Advanced W-Band Gallium Nitride (GaN) Monolithic Microwave Integrated Circuits (MMICs) For Cloud Doppler Radar

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Outline

1) Purpose and Objective
2) Gallium Nitride (GaN) background
3) New GaN MMIC amplifiers
4) Future GaN developments
5) Summary
6) Acknowledgements

Purpose and Objective

- **Purpose** is to support the Aerosol/Cloud/Ecosystem (ACE) Decadal Survey Mission and the Cloud and Precipitation Processes Mission (CaPPM) concepts by developing new components that will improve future cloud radar systems for these missions
- ACT10 project **objective** is to develop new gallium nitride transistor amplifiers to enable agile W-band (75-110 GHz) electronically scanning linear arrays to dramatically increase new science data retrieval rates
- Advanced concepts such as ***"Three Band Cloud and Precipitation Radar (3CPR)"*** (Sadowy IIP13) will utilize the W-band GaN amplifiers we are developing as part of the instrument to **satisfy all *Goals* of the ACE mission and target the primary science instrument of the CaPPM concept**

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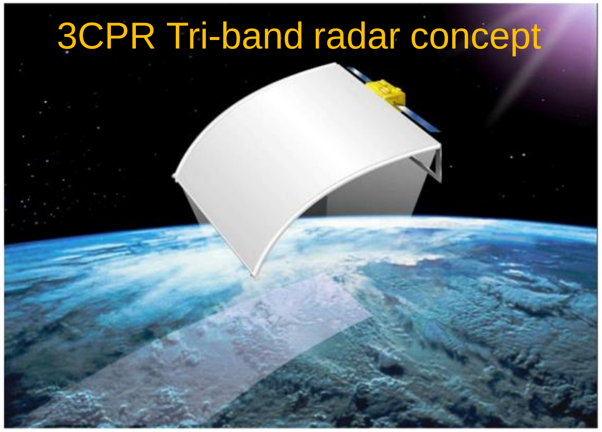
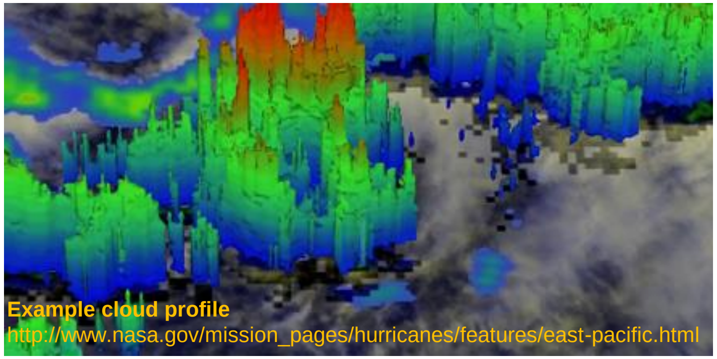
Three-Band Cloud and Precipitation Radar Instrument (3CPR concept, Sadowy IIP13)

This ACT project targets developing the **GaN MMICs** to enable the **Scanning Array Tile**



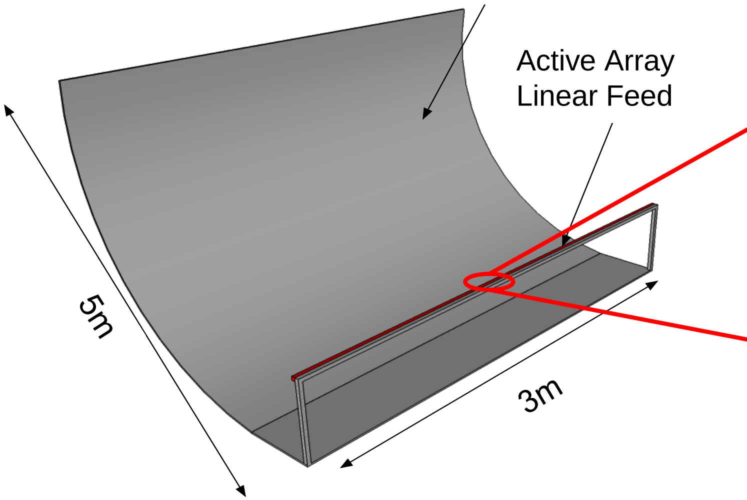
Science →

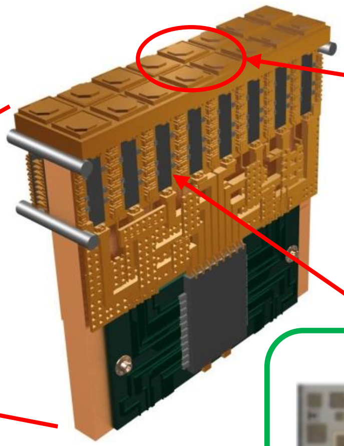


Technology ↑

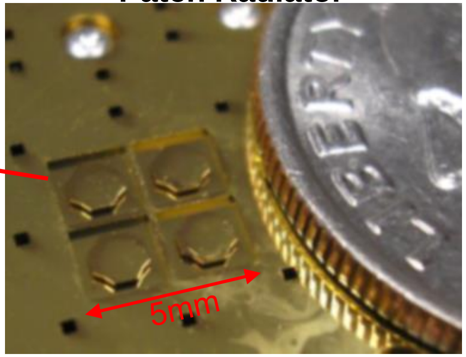
Scanning Array Tile

Cylindrical Parabolic Reflector

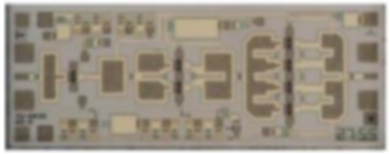




Micro-Machined All-Metal Patch Radiator



GaN MMICs



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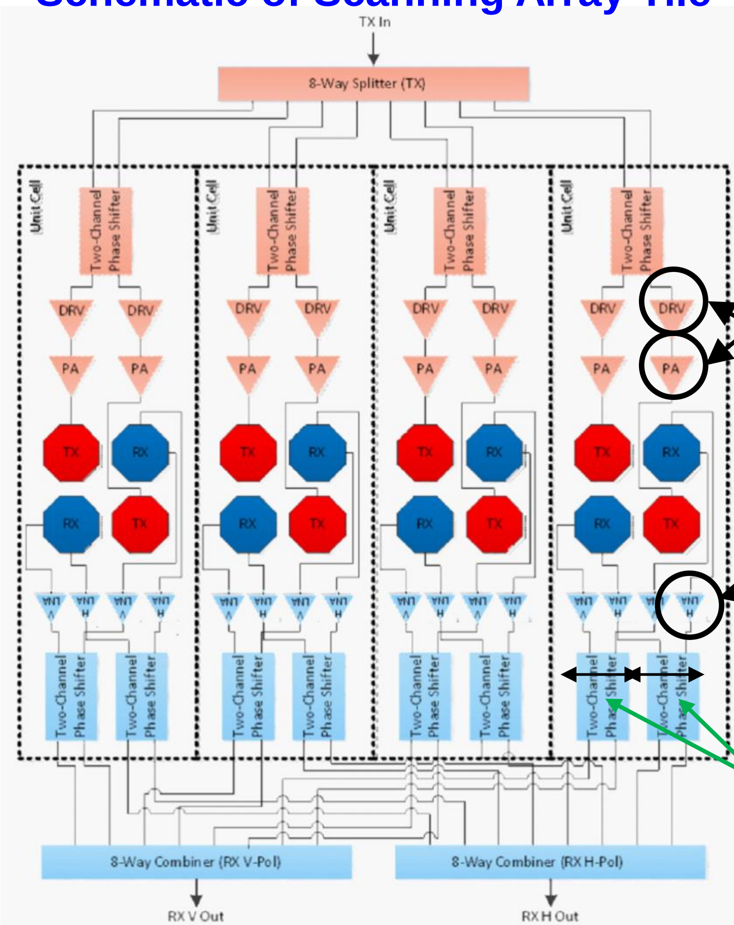
GaN MMICs for the Scanning Array Tile

GaN MMICs best satisfy the RF output transmit power, input receive power handling, and physical size requirements for the Scanning Array Tile design

Schematic of Scanning Array Tile

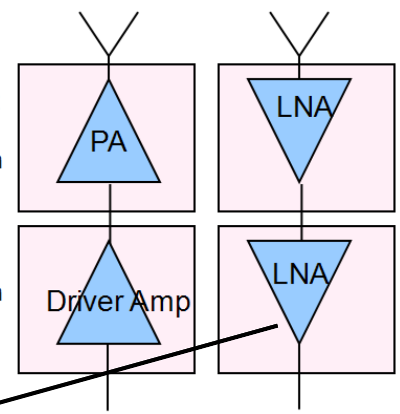


ACT Project: GaN MMIC Target Specifications

Transmit and Receive Frontend

PA:
- 12 dB gain @ 1W Pout
- 20% PAE
- 15 dB small signal gain
- Area: 4x1mm^2

Driver PA:
- 17 dB small signal gain
- Area: 2.6x1mm^2



LNA:
- NF < 6 dB
- 17 dB gain
- Area < 2.6x1mm^2
- 250 mW Pin Off-Sate Handling

LNA:
- NF < 6 dB
- 17 dB gain
- Area < 2.6x1mm^2

Center Frequency = 94 GHz

2.5mm →

- 2.5 mm critical dimension
- ✓Width of 1 PA must fit within
- ✓Width of 2 LNA must fit within

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Material Properties of Common Semiconductors

Semiconductor		Gallium Nitride	Silicon Carbide	Indium Phosphide	Gallium Arsenide	Silicon
Bandgap	eV	3.49	3.25	1.35	1.42	1.1
Breakdown Field	MV/cm	3.3	3	0.5	0.4	0.3
Electron Mobility	$cm^2/V*s$	1,000-2,000	700	5,400	8,500	1,500
Thermal Conductivity	W/(cm*K)	2.0	4.5	0.68	0.54	1.56
Dielectric Constant	εr	9	10	12.5	12.8	11.8

D. Runton et al., *"History of GaN: High-Power RF Gallium Nitride (GaN) from Infancy to Manufacturable Process and Beyond,"* IEEE Microwave Magazine 2013.
http://www.aps.org/units/fiap/meetings/presentations/upload/khan.pdf

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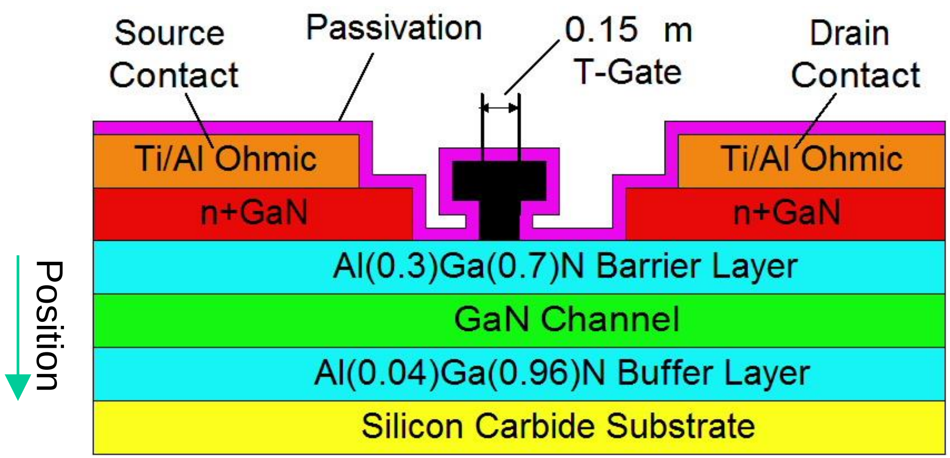
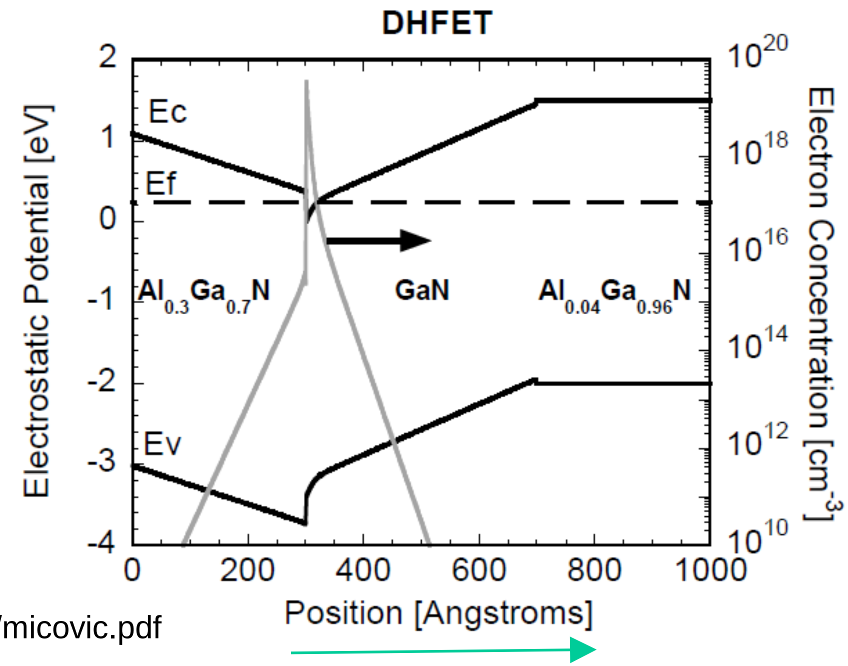
Example HRL GaN Transistor Cross Sectional Structure and Energy Band Diagram

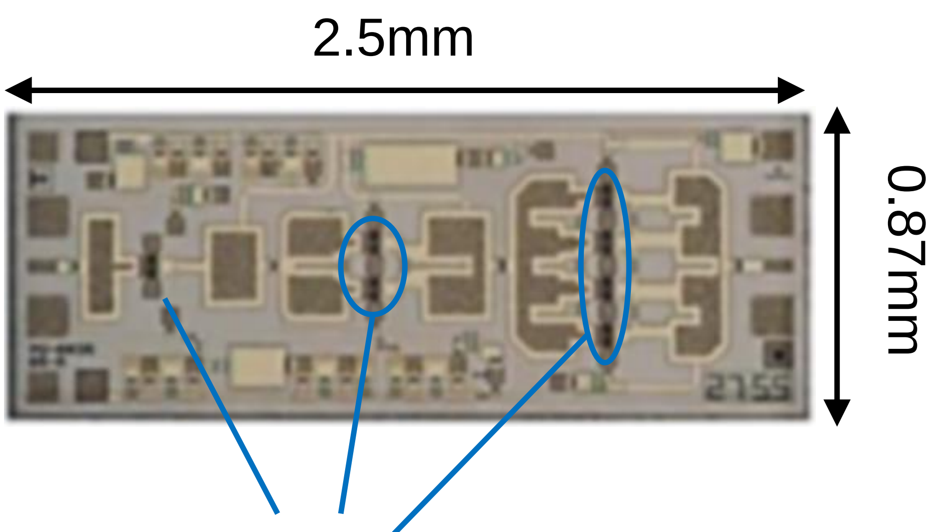




HRL LLC Example: Micovic et al., IEDM 2004
http://www.kiss.caltech.edu/workshops/mmic2008/presentations/micovic.pdf

- **High electric field breakdown** GaN semicondutor
  - => High output power capability
- **Short gate length** 0.15 μm with **good electron mobility**
  - => High frequency W-band functionality
- Optimize epitaxial structure and material quality
  - => Low off state leakage current and higher transconductance gain (Gm)

Example Raytheon 91 GHz GaN MMIC



A. Brown et al., *“W-Band GaN Power Amplifier MMICs,”* IEEE MTT-S 2011.

•3-stage PA: 1>2>4 transistors
•>1 Watt RF output power
•20% efficiency
•Semiconductor approach is most practical for implementing arrays
=> Compact, lower supply voltages, robust, and cost effective
•GaN versus other semiconductors
- Higher power density => more compact amplifier, less semiconductor real-estate/packaging/power combining cost
- Higher efficiency => lower power consumption, less thermal dissipation for the same output power that is sourced

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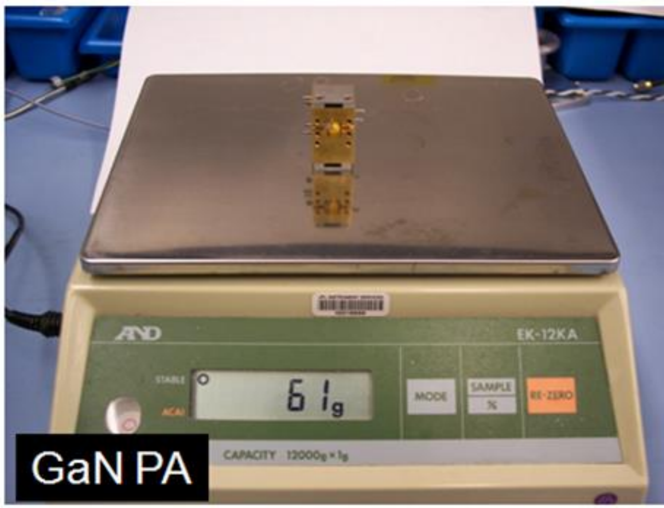
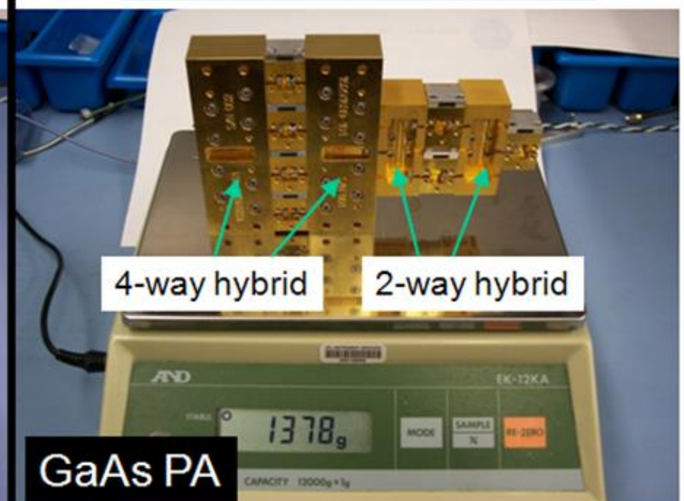
Example JPL Packaged Gallium Nitride vs. Gallium Arsenide (GaAs) Power Amplifiers

Can be reduced in size





<u>GaN Single MMIC Power Amplifier:</u>
- GaN PA is driven with 14 V, 0.338 A
- frequency range ~ 84-95 GHz
- input power ~ 30-65 mW
- output power ~ 540-730 mW
- Pout,max power density ~ 1.2 W/mm
- PAE at Pout,max ~ 14.1 %
- module weighs 61 grams

<u>GaAs Four-Way Power Combined Amplifier:</u>
- each submodule is driven with 2.7 V, ~ 0.57 A
- GaAs PA has 7 submodules, total current ~ 4 A
- frequency range ~ 93-103 GHz
- input power ~ 50-70 mW
- output power ~ 500-700 mW
- Pout,max power density ~ 0.14 W/mm
- PAE at Pout,max ~ 5.8 %
- module weighs 1378 grams

8.5x power density, 2.4x efficiency

GaN improvement over GaAs

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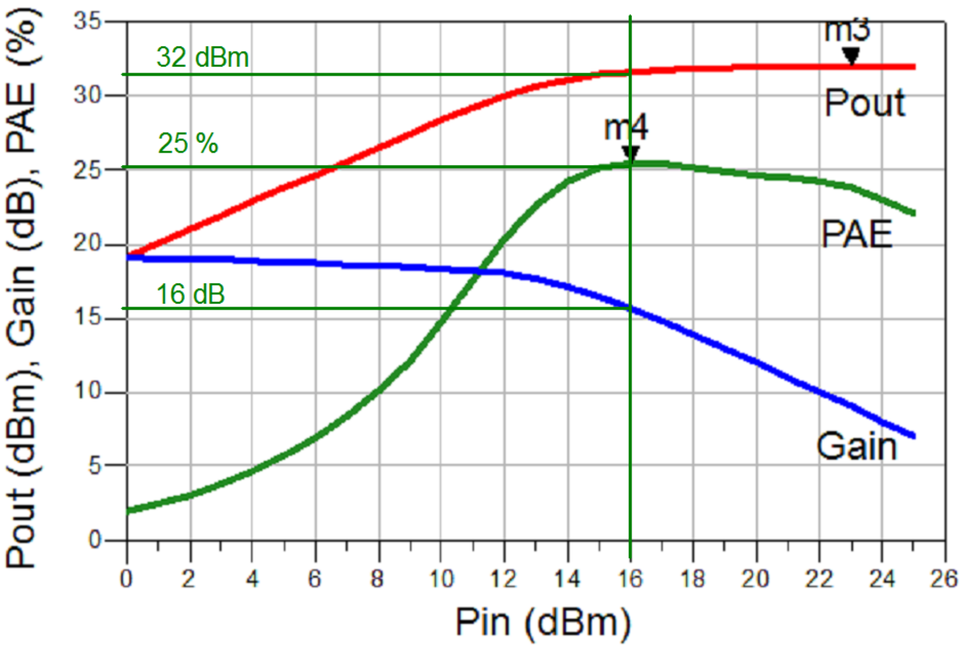
ACT10: New GaN Amplifier Designs
Power Amplifier Simulations

- Raytheon 3-stage power amplifier (PA) design
- Most goals satisfied: >1W (30dBm) Pout, >20% PAE, >12 dB gain, **1.16 mm** x 2.6 mm area

PA Layout Size

- **1.16 mm** critical dimension is larger than the 1 mm target design goal
- This will still be acceptable for IIP13 where the packaged PA will need to fit within a 2.5 mm critical dimension

94 GHz Input Power versus Output Performance



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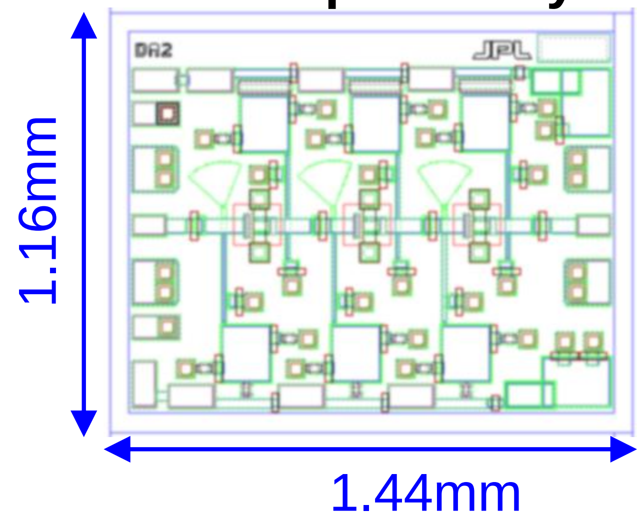
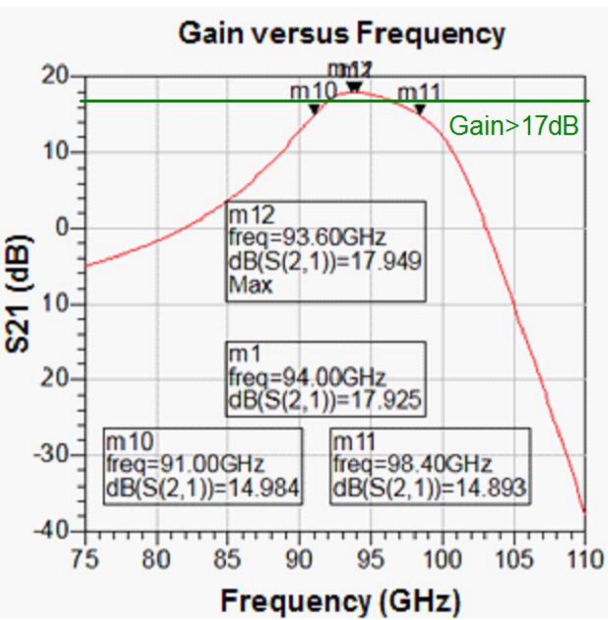
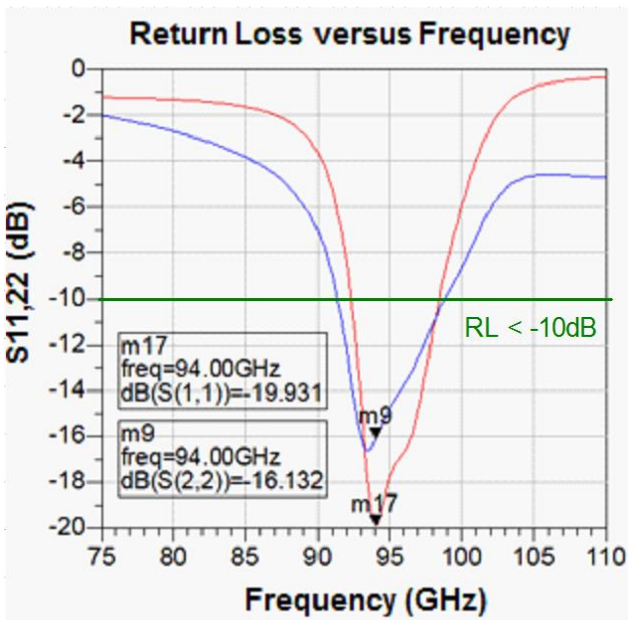
ACT10: New GaN Amplifier Designs
Driver Amplifier Simulations

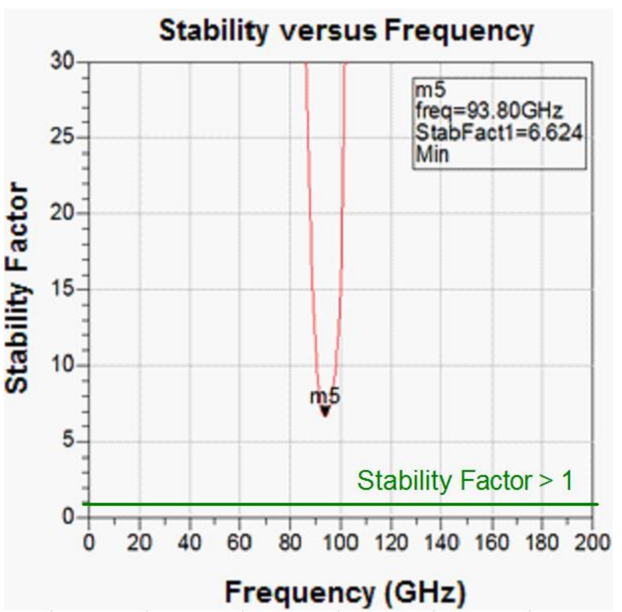
- JPL 3-stage 4x35 um HEMT driver amplifier
- Most goals satisfied: Gain S21 is 17.9 dB, **1.16 mm** x 1.44 mm area
  - **1.16 mm** critical dimension is larger than the 1 mm target design goal but will still be acceptable for IIP13

Driver Amplifier Layout









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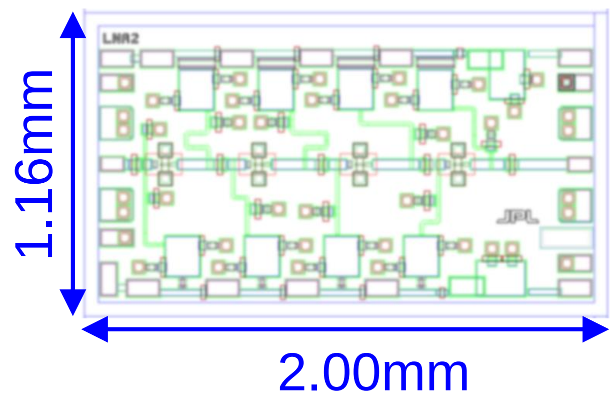
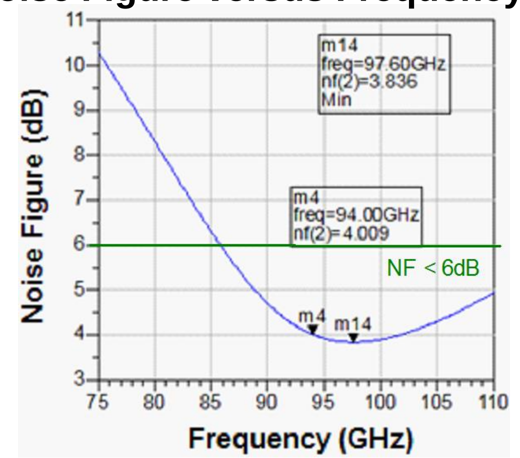
ACT10: New GaN Amplifier Designs
Low Noise Amplifier Simulations

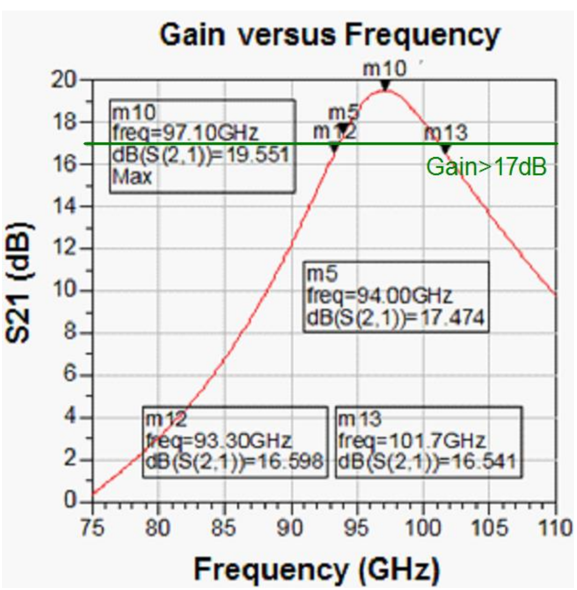
- JPL 4-stage 2x25um low noise amplifier
- Most goals satisfied: 17.5 dB gain at 94 GHz, 19.5 dB peak gain at 97.1 GHz, 1.16 mm x 2.00 mm area
  - **1.16 mm** critical dimension will still be acceptable for IIP13

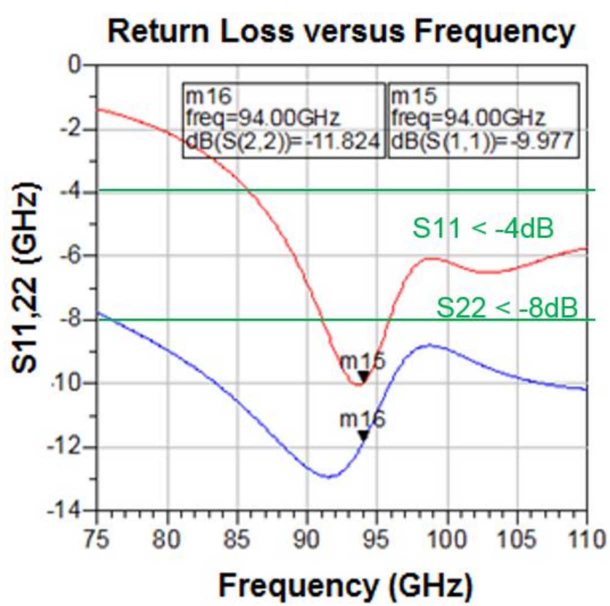
Low Noise Amplifier Layout

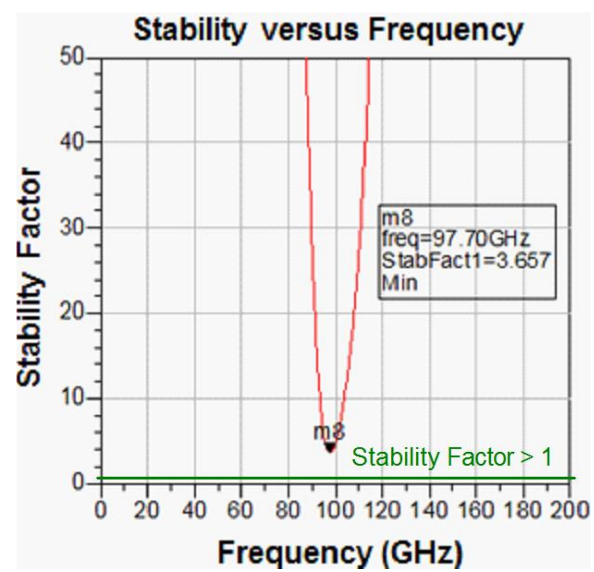


Noise Figure versus Frequency









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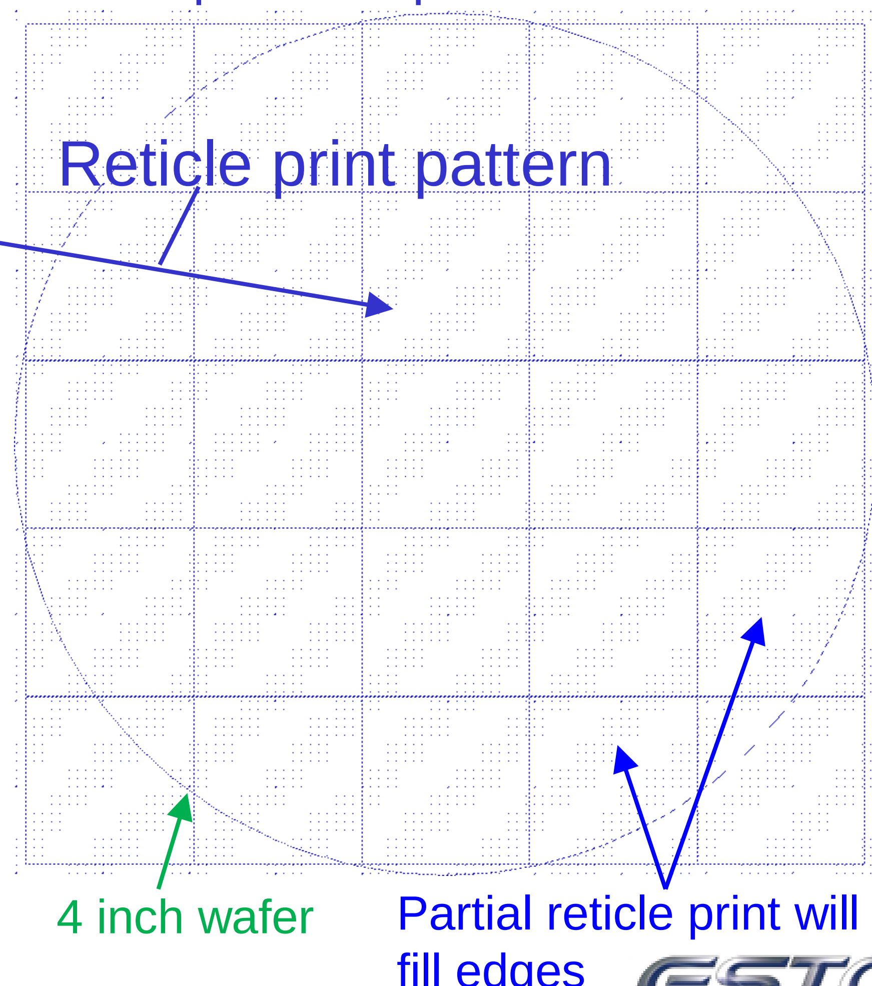
ACT10: GaN MMIC Microelectronic Fabrication In Process

Reticle Layout

Reticle size ~19.45 mm x 19.52 mm

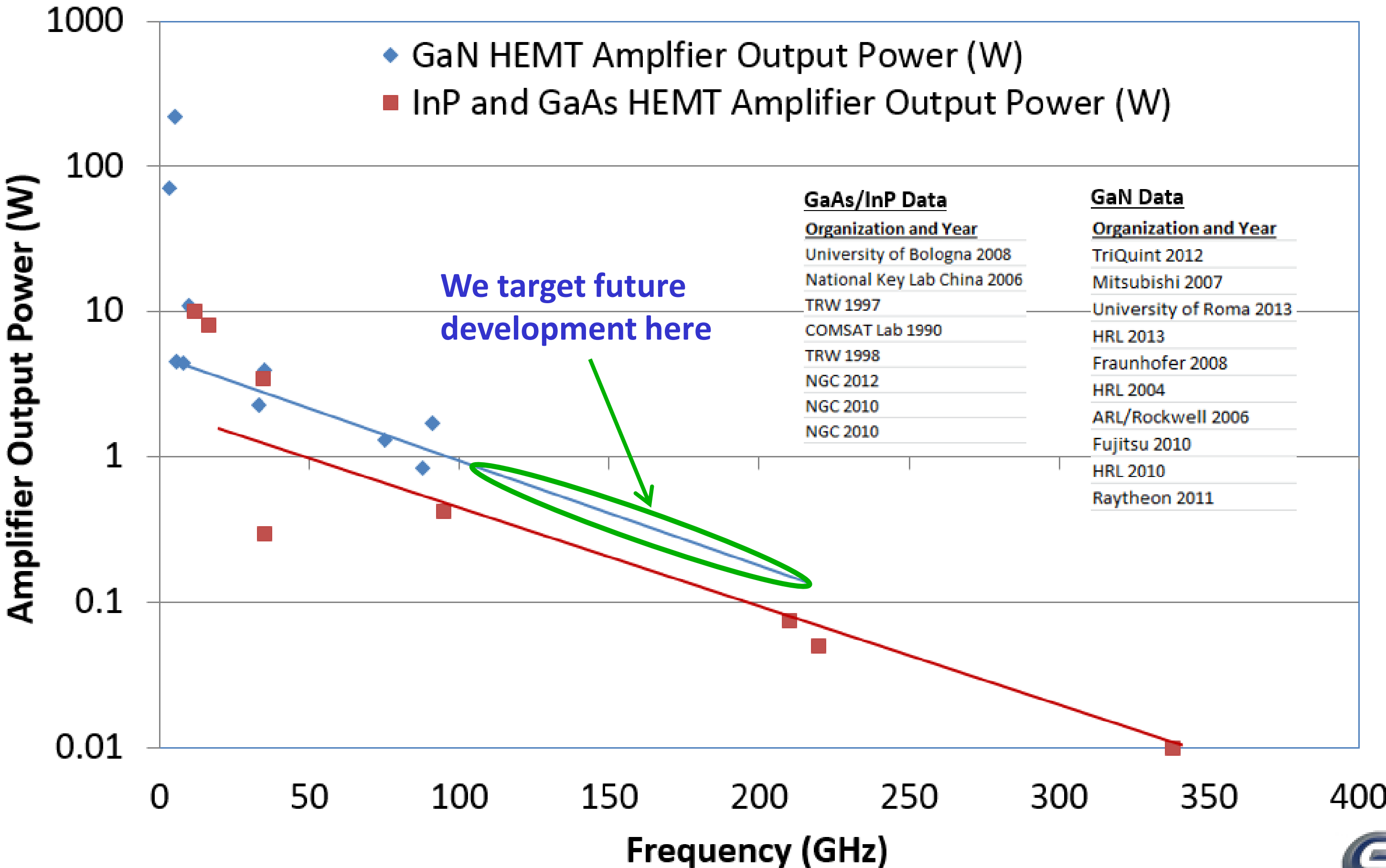
4 Inch Diameter Wafer

Reticle print is repeated over the wafer



Future GaN Development

- **We target a 4x output power improvement with GaN MMICs over GaAs and Indium Phosphide (InP) semiconductors in D & G-Band (110-220 GHz)**
  - **New 220 GHz GaN amplifiers will enable more efficient millimeter wave sources using less components**



Summary

- This effort supports the Aerosol/Cloud/Ecosystem (ACE) Decadal Survey Mission, and the Cloud and Precipitation Processes Mission (CaPPM) concepts by developing new components that will improve future cloud radar systems
- The new W-band GaN amplifiers in development under ESTO ACT10 can enable the most compact electronically steerable transceiver arrays for cloud Doppler radar that will dramatically increase new science data retrieval rates
- In W-band (75-110 GHz) GaN amplifiers are presently the highest RF output power density (>1 Watt per MMIC) with high efficiency (~20%) semiconductor technology available
- We have designed and currently fabricating new GaN PAs, driver amplifiers and low noise amplifiers for the 3-band Doppler radar instrument concept (Sadowy IIP13) targeting ACE and CaPPM requirements
- Future developments in GaN amplifiers will enable higher frequency radar arrays capable of characterizing even smaller particles beyond 110 GHz

Acknowledgement

This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration funded by ESTO ACT10.

We thank Mary Soria and Heather Owen for packaging support, and Robert Lin for package module design.