The DARPA Wide Band Gap Semiconductor for RF Applications (WBGS-RF) Program: Phase II Results

Mark J. Rosker

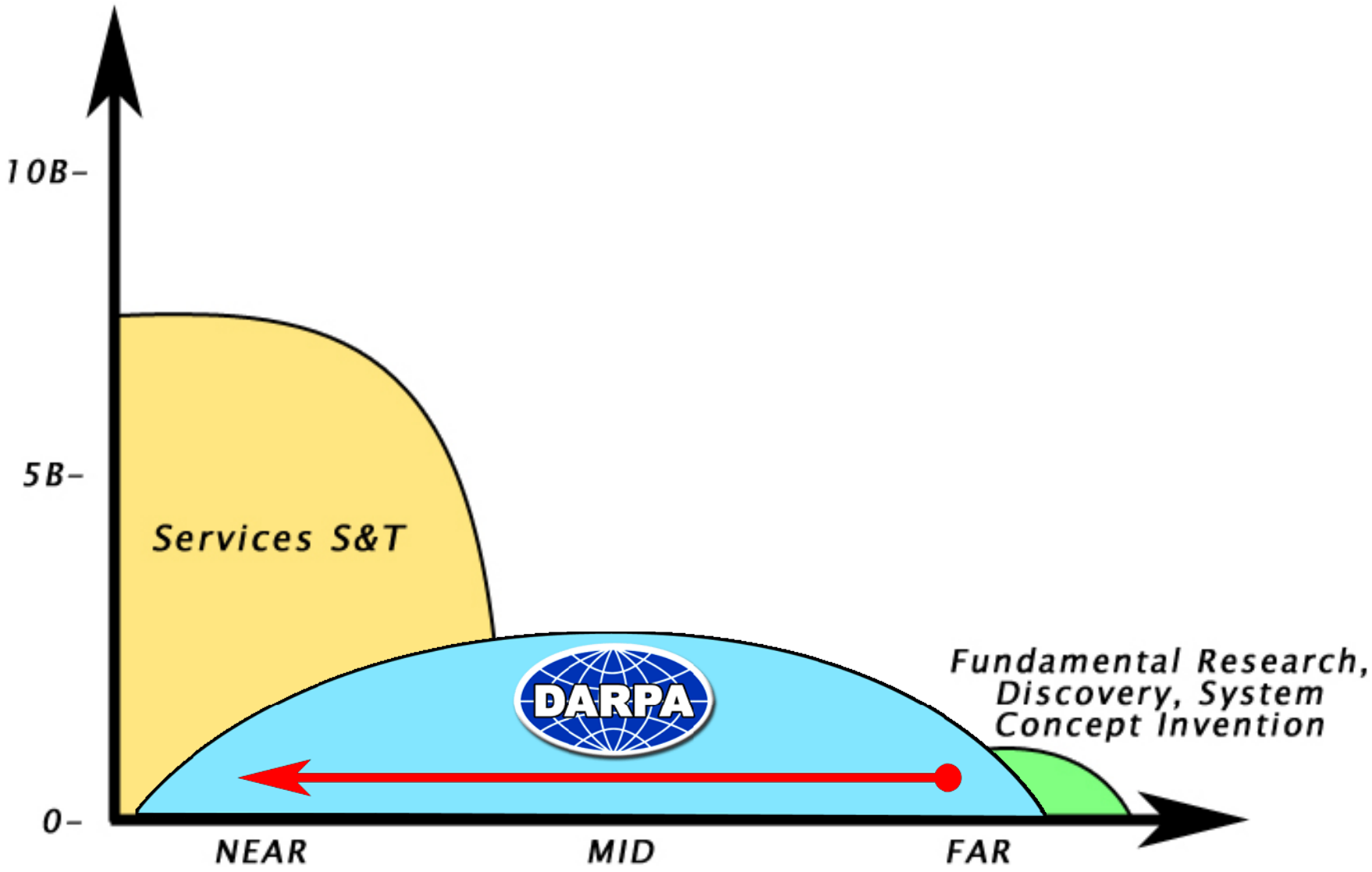
2009 International Conference on Compound Semiconductor Manufacturing Technology
Tampa, Florida, USA
19 May 2009

MICROSYSTEMS TECHNOLOGY OFFICE

The views, opinions, and/or findings contained in this article/presentation are those of the author/presenter and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense.

Approved for Public Release, Distribution Unlimited

DARPA's Role in Science and Technology



DARPA Technical Offices

Acting Director, Bob Leheny

Tactical Technology
Dave Neyland
Steve Walker

Air/Space/Land/Sea Platforms
Unmanned Systems
Space Operations
Laser Systems
Precision Strike

Strategic Technology
Barbara McQuiston
Larry Stotts, Brian Pierce

Space Sensors/Structures
Strategic & Tactical Networks
Information Assurance
Underground Facility Detection & Characterization
Chem/Bio Defense
Maritime Operations

Defense Sciences
Leo Christodoulou *(Acting)*
Ben Mann *(Acting)*

Physical Sciences
Materials
Biology
Mathematics
Neuroscience

Information Processing Techniques
Chuck Morefield
Charlie Holland, Mark Luettgen

Cognitive Systems
Command & Control Systems
Computer Language Translation
High Productivity Computing
Sensors & Processing

Microsystems Technology
Greg Kovacs
Dean Collins, Mark Rosker

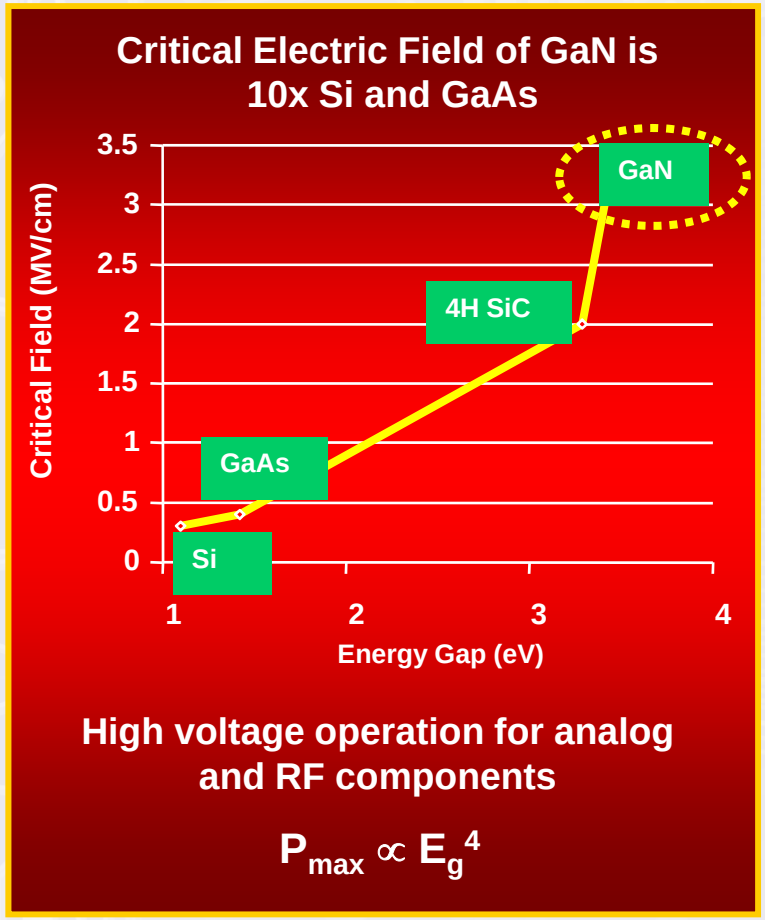
Electronics
Photonics
MEMS
Algorithms
Integrated Microsystems

Approved for Public Release, Distribution Unlimited

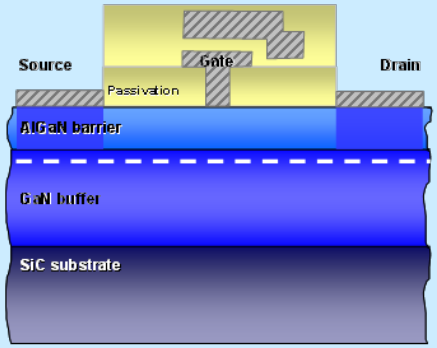
WBGS-RF Program Overview

Approved for Public Release, Distribution Unlimited

The Future of MMICs



Benefit of Using GaN HEMTs



Gallium Nitride HEMT on Silicon Carbide

Dramatically Higher

- Output power
- Efficiency
- Bandwidth

WBGS-RF GaN-on-SiC Program: The Next Generation of MMICs

WBGS-RF Program Timeline

2003	2004	2005	2006	2007	2008	2009	2010

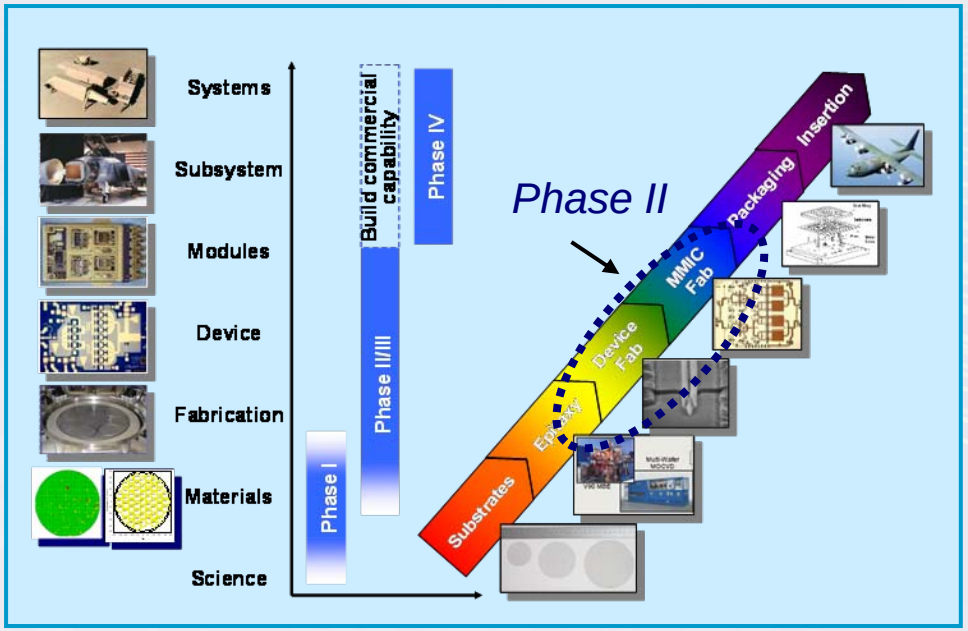
3/05

4/08

Phase I
Wide Band Gap
Semiconductor Materials

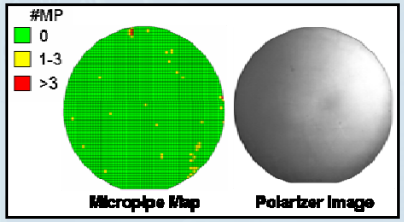
Phase II
Wide Band Gap Semiconductor
Device Technologies

Phase III
WBGS-RF
MMIC Technologies



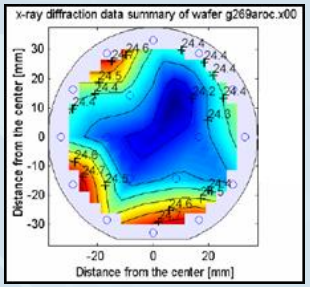
WBGS-RF Program Technical Challenge

Phase I
Wide Band Gap Semiconductor Materials



3"+ SiC substrates

Low defect density substrates, uniform epitaxy ✓



Uniform Al composition

Phase II
Wide Band Gap Semiconductor Device Technologies

Microwave
Field-plate approach

Raytheon
CREE — *X-band*

TriQuint SEMICONDUCTOR — *Wideband*

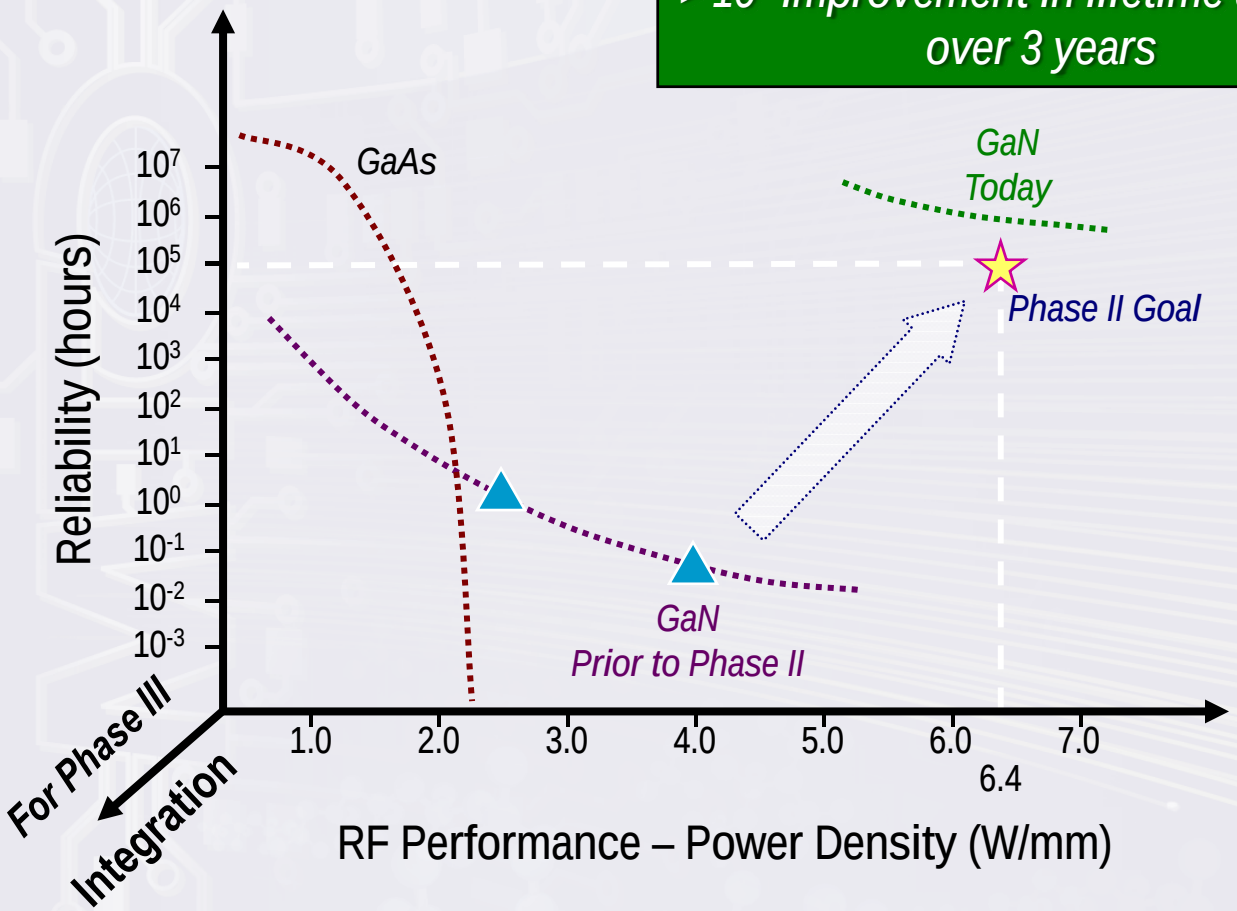
Understanding & eliminating degradation

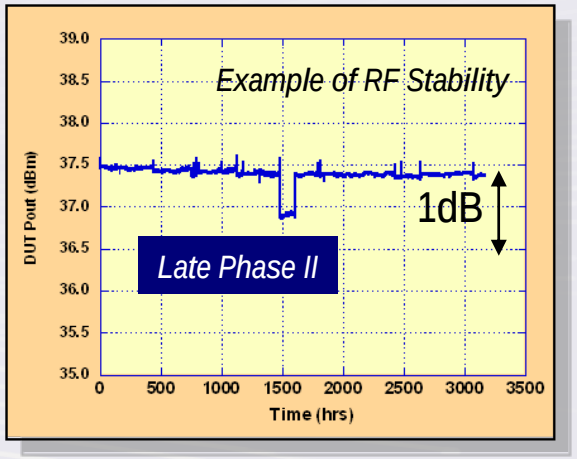
MMW
No field-plate

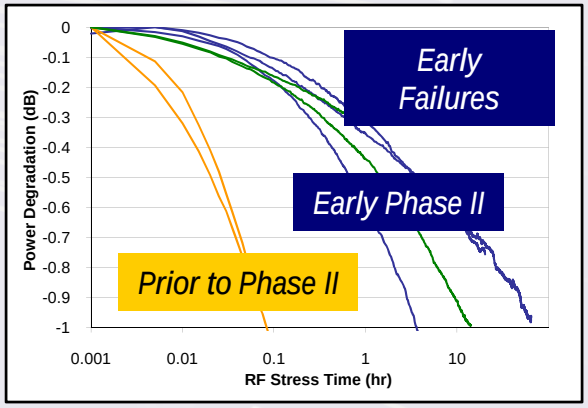
NORTHROP GRUMMAN — *Q-band*

Phase II Achievement
High Performance Without Degradation

> 10^5 improvement in lifetime achieved over 3 years







Prior to Phase II device failure mechanisms not understood

Approved for Public Release, Distribution Unlimited

Phase II Device GNG Milestones (April 08)

Track (Band)		Integration Level: Device					
		Raytheon/Cree (X-band)		Northrop Grumman (MMW)		TriQuint (Wideband)	
		High Efficiency		High Frequency		High Power/BW	
		GNG	Achieved	GNG	Achieved	GNG	Achieved
Number of Devices		100	198	100	300	100	251
Number of Wafers		3	4	3	3	3	5
Drain Bias	V	40	40	28	28	40	40
Cell Size	µm	1250	1250	500	500	1250	1250
Operating Frequency	GHz	8-12	8-12	40	40	8-12	8-12
Output Power*	W	7.94	8.1	1.58	1.8	7.94	8.5
Power Added Efficiency	%	60	62.1	35	36	60	62
Gain at Power	dB	12	12.1	8	8.3	12	12.3
RF Yield‡	%	50	91	50	69	50	83
Output Power Uniformity†	dB	1	0.1	1	0.22	1	0.2
PAE Uniformity†	% pts	3	1.5	3	1.5	3	2.1
Small Signal Gain Uniformity†	dB	1	0.1	1	0.33	1	0.2
Long Term Performance**	hrs	1.E+05	1.E+07	1.E+05	1.9E+09	1.E+05	1.5E+06

* Measured at compression corresponding to maximum PAE
† Uniformity defined as the standard deviation in measured values from 100 devices/MMICs on all validation wafers
‡ The fraction of devices from all validation wafers meeting or exceeding all relevant GNG requirements
** Failure is defined as a 1 dB decrease in output power compared with its level at the time that testing commences

All 3 Tracks Achieved All Phase II GNGs

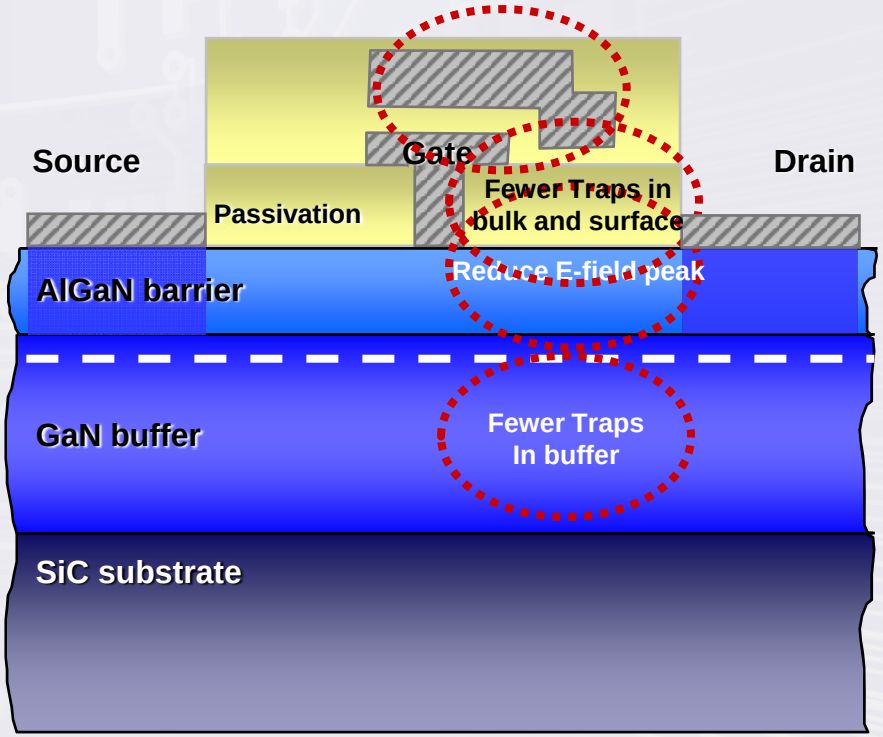
Approved for Public Release, Distribution Unlimited

Performance

Approved for Public Release, Distribution Unlimited

Design Innovations

High performance without degradation addressed by:



E-Field Profile Engineering

- Field plate geometry to distribute E-field

Gate Leakage Reduction

- Higher quality MBE-grown SiN
- Improved surface preparation for PECVD
- Nitride under gate

Buffer Leakage Reduction

- Buffer doping for charge compensation
- Buffer composition tailoring

Dominant physical mechanisms causing failures identified

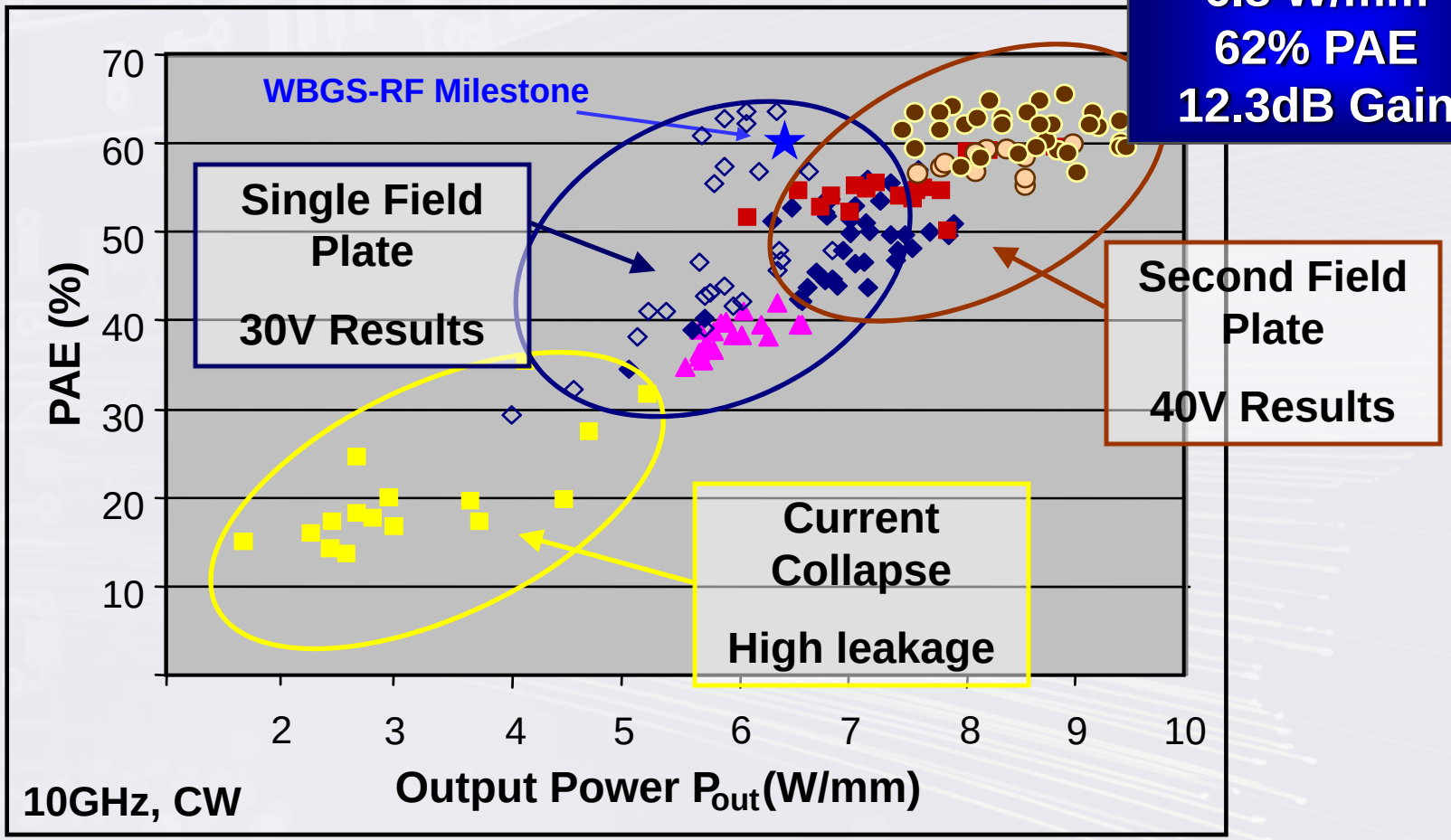
Increased understanding of interplay of reliability and high performance

…but optimized designs not identical across program

Approved for Public Release, Distribution Unlimited

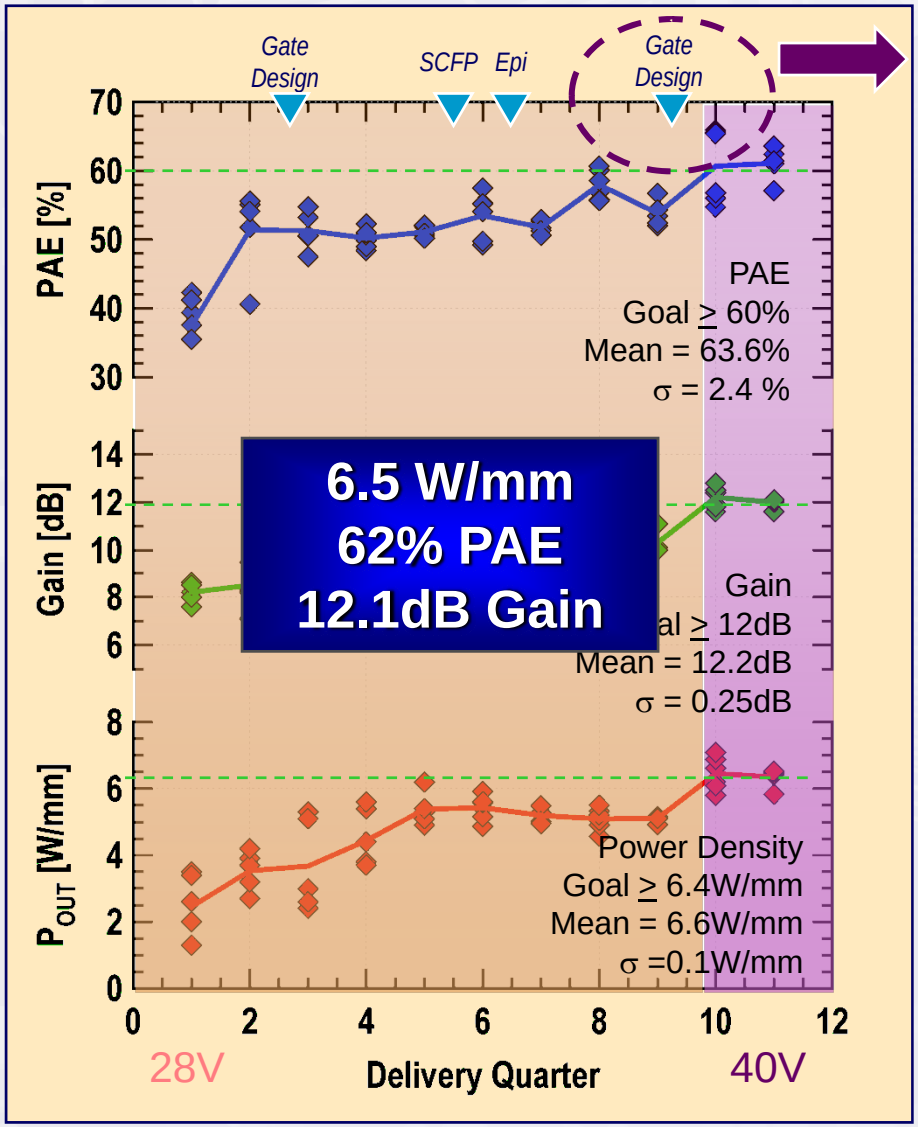
TriQuint Design Evolution

6.8 W/mm
62% PAE
12.3dB Gain

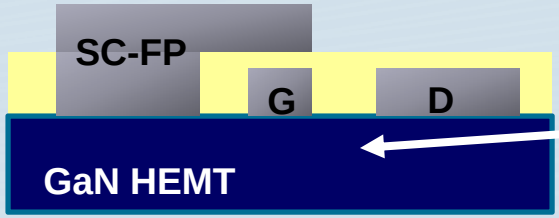


Consistent and steady advances in performance with stability

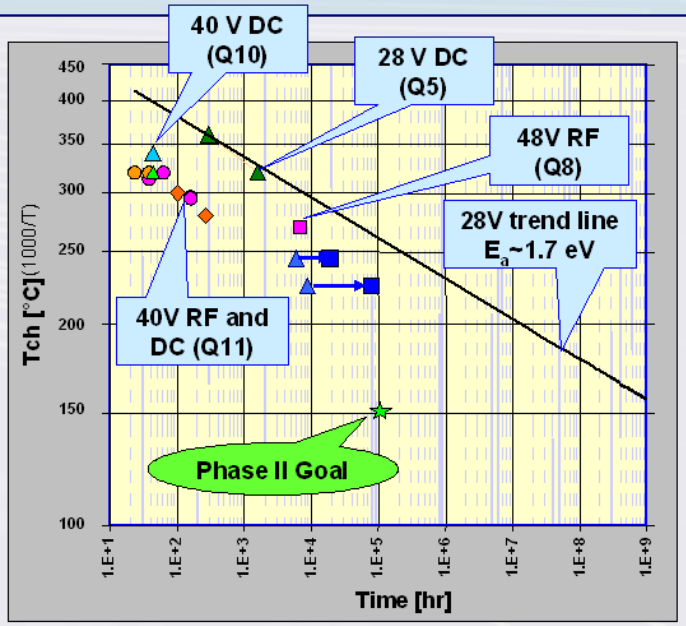
Raytheon Design Evolution



Primary innovation for reliability:
Source connected field-plate and Gamma gate
→ Improved uniformity for electric field between source and drain



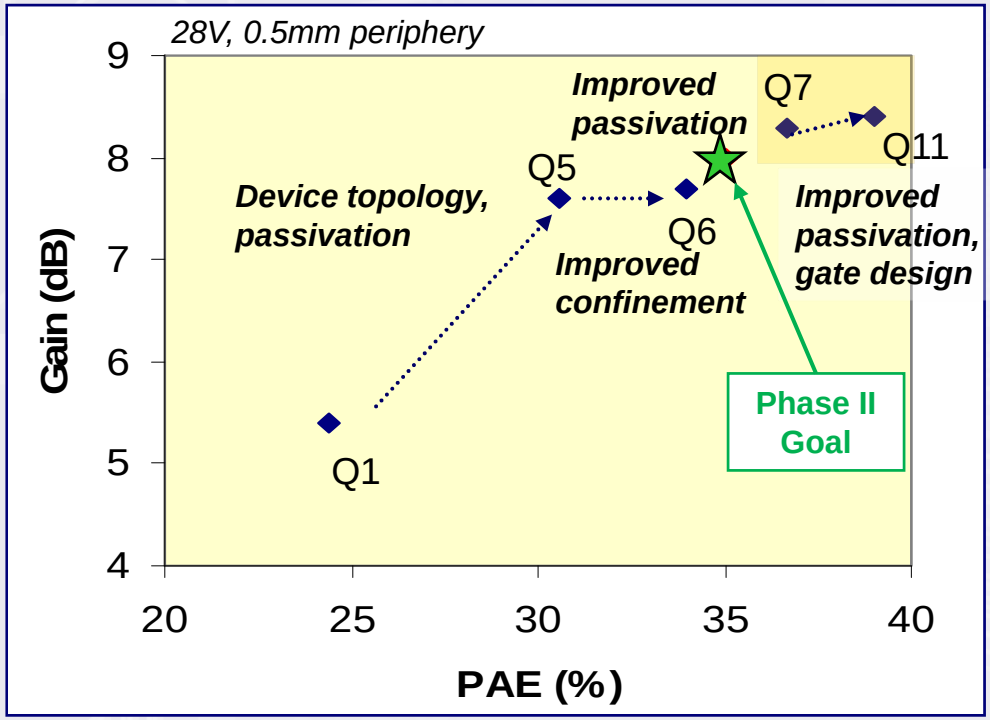
Electric field peak < critical field



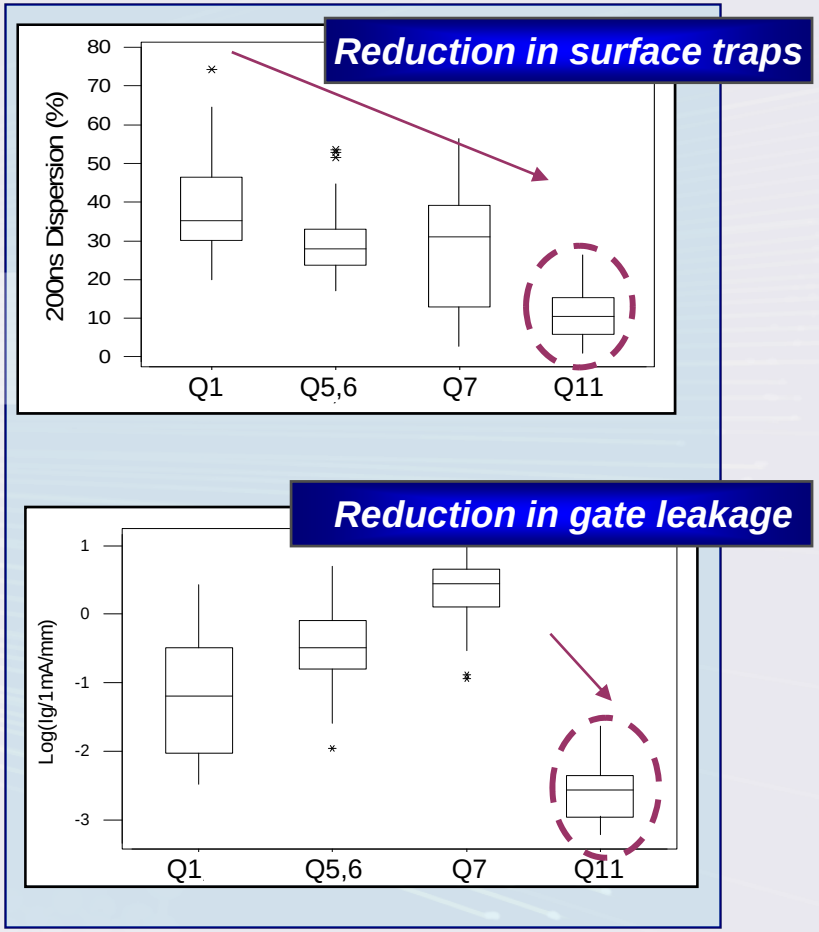
Raytheon

Approved for Public Release, Distribution Unlimited

Northrop Grumman Design Evolution



3.6 W/mm
36% PAE
8.3dB Gain



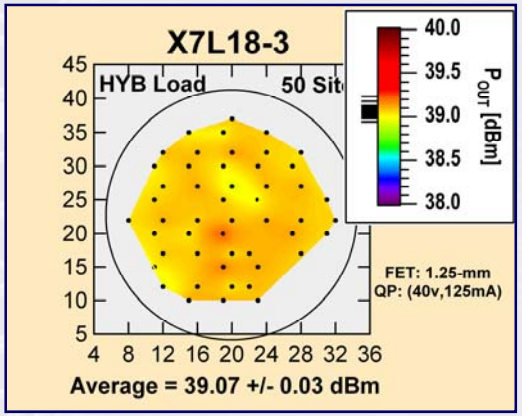
Yield

Approved for Public Release, Distribution Unlimited

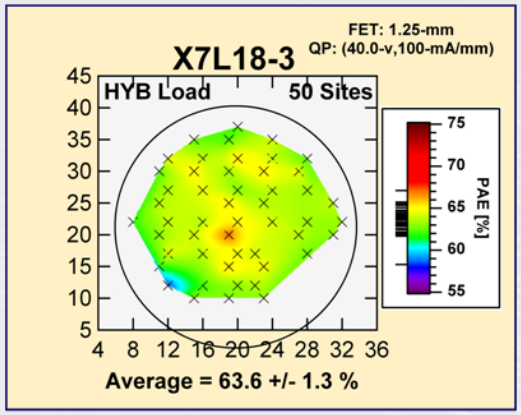
Raytheon RF Yield

Wafer ID	#dev	P_{OUT} [dBm]	G_T [dB]	PAE [%]	# pass	Yield
X7L18-1	50	39.0 ± 0.1	12.0 ± 0.1	62.4 ± 1.2	46	92%
X7L18-2	49	39.1 ± 0.1	12.1 ± 0.1	61.0 ± 0.9	44	90%
X7L18-3	50	39.1 ± 0.1	12.1 ± 0.1	63.6 ± 1.3	47	94%
X7L18-4	49	39.1 ± 0.1	12.1 ± 0.1	61.4 ± 0.7	45	92%

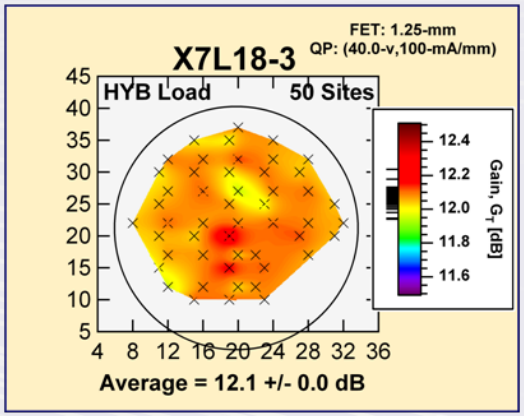
X7L18-3 Wafer Example



Power (dBm)



Power-Added Efficiency (%)



Gain (dB)

Phase II Go/No Go: 50%

Achieved: 91%

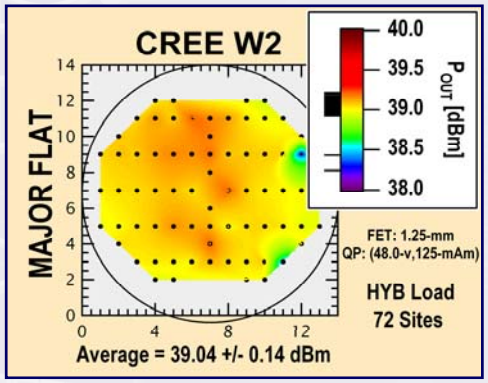
Approved for Public Release, Distribution Unlimited

Cree RF Yield

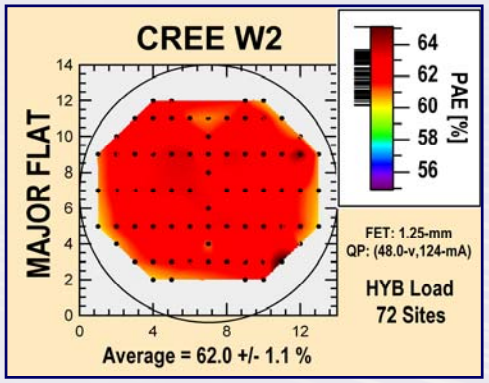
Wafer ID	#dev	P_{OUT} [dBm]	G_T [dB]	PAE [%]	# pass	Yield
1128E070926-2	74	39.0 ± 0.1	12.0 ± 0.1	62.0 ± 1.1	57	77%
1128E070926-4	74	39.0 ± 0.4	12.0 ± 0.4	61.9 ± 3.8	59	80%
112B12-1	74	39.2 ± 0.1	12.2 ± 0.1	61.8 ± 1.2	70	95%
112B12-2	74	39.2 ± 0.1	12.2 ± 0.1	61.6 ± 1.3	65	88%

48V bias

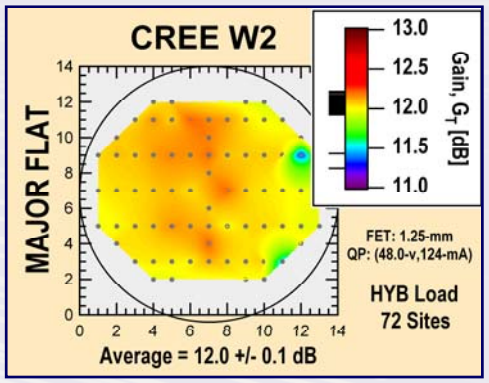
1128E070926-2 Wafer Example



Power (dBm)



Power-Added Efficiency (%)



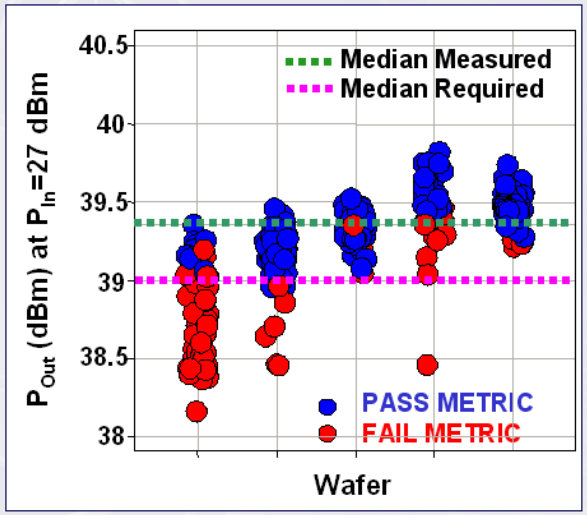
Gain (dB)

Phase II Go/No Go: 50%

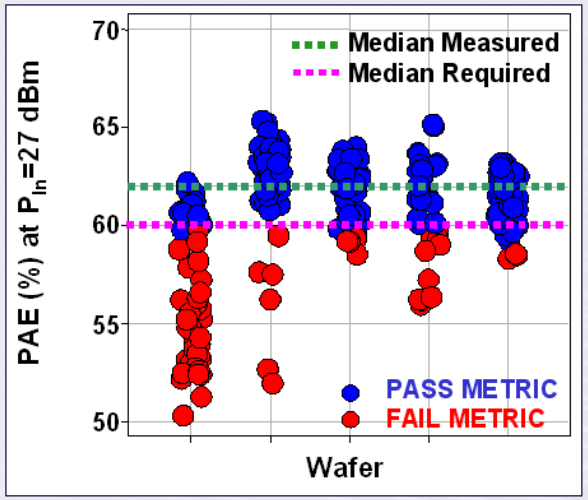
Achieved: 85%

Triquint RF Yield

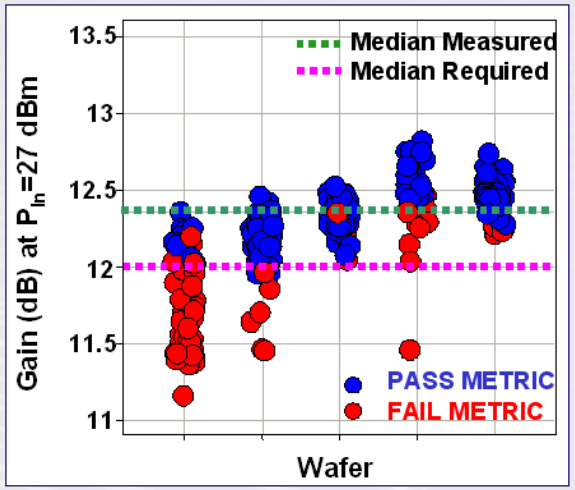
Power



Power-Added Efficiency



Gain

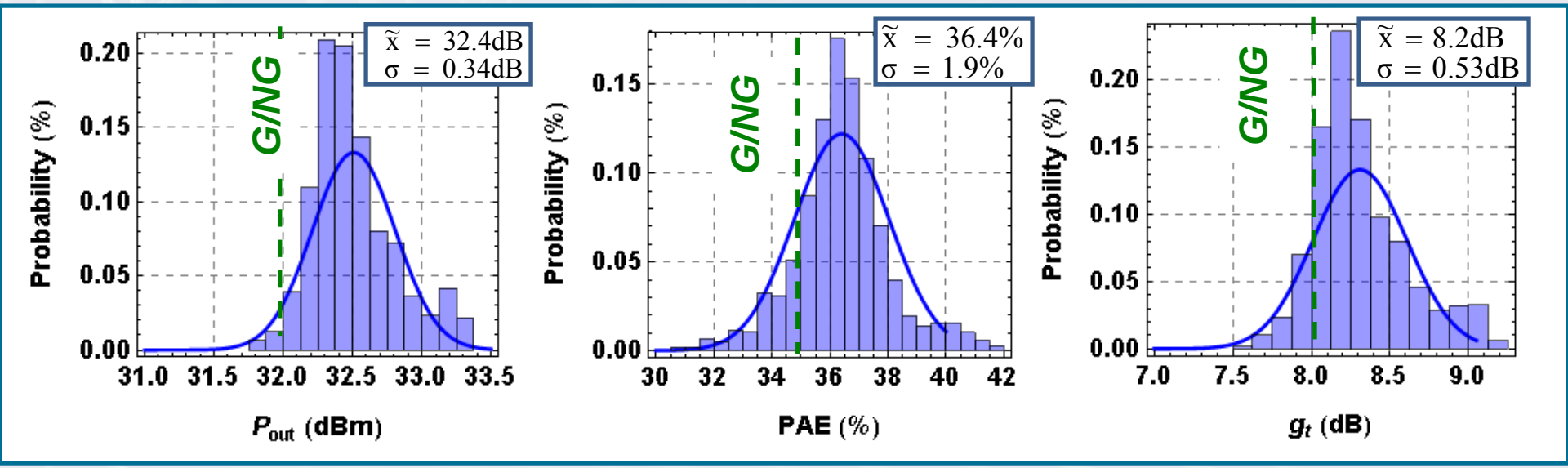


5 wafers

Phase II Go/No Go: 50%

Achieved: 83%

NGST RF Yield



1,400 devices on 14 wafers

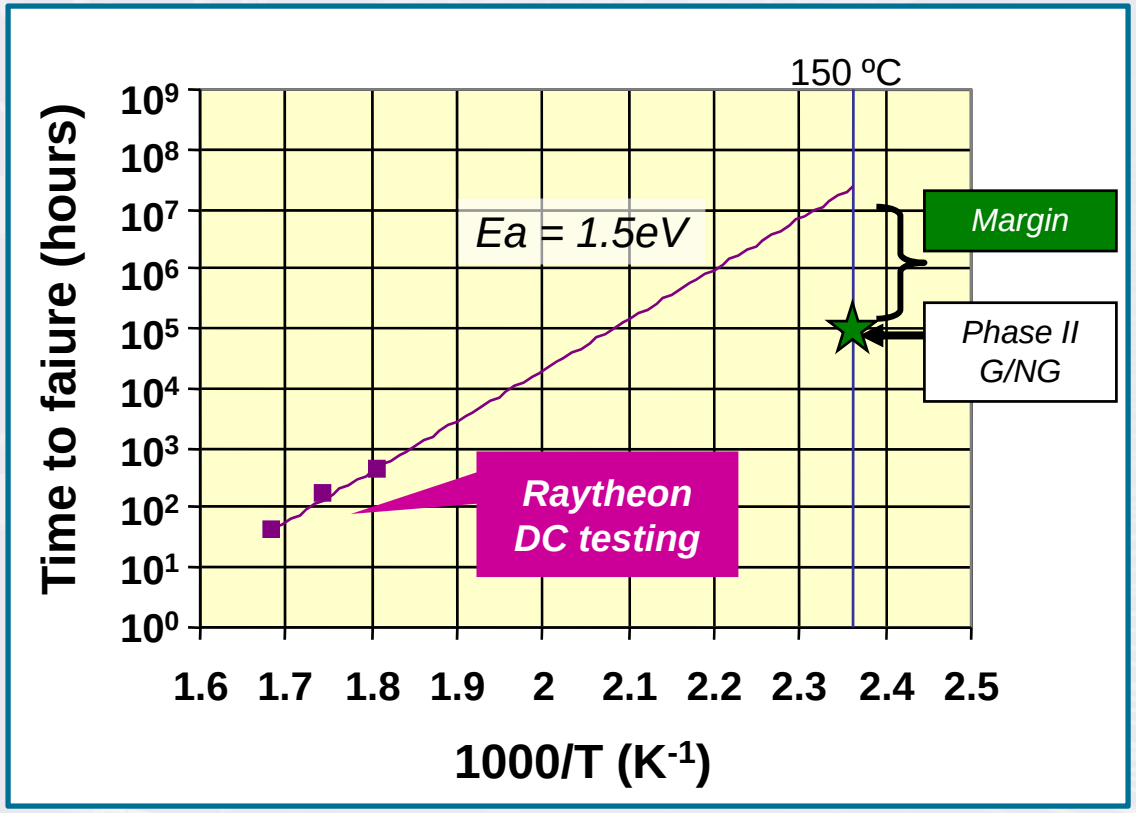
Phase II Go/No Go: 50%

Achieved: 69%

Long-Term Performance

Approved for Public Release, Distribution Unlimited

Raytheon (X-band) Lifetime



- **High temp RF test at NRL**
  - **Completed full tests at T_{ch} = 300 ºC, 280 ºC**
  - **Limited data from T_{ch} = 320 ºC**
  - **Additional parts on test at T_{ch} = 260 ºC**
- **High temp DC test at Raytheon**
  - **Completed full tests at T_{ch} = 320 ºC, 300 ºC**
  - **Data for T_{ch} = 280 ºC involves extrapolations for failure of last few parts**

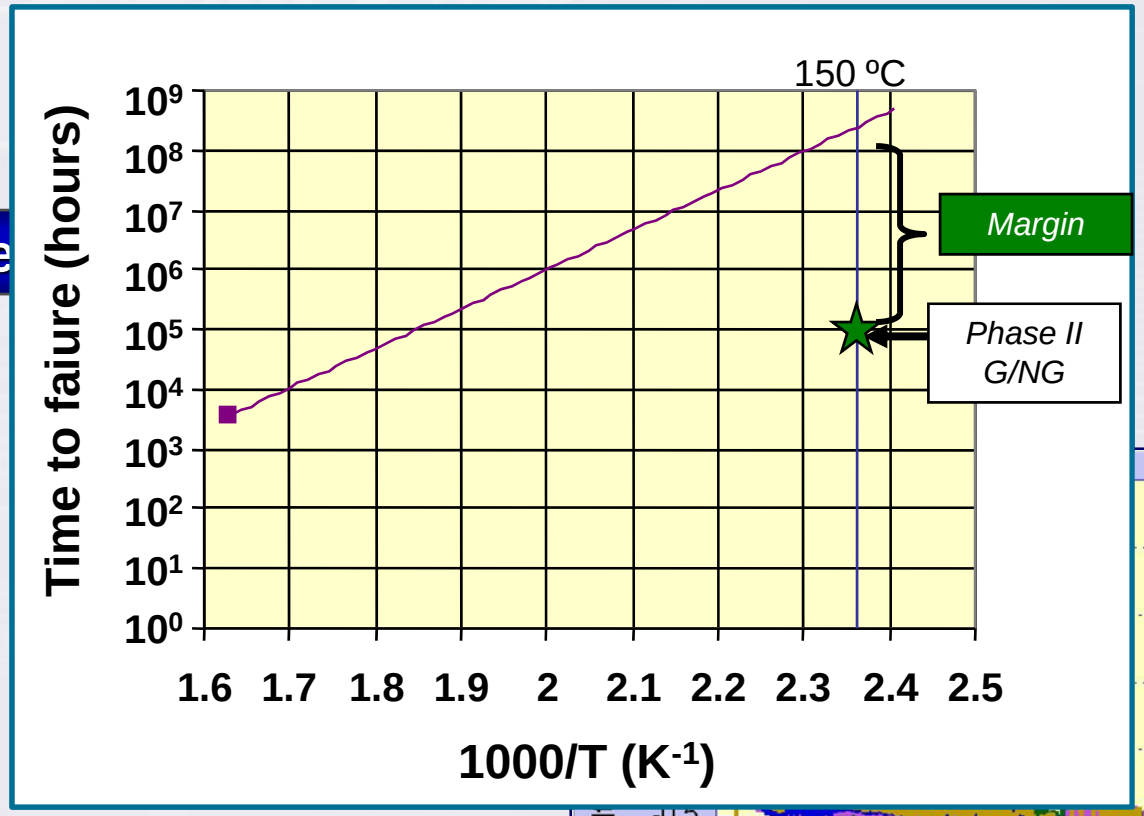
Phase II Go/No Go: 1E5 hours

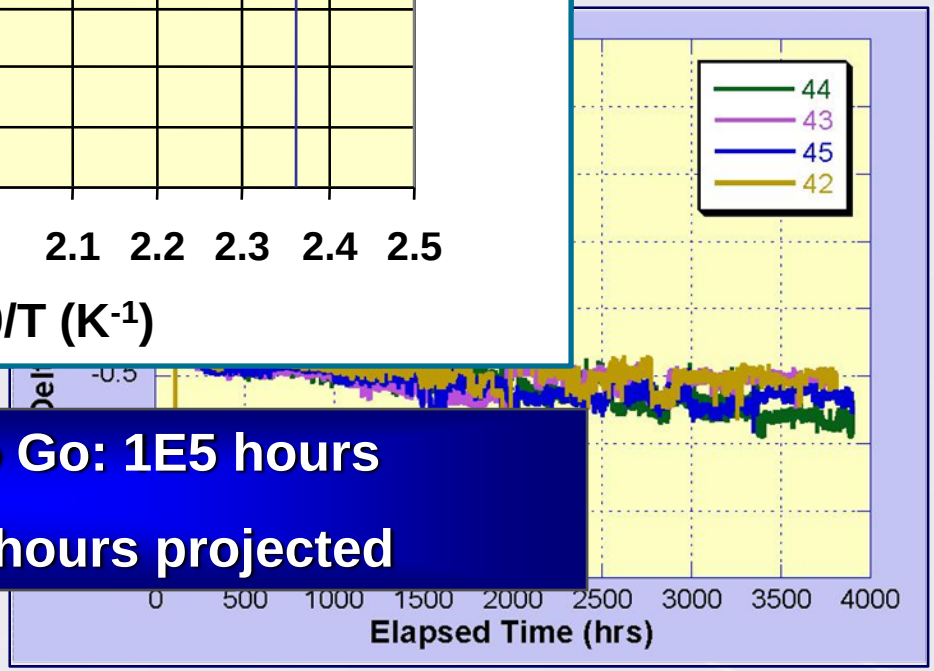
Achieved: 1E7 hours projected

Approved for Public Release, Distribution Unlimited

Cree (X-band) Lifetime

No failure

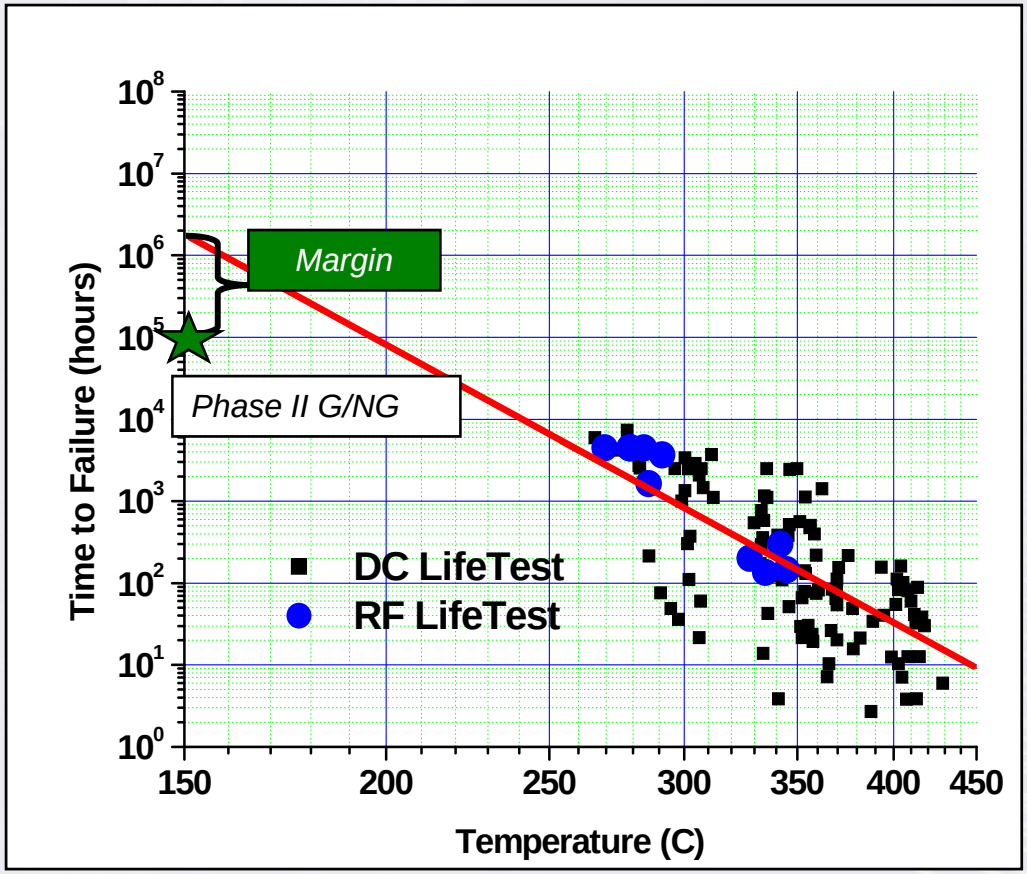




Phase II Go/No Go: 1E5 hours

Achieved: 1E8 hours projected

TriQuint (X-band/Wideband) Lifetime

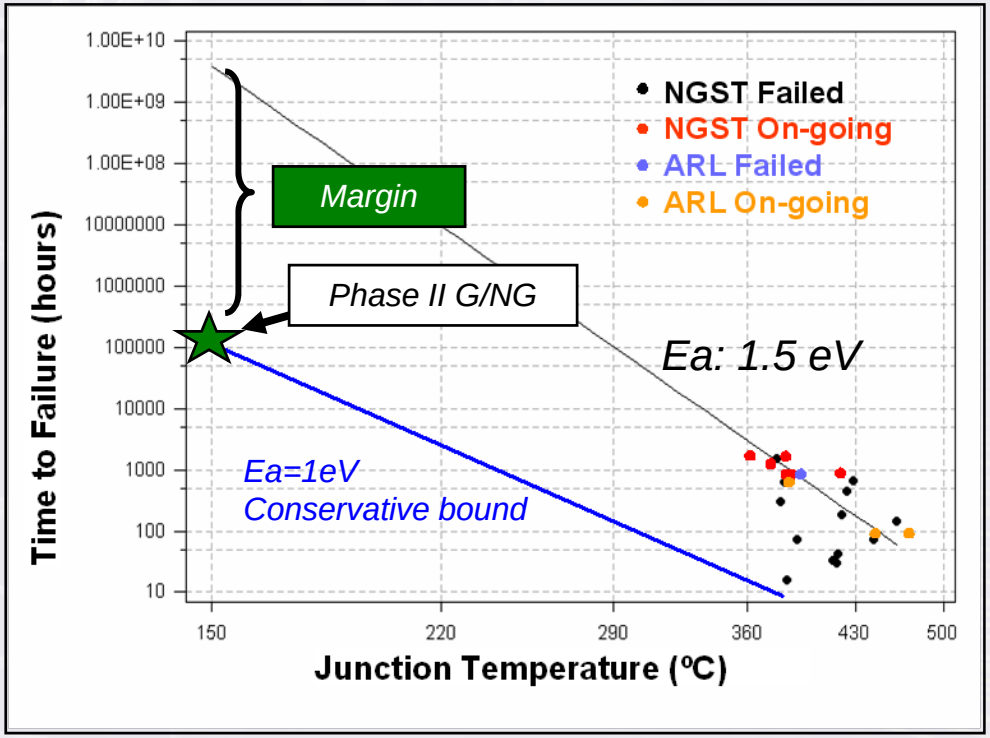


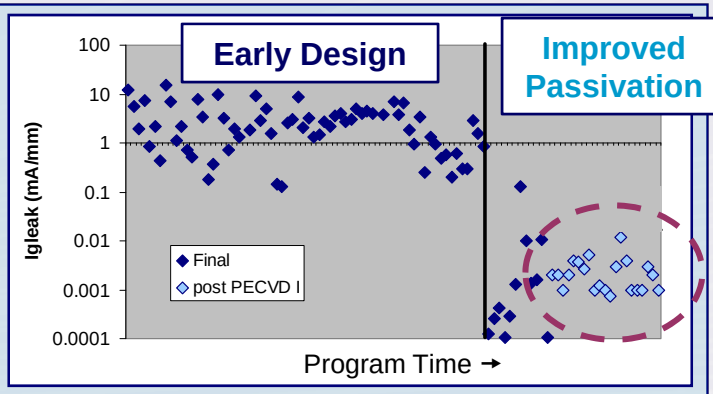
Phase II Go/No Go: 1E5 hours

Achieved: 1.5E6 hours projected

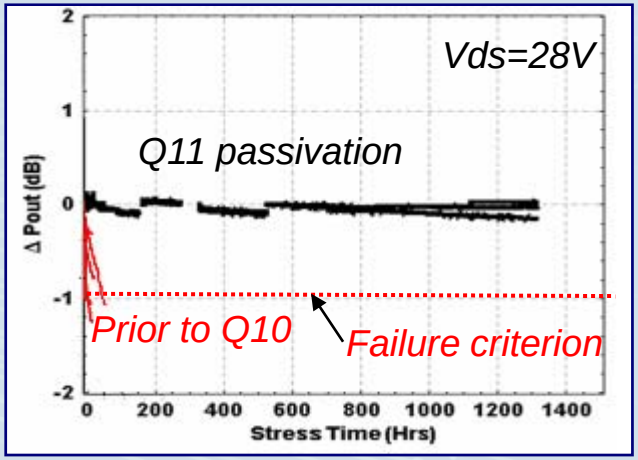
NGST (Q-band) Lifetime

MTTF = 4 10^9 Hr @150ºC





1,000x gate leakage reduction



Test Conditions:

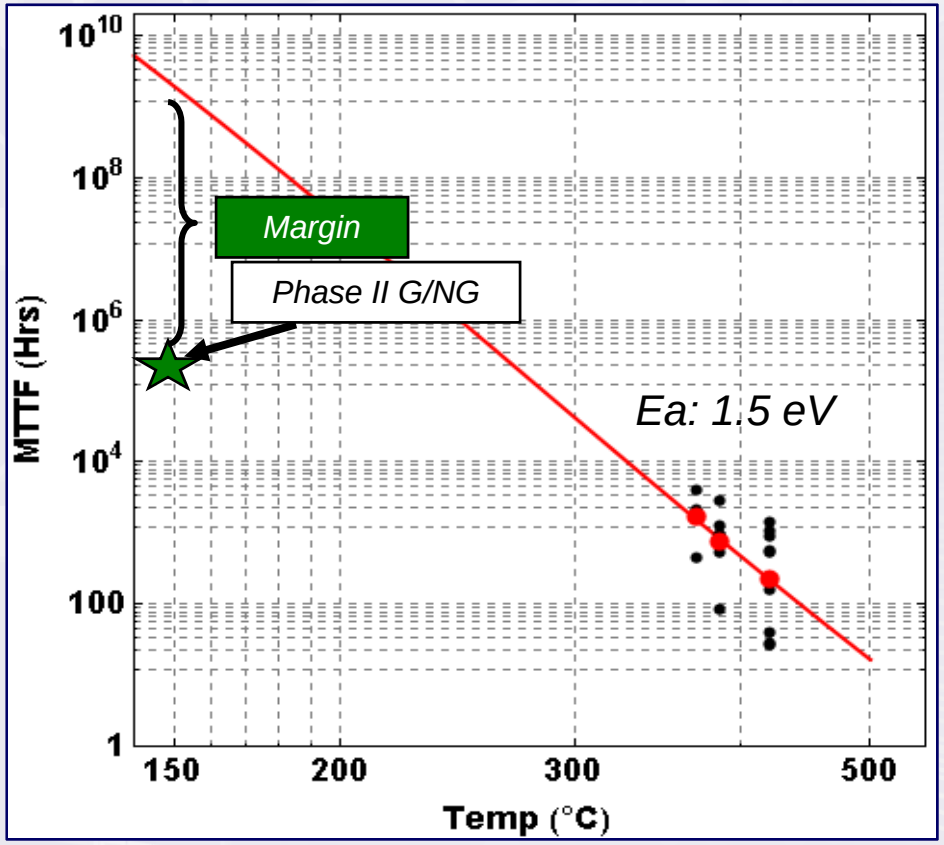
Freq=40GHz at Pin= 24.5dBm

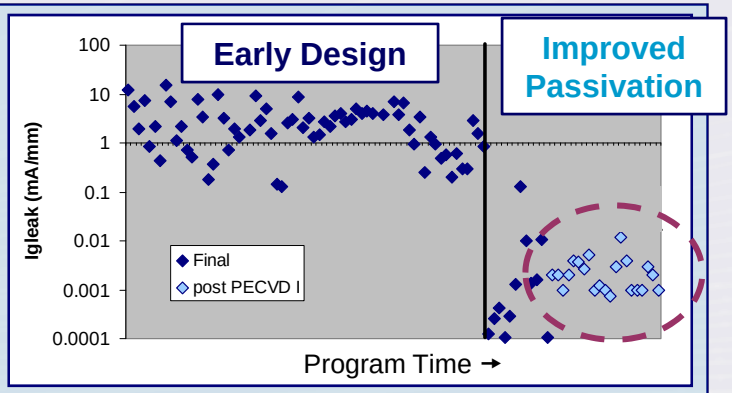
Bias: Vds=28V; Ids,q = 200mA/mm

Phase II Go/No Go: 1E5 hours

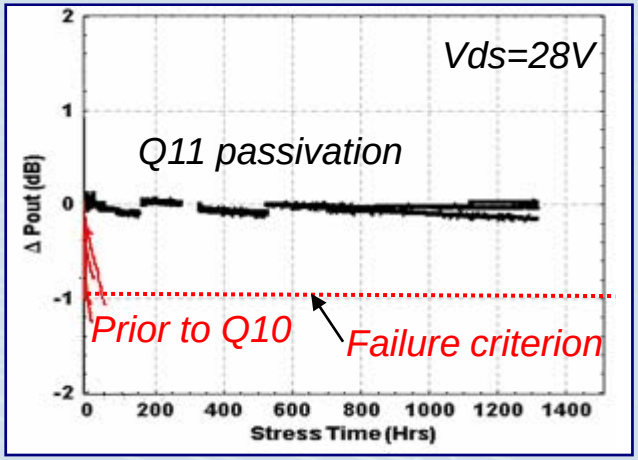
Achieved: 4E9 hours projected

NGST (Q-band) Lifetime





1,000x gate leakage reduction



Test Conditions:

Freq=40GHz at Pin= 24.5dBm

Bias: Vds=28V; Ids,q = 200mA/mm

Phase II Go/No Go: 1E5 hours

Achieved: 1.9E9 hours projected

Approved for Public Release, Distribution Unlimited

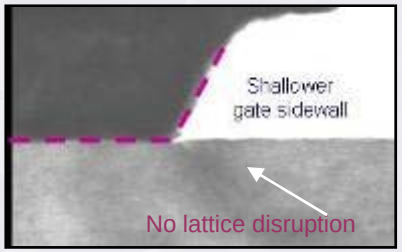
Phase II Limiting Failure Modes

Each team seeing distinct limiting failure

Raytheon

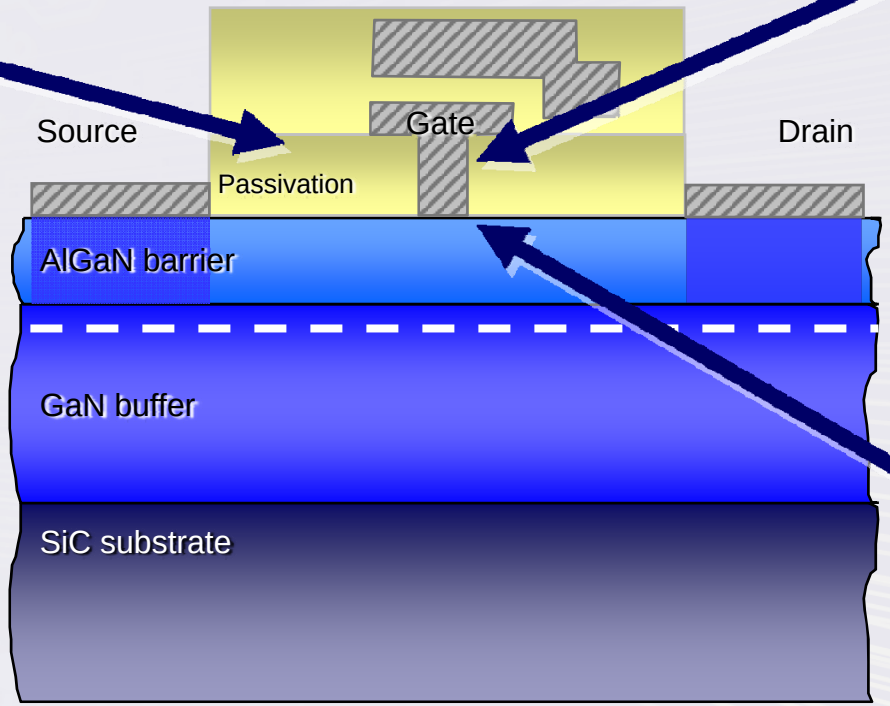
Nitride trap formation

- Distinct mechanism with linear degradation in drain current

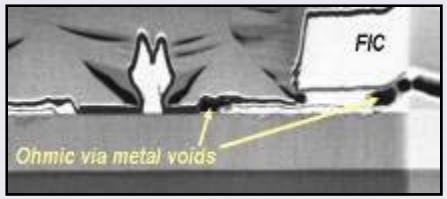


Lattice disruptions overcome

- Devices with shallow gate sidewalls mitigate formation of cracks
- No longer limiting failure



NORTHROP GRUMMAN



Gate Metallization Failure

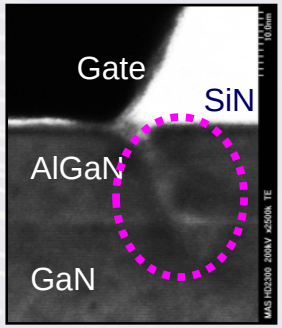
Catastrophic failure

- Sudden increase in gate current

Voids in ohmic via metal

- Inverse piezoelectric effect generating stress

TriQuint SEMICONDUCTOR



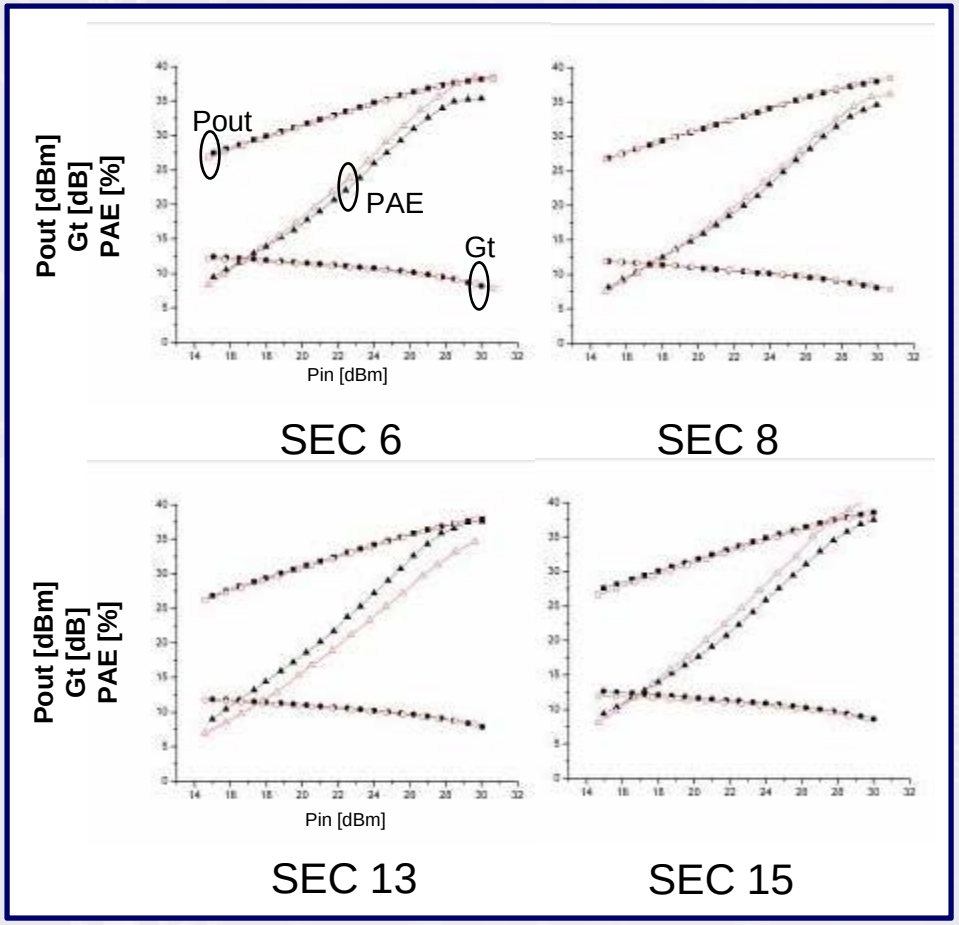
Lattice disruptions

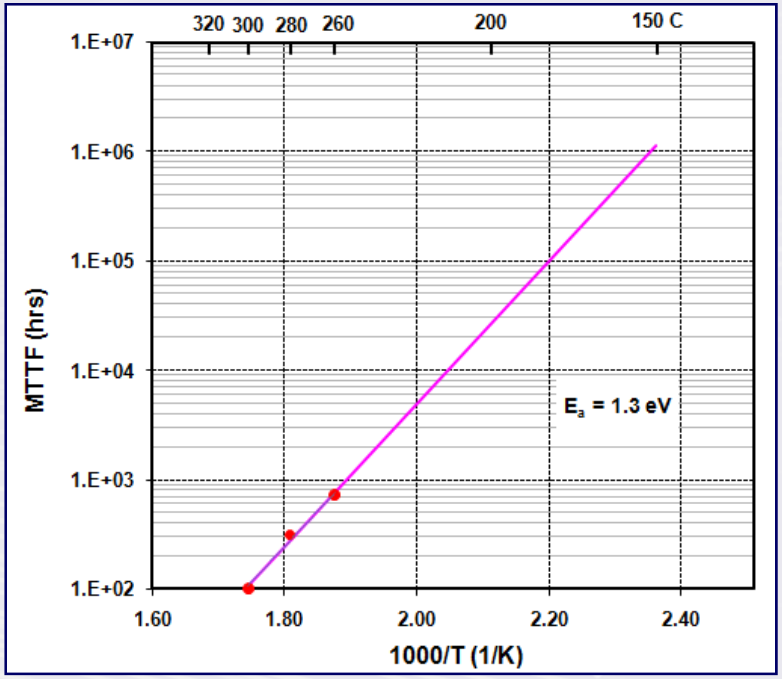
- Electric field driven phenomenon
- Inverse piezoelectric effect generating stress

WBGS-RF Phase II Summary

Approved for Public Release, Distribution Unlimited

TriService Performance Validation





TriService	Contractor
MTTF = 1E6 hours	MTTF = 6E6 hours
Ea = 1.3 eV	Ea = 1.45eV

Power Sweep Validated

RF Lifetime Validated

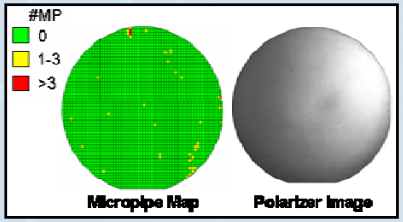
Approved for Public Release, Distribution Unlimited

WBGS-RF Phase III Program

Approved for Public Release, Distribution Unlimited

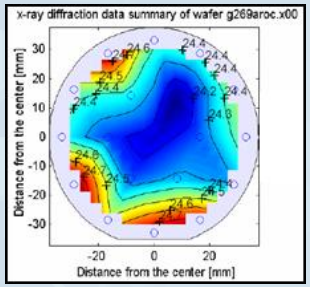
Program Technical Challenges

Phase I
Wide Band Gap Semiconductor Materials



3"+ SiC substrates

Low defect density substrates, uniform epitaxy ✓



Uniform Al composition

Phase II
Wide Band Gap Semiconductor Device Technologies

Increasing integration

Microwave

Understanding & eliminating degradation ✓

MMW

Phase III
Wide Band Gap Semiconductor MMIC Technologies

High Efficiency

- Reduce matching network losses
- Further increase device PAE

High Power/Bandwidth

- Thermal management for severe power dissipation
  - Trade-off unit cell area & gain
  - Maintain reliability despite piezoelectric induced strain
- Achieve broadband impedance match

High Frequency

- Wafer scale packaging to achieve power goal in limited area
- Heat dissipation in limited area

Approved for Public Release, Distribution Unlimited

Each Track Drives Distinct Performance Parameters

Phase II
Wide Band Gap Semiconductor Device Technologies

→ *Increasing integration* →

Phase III
Wide Band Gap Semiconductor MMIC Technologies

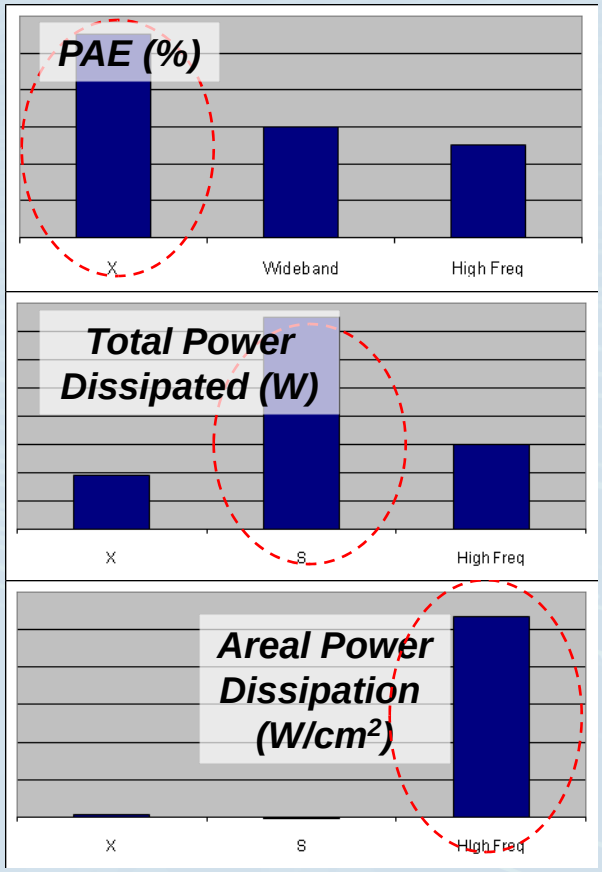
Microwave Devices

→ **High Efficiency**

→ **High Power/Bandwidth**

MMW Devices

→ **High Frequency**



Approved for Public Release, Distribution Unlimited

WBGS-RF Program Scope

DARPA WBGS-RF Scope

MMIC Development
- Demonstrate high performance simultaneous with long lifetime
- Advance understanding of physics of degradation
- Quantify design trade-offs for performance and reliability
- Establish cost models
- Establish production-ready manufacturing readiness

Independent testing
- Tri-Service evaluation

Program Deliverables
- Deliver MMICs to MOA partner

Form, Fit, Function MMICs

Acquisition Partner

Performance of MMICs
- Module testing
- Sub-system testing

Reliability testing
- Reliability under operational conditions in modules

Manufacture Capability
- Manufacturing program (Title III)

Summary

- WBGS-RF Phase II achieved > 10^5 increase in GaN HEMT lifetime over 3 years
- WBGS-RF advancing understanding of physics of reliability and trade-offs with performance
- 2 year Phase III program underway to develop high performance, long lifetime GaN-on-SiC MMICs

Anticipate Continued Rapid Advances for GaN MMIC

Acknowledgements

Raytheon/ Cree	TriQuint	Northrop Grumman	TriService Experts
Raytheon	TriQuint SEMICONDUCTOR	NORTHROP GRUMMAN	Air Force Research Laboratory
CREE	BAE SYSTEMS	emcore	ARL
UCSB	LOCKHEED MARTIN	University of Hawaii Maui Community College	Department of the Navy Naval Research Laboratory
	MIT	UCLA	
	NITRONEX CORPORATION	University of South Carolina	
	Rensselaer	NC STATE UNIVERSITY	
	II-VI	University of Florida	
	emcore		