Raytheon

Customer Success Is Our Mission


# Recent Advances in GaN MMIC Technology

Nicholas J. Kolias

29 September 2015

# Outline

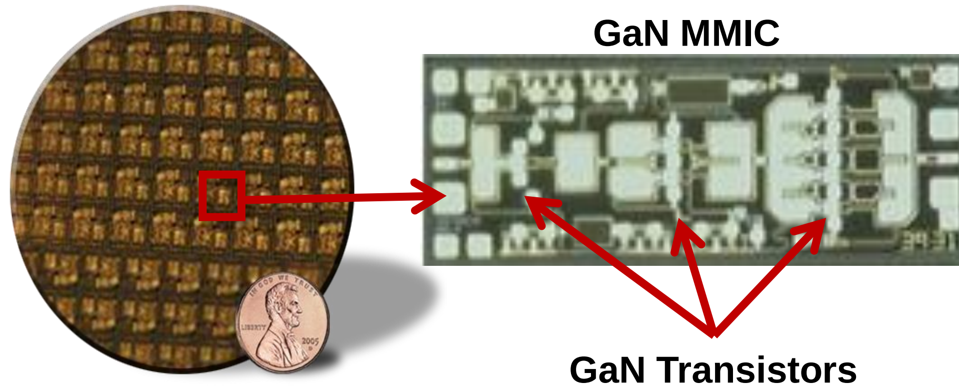
Raytheon
Integrated Defense Systems

- What is GaN?
- GaN System Benefits
- Today's GaN Technology
  - Microwave GaN
  - mm-Wave GaN
  - W-band GaN
- Next Generation GaN
  - Higher frequency GaN
  - GaN on Diamond
  - Heterogeneous Integration with Si CMOS
- Summary

# What is GaN?

- GaN (Gallium Nitride) is a compound semiconductor that is revolutionizing today's high power microwave defense systems (as well as the lighting industry)
  – GaN transistors have demonstrated **>5X** the power of other semiconductor technologies (GaAs, Si) at microwave frequencies
  – JFOM is a measure of high frequency power capability --- **GaN's JFOM is 27X Si, and 10X GaAs**

**4" GaN-on-SiC Wafer**




| | Si | GaAs | GaN |
|---|---|---|---|
| **$E_g$ (eV)** | 1.1 | 1.42 | 3.39 |
| **$v_{sat}$ ($10^7$cm/s)** | 1.0 | 2.1 | 2.5 |
| **$E_{br}$ (MV/cm)** | 0.3 | 0.4 | 3.3 |
| **Johnson Figure of Merit JFOM = $E_{br}$*$v_{sat}$/(2$\pi$)** | 1 | 2.7 | 27.5 |

**GaN is the Ideal Semiconductor for Microwave and mmWave Amplifiers**

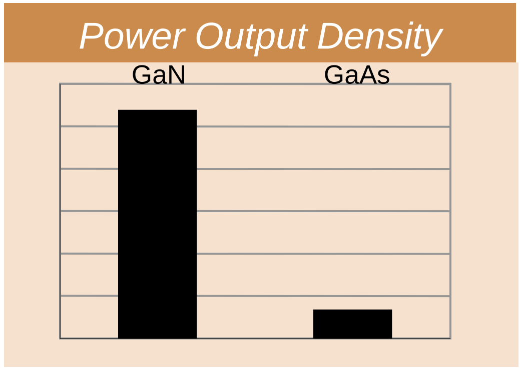
Raytheon
Integrated Defense Systems

# Why Gallium Nitride?

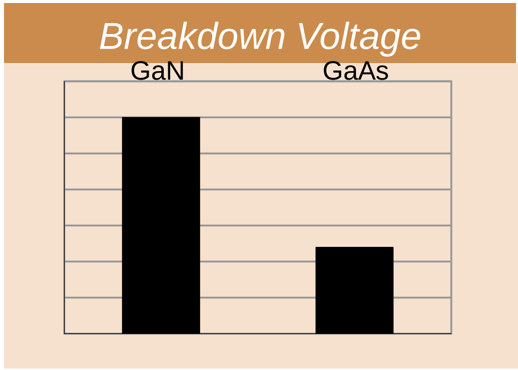
- GaN transistors have >5X higher RF power density than GaAs
  - *Higher RF power*
  - *Small footprint amplifiers*
  - *Lower cost per Watt*

- GaN transistors have exceedingly high breakdown voltage
  - *Production robustness margin*
- GaN transistors (on SiC) have excellent thermal conductivity
  - *Improved thermal management*
- GaN transistors result in high efficiency & lower DC power/life cycle costs
  - *Lower currents → lower I2R loss*
  - *Higher voltage operation & lower parasitics result in higher HPA efficiency*

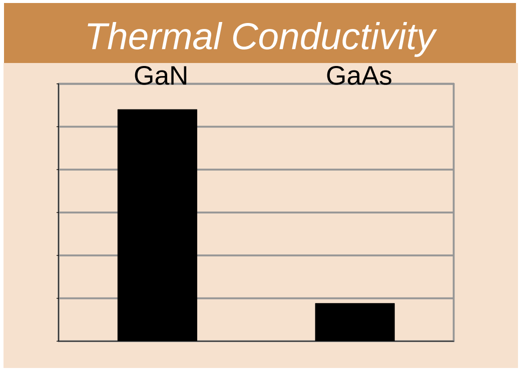
- GaN transistors have excellent noise figure and linearity
  - *Robust LNAs*



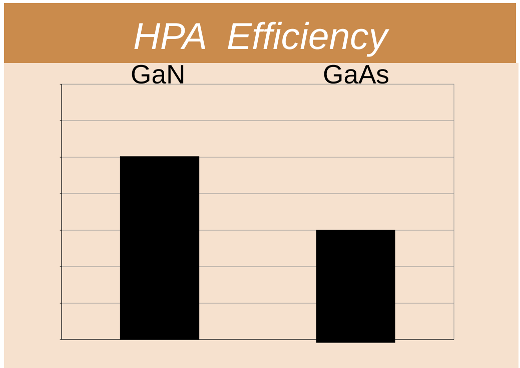

5-10X the RF Power Output Density of GaAs




>3X the Breakdown Voltage of GaAs




Nearly 6 Times the Thermal Conductivity of GaAs




Higher MMIC Efficiency Than GaAs

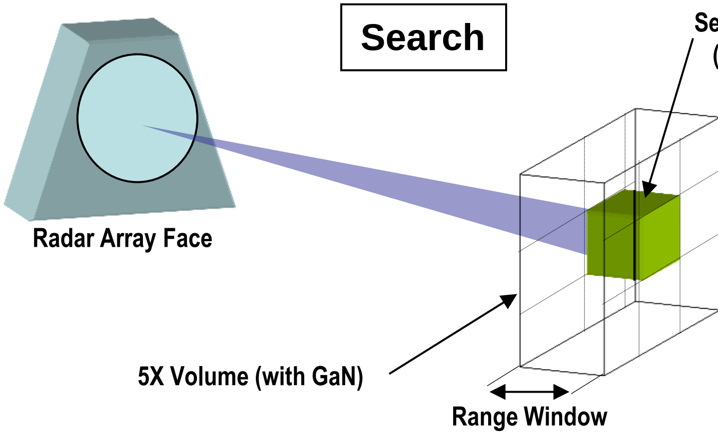
**Power, Efficiency, Thermal Management, and Robustness Advantages**

# Why is GaN Important for Radar Sensors?
# A 5X Increase in Pout Results in:

Raytheon
Integrated Defense Systems

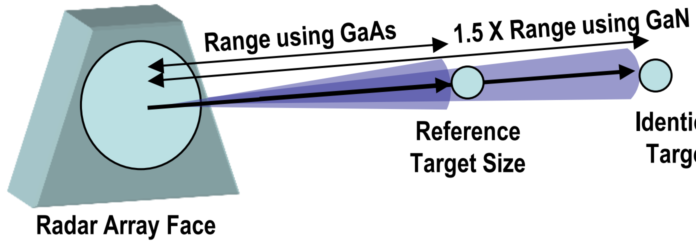
Sensors

**Search**



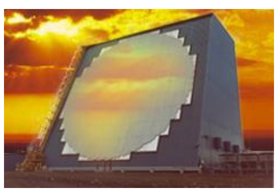

**OR**

**Track**




**1) 5X the search volume in same amount of time**

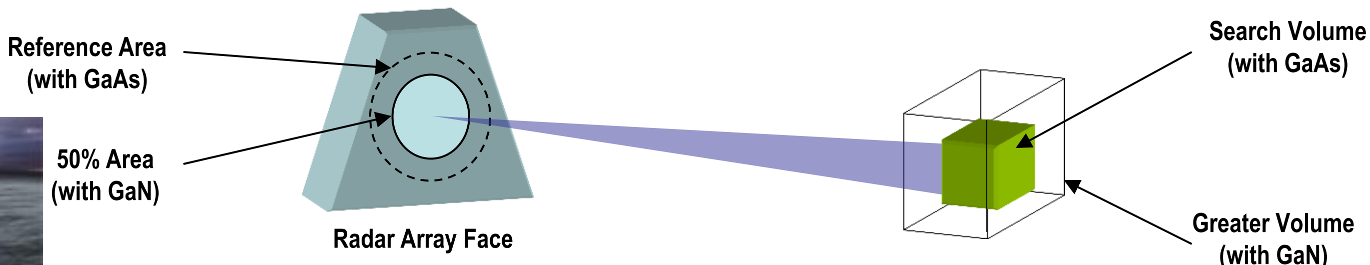
**2) 50% increase in range with the same sensitivity**



**OR**

**Aperture Size**

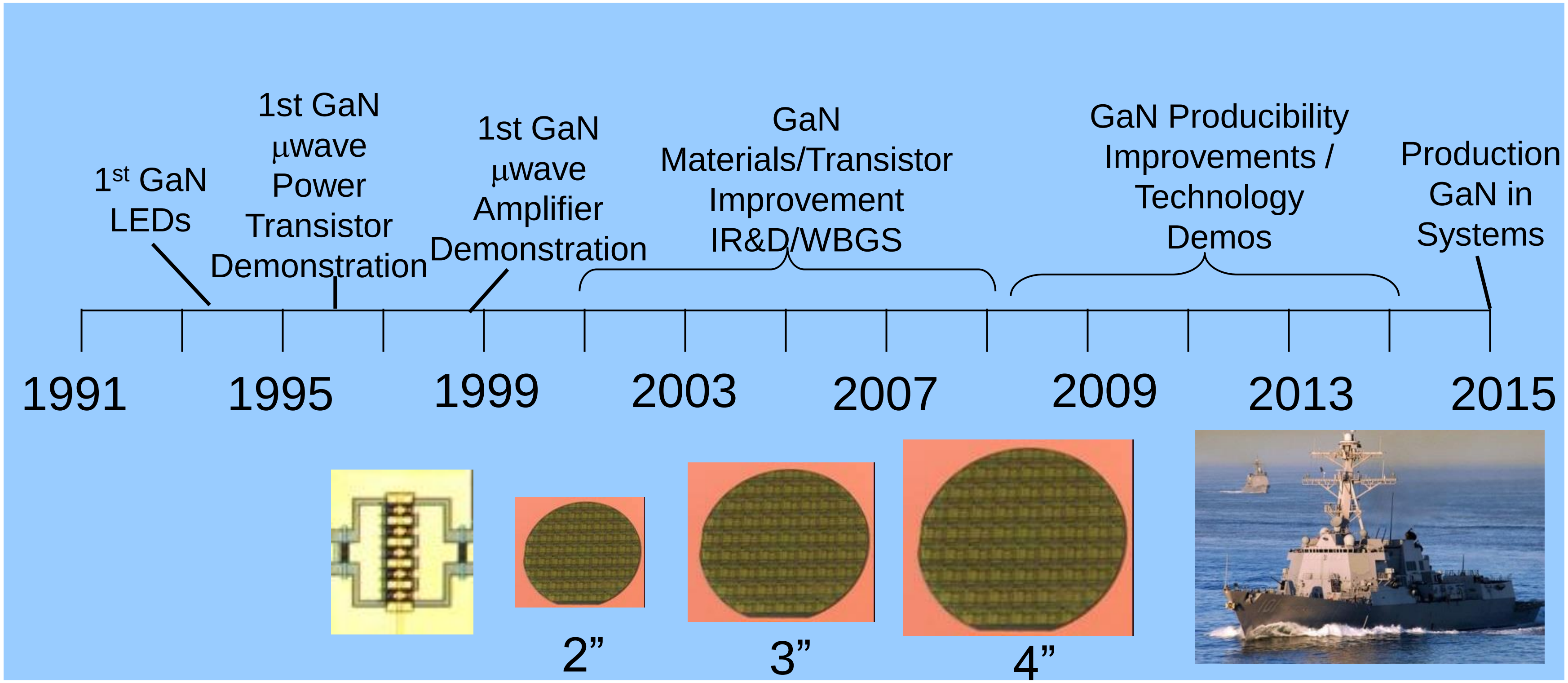
**OR**




**3) 50% reduction in antenna size with greater search volume**

Assumes GaN power = 5x GaAs power

# GaN Microwave Technology Timeline



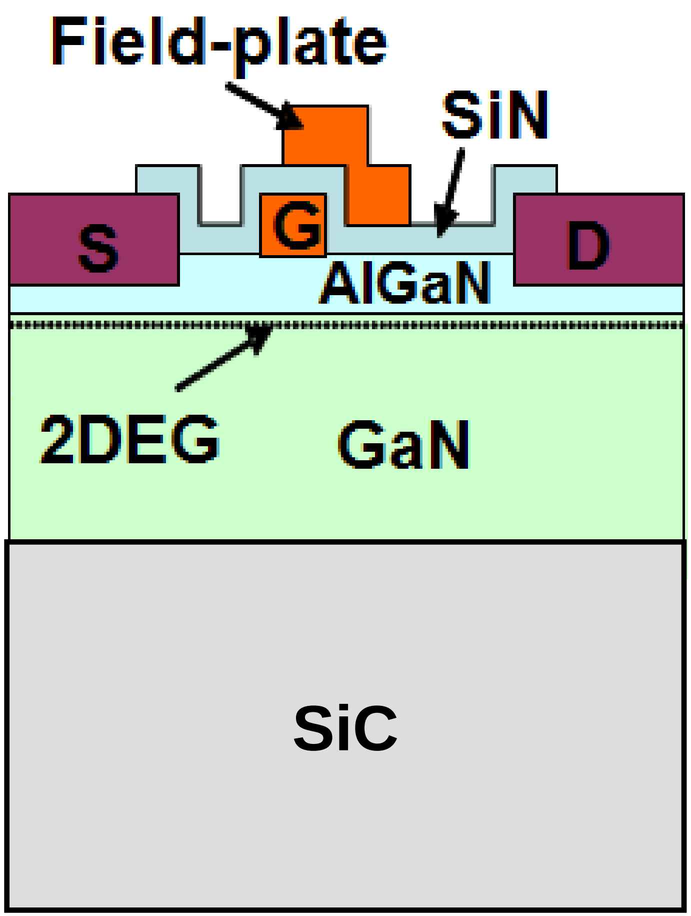

- Advent of GaN LEDs in the 1990s drove rapid improvement in GaN epitaxial material quality
- Focused research in the 2000s drove improvements in size/quality/cost of SiC substrates and GaN transistor reliability

**Exciting time --- after many years of development GaN is being inserted into systems**

# GaN Transistor Physics

Raytheon
Integrated Defense Systems

## Basic Device Cross-Section




U.K.Mishra et. al., *Proceedings of the IEEE*, vol. 96, issue 2, pp. 287-305, Feb 2008.

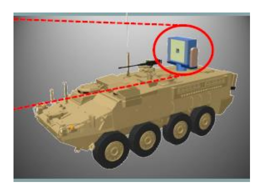
- GaN/AlGaN heterojunction
- Polar and piezoelectric nature of AlGaN results in creation of a 2DEG at junction
- Gate voltage modulates current flowing between drain and source
- Structure results in high current and breakdown voltage for high power density
- Field plates typically used to control the high fields on AlGaN surface
- Epi layers grown on SiC -> Typically 4"
- Max voltage (power) can be traded off with frequency
  - Size of field plate ↓, Freq ↑
  - Source drain spacing ↓, Freq ↑
  - Gate length ↓, Freq ↑

# GaN Processes

Raytheon
Integrated Defense Systems

| | Microwave GaN | mm-Wave GaN | W-band GaN |
|---|---|---|---|
| **Process Designator** | P80 | P81 | P82 |
| **Freq. Range** | Thru 20 GHz | Thru 50 GHz | Thru 110 GHz |
| **Operating Voltage (max)** | 40V | 28V | 18V |
| **Typical Fmax** | 69 GHz (8x100) | 120 GHz (4x60) | 200 GHz (4x35) |
| **Typical Power Density** | 6.4 W/mm (28V, 10 GHz) | 5.4 W/mm (20V, 35 GHz) | 2.8 W/mm (18V, 95 GHz) |

- Raytheon Foundry, Andover, MA
- Founded in 1984
- DoD Accredited Category 1A Trusted Foundry
- Processes run under CAM & SPC control w/ full PDK

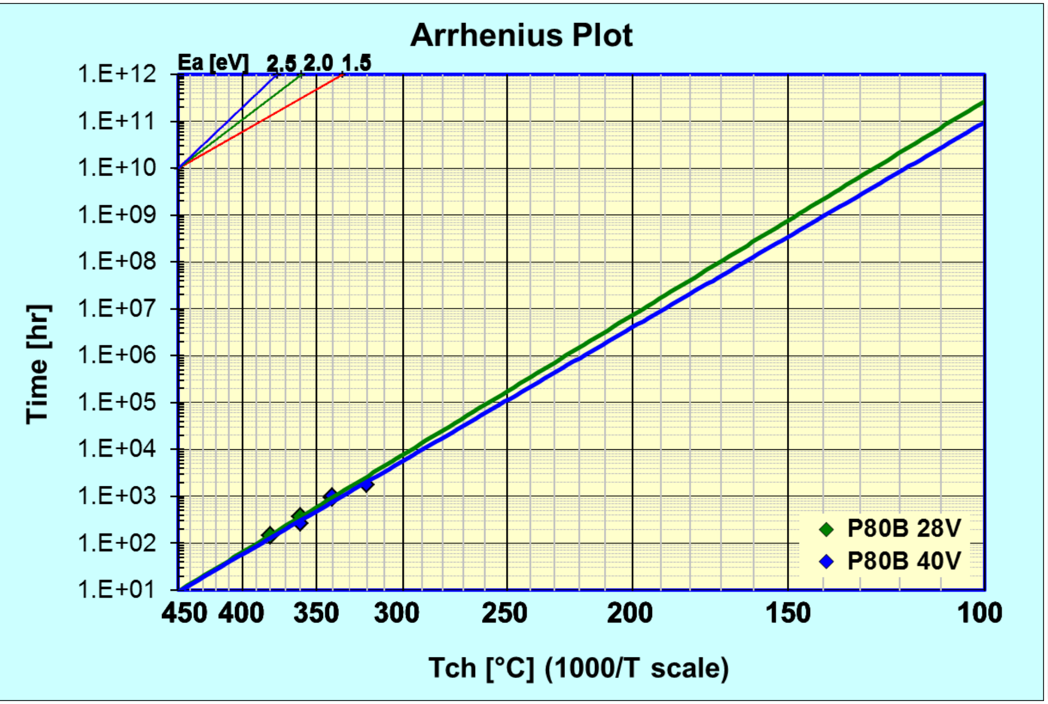


**3 GaN Processes Cover System Applications from 1 thru 110 GHz**

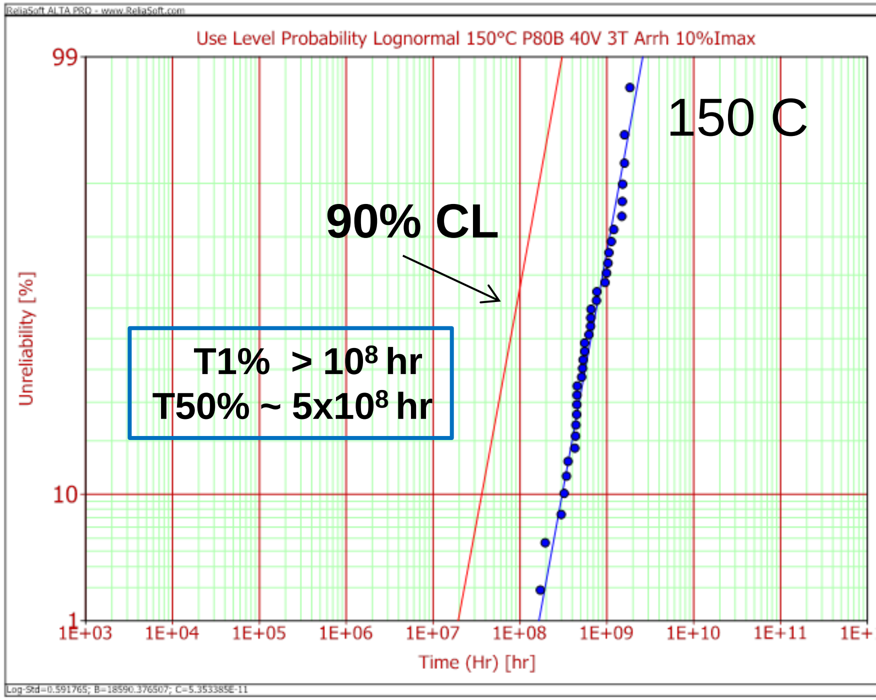
# Reliability: Microwave GaN DC Thermally Accelerated Life Testing (DC TALT)

Raytheon
Integrated Defense Systems

Arrhenius Plot




150 C Use Plot

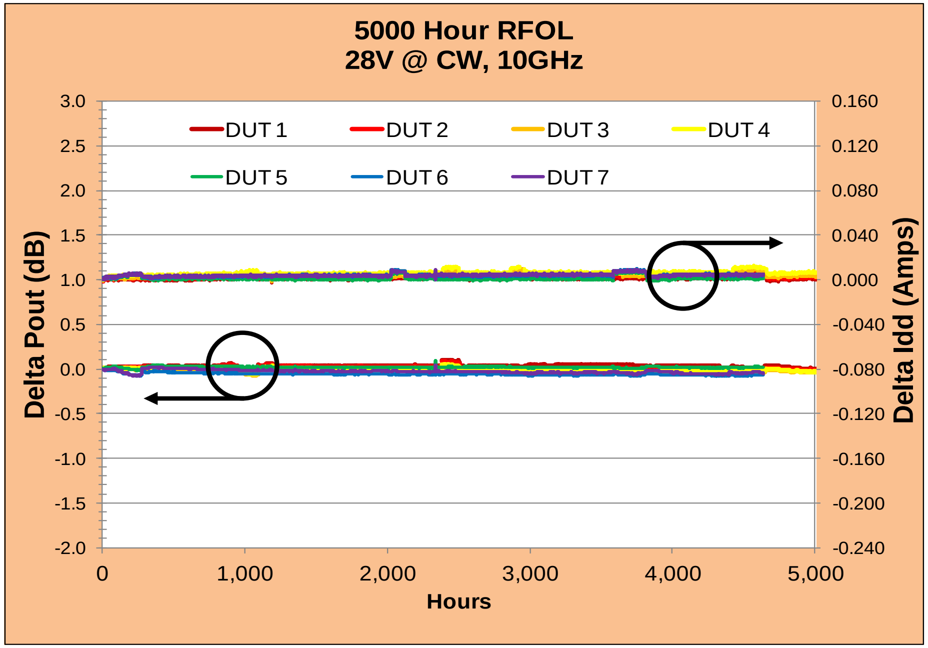


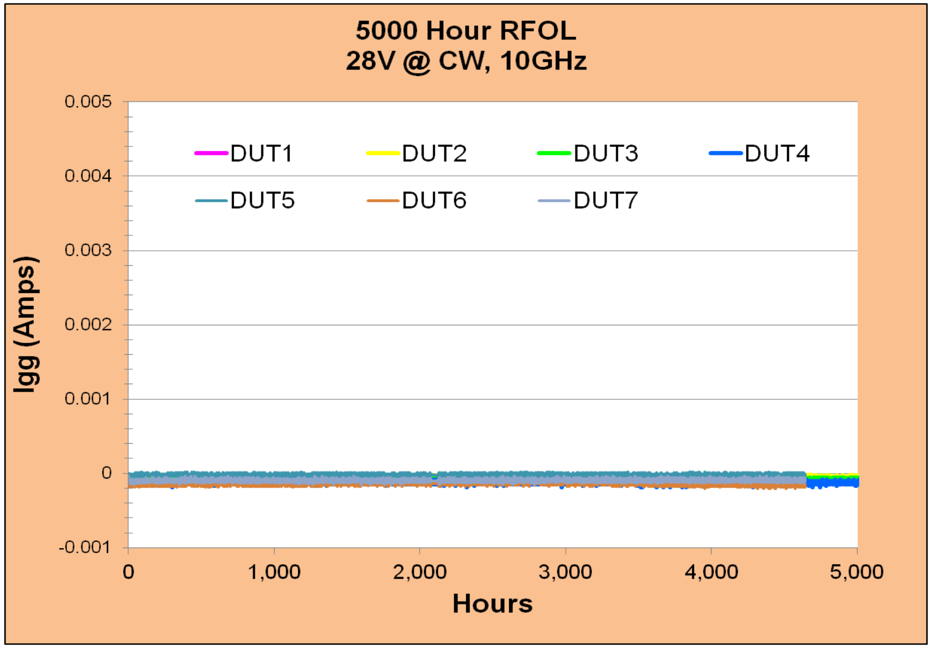

- Collected 1 million device-hours of DC Arrhenius tests
  - $>10^8$ hrs Mean-Time-To-Failure at 150C
  - 40V and 28V bias conditions show similar long lifetimes
- 1% TTF exceeds $10^8$ hrs at 150C mission requirements

**MTTF & 1% TTF Exceed Mission Life Requirements**

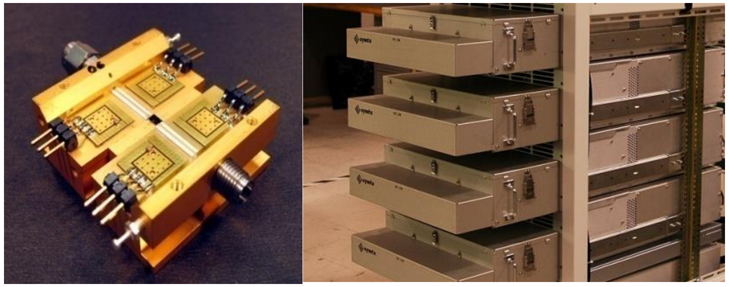
# Reliability: Microwave GaN RF Operating Life Testing (RFOLT)

Raytheon
Integrated Defense Systems



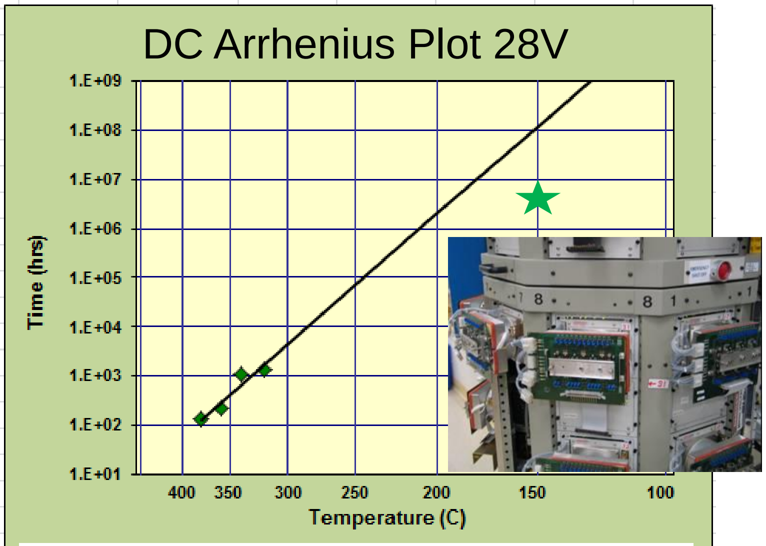

- Conducted 150K device hours of pulsed and CW RFOL MMIC Tests
  - No change in output power, drain current or gate current

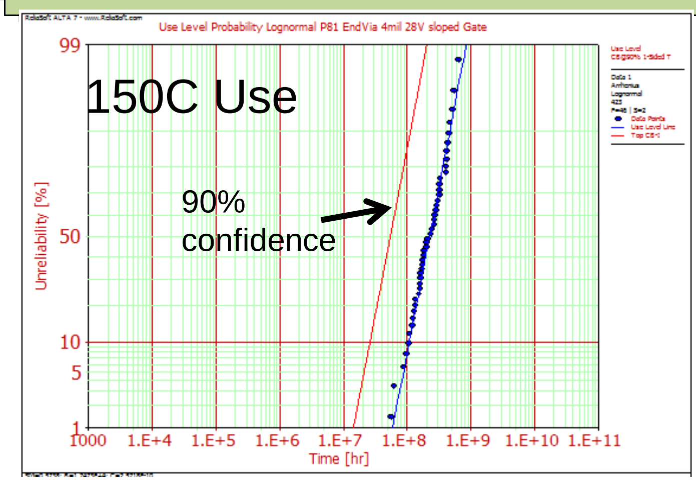


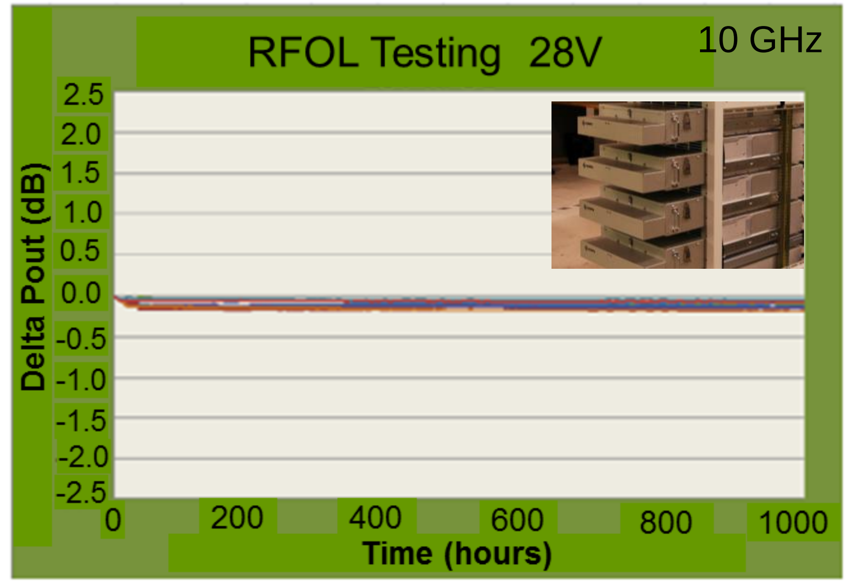
**Stable RF Operating Life Tests**

# Reliability: mm-Wave GaN Process

Raytheon
Integrated Defense Systems



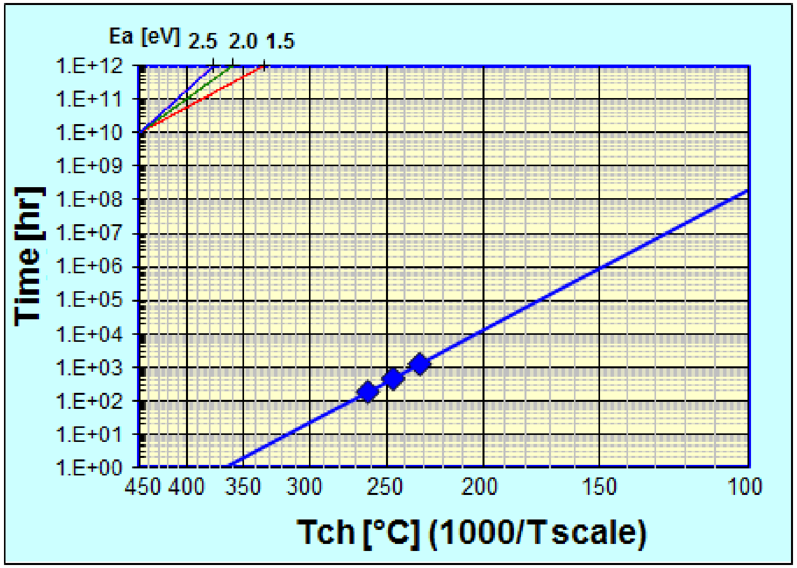

- MTTF for DC TALT for Millimeter Wave Process is ~1E+8 hrs at Tch=150C
- No Changes Over 1000 Hour MMIC Amplifier RF Operating Life Tests

**Excellent Reliability for mm-Wave GaN Process**

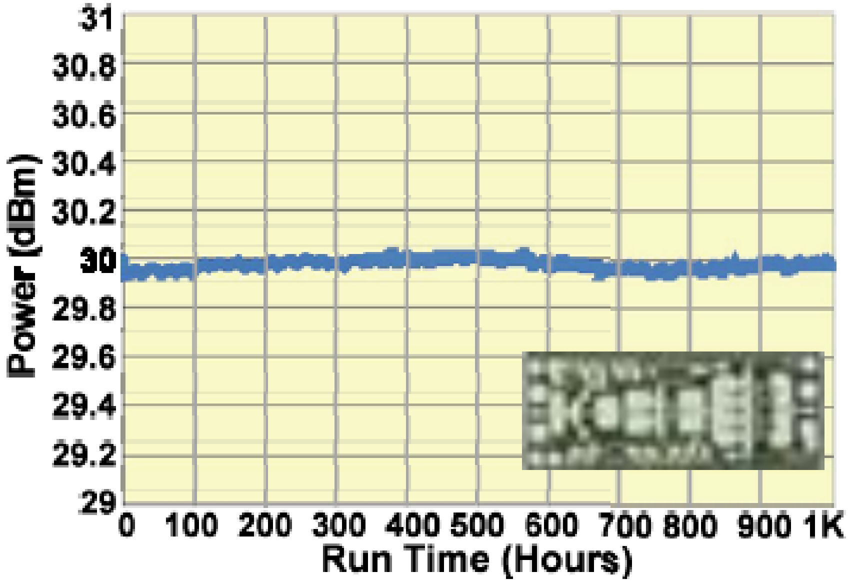
# Reliability: W-band GaN Process

Raytheon
Integrated Defense Systems

DC TALT Arrhenius




3-Stage W-band MMIC RFOL




MTTF ~1 Million Hours @150 C Channel Temperature

No power degradation after 1,000 hours of CW Operation

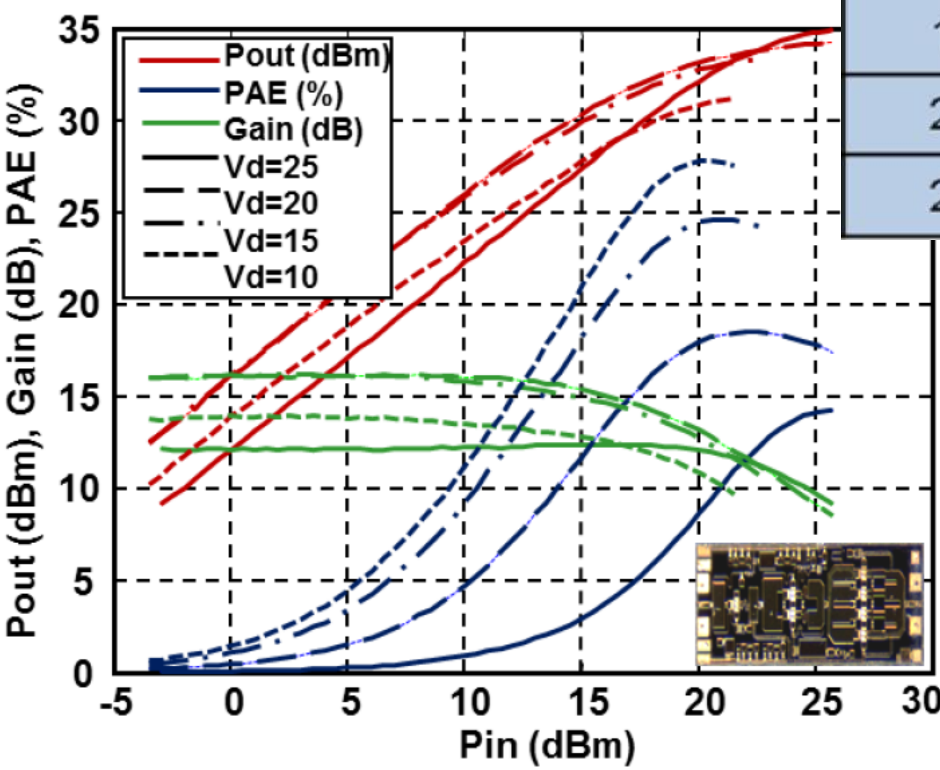
**Demonstrated Reliability at W-band**

# High Efficiency Power Amplifier Example: E-band Comms Amplifier (71-76 GHz)

Raytheon
Integrated Defense Systems

- Power performance measured at mid-band (74 GHz)
  - Adjusting Drain Voltage allows for trading off Output Power and Efficiency

| Vd | Pout | Gain | PAE |
|---|---|---|---|
| 10V | 1.3W | 10.5dB | 27.8% |
| 15V | 2.0W | 12.0dB | 24.6% |
| 20V | 2.4W | 11.3dB | 18.5% |
| 25V | 3.1W | 9.5dB | 14.2% |

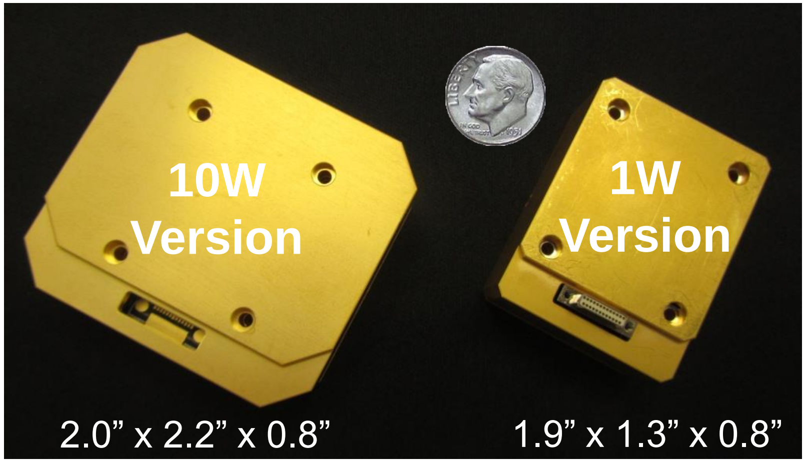


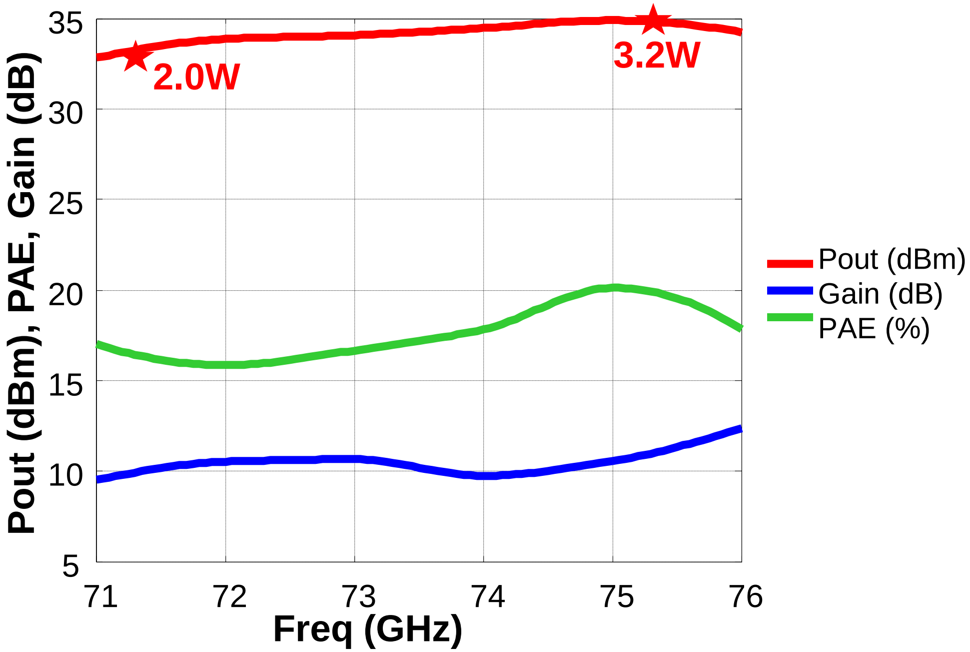

**Excellent Combination of Power and PAE**

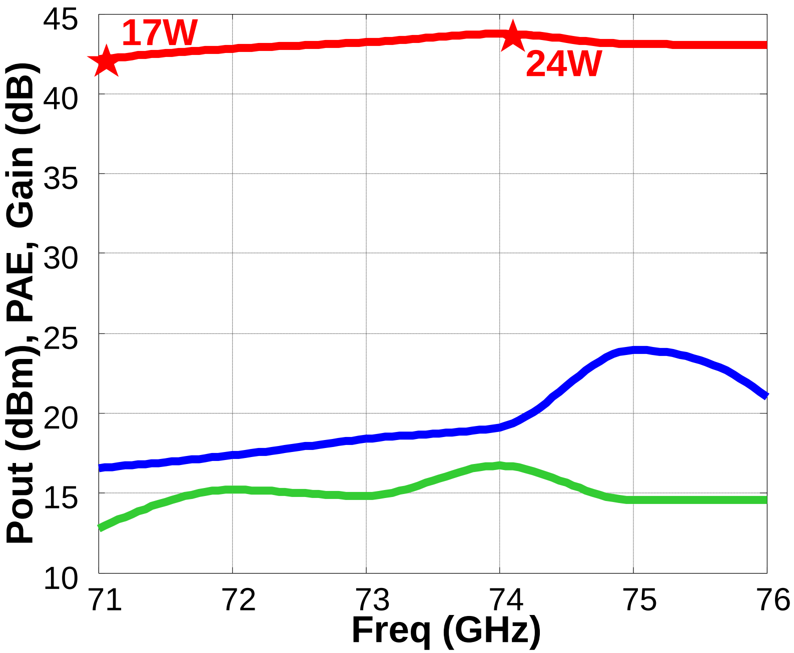
# Raytheon E-Band Mobile Hotspots XMTR Power Amplifiers

Raytheon
Integrated Defense Systems

- Extremely compact, broadband, high power, E-band power amplifiers
  - "1W" version
    - >5 GHz bandwidth
    - 2.0-3.2W RF output power
  - "10W" version
    - >5 GHz bandwidth
    - 17-24W RF output power
- Key enabler for long-range, wideband mmW comms

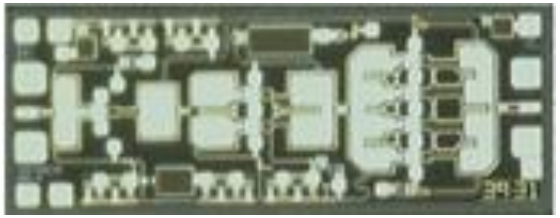


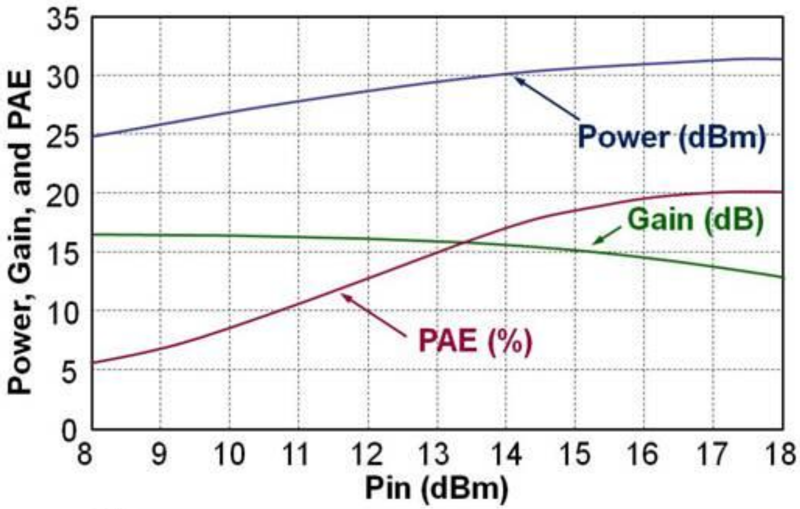



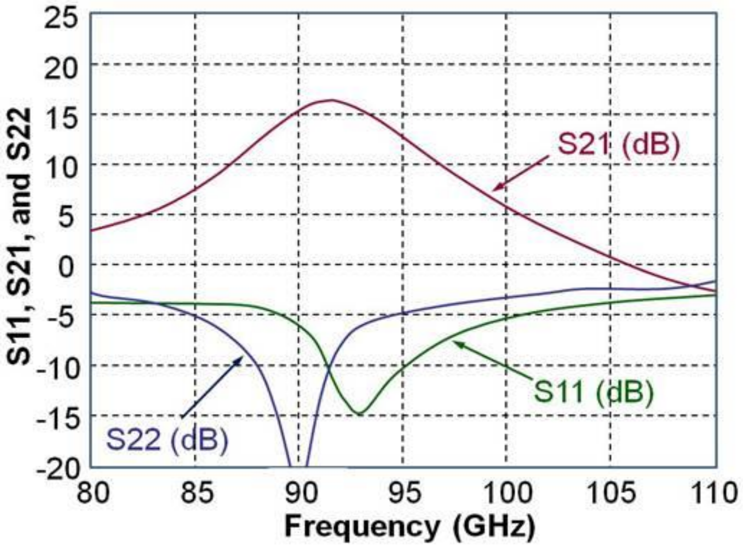
# W-Band High Efficiency Power Amplifier MMICs








- Three-stage High Efficiency PA
  - Chip size: 2.5 mm x 0.9 mm
- Typical Performance (17.5V bias):
  - Pout @ 3dBc = 1.2 Watts
  - Associated PAE of >20%




**Thousands Inserted into Systems**

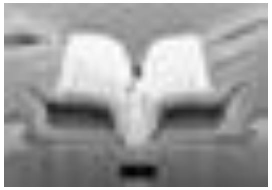
# Raytheon W-Band Spatial Array for Directed Energy Systems

Raytheon
Integrated Defense Systems

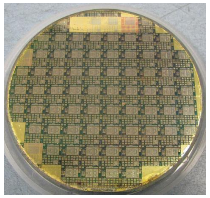
**Successful W-Band Spatial Array Demo**

# What's Next?

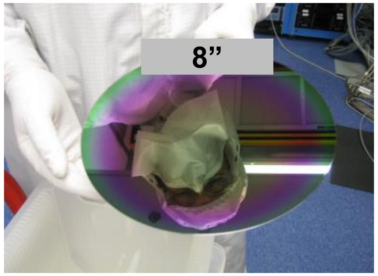
- Higher Frequency (> 200 GHz) GaN
  - Aggressively scaling GaN transistors to achieve GaN power amplifiers at higher freqs
  - DARPA NEXT demonstrated GaN $f_{max}$ over 400 GHz
- GaN on Diamond
  - Ultimate in thermal performance for GaN amplifiers (3X power density at same channel temp)
  - Present focus on maturing larger diameter wafers and proving reliability
- GaN on 8" Silicon
  - Enabler for lower cost GaN and heterogeneous integration with CMOS
  - Present focus is demonstrating performance/reliability and demonstrating heterogeneously integrated MMICs



200 GHz
GaN Transistor



3" Diameter GaN
on Diamond

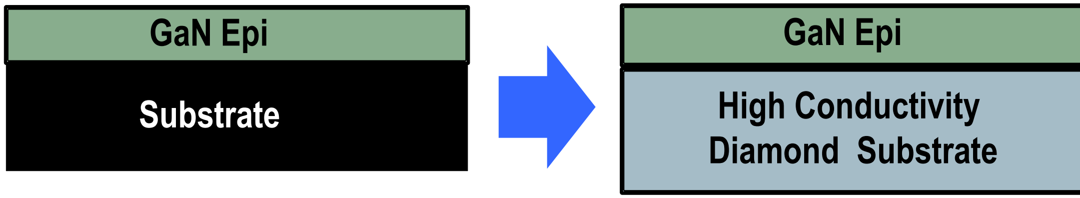


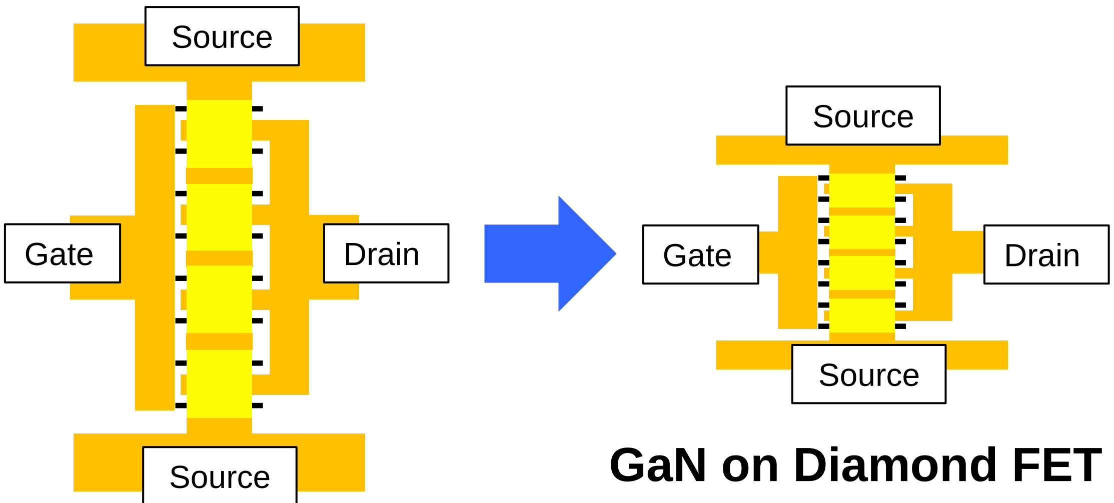

8" Diameter
GaN on Silicon

# What is GaN on Diamond?



- GaN on Diamond wafers consist of GaN epi on high thermal conductivity diamond substrates
- Diamond's superior thermal conductivity (1200-2000 W/m*K) over SiC (300 W/m*K) enables significant improvements to any application or program using GaN devices
  - Improved device performance and reliability through lower channel temperatures
  - Compact FET geometries since gates can be placed closer together




**GaN on SiC FET**

**GaN on Diamond FET with 3X Reduced Gate to Gate Spacing**

Tyhach et. al., *IEEE Lester Eastman Conference on High Performance Devices (LEC)*, pp. 1-4, Aug. 2014.

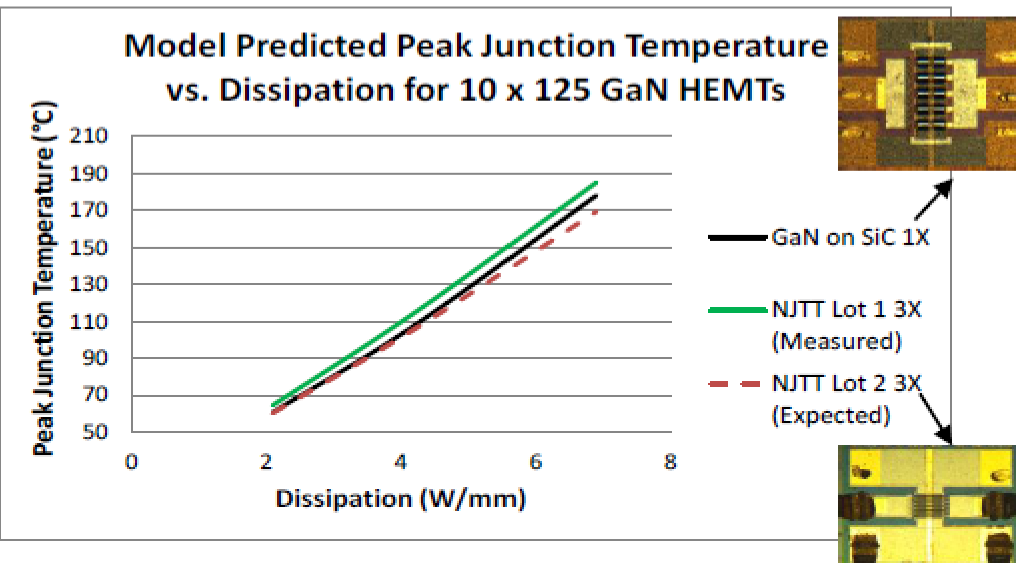
**GaN on diamond provides the ultimate in GaN thermal performance**

# DARPA NJTT GaN on Diamond Thermal and Electrical Results

Raytheon
Integrated Defense Systems

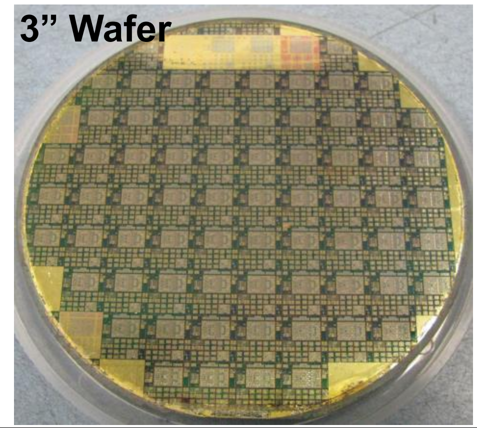
## Thermal Summary

- NJTT improved GaN/Diamond thermal interface resistance (TIR): 47.6 $m^2K/GW$ to 29$m^2K/GW$




## Electrical Summary

- 70% 10x125um transistor yield




| | G2G | POW (W/mm) | Pout ($W/mm^2$) Relative to SoA | PAE (%) |
|---|---|---|---|---|
| Prod. SiC | 40 | 5.50 | 1.00 | 61.5 |
| Diamond | 40 | 5.85 | 1.06 | 49.9 |
| Diamond | 40 | 5.49 | 1.00 | 50.4 |
| Diamond | 10 | 5.32 | 3.87 | 51.4 |
| Diamond | 10 | 5.09 | 3.70 | 55.7 |
| Diamond | 10 | 5.05 | 3.68 | 56.6 |
| Diamond | 10 | 5.03 | 3.66 | 55.1 |
| Diamond | 10 | 5.01 | 3.65 | 55.2 |

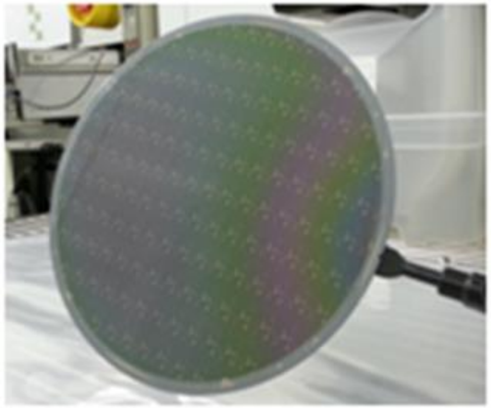
Tyhach et. al., *IEEE Lester Eastman Conference on High Performance Devices (LEC),* pp. 1-4, Aug. 2014.

**Measurements show GaN on diamond has 3X the areal power density of GaN on SiC at the same channel temperatures**

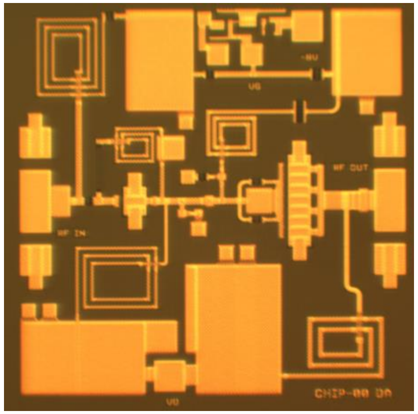
# GaN-on-Silicon

Raytheon
Integrated Defense Systems

- Historically III-V MMIC processing has been unable to be done in Silicon fabs – GaN is changing this:
  - Contamination: GaN has been shown to not be detrimental to CMOS in terms of contamination control ☑
  - Temperature stability: GaN is chemically stable over most of the temperature range of Si CMOS processing ☑
  - Wafer size: Quality GaN epi can be grown on large (200mm) diameter wafers ☑
- Potential enabler for low cost, high yield GaN processing in silicon fabs for both power conversion and RF/microwave applications



**200mm diameter GaN on Si wafer processed in Novati's silicon foundry using gold free (Cu Damascene), CMOS compatible subtractive processing**



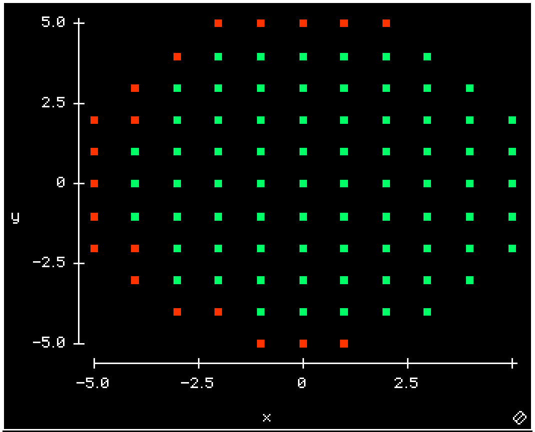
**Cu Damascene GaN on 200mm Si MMIC at final metal**

**Unlike other III-V's, GaN can be processed in a silicon fab**

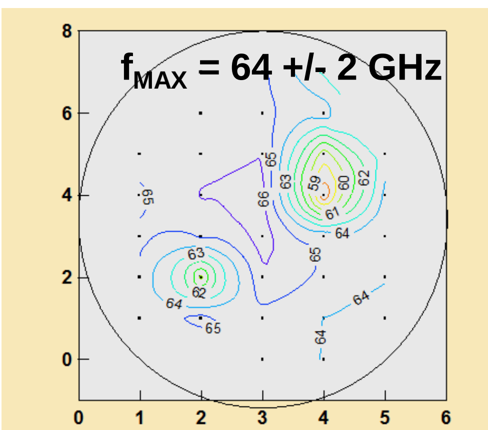
# Subtractively Processed GaN on 200mm Si Transistor Yield and Performance

Raytheon
Integrated Defense Systems

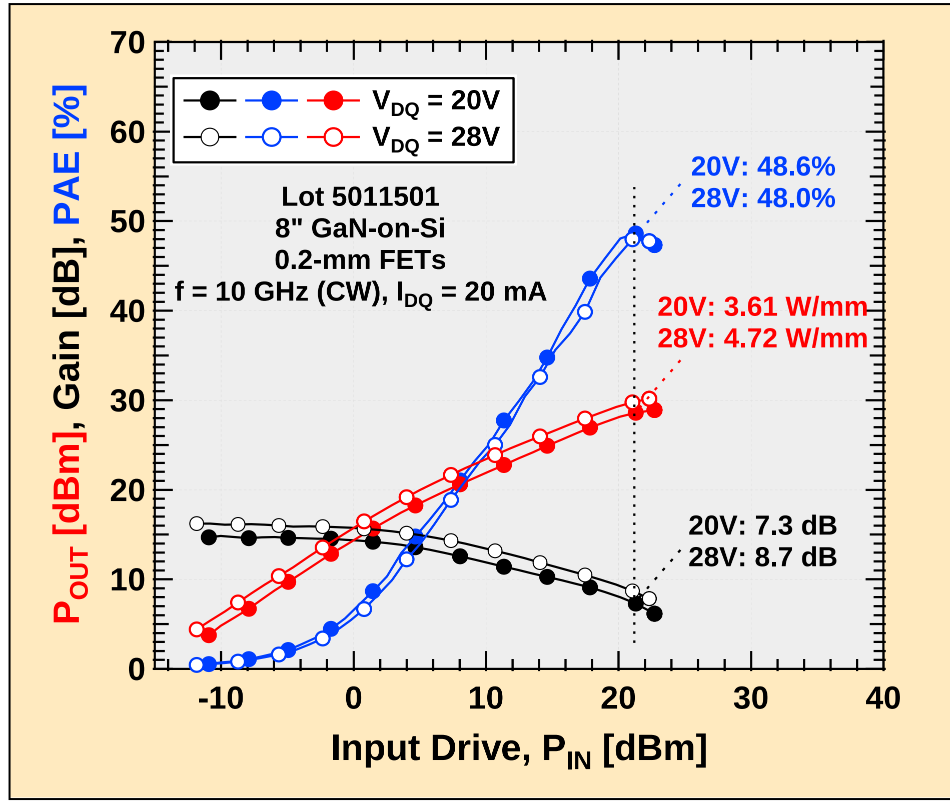
## DC Yield 100% (excluding edge die)




## Small Signal RF Performance:




## Large Signal RF Performance (CW Load Pull):




**28V: 4.7 W/mm, 48% PAE, ~9dB Gain**

**Excellent yield and small signal uniformity across 200 mm wafer**

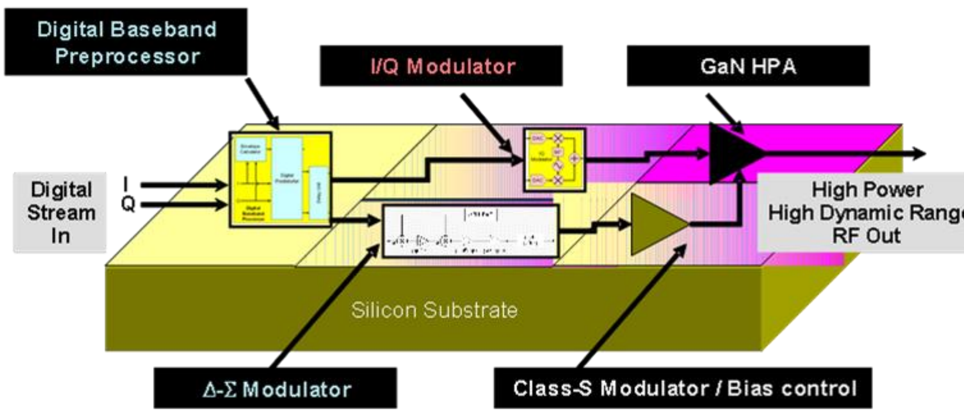
**Large signal performance approaching GaN-on-SiC**

# Heterogeneous Integration of GaN & CMOS

## 200mm GaN on Silicon is a Key Enabler for 200mm Wafer Level Heterogeneous Integration of GaN and CMOS

**Advanced Circuit Possibilities:**

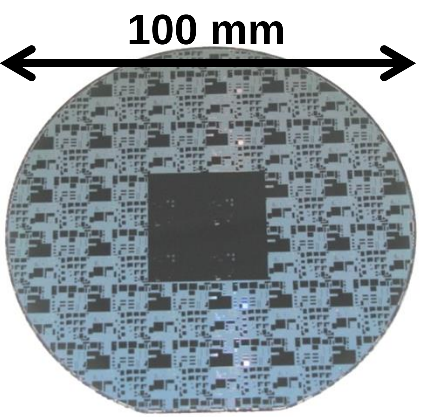
- High power digital-to-analog converters
- Active/adaptive bias control
- Linearized, reconfigurable power amps
- High dynamic range rcvrs/transceivers
- Active mixers
- On-wafer wireless transmitters
- On-wafer optoelectronic driver stages
- Power amps coupled to Si linearizers
- High efficiency power converter / power conditioning circuits / power distribution networks
- High speed (high power) differential amps
- Ultra-low-power electronics buffer stages




**Integration of GaN with CMOS provides unprecedented flexibility for advanced circuit design**

# GaN and CMOS Heterogeneous Integration Demonstration:

**Raytheon**
**Integrated Defense Systems**




Starting Substrate (SOI on Si<111>)

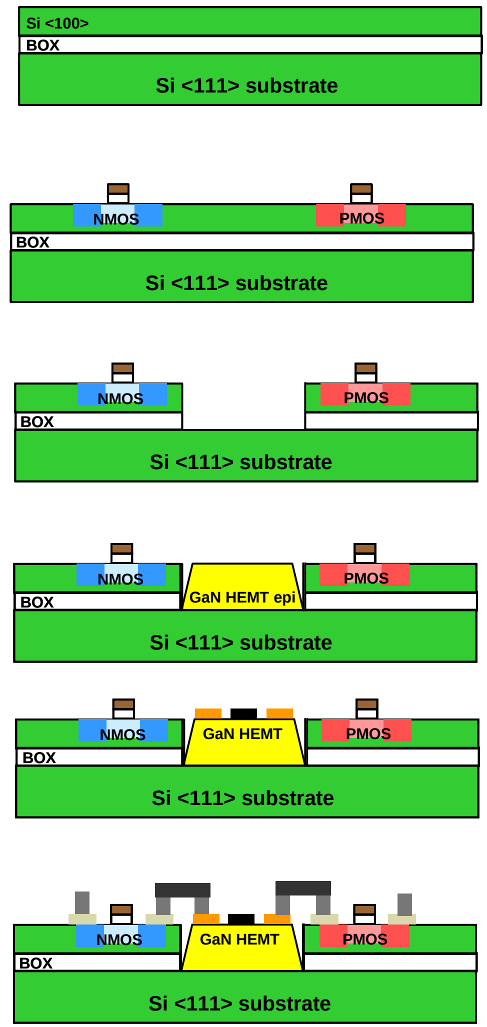
Fabricate CMOS

Etch window To <111> Si

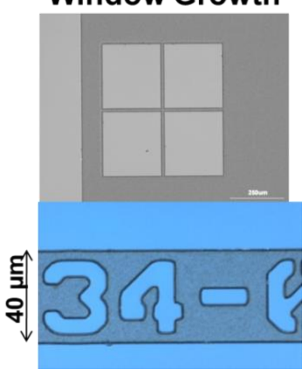
Grow GaN HEMT epi

Fabricate GaN HEMT

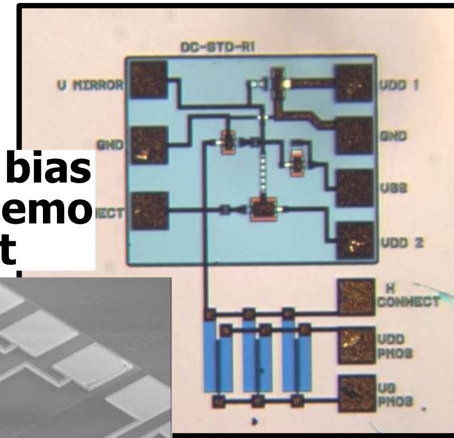
Heterogeneous Interconnects

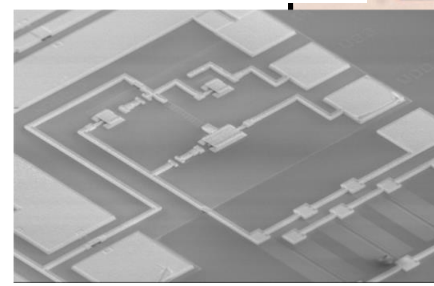


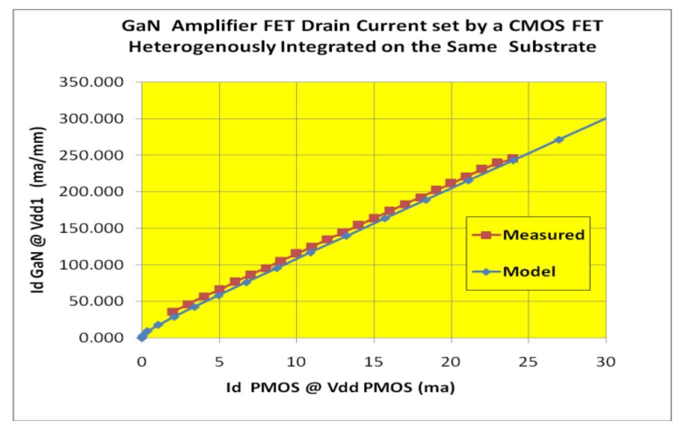

Window Growth




CMOS Gate bias Control Demo Circuit






**First demonstration of GaN – Si CMOS heterogeneously integrated RFIC**

T.E. Kazior et. al., *IEEE Intl. Electron Devices Meeting (IEDM), 2013, pp. 28.5.1 - 28.5.4*

# Summary

- GaN technology is revolutionizing RF/microwave systems with its high power density and improved efficiency
- After many years of development, GaN technology is now reliable and mature
- GaN processes have been optimized to operate in different frequency bands covering 1 GHz to 110 GHz
- New emerging GaN processes:
  - Higher frequency GaN (> 200 GHz)
  - GaN-on-Diamond (Ultimate in thermal performance)
  - GaN on 200mm Silicon / Heterogeneous integration with Si CMOS

For more information on Raytheon GaN Please Contact:

**Ronald Gyurcsik, Ph.D.**
Director, Foundry Business Development and Strategy
Integrated Defense Systems
**Raytheon Company**
(business) +.978.684.5428
ronald.gyurcsik@raytheon.com

# Acknowledgements


- Raytheon GaN Team
- DARPA NJTT
- DARPA DAHI
- DARPA Mobile HotSpots
- ARDEC RDECOM
- OSD GaN Title III