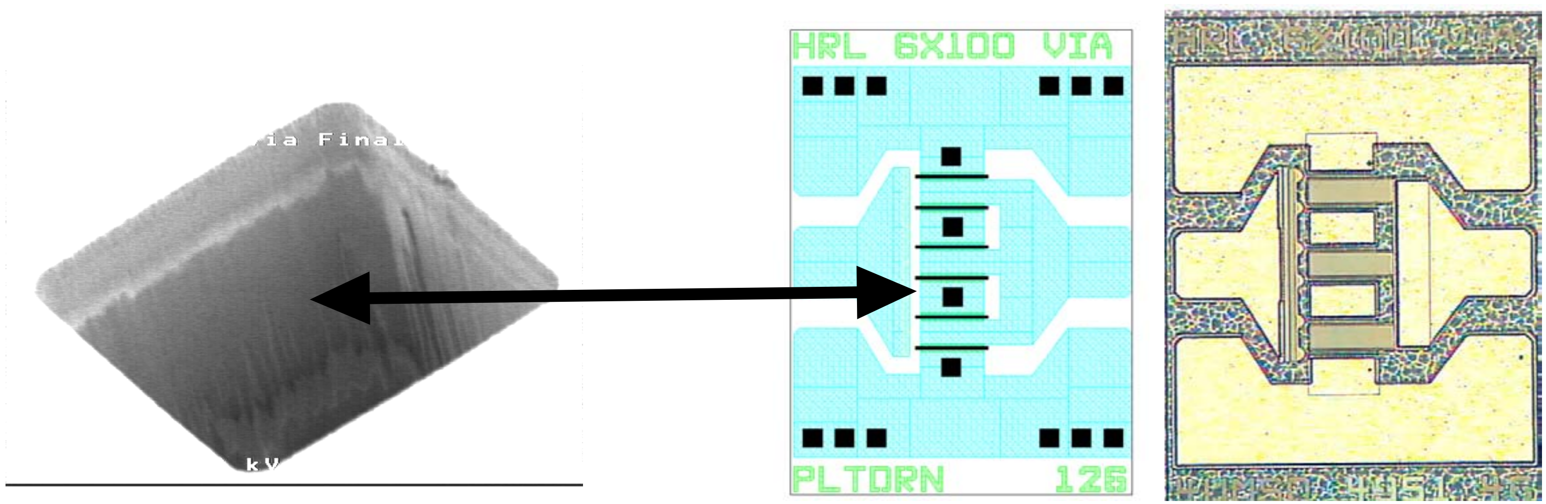


Epi Thickness 0.90 % **AlGaN % 0.68 %** **Sheet resistance 0.46 %**

Uniformity = Std. Dev. / Mean No edge exclusion

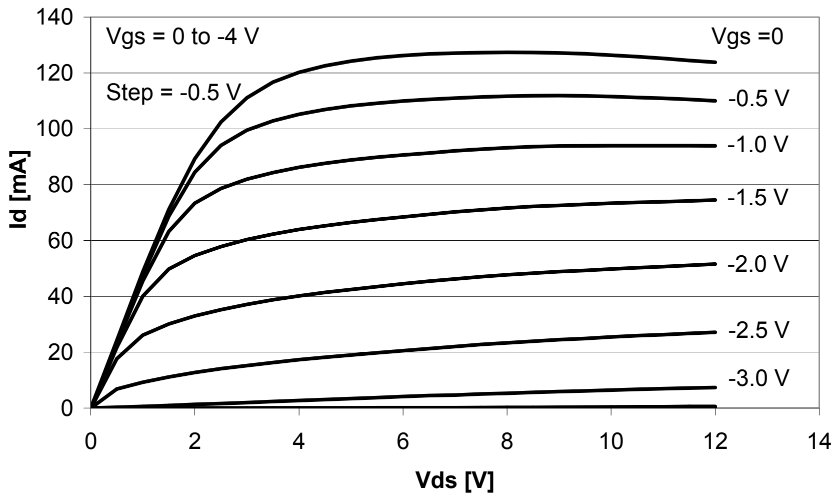
Individual Source Vias

- 30x30 vertical wall vias in 50 μm substrate
- Enables microstrip MMICs
- Low source inductance < 10 pH
  - Critical for high power W-band power amp performance

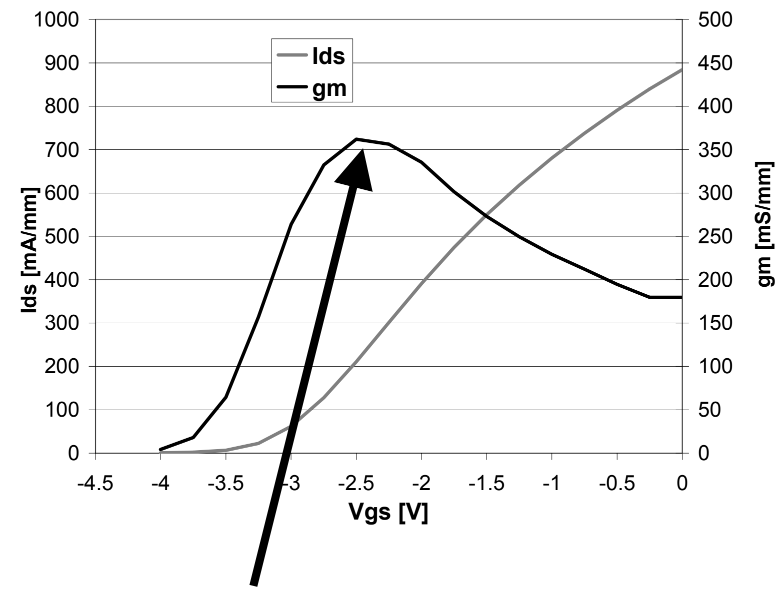


DC Device Characteristics

L_g = 0.1 μm, W_g = 4 x 37.5 μm GaN HFET

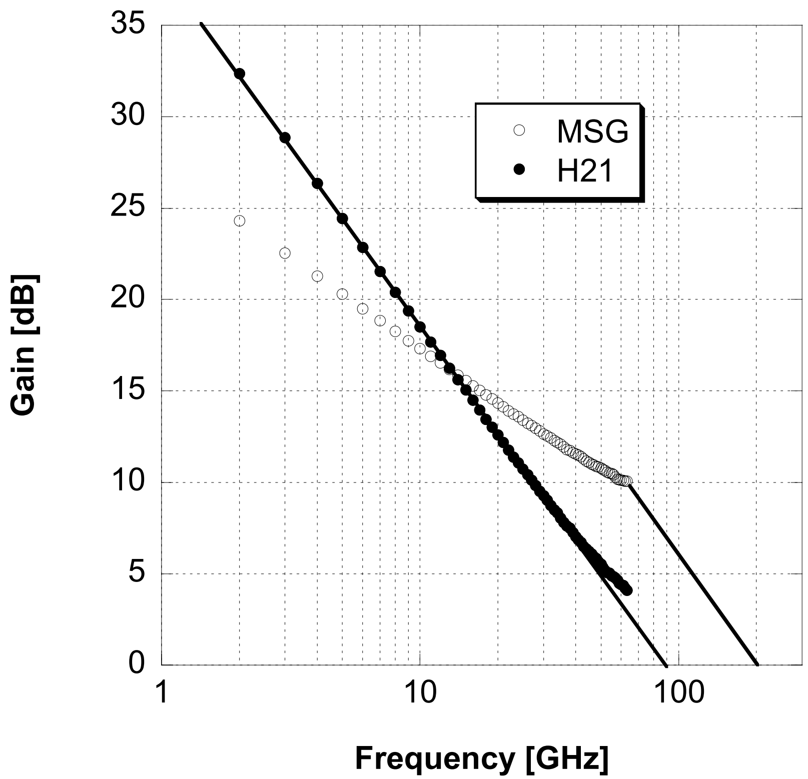


Id_{ss} = 900 mA/mm



g_m of 360 mS/ mm at V_{ds} = 12 V

Small Signal RF Performance

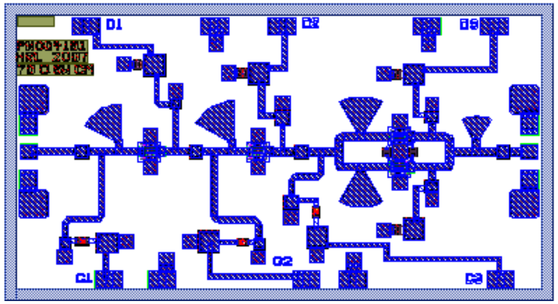


f_T = 90 GHz

f_{max} = 200 GHz

L_g = 0.1 μm, W_g = 4 x 37.5 μm GaN HFET V_{ds} = 10 V, I_{ds} = 45 mA.

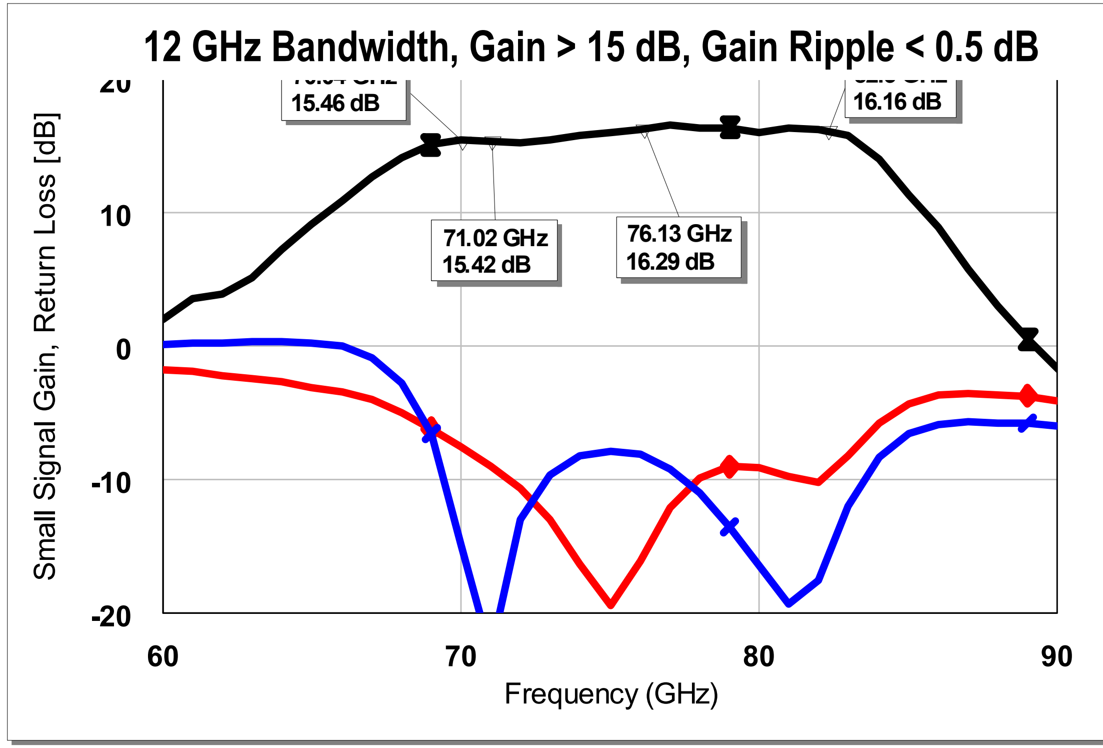
500 mW 70 GHz GaN MMIC PA



70 GHz MMIC Chip Layout
Size 3.4 mm x 1.3 mm

Operating Voltage = 15 V

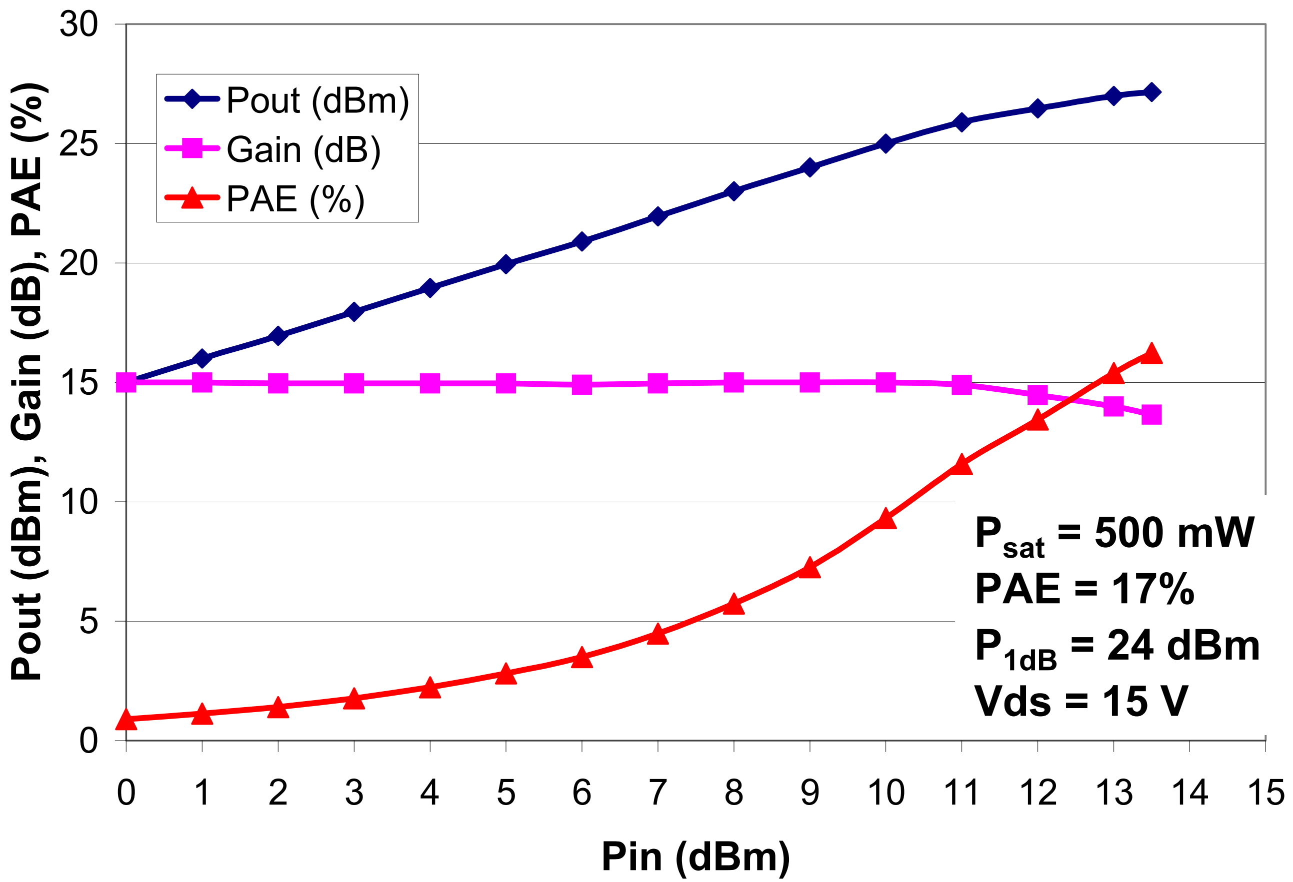
Measured Gain > 15 dB



Measured small signal gain of 70 GHz 500 mW GaN MMIC PA.

Performance meets design goal.

Output power of 70 GHz MMIC measured at a frequency of 76 GHz

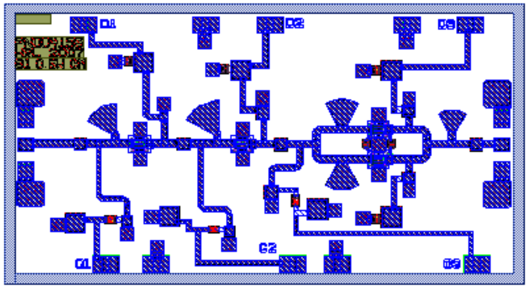


Comparison of 70 GHZ MMIC Performance with the best commercial pHEMT

Parameter	70 GHz GaN MMIC PA	Commercial GaAs pHEMT
Gain	>14 dB	> 5 dB
P_{1dB}	24 dBm	20 dBm
Psat	27 dBm	22 dBm
PAE	16.5 %	
Input return loss	< -8 dB	< -4 dB
Output return loss	< - 8 dB	< -2 dB

The most powerful MMIC reported to date at 70 GHz

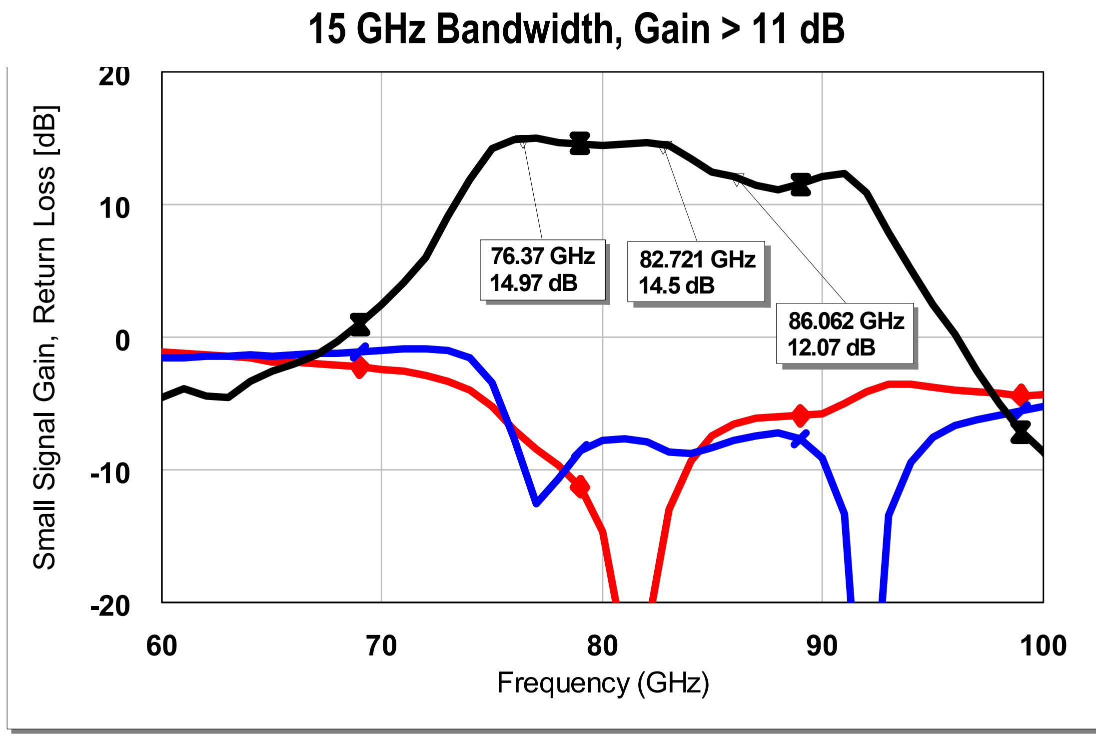
500 mW 80 GHz GaN MMIC PA



80 GHz MMIC Chip Layout
Size 3.4 mm x 1.3 mm

Operating Voltage = 15 V

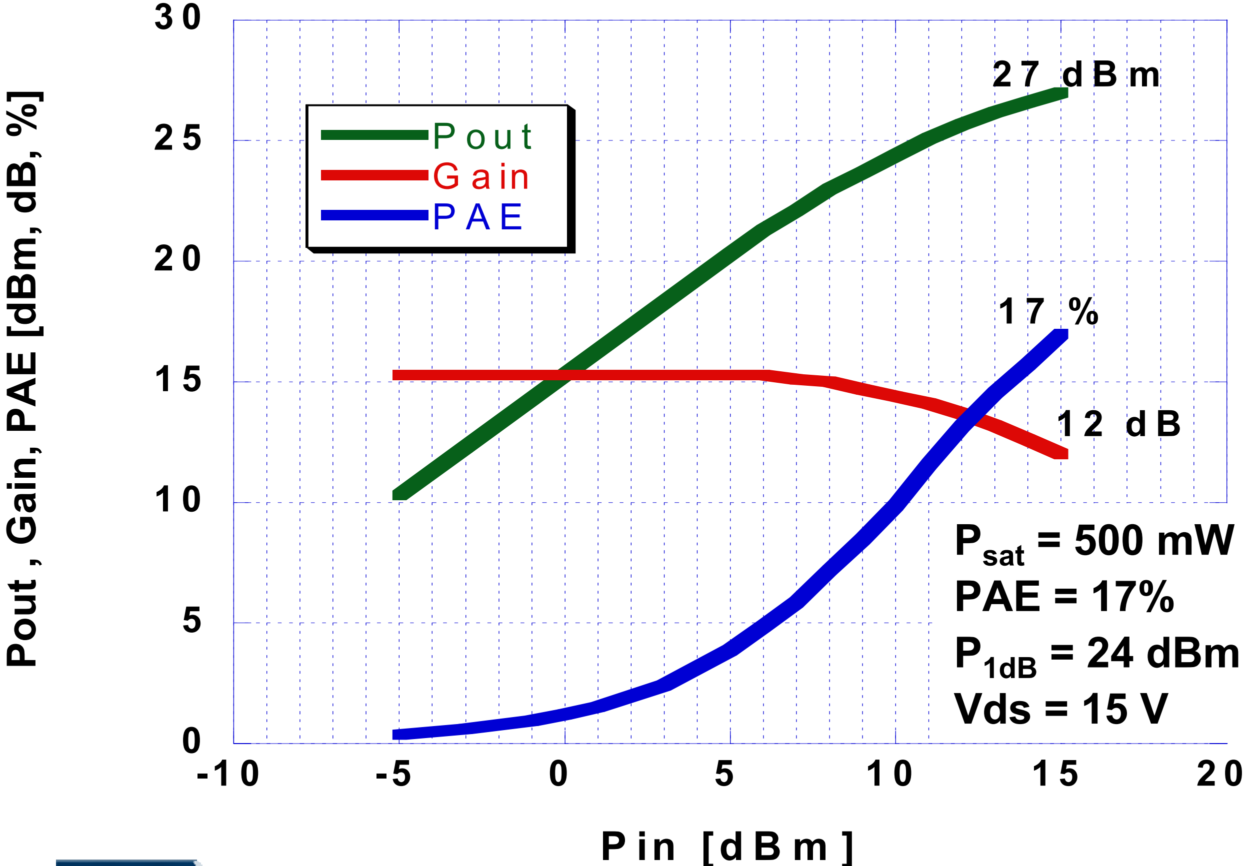
Measured Gain > 11 dB



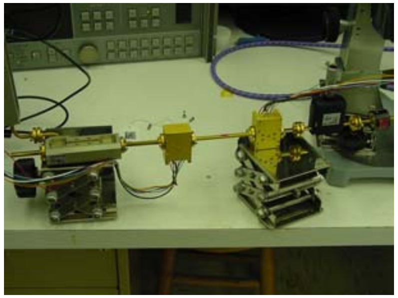
Measured small signal gain of 80 GHz 500 mW GaN MMIC PA.

MMIC Designed for E-band Radio Band

Output power of 80 GHz MMIC measured at a frequency of 83 GHz



P_{sat} = 500 mW
PAE = 17%
P_{1dB} = 24 dBm
Vds = 15 V



Power modules using 2006 GaN SR parts used as a power source.

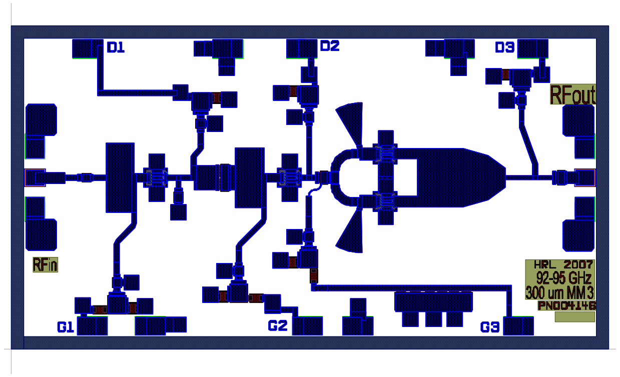
Highest Output Power and Efficiency reported for a solid state source at this frequency.

Comparison of 80 GHZ MMIC Performance with the best commercial pHEMT

Parameter	80 GHz GaN MMIC PA	Commercial GaAs pHEMT
Gain	>11 dB	> 5 dB
P_{1dB}	24 dBm	20 dBm
Psat	27 dBm	22 dBm
PAE	17 %	
Input return loss	< -7 dB	< -4 dB
Output return loss	< - 7dB	< -2 dB

The most powerful MMIC reported to date at 80 GHz

500 mW 90 GHz GaN MMIC PA

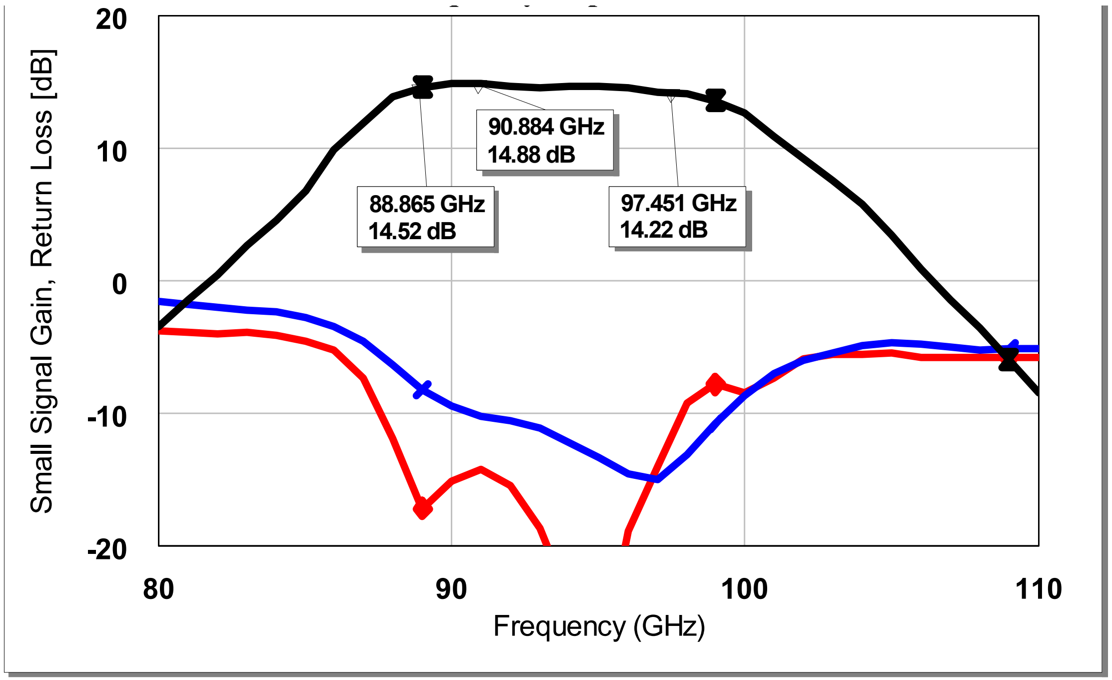


90 GHz MMIC Chip Layout
Size 2.4 mm x 1.3 mm

Operating Voltage = 15 V

Measured Gain > 15 dB

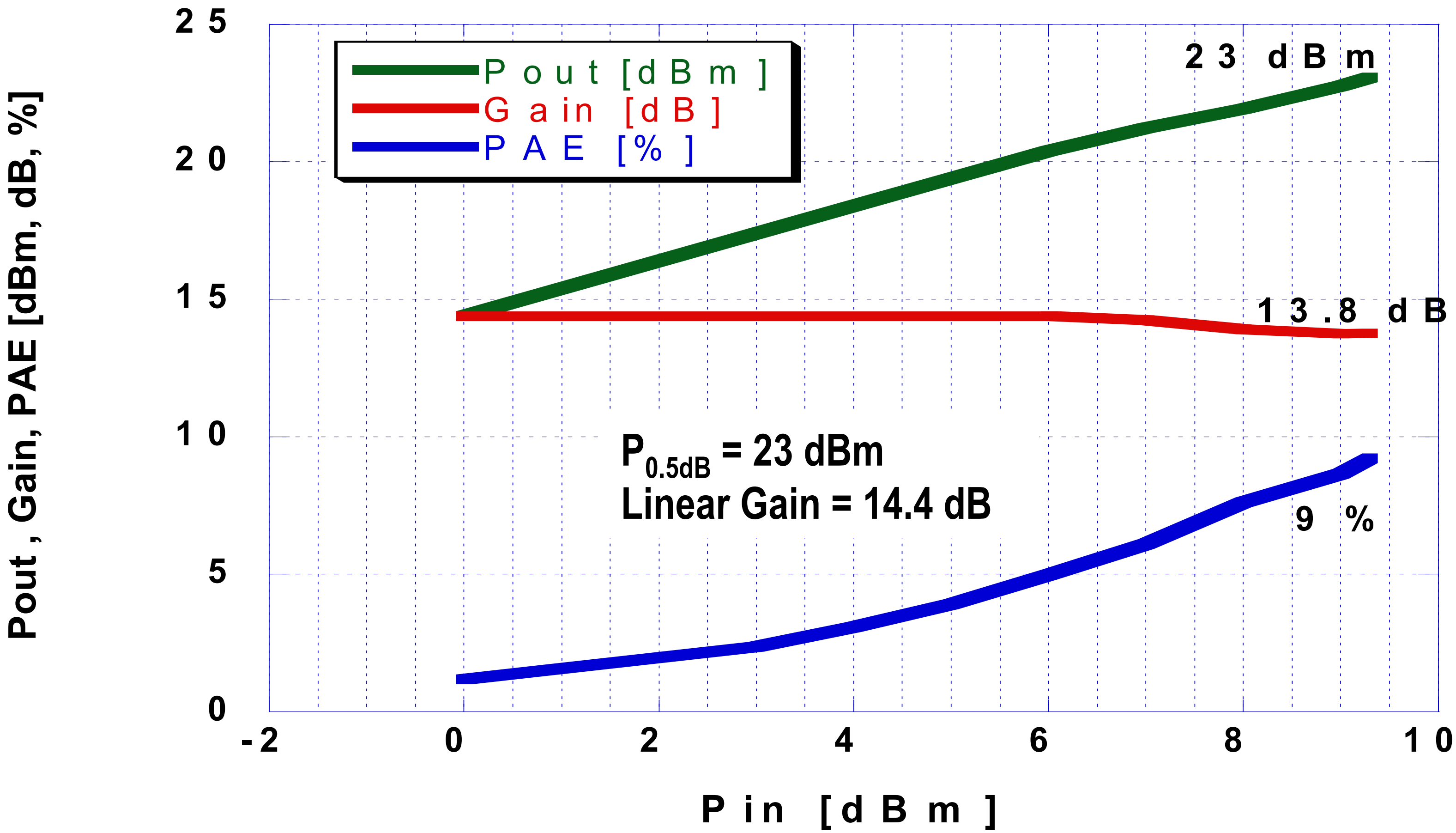
Flat Response over 92 GHz- 95 GHz frequency band.
9 GHz Bandwidth, Return Loss < -10 dB



Measured small signal gain of 90 GHz 500 mW GaN MMIC PA.

Performance Meets Design Goals

Output Power of 90 GHz GaN MMIC measured at a frequency of 94.75 GHz

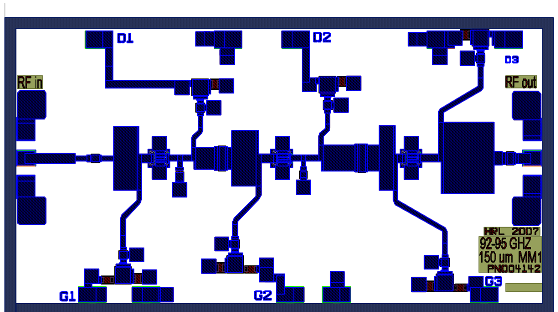


Output power limited by available input drive, circuit less than 0.5 dB compressed. HRL is building a power source using GaN MMIC to test the power.

Comparison of 90 GHZ MMIC Performance with best commercial GaAs pHEMT

Parameter	HRL 90 GHz GaN MMIC PA	GaAs pHEMT
Gain	>14 dB	> 10 dB
Gain Ripple	< 0.5 dB	< 1 dB
P_{1dB}	>23 dBm	20 dBm
Psat	To be measured	23 dBm
PAE	To be measured	
Input return loss	< -10 dB	< -8 dB
Output return loss	< - 10dB	< -8 dB

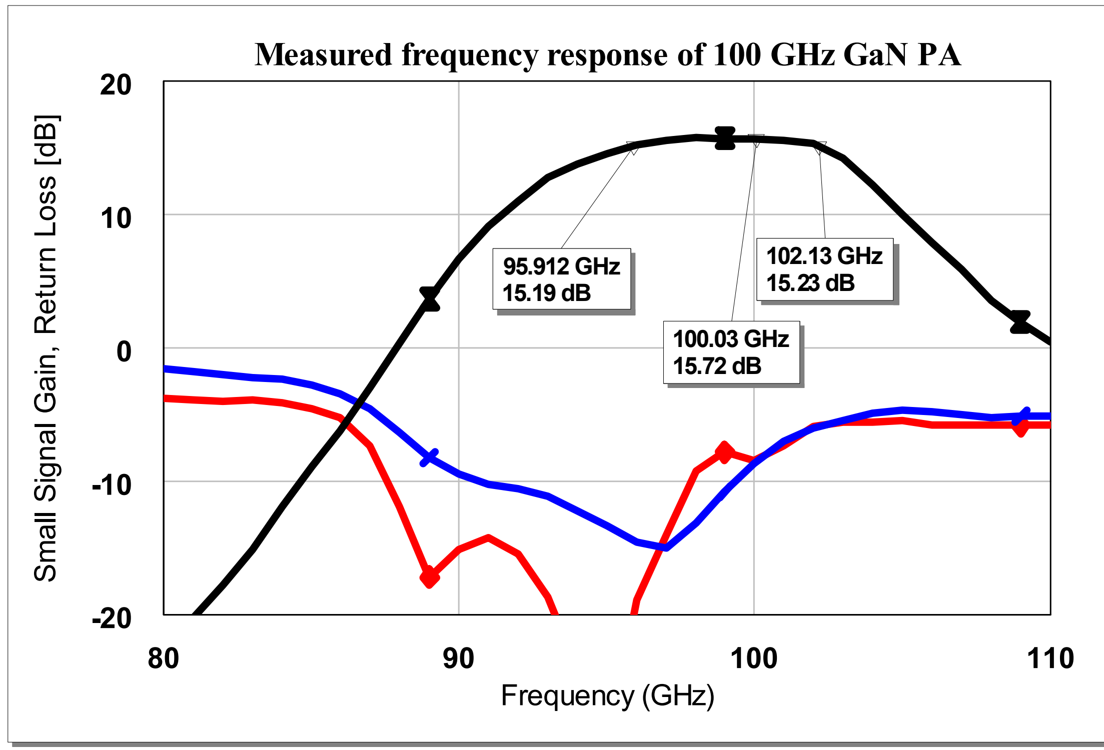
250 mW 100 GHz GaN MMIC PA



100 GHz MMIC Chip Layout
Size 2.4 mm x 1.3 mm

Operating Voltage = 15 V

Measured Gain > 15 dB



Measured performance of the first 100 GHz GaN MMIC chip.

Fastest GaN MMIC Circuit

Near Term Potential for 150 GHz – 220 GHz

Summary

- GaN MMIC technology will dominate high frequency > 50 GHz solid state RF power technology.
- Key challenges for MMW GaN:
  - Ohmic Contacts
  - Short gate lengths
  - Device Structure
- GaN MMICs exceeding power of best GaAs and InP MMICs at 95 GHz demonstrated.
- GaN MMICs with 5 x power of the best InP MMICs are on the road map for 2009.

MMW GaN MMIC technology enables new systems, applications and services.