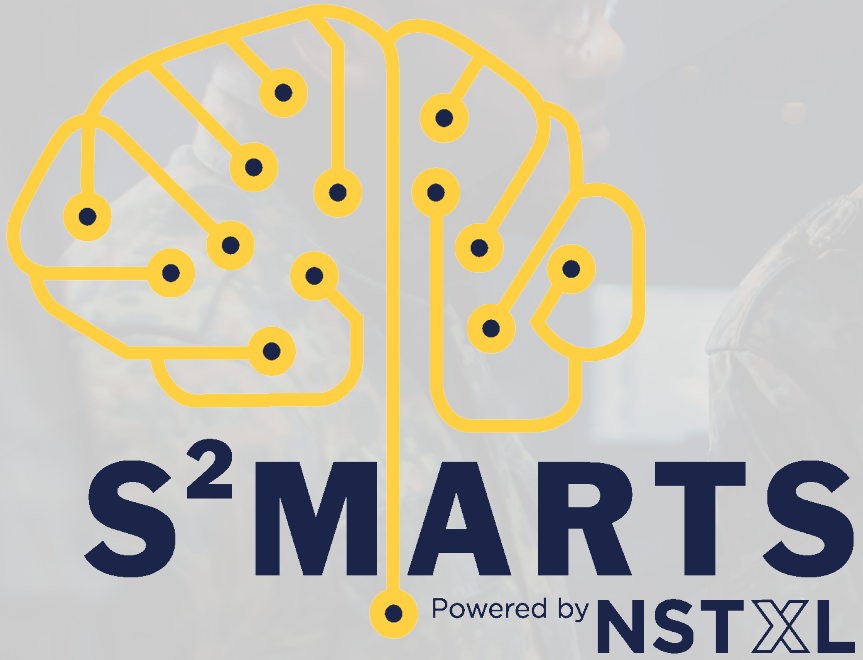


Welcome to the

AWARENESS DAY

for

Advanced Integration Interconnection & Fabrication Growth for Domestic SOTA Radio Frequency Gallium Nitride (Starry Nite)

Wednesday, October 19, 2022

Please ensure audio is muted

Administrative Notes

Please ensure your audio is muted unless presenting

NSTXL will be driving the slide deck. Please utilize the “next slide” prompt when you wish to transition

Rules of Engagement

- Be transparent & respectful
- Do not hesitate to ask questions
- If questions arise, please use the raise hand feature

Intent of Session

- Awareness of project objectives and the importance of DIB partners participating through the submission of designs and MPW programs
- Awareness of OSD goals and STARRY NITE’s alignment to those goals
- Understanding of how designs can be submitted through respective foundries and the submission process

Agenda

13:00 Opening Remarks by NSTXL
13:15 State-of-the-Art Radio Frequency Gallium Nitride Presentation
13:30 Application & Submission Process
13:45 Northrop Grumman Foundry Process Overview with Q&A (Mike Barsky)
14:30 Qorvo Foundry Process Overview with Q&A (Paul Schmid and Marvin Harris will assist with Q&A)
15:15 HRL Foundry Process Overview with Q&A (Dave Fanning, Harris Moyer, and Andy Fu will be presenting in that order)
16:00 Closing & Wrap-up

Please ensure audio is muted

STARRY NITE – Industry Day for Designers

State-of-the-Art Radio Frequency Gallium Nitride

Joshua Hawke, Ph.D.

RF & Optoelectronics Execution Lead
OUSD(R&E) Trusted & Assured Microelectronics

Chief Engineer, RF & Optoelectronics
Naval Surface Warfare Center, Crane

19 Oct 2022

Controlled by: OUSD(R&E) Critical Technologies Office
Trusted & Assured Microelectronics Program
Distribution: A
POC: Joshua Hawke,

https://info.nstxl.org/starry-nite-mpw-program

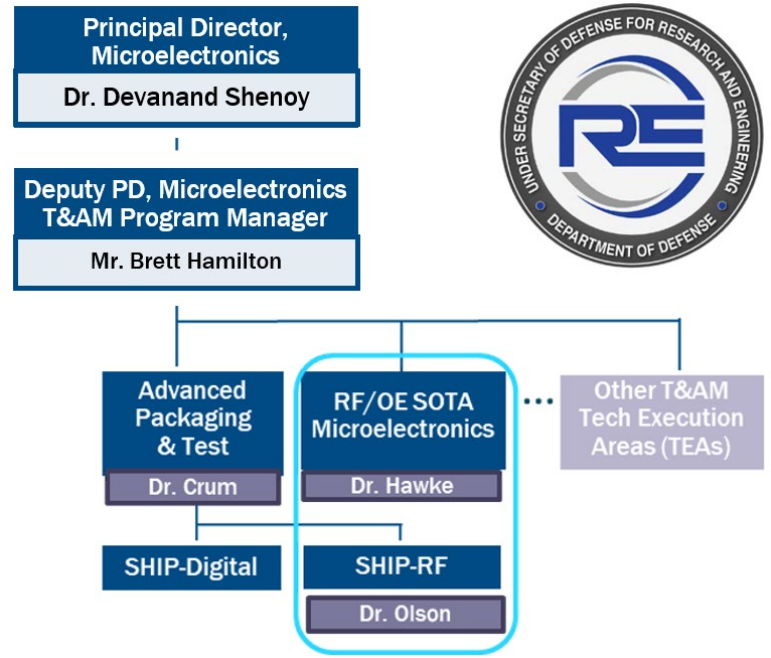
Presentation Overview

- OSD Alignment & Goals
- Why RF GaN?
- MPW Program
  - Offerings & Schedule
  - Focus Areas & Trade Spaces
  - How to Apply
  - Deliverables & Data Rights

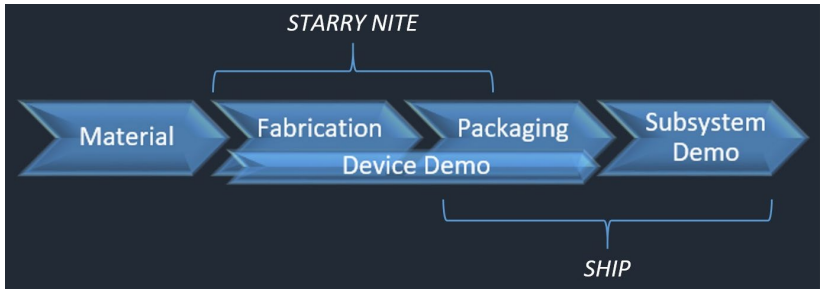
Program Alignment & Goals

T&AM	Trusted & Assured Microelectronics
RF/OE	Radio Frequency & Optoelectronics
SHIP-RF	State-of-the-Art Heterogeneously Integrated Packaging for RF

- **T&AM RF/OE alignment**
  - directly supports OSD's Modernization Priority of Microelectronics
  - seeks transition alignment with T&AM Advanced Packaging (e.g., SHIP-RF)
- **The RF/OE mission**
  - Develop secure access to state-of-the-art RF GaN and Si Photonic materials, foundrie next generation sensors and communications
  - Demonstrate state-of-the-art prototypes and IP, which transition to DoD programs an
- **STARRY NITE project goals**
  - Establish domestic production pilot lines for mmW RF GaN foundries and advanced i
  - Offer multi-project wafer (MPW) runs for millimeter wave designers and foster produc Packaging ecosystem.

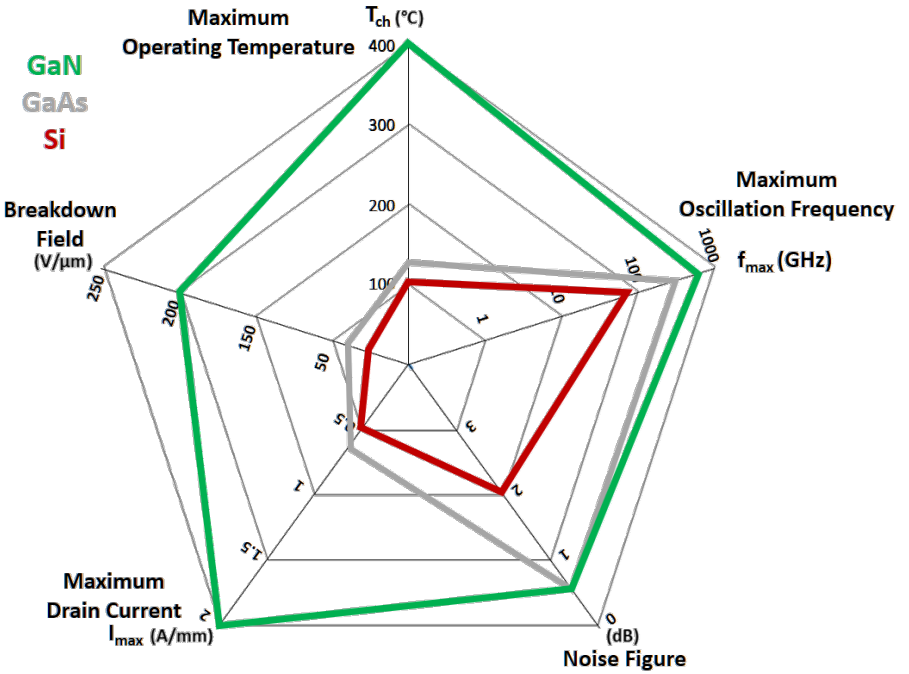


Debuted at Industry Day for Designers



A Case for RF GaN

- RF GaN performance enables critical DoD applications, such as Radar, Electronic Warfare, and Communications
  - High PAE → low loss/cost
  - High power out → smaller sensors/platforms
  - Wide bandwidth → fewer components
  - Ruggedness and radiation hardened → reliability
- Strong dual-use applications, such as 5G, SATCOM, etc.



Drain Current + Breakdown Field → **High Power**

Max Freq + Breakdown Field → **Efficiency**

Max Temp + Breakdown Field → **Robust Operation**

STARRY NITE MPW Program

The STARRY NITE MPW Program…

- Provides domestic designers free MPW space on SOTA RF GaN nodes
  - HRL (40nm T3)
  - Northrop Grumman (90nm)
  - Qorvo (90nm & 150nm)
- Captures designs in a secure IP Repository at each foundry
  - Note: only approved government employees can access the “IP Vault”
- Facilitates transition of designs by inviting top designers to brief transition partners at Defense Industrial Base (DIB) Demo Days
- Does NOT provide stipends for labor, EDA tools, or other expenses associated with design and test
  - Note: this is an ideal opportunity to leverage internal R&D funds and/or cost-share with other DoD-funded design projects

2022 STARRY NITE MPW Schedule

STARRY NITE MPWs			2022		2023												2024		
			Q4		Q1			Q2			Q3			Q4			Q1		
Foundry	Process	Offering	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Qorvo	GaN09	90nm					31												
	GaN15	150nm				28													
	GaN09	90nm		1		1			1								15		
	GaN15	150nm		1		1			1								15		
	GaN15+AIC	150nm														1		1	
	GaN09	90nm														1		1	
NG	GaN09	90nm	10						25										
			18	16			10					25							
HRL	T3 GaN04	40nm		16															
							31												
					20														
			1	1			24												
						22	17			9									
									10	2		25							

Application Due
Nov 1, 2022

Award Announced
Dec 1, 2022

Submit Design
Mar 24, 2023

Receive Die for T&E
Sept TBD, 2023

Legend
Application Deadline
Performer Space Awarded
Design Submission
Die Delivered

- HRL – 40nm T3

- 3 Design Focus Areas
  - Radar
  - Electronic Warfare
  - Communications
- DoD Trade Space Interests (see next slides)

GaN-Based RF Components (Examples)

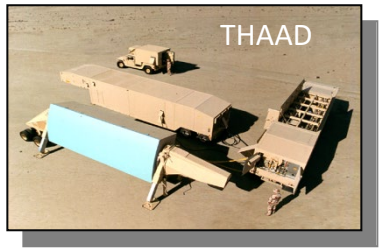
- Power Amplifiers
  - High power added efficiency at higher power
  - Wideband operation
  - Size and weight reduction
- Low Noise Amplifiers
  - Offer low noise and higher input RF power survivability
- Switches
  - High peak power out
  - Can withstand high input power
- Mixers
  - Better linearity and more input power compared to GaAs above S-band

Transmit (Power Amplifiers)

Focus Areas: Radar, EW, and Comm
Trade Space: Power/Efficiency, Frequency, Bandwidth

- Reduced system size, weight, cost
- Manufacturable

- Transmit: higher power, reduced cooling

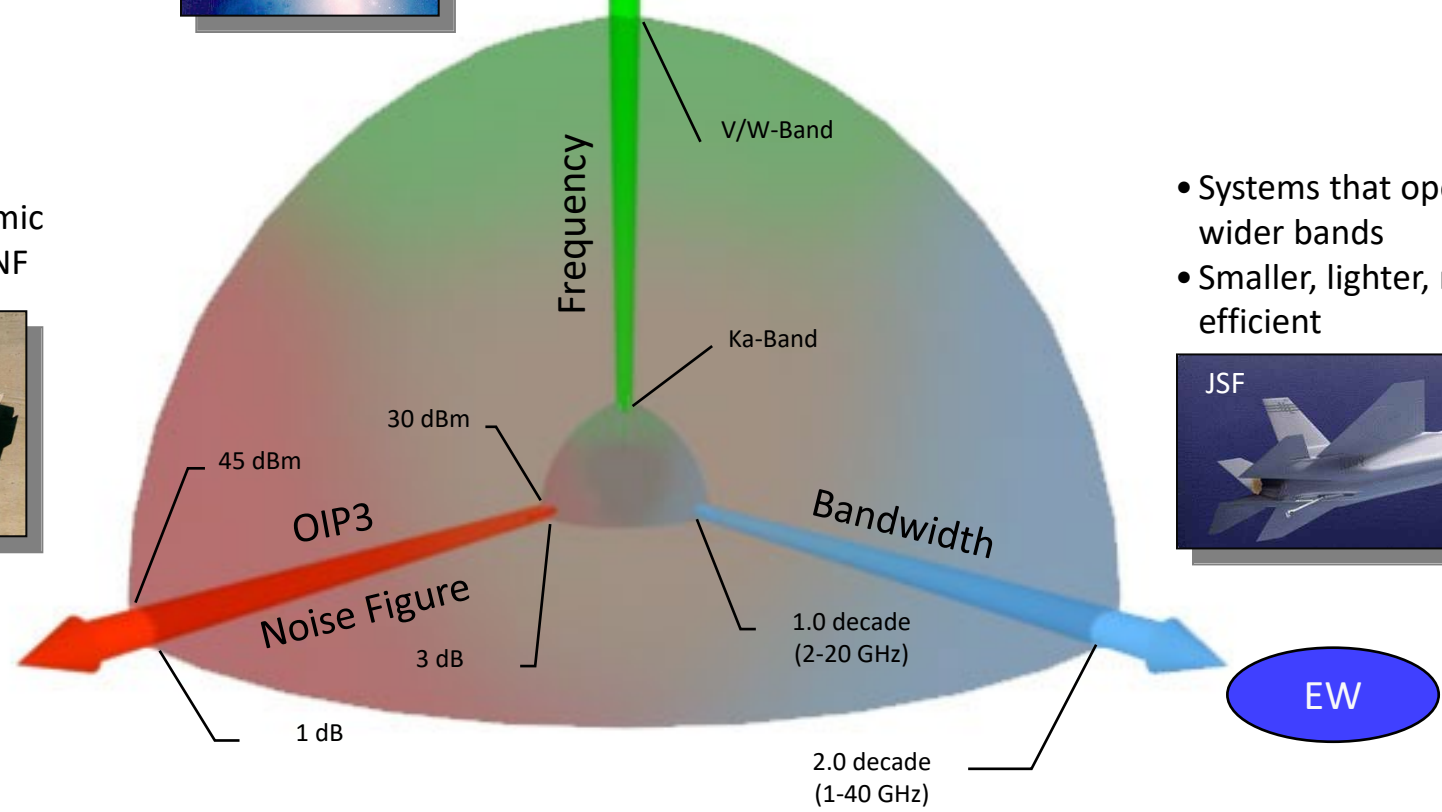


- Systems that operate over wider bands
- Smaller, lighter, more efficient

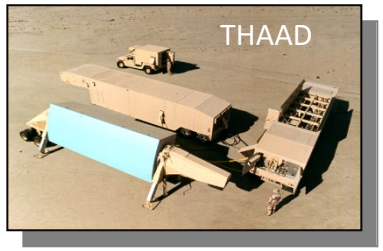
Receive (Low Noise Amplifiers)

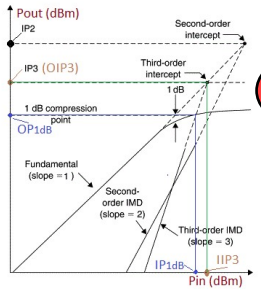
Focus Areas: Radar, EW, and Comm
Trade Space: OIP3/NF, Frequency, Bandwidth

- Reduced system size, weight, cost
- Manufacturable



- Receive: higher dynamic range, lower system NF





IIP3 vs OIP3 | difference between IIP3 and OIP3 (rfwireless-world.com)

- Systems that operate over wider bands
- Smaller, lighter, more efficient

How to Apply

Before You Apply

- Review MPW Schedule
- Download Request for Design Application (RFDA)
- Download Industry Day Brief
- Review Design Submission Requirements
- Work NDA with foundry (optional)

To Apply

- Submit completed Application Form to respective foundry prior to application deadline
- Work NDA with foundry (optional)
- Complete PDK training (optional/if available)

If awarded

- Complete the NDA with respective foundry
- Complete Collaboration Agreement with respective foundry
- Complete design by design submission date (i.e., DRC)
- Submit design package to be retained in IP Vault

https://info.nstxl.org/starry-nite-mpw-program

Deliverables & Data Rights

	Govt Purpose Rights	Limited Purpose Rights	No Govt Rights
Design Submission Package • Circuit layouts in GDS-II • Schematics • Simulation Plots • Information on PDK Version • EDA tools used and version • Any other simulation tools used and version	Required. Captured as GPR in IP Vault.	Required. Captured as LP in IP Vault	Schematics & Circuit Layouts in GDS-II only. Not in IP Vault.
Post-Design Submission Package • Packaged MMICs for IV&V by USG • Raw and summarized test data • Virtual outbrief (see Final Report)	Preferred/Optional		
Final Report • Design & Application • Measured Results vs Simulation • Analysis of PDK & Device Model • Lessons learned for future efforts • Feedback on foundry process	Preferred/Optional		
DIB Demo Day Pitch • Brief on full design of package and evaluation board • Evaluation Board and test code	Optional upon request		

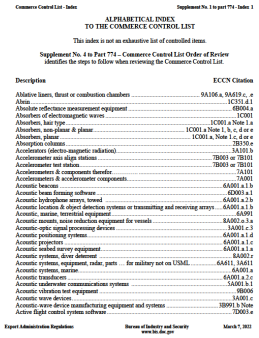
Notes

- GPR is preferred. Explanations are required in RFDA to select LP or No Govt Rights.
- USG reserves the right to award space to the most competitive proposals.
- Only approved USG employees may access the IP Vault.
- STARRY NITE does not fund labor and materials. Competitive proposals require cost-share (e.g., IRAD).
- Optional tasks intended to facilitate technology transition and provide foundry feedback

Export Controls – US Persons Required

- RF GaN MMICs are listed on the Commerce Control List and are therefore subject to Export Controls
  - Note: the EAR/CCL regulations apply regardless of funding source or propriety

Click here to read the list →



Commerce Control List - Index — Supplement No. 1 to part 774 - Index 1

ALPHABETICAL INDEX
TO THE COMMERCE CONTROL LIST

This index is not an exhaustive list of controlled items.

Supplement No. 4 to Part 774 – Commerce Control List Order of Review
Identifies the steps to follow when reviewing the Commerce Control List.

Description — ECCN Citation

Ablative liners, thrust or combustion chambers ..... 9A106.a, 9A619.c, .e
Abrin 1C351.d.1
Absolute reflectance measurement equipment 6B004.a
Absorbers of electromagnetic waves 1C001
Absorbers, hair type ..... 1C001.a Note 1.a
Absorbers, non-planar & planar ..... 1C001.a Note 1, b, c, d or e
Absorbers, planar ..... 1C001.a, Note 1.c, d or e
Absorption columns 2B350.e
Accelerators (electro-magnetic radiation) 3A101.b
Accelerometer axis align stations ..... 7B003 or 7B101
Accelerometer test station ..... 7B003 or 7B101
Accelerometers & components therefor 7A101
Accelerometers & accelerometer components 7A001
Acoustic beacons 6A001.a.1.b
Acoustic beam forming software 6D003.a.1
Acoustic hydrophone arrays, towed 6A001.a.2.b
Acoustic location & object detection systems or transmitting and receiving arrays 6A001.a.1.b
Acoustic, marine, terrestrial equipment 6A991
Acoustic mounts, noise reduction equipment for vessels 8A002.a.3.a
Acoustic-optic signal processing devices 3A001.e.3
Acoustic positioning systems 6A001.a.1.d
Acoustic projectors 6A001.a.1.c
Acoustic seabed survey equipment 6A001.a.1.a
Acoustic systems, diver deterrent 8A002.r
Acoustic systems, equipment, radar, parts ... for military not on USML 6A611, 3A611
Acoustic systems, marine 6A001.a
Acoustic transducers 6A001.a.2.c
Acoustic underwater communications systems 5A001.b.1
Acoustic vibration test equipment 9B006
Acoustic wave devices 3A001.c
Acoustic-wave device manufacturing equipment and systems ..... 3B991.b Note
Active flight control system software 7D003.a

Export Administration Regulations — Bureau of Industry and Security www.bis.doc.gov — March 7, 2013

- STARRY NITE MPW Applicants must
  - disclose names of individuals accessing foundry PDKs
  - indicate if any such individual is not a U.S. person (as defined under U.S. export control laws)

USD(R&E)

NORTHROP GRUMMAN

Starry Nite Foundry Access at Northrop Grumman

MPW Runs

Mike Barsky
General Manager of
Microelectronics Foundry Services
Northrop Grumman

October 19, 2022

Outline

- Overview of Northrop Grumman
- Overview of the Microelectronics Foundry at Northrop Grumman
- Overview of the Starry Nite MPW runs with Northrop Grumman
- How to Engage with NG for MPW Runs

Northrop Grumman Today

Leading global security company

$36.8 billion sales in 2020

- 86% U.S. / 14% International

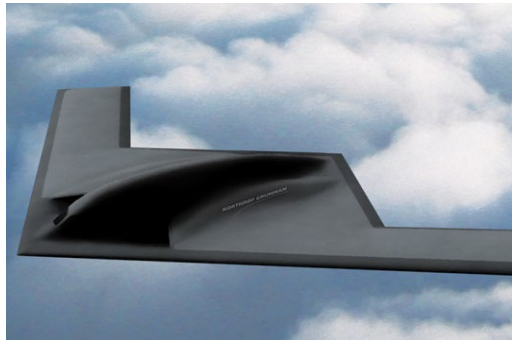
$81 billion total backlog

(as of Dec. 31, 2020)

~97,000 employees

Leading capabilities in:

- Space
- Missiles
- Advanced Weapons
- Aeronautics
- Mission Systems



Four Operating Sectors at a Glance

Aeronautics Systems


Autonomous Systems

Aerospace Structures

Advanced Technologies and Concepts

Aircraft Design, Integration and Manufacturing

Long-range Strike

Multi-Domain Integration and Operations

Intelligence, Surveillance and Reconnaissance

Battle Management

Defense Systems


Integrated Air & Missile Defense

Defensive Cyber and Information Operations

Platform Modernization and Fleet Operations Support

Advanced Weapons

Precision Munitions

Software Systems Modernization and Sustainment

Training and Simulation

Propulsion Systems

Mission Systems


Airborne Sensors and Networks

Artificial Intelligence/Machine Learning

Cyber and Intelligence Mission Solutions

Navigation, Targeting and Survivability

Maritime/Land Systems and Sensors

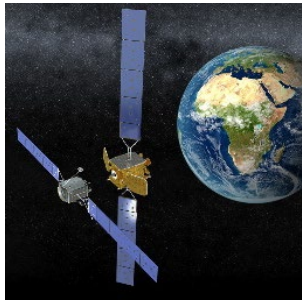
Engineering & Sciences

Emerging Concepts Development

Multi-domain C2

Agile/DevSecOps Systems

Space Systems

Launch Vehicles

Propulsion Systems

Commercial Satellites

Military and Civil Space Systems

Science and National Security Satellites

Human Space and Advanced Systems

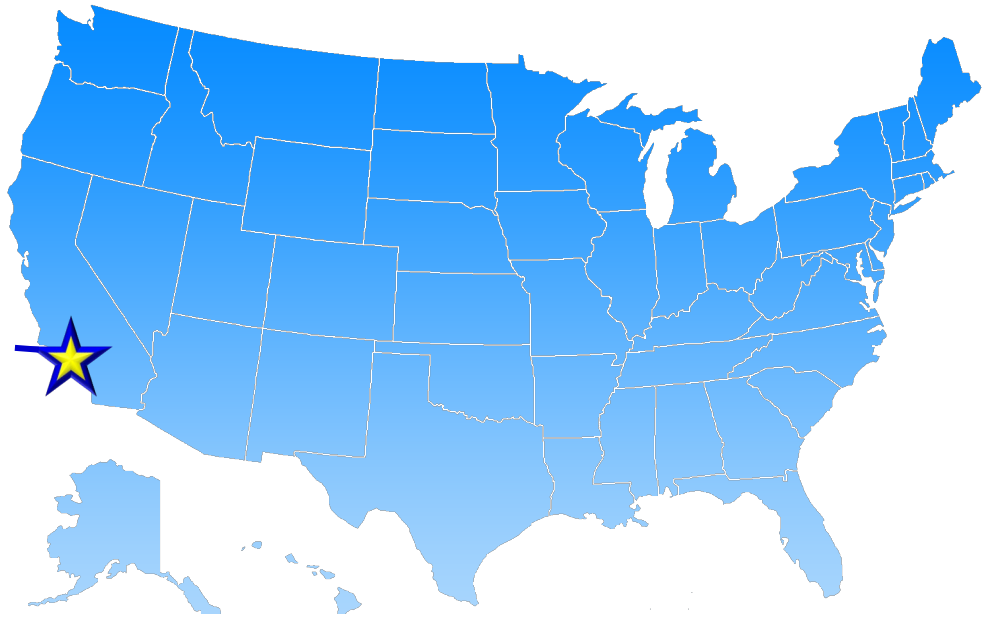
Space Components

Missile Defense

Space Exploration

Space ISR Systems

NG Microelectronics Foundry



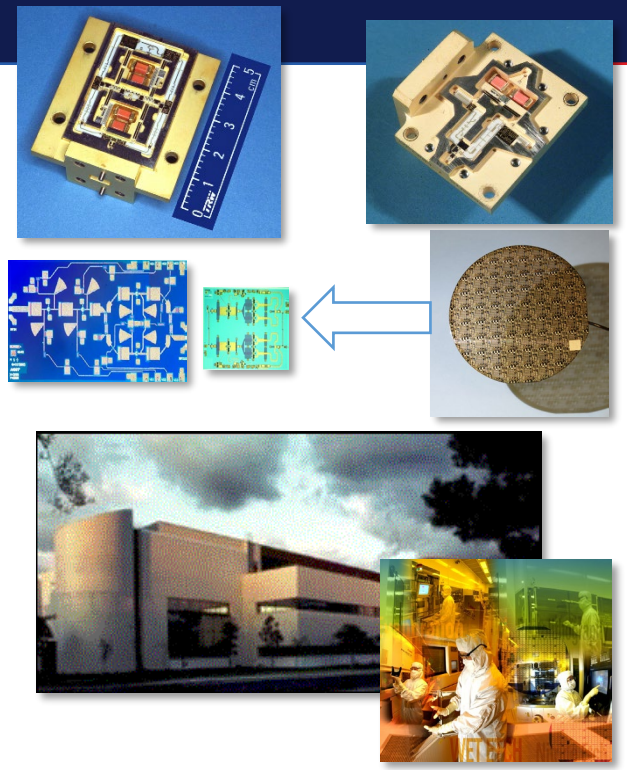
Provide advanced microelectronics capabilities for DoD and commercial products

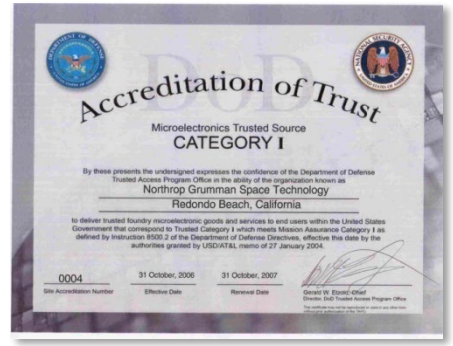
Microelectronics Products & Services (MPS) Strategic Business Unit Overview

NORTHROP GRUMMAN

- MPS is the storefront for internal and external access to the Redondo Beach microelectronics and microelectronic-based products
- Product portfolio includes MMIC sales, foundry services and RF unit product developments
- Leverages Redondo Beach-based microelectronics foundry technologies utilized in NG space, airborne and ground products
- NG Space Park foundry:
  - Design/fab/test/qualify MMICs for Space and Commercial applications
  - 100 mm fabrication HEMT (GaAs, InP, GaN), HBT (GaAs, InP) lines
  - Trusted foundry designation

- MPS business predominately operates under fixed price contracts, commercial terms





- *Department of Security Services (DSS) Facility Clearance to the SECRET level (Form DD254)*
- *Certification of SECRET level Networking capability*

Foundry Services Technology Offering

- NG Space Park foundry:
  - Design/fab/test/qualify MMICs for Space and Commercial applications
  - 100 mm fabrication HEMT (GaAs, InP, GaN), HBT (GaAs, InP) lines
  - Trusted foundry designation
- NG offers full or shared mask options
- Shared mask is where we divide the wafer into three/four areas for multiple customers

Parameter/ Technology	$f_{T,peak}$ (GHz)	β or G_m	V_{ce}/V_{ds} (V)	Operating Current Density	Wafer Thickness (μm)	Applications
0.15 μm GaAs PHEMT	80	550 mS/mm	5	250 mA/mm	50 & 100	• High power amps < 5W up to 60GHz • Linear amplifiers • Driver amplifiers • Up/Down converters
0.1 μm GaAs PHEMT	120	650 mS/mm	4	250 mA/mm	50 & 100	• Low noise amplifiers up to 100GHz • Power amplifiers < 1W up to 100GHz • Up/Down converters
1 μm power InP HBT	80	25	7.5	0.7 mA/μm^2	75	• Mixed signal designs • ADC/DAC
0.8 μm digital InP HBT (2met)	160	80	5	1.5 mA/μm^2	75	• Fiber optic applications up to 25Gbps • High speed digital circuitry
0.6 μm digital InP HBT (4met)	>250	80	4	2.5 mA/μm^2	75	• Fiber optic applications up to 40Gbps • High speed digital circuitry
0.1 μm InP PHEMT	180	1200 mS/mm	1.2	150 mA/mm	75	• Very low noise amplifiers • mmW sensors • Lower power dissipation
0.2 μm GaN HEMT	60	350 mS/mm	28	250 mA/mm	100	• High power amplifiers < 10W up to 40GHz
0.15 μm GaN HEMT	80	410 mS/mm	28	250 mA/mm	100	• High power amplifiers < 10W up to 60GHz

MPS Standard Products (YesWeGaN.com)

GaN Power Amplifiers

Part	Description	Frequency (GHz)	Gain (dB)	P1dB (dBm)	Psat (dBm)	Form	Availability
APN267	GaN HEMT Distributed Amplifier	2-18	10	35	38	Die	Stock
APN270	GaN HEMT Power Amplifier	9-13.2	12	39	41	Die	Stock
APN252	GaN HEMT Driver Amplifier	10-14	25.5	34	38	Die	Stock
APN250	GaN HEMT Power Amplifier	10-14	13	39	42	Die	Stock
APN226	GaN HEMT Power Amplifier	13-16	20	36	39.5	Die	Stock
APN232	GaN HEMT Power Amplifier	13.5-15.5	13	38.5	42	Die	Stock
APN237	GaN HEMT Dual Channel Power Amplifier	13.5-15.5	12.5	40.5	44	Die	Stock
APN293	GaN HEMT Power Amplifier	16-20.5	10	36.5	39.5	Die	Stock
APN279	GaN HEMT Power Amplifier	16-20.8	17	39.5	42.5	Die	Stock
APN149	GaN HEMT Power Amplifier	18-23	20	36	39	Die	Stock
APN243	GaN HEMT Power Amplifier	23-28	20	38	40.5	Die	Stock
APN244	GaN HEMT Power Amplifier	23-28	21	37	39	Die	Stock
APN228	GaN HEMT Power Amplifier	27-32	19.5	39	41.2	Die	Stock
APN229	GaN HEMT Power Amplifier	27-32	20	17	39	Die	Stock
APN248	GaN HEMT Power Amplifier	27-31	17.5	42	44	Die	Stock
APN292	GaN HEMT Power Amplifier	27-31	20	42	42	Die	Stock
APN311	GaN HEMT Power Amplifier	27-31	20	43	45	Die	Stock
APN173	GaN HEMT Power Amplifier	34-36	19.5	TBD	37.5	Die	Stock
APN236	GaN HEMT Power Amplifier	34.5-35.5	16	38	40	Die	Stock
APN167	GaN HEMT Power Amplifier	43-46	20	35.5	38.5	Die	Stock
APN318	GaN HEMT Power/Driver Amplifier	47.2-51.4	15	–	40	Die	Pre-Production
APN319	GaN HEMT Power/Driver Amplifier	47.2-51.4	16	–	37	Die	Pre-Production

MPS also offers standard products in different III-V technologies

APN292
27 – 31 GHz
GaN Power Amplifier

Revision 2022-1

NORTHROP GRUMMAN

Absolute Maximum Ratings

Parameter	Value	Unit
Drain Voltage	28	V
Gate Voltage Range	-8 to 0	V
Drain Current	4440	mA
Gate Current	4.32	mA
Power Dissipation*	92.4	W
Soldering Temperature	320	°C

*7W/mm of gate periphery

Electrical Specifications

Paramter	Min
Operational Frequency	27
Small Signal at 28	
Small Signal Linear Gain	19
Input Return Loss	-23.5
Output Return Loss	-15
On-Wafer Pulsed Powe	
Psat (at 34 dBm)	45
Power Gain (at 34 dBm)	11
P1db	41.4
PAE (at 34 dBm)	21
Max PAE	26
Fixtured CW at 24V, 25°C	
Psat (at 29 dBm)	42.7
Power Gain (at 29 dBm)	13.7
PAE (at 29 dBm)	20
Max PAE	21
Drain Voltage	
Stage 1 Gate Voltage	
Stage 2 Gate Voltage	
Stage 1 Idq	
Stage 2 Idq	

Preliminary Information: The data contained in this document describes new produc
and is for information only. Northrop Grumman reserves the right to change without
apply to this product. The product represented by this datasheet is subject to U.S. E

3/14/2022

Web: http://www.as.northropgr
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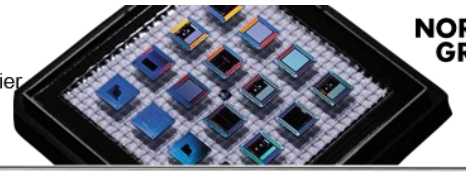
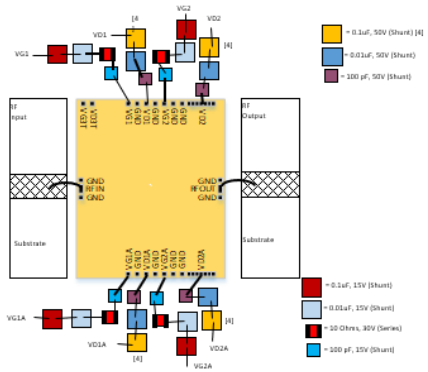


APN292
27 – 31 GHz
GaN Power Amplifier

NORTHROP GRUMMAN

Revision 2022-1

Suggested Bonding Arrangement



Recommended Assembly Notes

1. Bypass caps should be 100 pF (approximately) ceramic (single-layer) placed no farther than 30 mils from the amplifier.
2. Best performance obtained from use of <10 mil (long) by 3 by 0.5 mil ribbons on input and output.
3. Part must be biased from both sides as indicated.
4. The 0.1uF, 50V capacitors are not needed if the drain supply line is clean. If Drain Pulsing of the device is to be used, do **NOT** use the 0.1uF , 50V Capacitors.

Mounting Processes

Most NGSS GaN IC chips have a gold backing and can be mounted successfully using either a conductive epoxy or AuSn attachment. NGAS recommends the use of AuSn for high power devices to provide a good thermal path and a good RF path to ground. Maximum recommended temp during die attach is 320°C for 30 seconds.

Note: Many of the NGSS parts do incorporate airbridges, so caution should be used when determining the pick up tool.

CAUTION: THE IMPROPER USE OF AuSn ATTACHMENT CAN CATASTROPHICALLY DAMAGE GaN CHIPS.

PLEASE ALSO REFER TO OUR "GaN Chip Handling Application Note" BEFORE HANDLING, ASSEMBLING OR BIASING THESE MMICS!

Preliminary Information: The data contained in this document describes new products in the sampling or preproduction phase of development and is for information only. Northrop Grumman reserves the right to change without notice the characteristic data and other specifications as they apply to this product. The product represented by this datasheet is subject to U.S. Export Law as contained in ITAR or the EAR regulations.

3/14/2022

Web: http://www.as.northropgrumman.com/mps
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Approved for Public Release: Northrop Grumman Case 15-xxxx, 06/xx/15

Starry Nite Multi-Project Wafer Runs Overview

- As part of the Starry Nite program, open foundry access to NG's 90 nm GaN process is offered through multi-project wafer (MPW) runs

Preliminary Technology Performance Parameters

Technology	f_T (GHz)	f_{max} (GHz)	G_m (mS/mm)	$V_{DS,max}$ (V)	I_{max} (A/mm)	Wafer Thickness (μm)	Airbridged Metal Available	Backside Vias	Wafer Size (mm)
90 nm GaN HEMT	100	>250	500	15 - 18	1.2	50 um	Yes	Yes	100

- The 90 nm GaN process is not a frozen process
- Three model updates are planned during the program
  - 1st updated PDK just released (ADS only)
  - Targeting AWR PDK release for MPW3
- Starry Nite only pays for mask and fabrication
- Designs/Design Package archived into a repository
- Currently offering 5 x 5 mm^2 space for each awarded design package
- Testing and subdicing available at additional cost through MPS

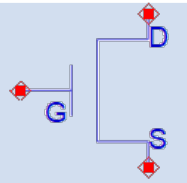
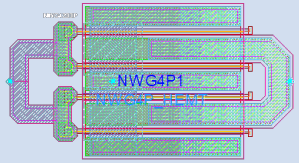
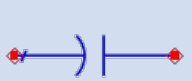
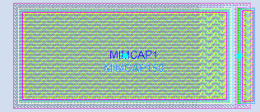
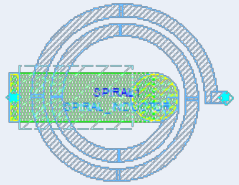
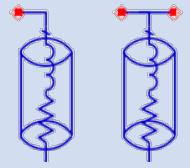
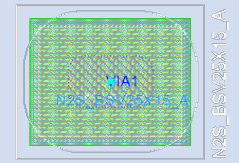
Starry Nite Multi-Project Wafer Runs Overview

- Wafers will be assessed with passive structures and discrete transistor measurements
- Targeting 30 parts minimum delivered to the performer per MPW design
- Targeting 10 parts minimum delivered to the Government per MPW design

Assessment	Parameter
Transistor	Pinch-off
	maximum drain current
	gate leakage current
	breakdown voltage
	f_T
	maximum available gain
Passive	epi sheet resistance
	ohmic contact resistance
	isolation leakage current
	thin-film resistor sheet resistance
	MIM sheet capacitance

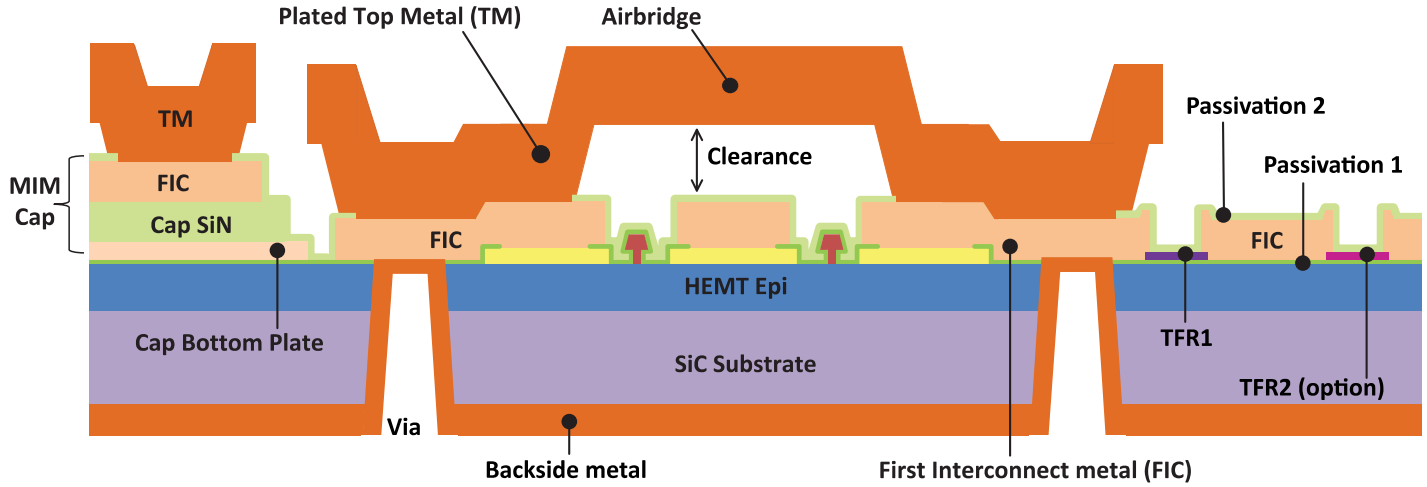
PDK/Model Overview

- Initial PDK in ADS only
  - AWR PDK release by MPW3
- PDK features
  - Schematic capture and simulation
  - Layout generation and EM simulation
  - Models of passives and transistors
  - User adjustable component geometries
  - Design Rule Checking (DRC)
  - Layout Versus Schematic (LVS) check
- NDA required for PDK access

Circuit Element	Schematic Symbol	Layout Cell
Transistors		
Resistors		
Capacitors		
Inductors		
Through-Substrate Vias		

Overview of MMIC Technology

- MMIC process includes
  - Thin film resistors
  - MIM capacitors
  - Through substrate vias (TSVs)
  - Airbridges
  - Spiral inductors



How to Engage with NG for MPW Runs

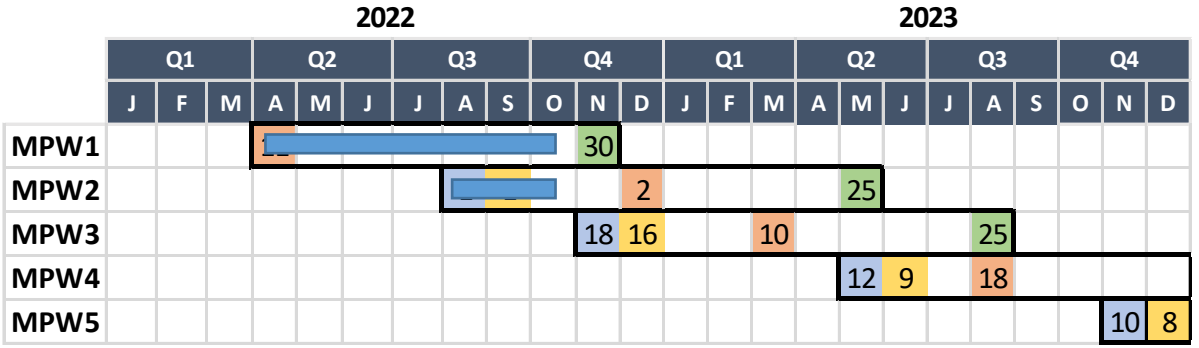
MPW Application
- Visit NSTXL Starry Nite Webpage
- Decide on desired MPW run from schedule
- Contact Mike Barsky/Farman Mesdaghi to initiate NDA and collaboration agreement
- Download, complete and submit application form to foundry

Performer Space Awarded
- Completed application forms will be reviewed by the government
- NG and government provide award notices

Design Submission
- Completed design and design package submitted to NG
- Mask layout by NG
- Design archived in repository

Die Delivered
- Wafers will be fabricated and cingulated
- Targeting a minimum of 30 parts delivered to designers by mail
- Targeting 10 parts delivered to the government by mail

2022/2023 Starry Nite MPW Runs Calendar



Application deadline

Space awarded

Design submission

Die delivered

Name	email
Mike Barsky	mike.barsky@ngc.com
Farman Mesdaghi	farman.mesdaghi.@ngc.com

Website: YesWeGaN.com

USD(R&E)

Qorvo MPW Foundry Offering

STARRY NITE Design Opportunity Day

Qorvo High Performance Analog - Research

October 19, 2022

Agenda

- Qorvo Overview
  - Qorvo Business Overview
  - Qorvo Foundry Services
  - Qorvo GaN Technology
- Qorvo STARRY NITE Overview
- Qorvo STARRY NITE MPW Runs
  - MPW Overview
  - PDKs
  - Design Space
  - Schedule
  - Design IP Repository
- Q&A

Qorvo Business Overview

Qorvo

A leading global supplier of connectivity and power solutions

- We supply innovative semiconductor solutions that make a better world possible
- 8,900 global employees
- FY22 revenue: $4.65 billion
- An S&P 500 company – Nasdaq: QRVO

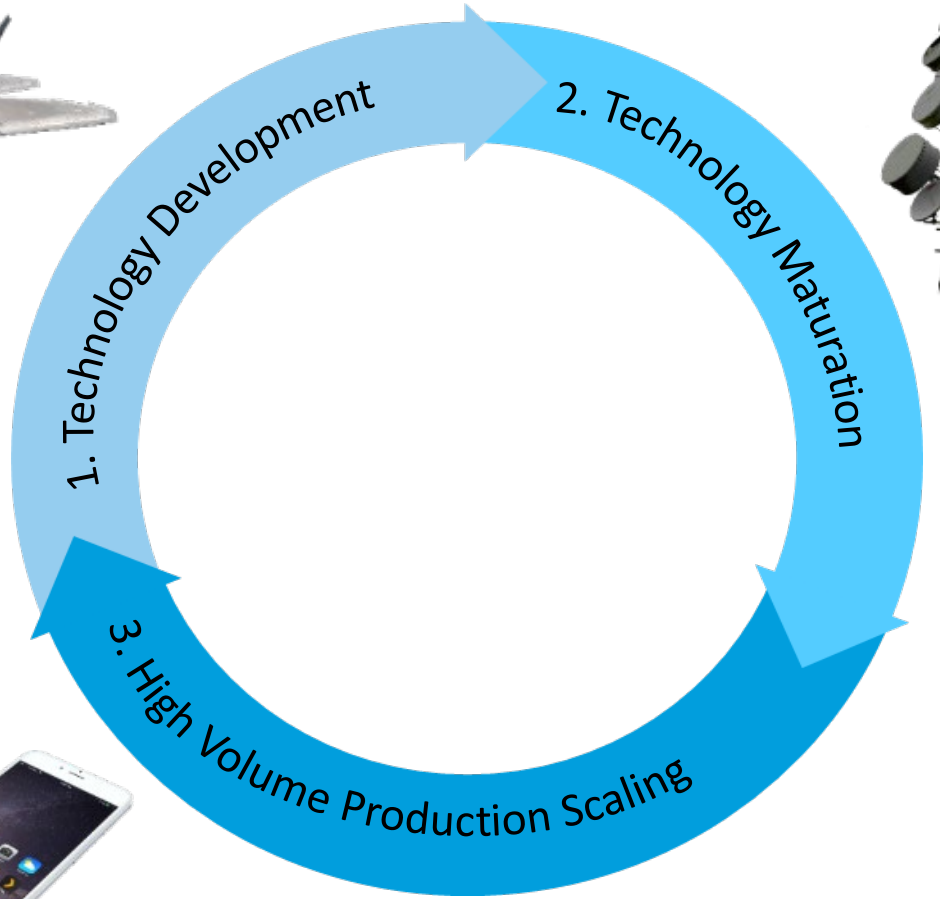
qorvo®
all around you

Advancing Technology – Leveraging Dual Use Applications

- Synergy: Each Product Market Benefits the Other

DEFENSE

Provides advanced RF technologies to U.S. DoD and partner countries



NETWORK INFRASTRUCTURE

Early adopter of RF technology for commercial markets

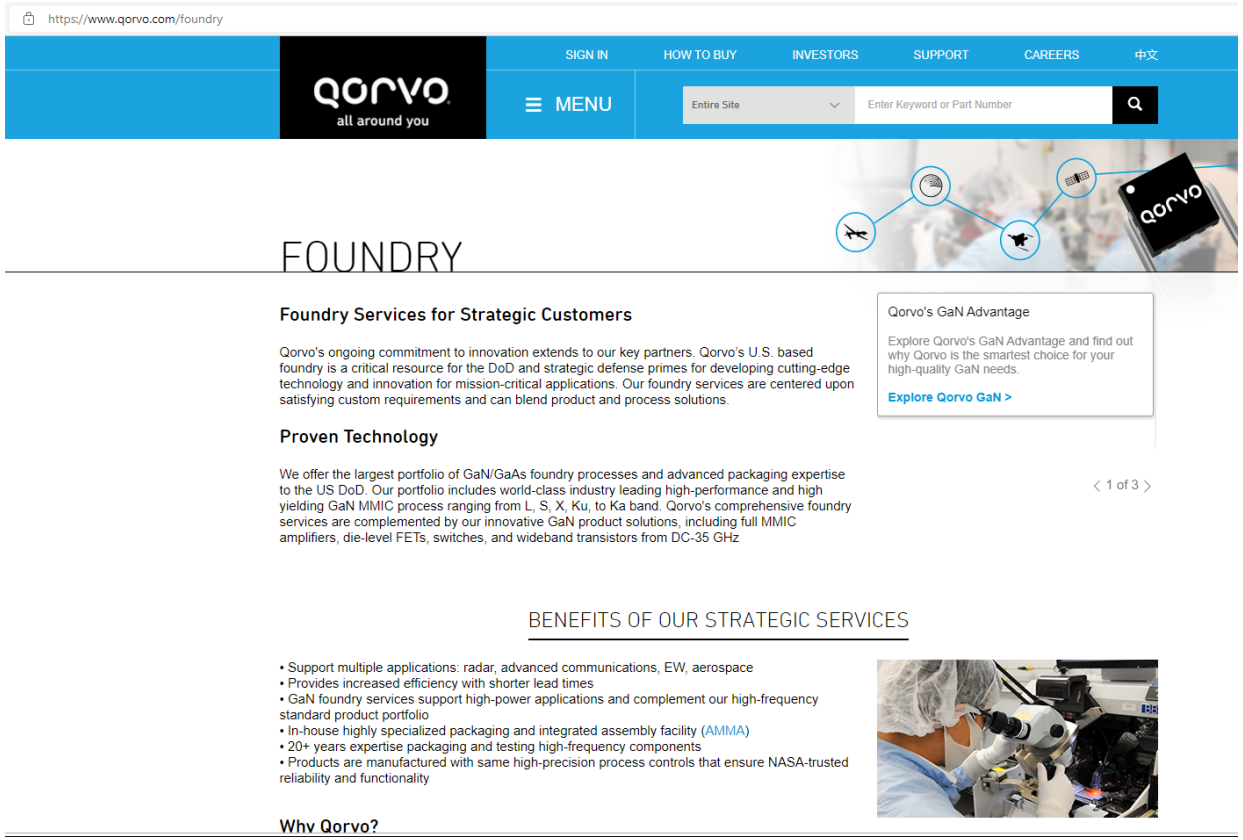
MOBILE / CONSUMER RF

Provides large manufacturing scale

Qorvo Foundry Services

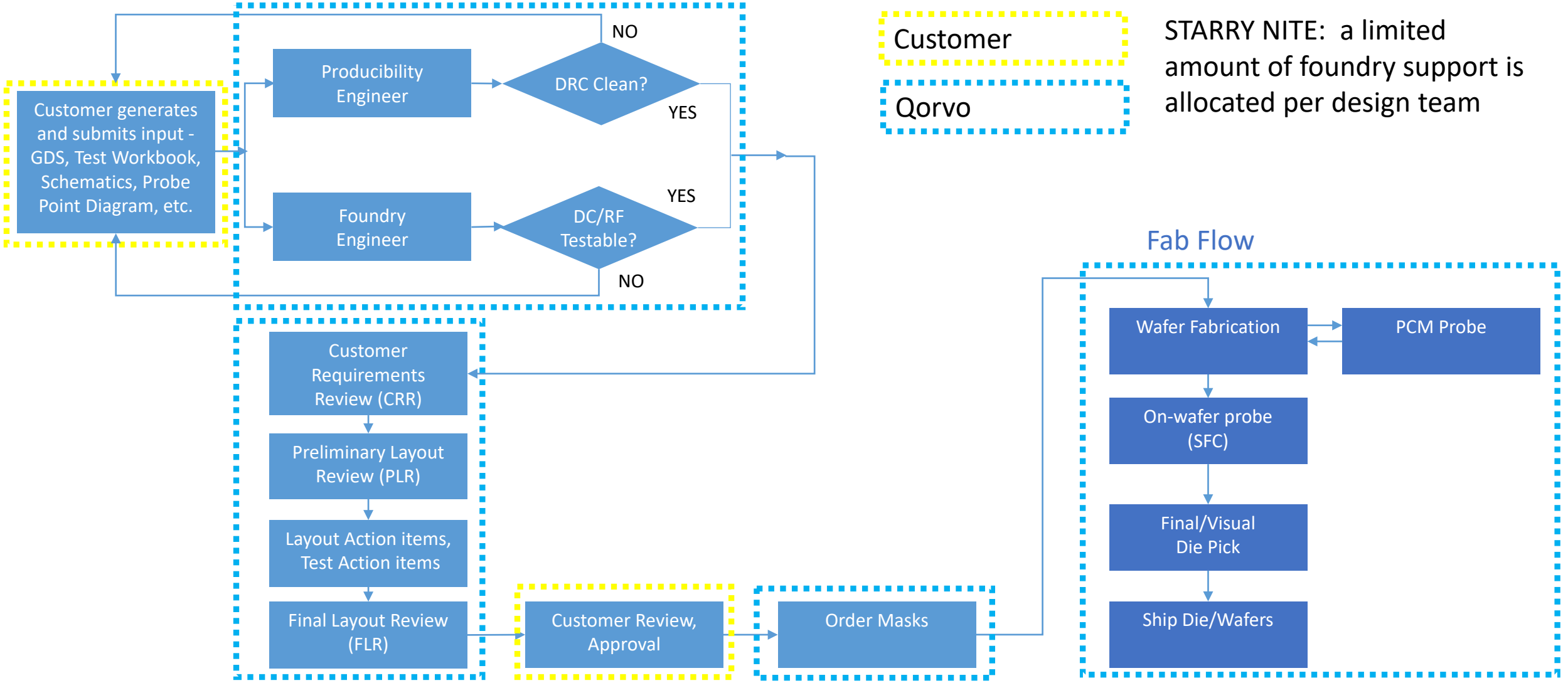
Qorvo Foundry Services

- Open Access
- Broad and diverse active customer base
  - Services large business, small business, universities, and government labs
- Leading US defense supplier for >30 years
  - Supply to a large cross-section of the defense industrial base
- Large portfolio of GaN / GaAs foundry processes
- Offer early access of advanced & unreleased GaN / GaAs processes to DIB and DoD collaborators
- Trusted CAT1A DoD supplier
- Scale enables cost effective manufacturing – commercial applications drives high volume manufacturing, rapid cycles of learning, improved process control and process maturation



https://www.qorvo.com/foundry

Qorvo Texas Fab Typical Foundry Input Flow



STARRY NITE: a limited amount of foundry support is allocated per design team

Qorvo GaN Technology

Qorvo GaN Technology

- Qorvo has the broadest GaN technology production portfolio in the industry
  - 5 production releases MMIC process nodes supporting applications through 60 GHz
  - Maturing 90nm GaN to support applications in V- and W-band
- Qorvo GaN research and development dates to 1990's
- Qorvo GaN initial production release was QGaN25 in 2008
- Qorvo GaN is deployed worldwide in defense and commercial operations
- Qorvo GaN MMIC processes provide industry leadership in:
  - RF performance
  - Functional integration
  - DC & RF reliability
  - Manufacturing maturity and scalability

Distribution Statement A (Pending) Public Release, Distribution Unlimited

Qorvo RF GaN Foundry Processes

	QGaN50-ES	QGaN45-ES	QGaN25 HV-ES	QGaN25-ES	QGaN15-ES	QGaN09-ES
Vdd	65V	50V	50 V	40 V	28V	18V
P_{out}	10 W/mm	8 W/mm	8 W/mm	6 W/mm	4 W/mm	2.5 W/mm
Gain	21 dB (2.7 GHz)	20 dB (3.5 GHz)	21 dB (3.5 GHz)	13 dB (10 GHz)	9 dB (35 GHz)	6 dB (80 GHz)
F_t peak	> 20 GHz	> 20 GHz	> 25 GHz	> 35 GHz	> 65 GHz	> 115 GHz
MTTF (200C)	$>10^7$h (at 65V)	$>10^7$h (at 50V)	$>10^7$h (at 50V)	$>10^7$h (at 40V)	$>10^7$h (at 28V)	$>10^7$h (at 18V)
Substrate	100um	100um	100um	100um	100 & 50 um	100 & 50 um
Application Range	DC – 8 GHz	Linear PA DC – 8 GHz	DC – 12 GHz	DC – 25 GHz	DC – 60 GHz	DC – 100 GHz
Status	Production	Production	Production	Production	Production	In Development

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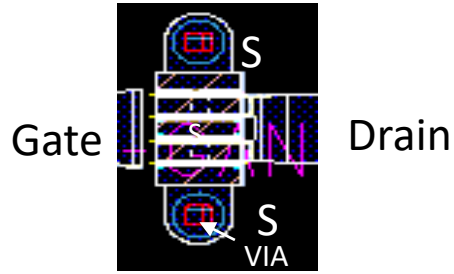
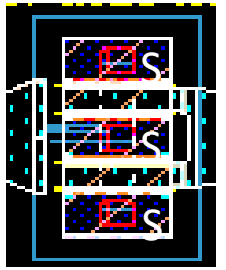
Common GaN Design Feature Set for Production GaN

- GaN QGaNxx
  - 3 metal layers
  - 3 capacitor densities
  - 50 µm & 100 µm thick substrates
  - With Slot Vias
  - XM2 - thick metal
  - With or without BCB
  - HAST compatible FETs
  - Broadside-coupled lines

FET Layout



Conventional End Via



Red shape: ISV

Individual Source Via (ISV)

Distribution Statement A: Approved for Public Release, Distribution Unlimited

Qorvo STARRY NITE Objectives

Qorvo's STARRY NITE Scope & Objectives – MPW's

- **Task B**: Offer **MPW runs (15) and create Design IP Repository**
  - MPW runs with 3rd party, Govt, and Qorvo designs
  - USG makes the selection of participant designs for each MPW mask run
  - Create a Design IP Repository for USG access
- Total of 15 MPW runs planned in the program

Year (total # of runs)	Year 1 (2)	Year 2 (2)	Year 3 (3)	Year 4 (4)	Year 5 (4)
	CY 2022	CY 2023	CY 2024	CY 2025	CY 2026
Technology (# of MPW runs)	GaN15 (1)	GaN15 (1)	GaN15 w AIC (1)	GaN15 w AIC (2)	GaN15 w AIC (2)
	GaN09 (1)	GaN09 (1)	GaN09 (2)	GaN09 (2)	GaN09 w AIC (2)

- AIC features are added overtime as the maturity occurs with each GaN node
- Each MPW mask to include …
  - 3 external party designs
  - At least 1 USG design
  - At least 1 Qorvo design

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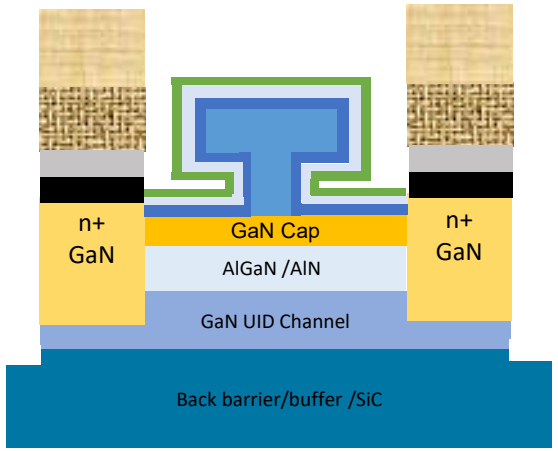
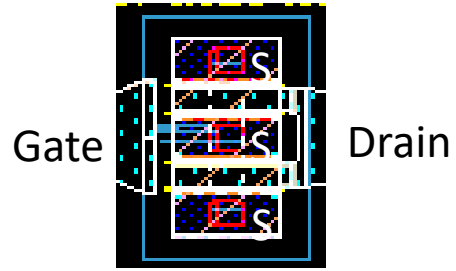
90 nm GaN (QGaN09) Feature Set

- 90 nm GaN technology at MRL-8
  - 150mm wafer diameter on SiC substrates
  - 50µm (2-mil) wafer thickness
  - 3 metal interconnect layers
  - 3 capacitor values
  - Full backside processing
  - Individual Source Vias (ISVs)
  - Capable of W-band performance



Individual Source Via (ISV)

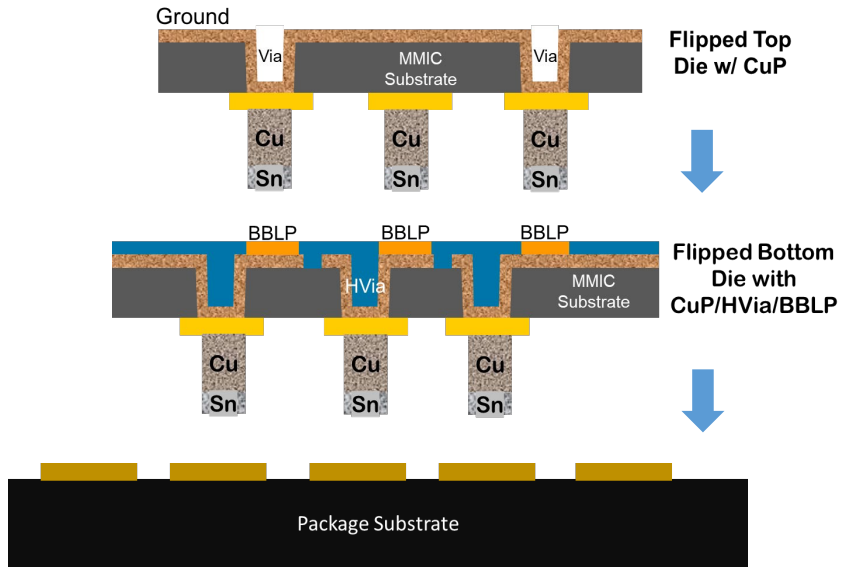


Red shape: ISV

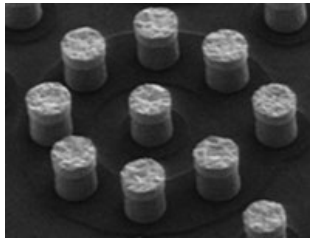
Advanced Interconnect (AIC) Feature Set

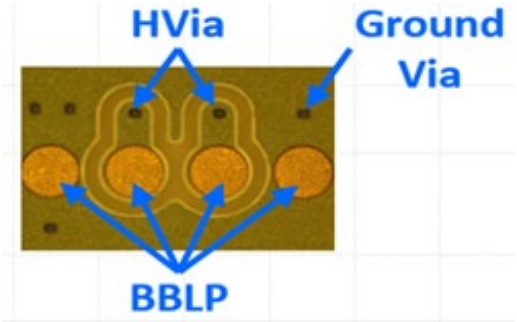
- Advanced Interconnect (AIC) features at MRL-8:
  - Two (2) high frequency GaN nodes (90 nm & 150 nm GaN)
  - 150mm diameter wafer production platform
  - 50µm (2-mil) wafer thickness
  - Three (3) AIC features are Cu pillars (CuP), Hot Via (HVia),and Backside Bump Landing Pads (BBLP)
  - Enables advanced compact packaging technology for wire bond free 2D/2.5D/3D heterogeneous integration schemes required for high frequency applications

Example of AIC enabling 2D/2.5D/3D stacking



CuP





Qorvo STARRY NITE MPW Runs

Qorvo STARRY NITE MPW Runs – Year 2

- MPW Overall Schedule
- Process Technologies/PDKs
- Design Space
- Schedule, Design Process Flow
  - Key Dates
  - DRC
  - Services/options offered
- Design IP Repository

Distribution Statement A (Pending) Public Release, Distribution Unlimited

Qorvo's STARRY NITE MPW – Overall Schedule

Year 1 MPW in Progress

- GaN09 (1run) & GaN15 (1run)
- Design submission Aug '22
- Tape out Oct '22
- Die delivery Mar & Apr '23

Year 2 MPW Plan

- GaN09 (1run) & GaN15 (1run)
- Application CY22 Q4 (Oct – Dec)
- Designer selection CY23 Q1 (Feb)
- Design submission CY23 Q2 (May)

Qorvo STARRY NITE MPW Offerings			2022												2023												2024												2025												2026											
			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4		
SN Year	Process	MPW#	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Year1	GaN09	Run1				22	31			31		15					31																																													
	GaN15	Run2				22	31			31		15				28																																												
Year2	GaN09	Run3										19		1		1			1	15							15																																		
	GaN15	Run4										19		1		1			1		15						15																																		
Year3	GaN15+AIC	Run5																						15		1		1						1	15						15																	
	GaN09	Run6																						15		1		1			1	15							15																	
	GaN09	Run7																						15		1		1			1		15						15																	
Year4	GaN15+AIC	Run8,9																																15		1			1			1	1	15						15					
	GaN09	Run10,11																																15		1			1	1	15							15					
Year5	GaN15+AIC	Run12,13																																										15		1			1	15					15
	GaN09+AIC	Run14,15																																										15		1			1	15					15

Legend

- solicitation date
- application deadline
- performer space awarded
- design submission
- mask ordered
- die delivered

Estimated schedule dates for MPW's by year … subject to change

Year 2 MPW - Qorvo Process Technologies/PDKs available

- MPW Run 3 (**GaN09**)
  - 2 mil (50 um) wafer thickness
  - Technology under development (not released)
  - QGaN09 THN PDK will be available through the portal
  - AWR and ADS available
  - No AIC features included

- MPW Run 4 (**GaN15**)
  - 2 mil (50 um) wafer thickness
  - Standard production released GaN technology
  - QGaN15 THN PDK available through the portal
  - AWR and ADS available
  - No AIC features included

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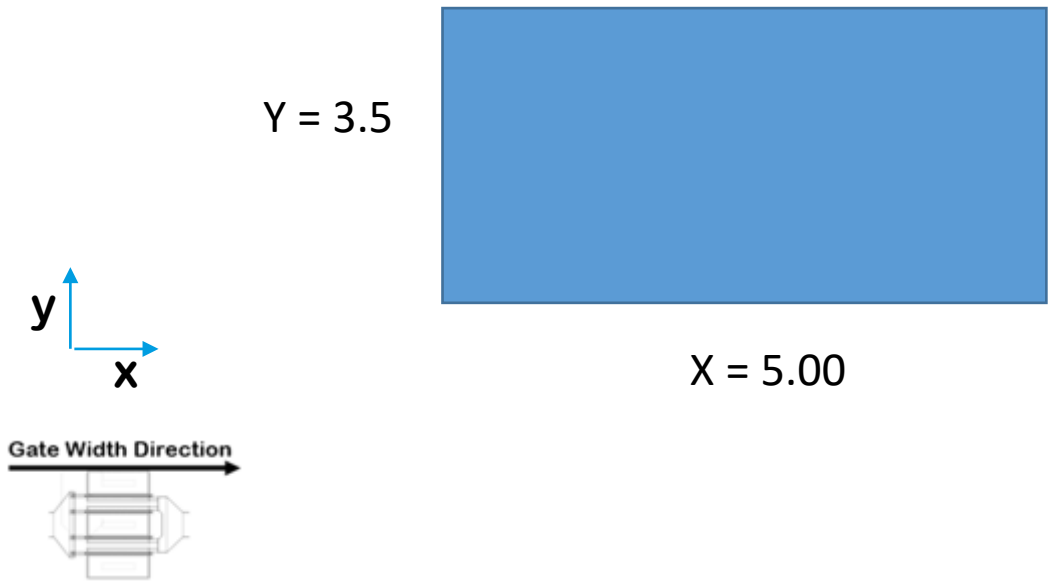
Design Space (MPW Runs 3 & 4)

- Each design team will have the following space:
  - **5.00 mm** x **3.50 mm***



Reticle will consist of at least
- 3 external designs
- 1 USG design
- 1 Qorvo design
- Plug bar (test structures)

*** Note: The design space size is subject to change if needed based on the design applications received and approved by USG.**

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Key Dates for GaN09 and GaN15 Year 2 MPW Offerings

Item	Date	Who
Year2 Design Opportunity Day	**Oct 19 '22 - today**	USG, SN Performers, Design Applicants
Design Applications Due	Dec 01 '22	Design Applicants
Design Participant Selection	Feb 01 '23	USG
NDAs signed	Feb 01 '23	Design Participants
Collaboration Agreement signed	May 01 '23	Design Participants, Qorvo
Design Submissions Due	May 01 '23	Design Participants
Mask Tapeout – Run3/GaN09	Jun 15 '23	Qorvo
Mask Tapeout – Run4/GaN15	Jul 15 '23	Qorvo
Die Delivery – Run3/GaN09	Jan 15 '24	Qorvo
Die Delivery – Run4/GaN15	Jan 15 '24	Qorvo

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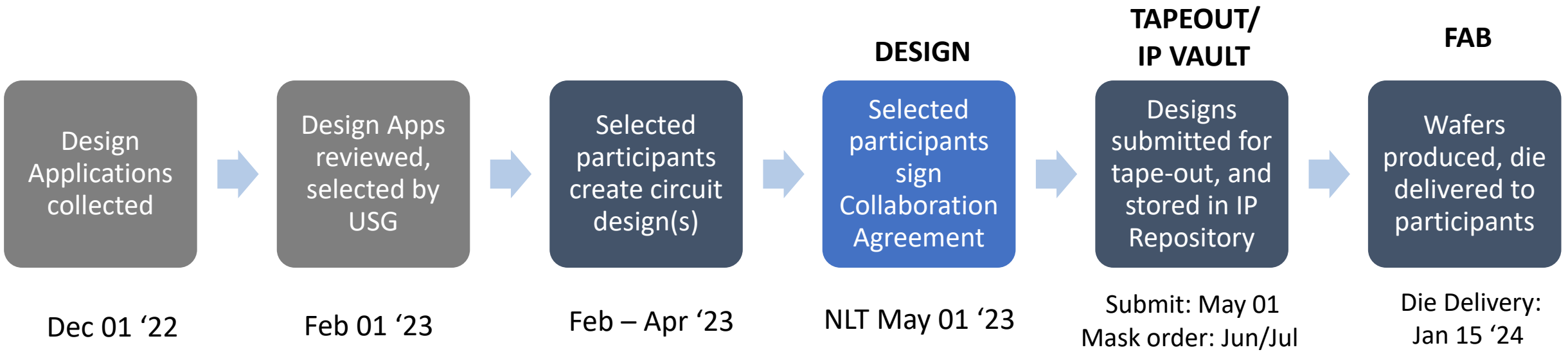
MPW Run Procedure

- After being selected, Design Participants (“Collaborators”) to sign:
  - **NDA** (required for PDK access)
  - **Collaboration Agreement** (required to be on the mask)
- Collaborators make design, then submit design by deadline in order to have design included in mask



GaN15 & GaN09 - DRC

- Run the **DRC (Design Rule Check)** throughout design effort
  - Do not wait to run DRC until right before deadline!

- DRC is **to be performed via mailtools**
  - Set up a SFTP (secure FTP) account thru Foundry for **mailtools**
  - Different than Year1 - GaN15 & GaN09 will use the same process

- Final design submissions must be:
  - **DRC-clean**
  - **Received by submission deadline (planning for May 01, 2023)**

Distribution Statement A (Pending) Public Release, Distribution Unlimited

GaN09 – models, FETs

- New for Year 2 MPWs – GaN09 models and FET cells will be included in the GaN PDK
- These preliminary models will be available by the start of the design period.
- The MPW runs are providing “early access” to unreleased technology. Since the GaN09 process is being refined and matured throughout STARRY NITE, differences between the models and the MPW wafer performance are to be expected.

- GaN09ES THN models & FET cells expected to be available (in AWR & ADS):

Non-Linear Models
- EG3920F, 15V, 25 mA/mm (4ISV)
  - 8 x 50 um

Linear Models
- EG3920 C, G, and F (25C, 85C, -40C)
  - 2 x 25 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (2 End Via)
  - 2 x 40 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (2 End Via)
  - 2 x 50 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (2 End Via)
  - 4 x 25 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (3ISV)
  - 4 x 40 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (3ISV)
  - 4 x 50 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (3ISV)
  - 6 x 25 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (4ISV)
  - 6 x 40 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (4ISV)
  - 6 x 50 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (4ISV)
  - 8 x 50 um: 5V, 7.5V, 10V, 12.5V: (25, 50, 100,200) mA/mm (4ISV)

- Scaling of GaN09 FET cells:
  - The Linear models – likely to be allowed
  - The Nonlinear models – will not be allowed

Distribution Statement A (Pending) Public Release, Distribution Unlimited

Services Offered/ Not Offered (for SN MPW Runs)

Offered:

- DC Probe data to check device functionality can be provided by request based on wafer SFC (standard FET cells)
- Die in gel-paks

Not Offered:

- DC, RF probing of MMIC ckts
- Sub-dicing of ckts
- Packaging of ckts

Design IP Repository

- Collaborators' submitted designs will become part of the **STARRY NITE Intellectual Property (IP) Repository**, subject to the Terms of Use set forth by Qorvo and the Government
- STARRY NITE IP storage will be implemented in secure USG-approved Repository. **Access will be USG only.**
- Required items for each submission:
  - Design Layout (GDSII file)
  - Design Schematic (can be encrypted)
  - Document (PPT file) with design info summary (design description, frequency of operation, simulation data, representative measured data)

Distribution Statement A (Pending) Public Release, Distribution Unlimited

Q & A

HRL T3 Foundry Overview

STARRY NITE Design Opportunity Day

David Fanning // Harris Moyer // Andy Fu
HRL Laboratories

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HRL Laboratories agenda

- STARRY NITE Design Opportunity Day

- Overview	Dave Fanning	STARRY NITE PM, SEL
- **PDK and designer info**	**Harris Moyer**	MMIC & RFIC group lead, SEL
- MPW and foundry info	Andy Fu	Foundry Services Manager, MTL

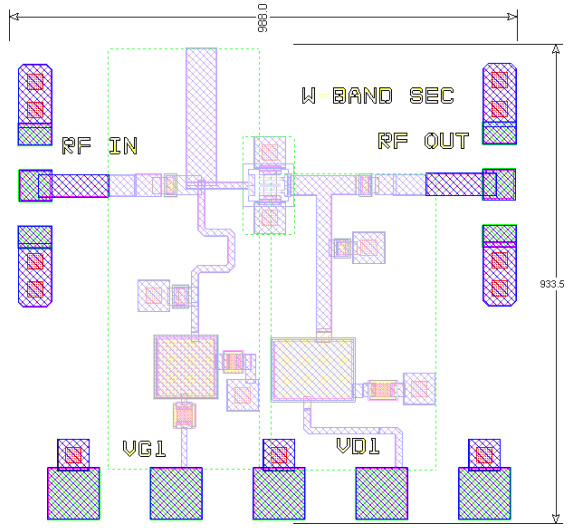
Understanding GaN T3 Device Performance

- T3 GaN data sheet
- Typical results from a 77 GHz single stage Standard Evaluation Circuit (SEC)
  - Comparison with device model
- Introduction of new GaN device model ‘239’ with tunable parameters
- Comparison of current PDK model (‘227’) with new ‘239’ model
  - Based on 94 GHz load pull data
  - Demonstration of how adjustable parameters in the 239 model can tune to fit measured performance

Presenting new adjustable nonlinear model for use in next generation PDK

Test Circuit: W-band SEC

- **W-band SEC is a single stage PA centered at 77 GHz**
- **Power was measured at 75,77 and 79 GHz and 12 V @ 100 mA/mm**

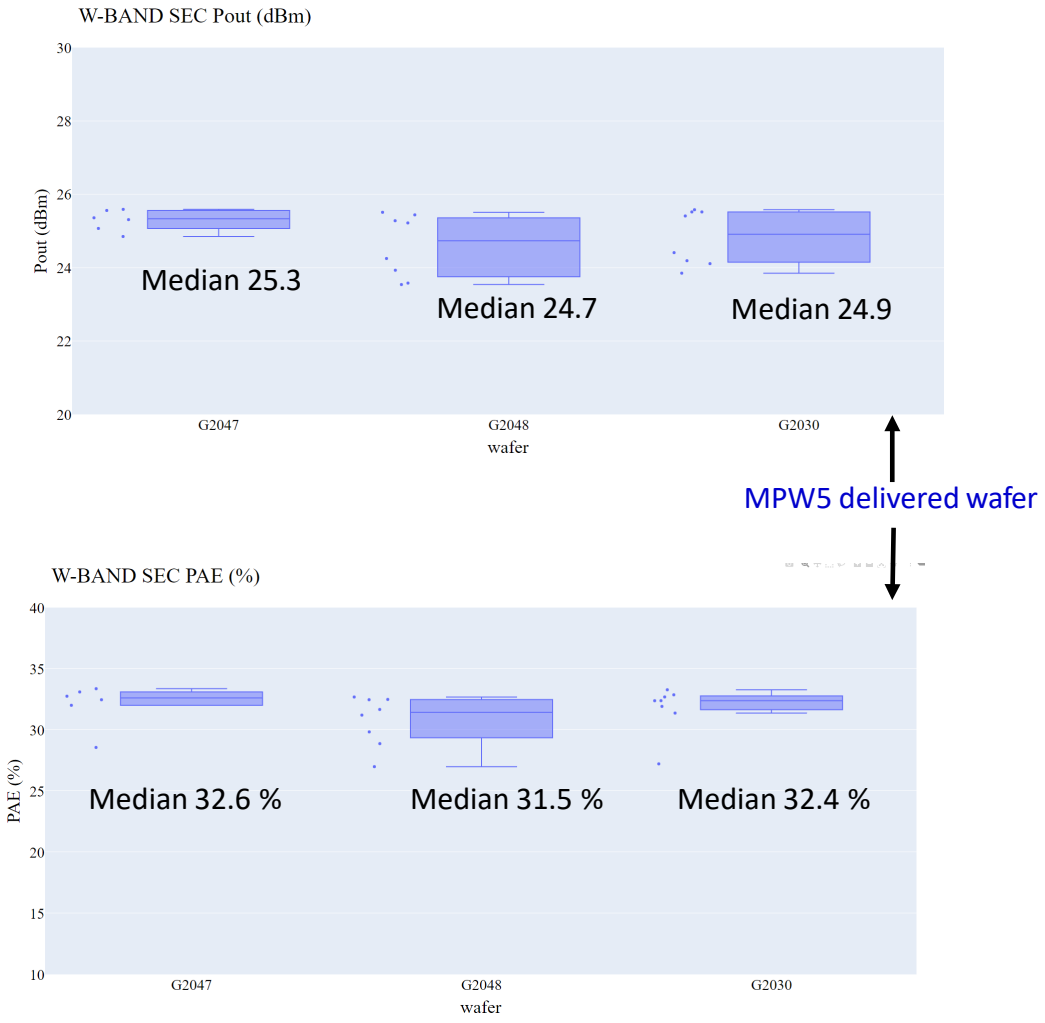


Specifications:

Parameter	Lower limit	Median	Upper limit
P1dB (77 GHz)	20.3 dBm	21.8 dBm	23.3 dBm
Psat (77 GHz)	21.5 dBm	23 dBm	24.5 dBm
PAE (77 GHz)	23 %	28 %	33 %
Return loss	6	7.7 dB	10
Small signal gain	6	7.5	9

Example of W-band SEC Power results

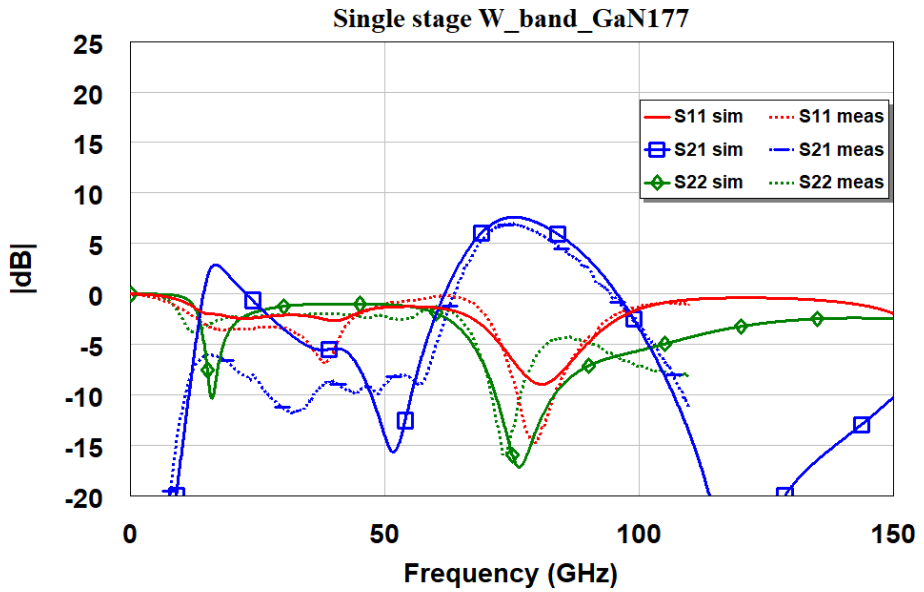
77 GHz data

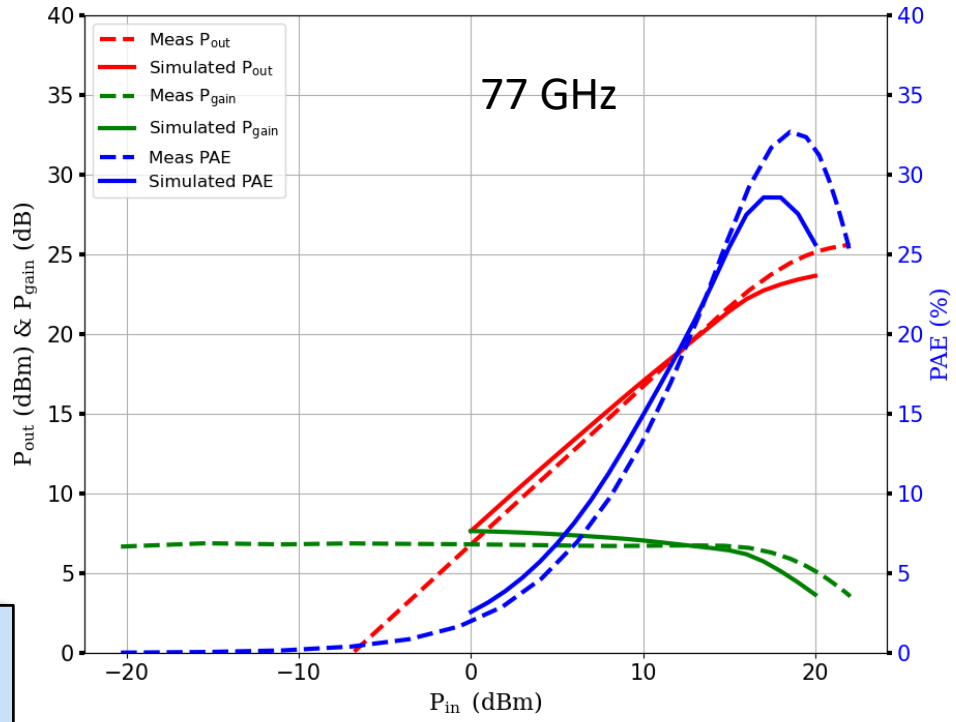


- **Measured every W-band SEC on recent MPW5 lot**
- **Some variation but all of them showed good performance**
- **Median max PAE≈ 32% across the 3 wafers**
- **Median output power ≈ 24.9 dBm (2.1 W/mm) across the 3 wafers**

Represents the high end of expected performance

MPW5 W-band SEC Measured vs. Simulated





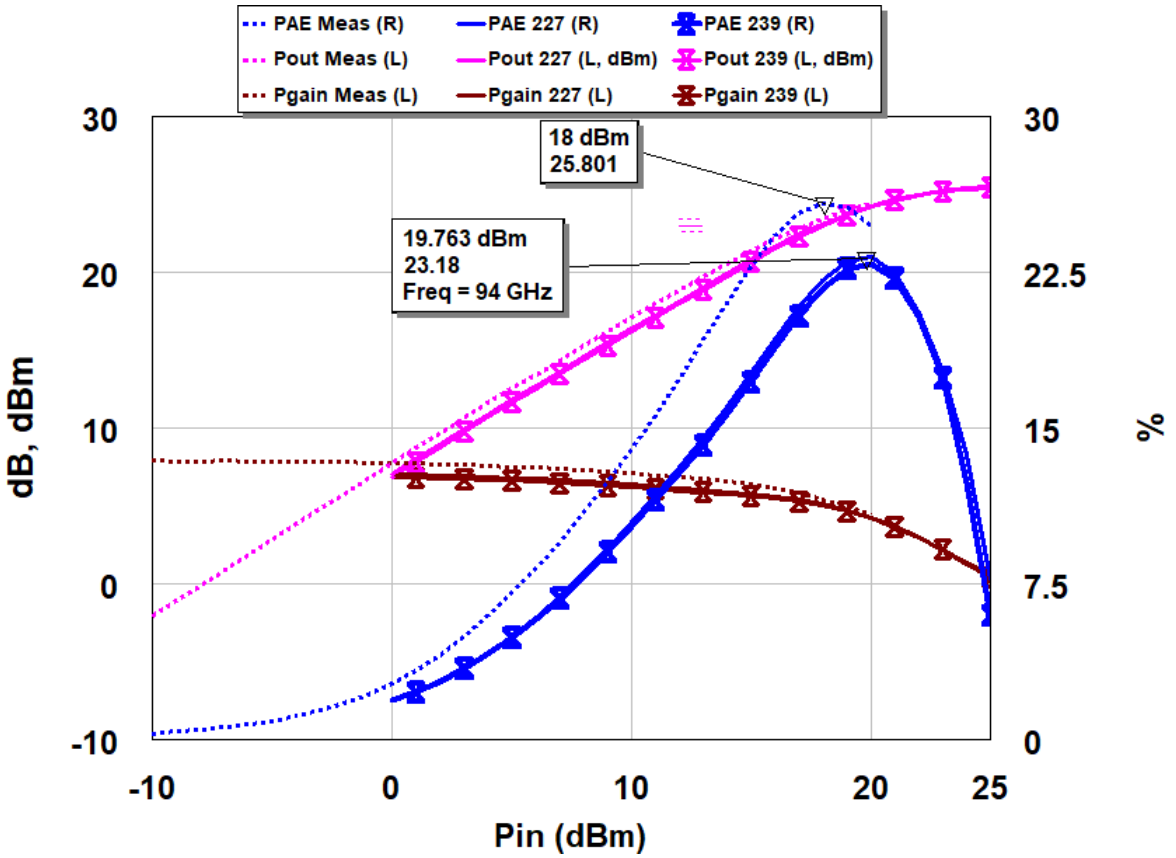
- **Really good agreement between simulation and measurements!**
- **Max measured PAE= 33%**
- **Max Pout= 25 dBm**
- **Small Signal Gain= 7 dB**

Model used is GaN T3 model ('227') from current PDK which cannot be modified

Measured vs. Simulated load pull power sweep at 94 GHz 4x37.5μm

Measured data from
load pull at 94 GHz

Bias: 12 V, 15 mA (100mA/mm)
Z_{source}=.69 < 172°
Z_{load}=.55 < 119°
Input and output harmonics
Z=0 < 0



Both 227 and 239 (default) models have reasonable agreement with measurements

New 239 Model has six Adjustable Parameters

Parameters are based on the % of the nominal model value: +/- 50% (0.5 to 1.5)

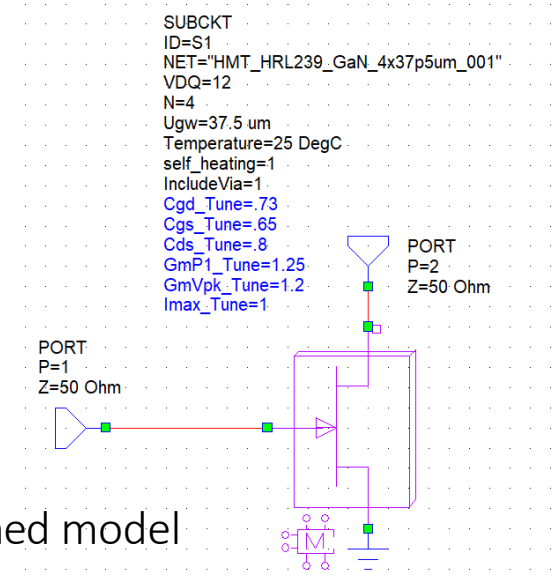
Most important parameter is Imax which adjusts for variation in current collapse:
Important for power amplifier designs

Also includes variable gm and a gm shaping parameter

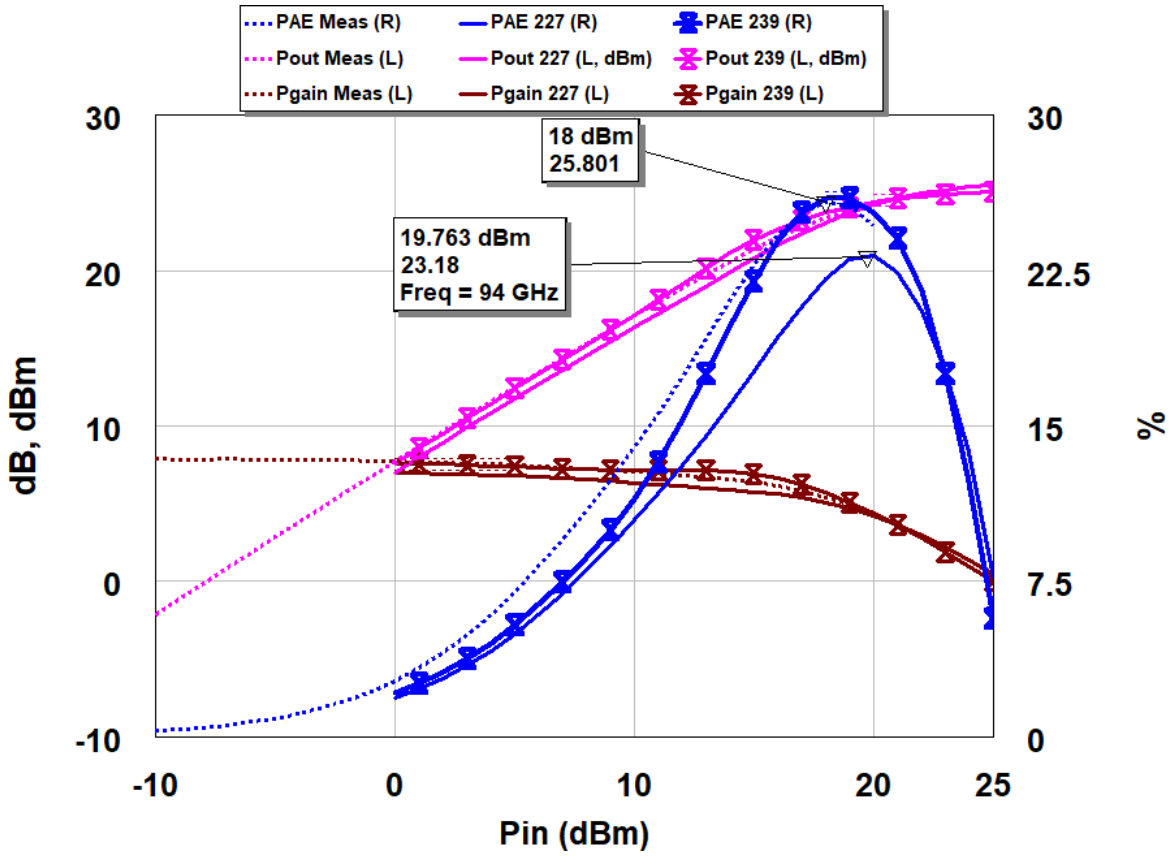
New 239 model has adjustable parameters to simulate process variations

Adjust 239 Model to Match Measured Performance

Measured data from load pull at 94 GHz (AFRL)



Tuned model



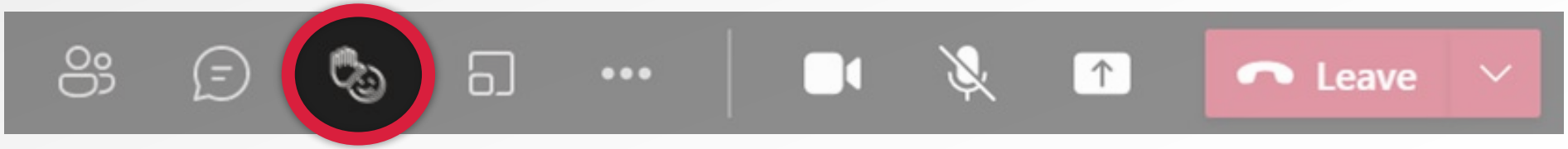
The tuned 239 model has excellent agreement with measurements

Near term plans

- Upgrade PDK (current version is 1.0.4.4) in both Cadence AWR and Keysight ADS
  - Incorporate new 239 model
  - Correct small layout errors in passive devices
  - Add LVS capability to Keysight ADS
- HRL is adding W-band load pull capability
  - Will allow for model verification
  - Have added a new SEC to verify performance in the 90-95 GHz band
- Work on better understanding process variations to enable accurate Monte Carlo simulations
  - Add more variable parameters to model
  - Better understanding of parameter variation

Questions?

Virtual Audience:
Please use the Raise Hand feature to ask a question



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