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:** The decadal survey on Earth science and applications recommends for NASA the Aerosol/Cloud/Ecosystem (ACE) mission with an instrument that is capable of cross-track scanning with multi-frequencies for measuring cloud droplet size, nucleation height and cloud height
- **Objective:** 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
- **Enable:** Advanced instrument concepts such as ***"Three Band Cloud and Precipitation Radar (3CPR)"*** (Sadowy IIP13) that will **satisfy all *Goals* of the ACE mission and the primary science instrument requirements of the** Cloud and Precipitation Processes Mission (**CaPPM)** concept

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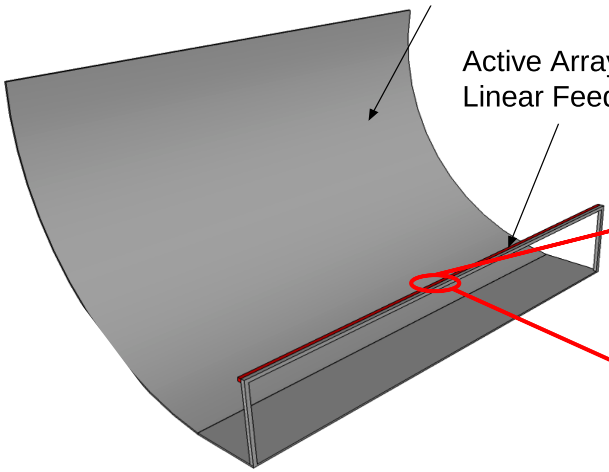
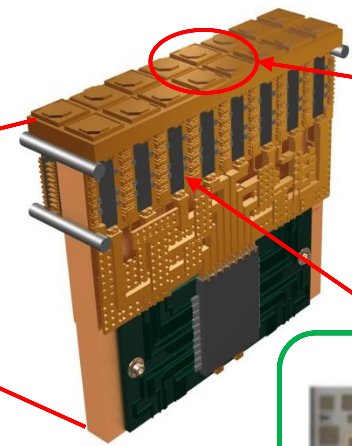
Three-Band Cloud and Precipitation Radar Instrument (3CPR concept, Sadowy IIP13)

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

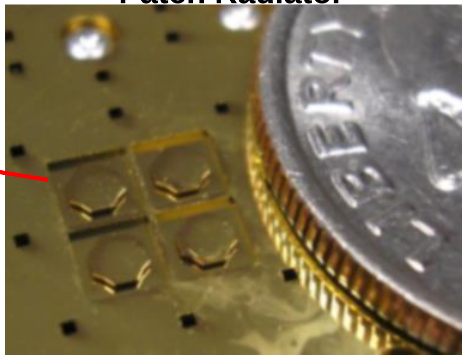
Cylindrical Parabolic Reflector



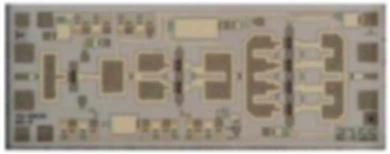
Scanning Array Tile



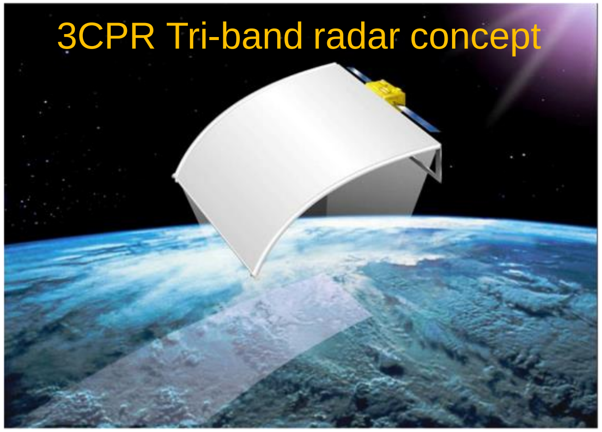
Micro-Machined All-Metal Patch Radiator



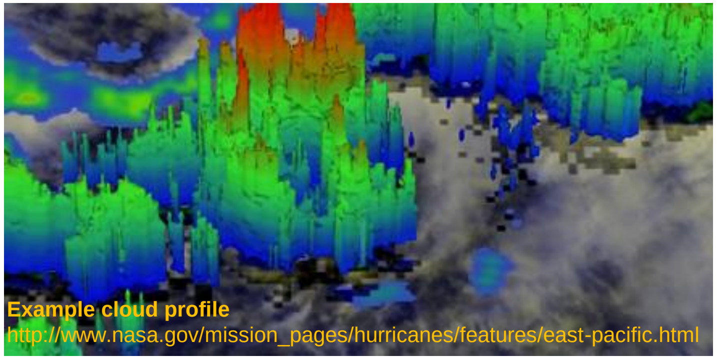
GaN MMICs



Technology



Science



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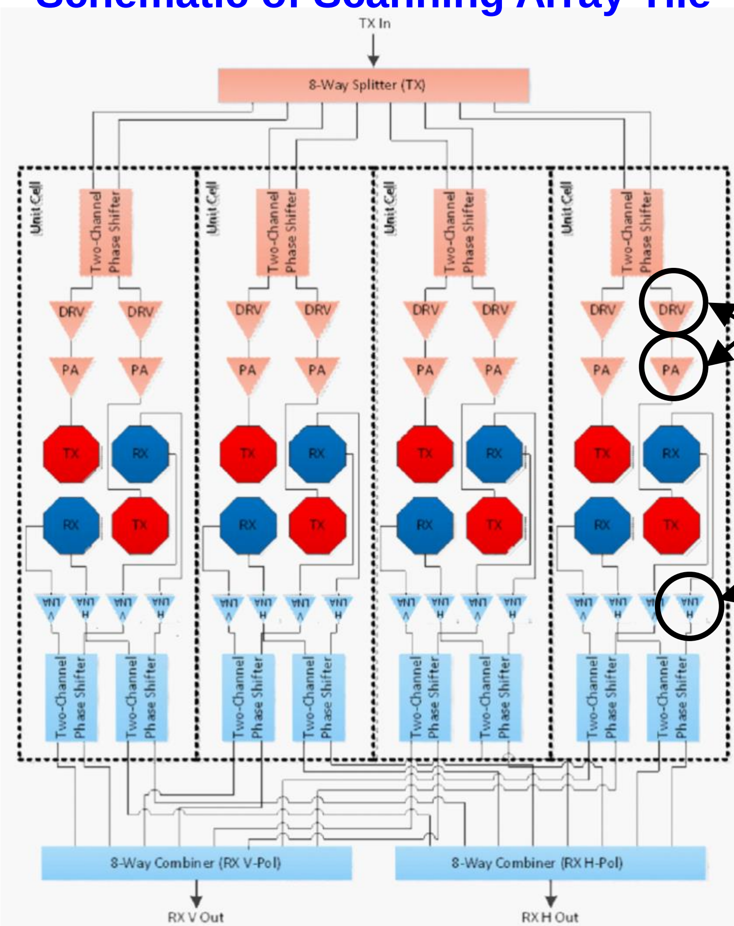
GaN MMICs for the Scanning Array Tile

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

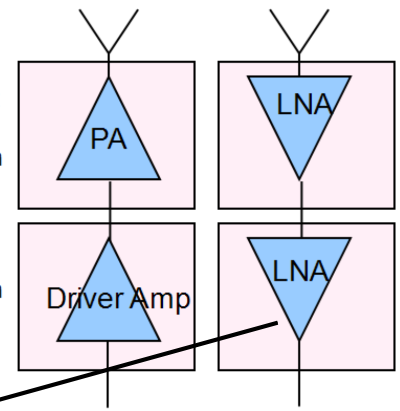


ACT Project: GaN MMIC Target Specifications

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

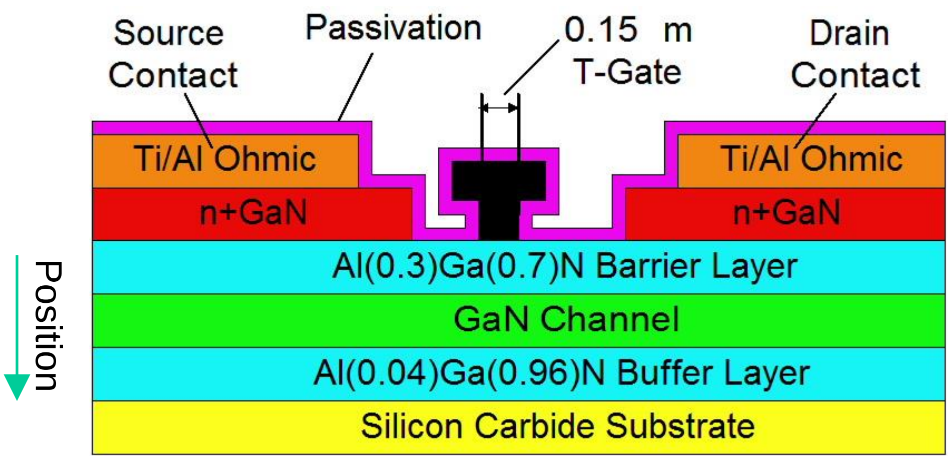
Center Frequency = 94 GHz

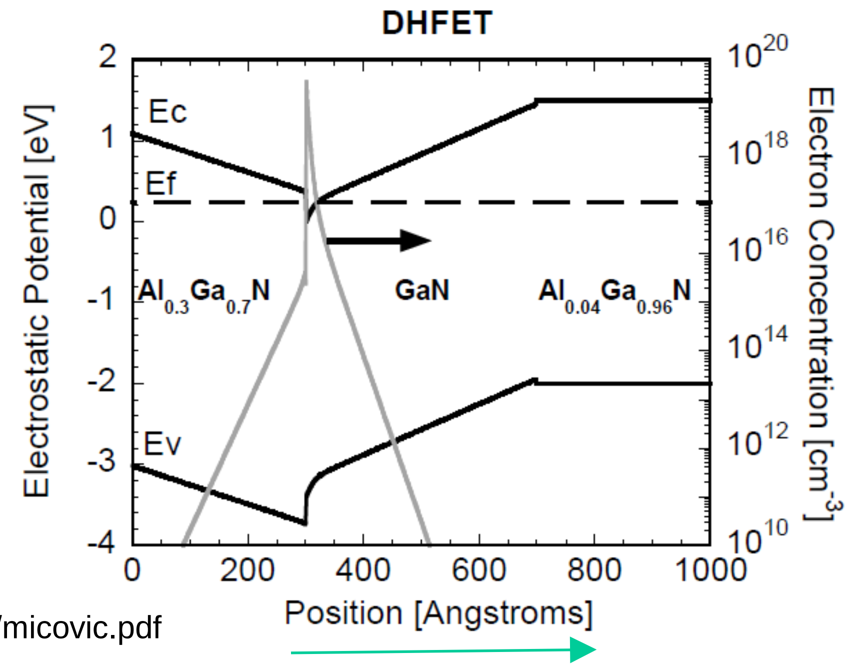
Material Properties of Common Semiconductors

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

Example HRL GaN Transistor Cross Sectional Structure and Energy Band Diagram

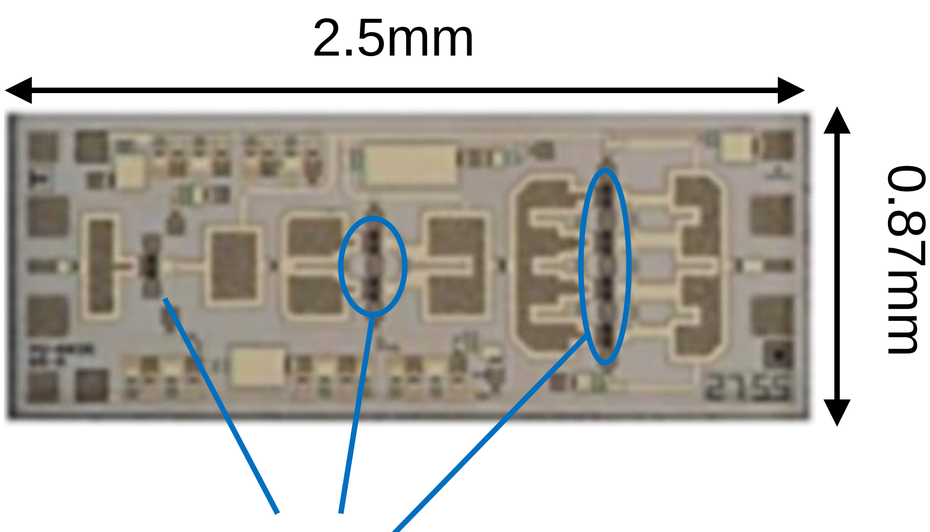




HRL LLC Example: Micovic et al., IEDM 2004
http://www.kiss.caltech.edu/workshops/mmic2008/presentations/micovic.pdf

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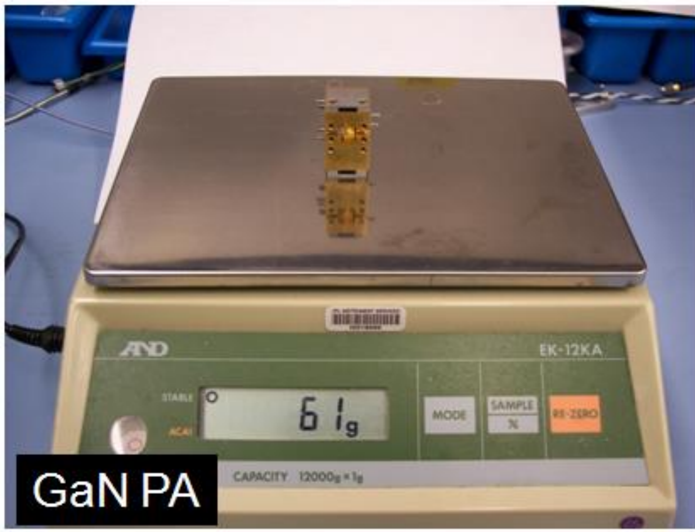
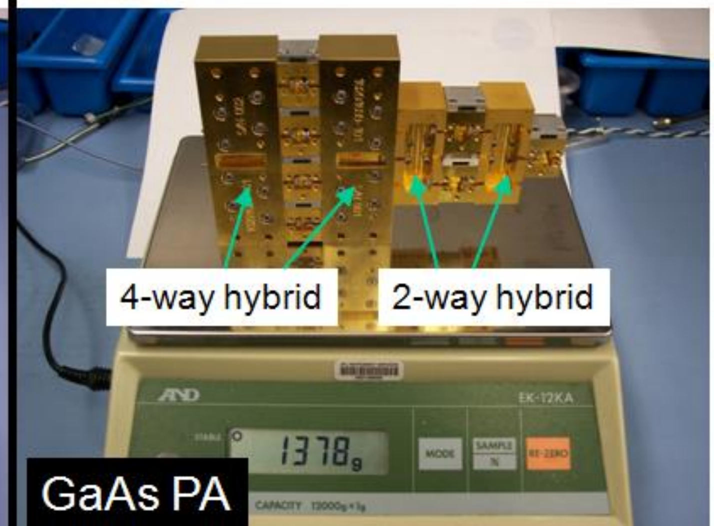
Example JPL Packaged Gallium Nitride vs. Gallium Arsenide (GaAs) Power Amplifiers

GaN improvement over GaAs





GaN Single MMIC Power Amplifier:
- 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

GaAs Four-Way Power Combined Amplifier:
- 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

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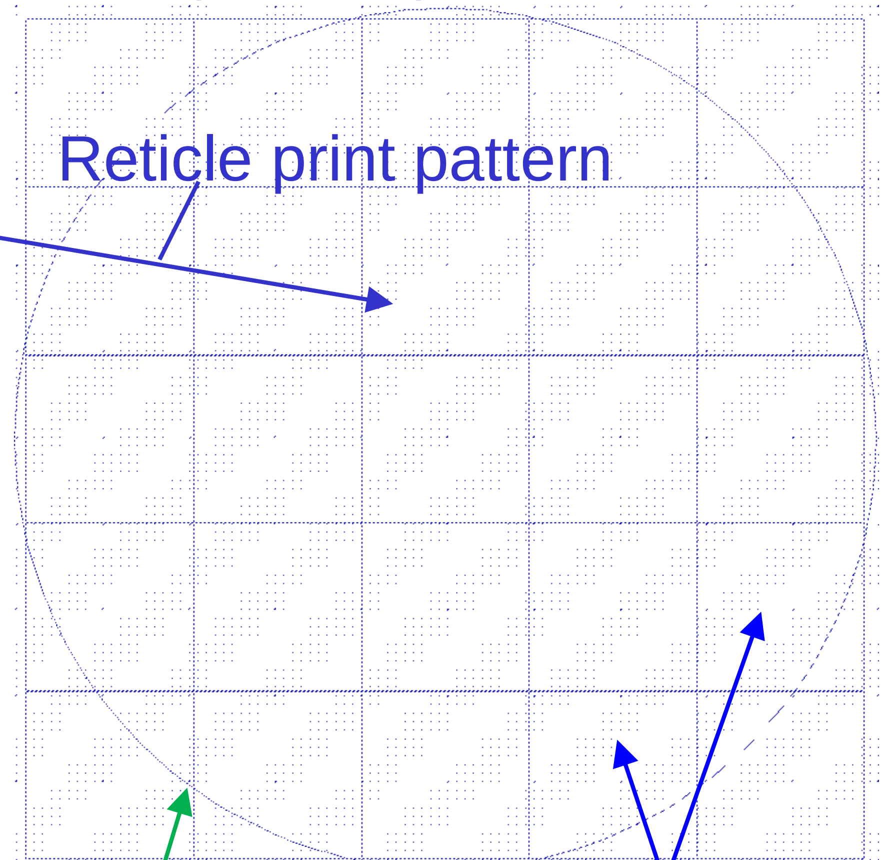
GaN MMIC Microelectronic Fabrication

Reticle Layout

4 Inch Diameter Wafer

Reticle print is repeated over the wafer

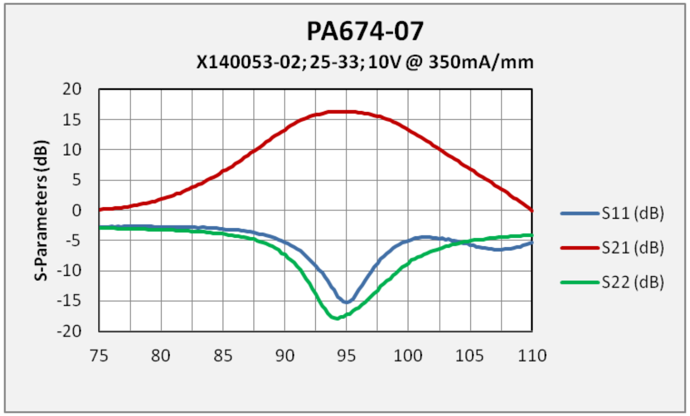


Raytheon PA Design

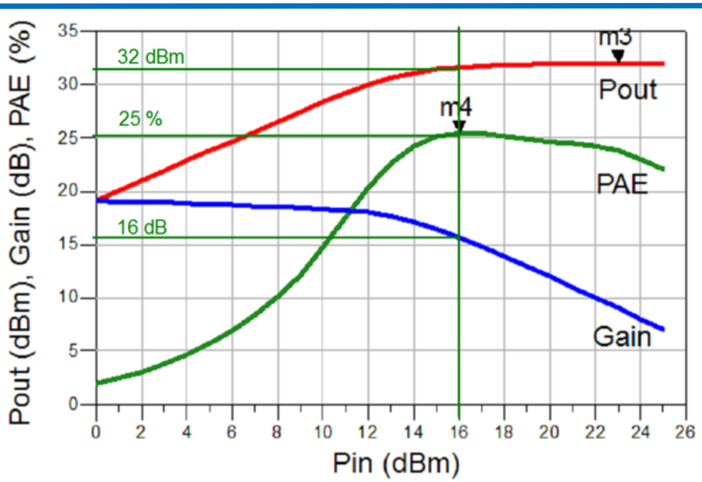
- Raytheon 3-stage PA based on re-optimizing prior design
- Most design goals satisfied in simulation: >1W Pout, >20% PAE, >12 dB gain, **1.16 mm** x 2.6 mm area
  - **1.16 mm** critical dimension is larger than the 1 mm target design goal
  - This will still be acceptable for IIP13 where the packaged PA will need to fit within a 2.5 mm critical dimension

Fabricated Circuit

Post Fabrication Measured On-Wafer S-Parameters



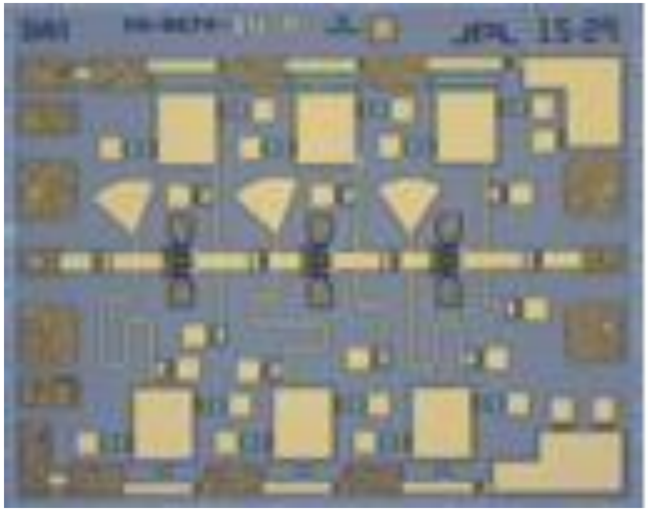
Simulated 94 GHz Design Performance



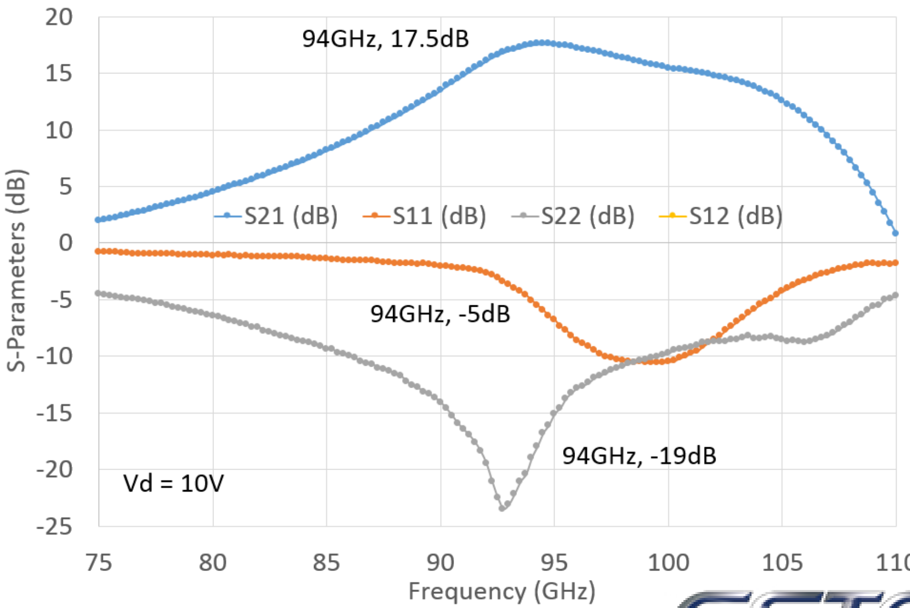
JPL Driver Design

- JPL 3-stage HEMT tuned driver amplifier
- Simulated design: 94 GHz gain S21 is 17.7 dB, S11 is -12.3 dB, S22 is -15.4 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

Photo of Fabricated Circuit



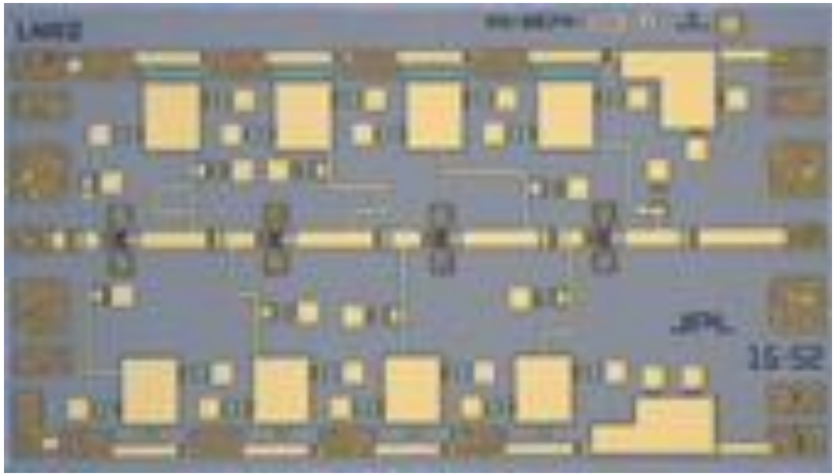
Post Fabrication
Measured On-Wafer S-Parameters



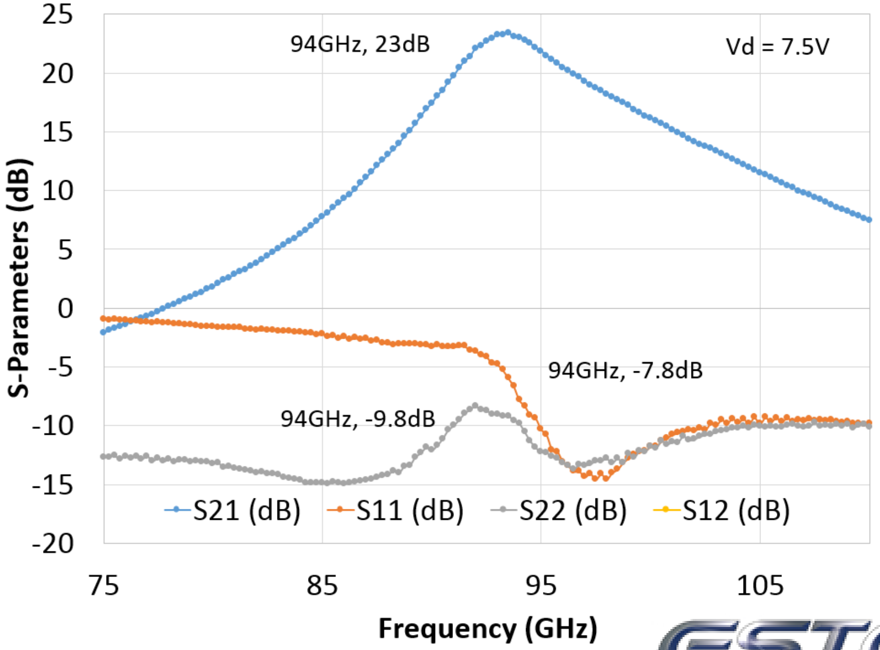
JPL LNA Design

- JPL 4-stage tuned low noise amplifier
- Simulated design: 94 GHz gain S21 is 20.2 dB, S11 is -9 dB, S22 is -11 dB and NF 3.8 dB, 1.16 mm x 2.00 mm area
  - **1.16 mm** critical dimension will still be acceptable for IIP13

Photo of Fabricated Circuit



Post Fabrication Measured On-Wafer S-Parameters



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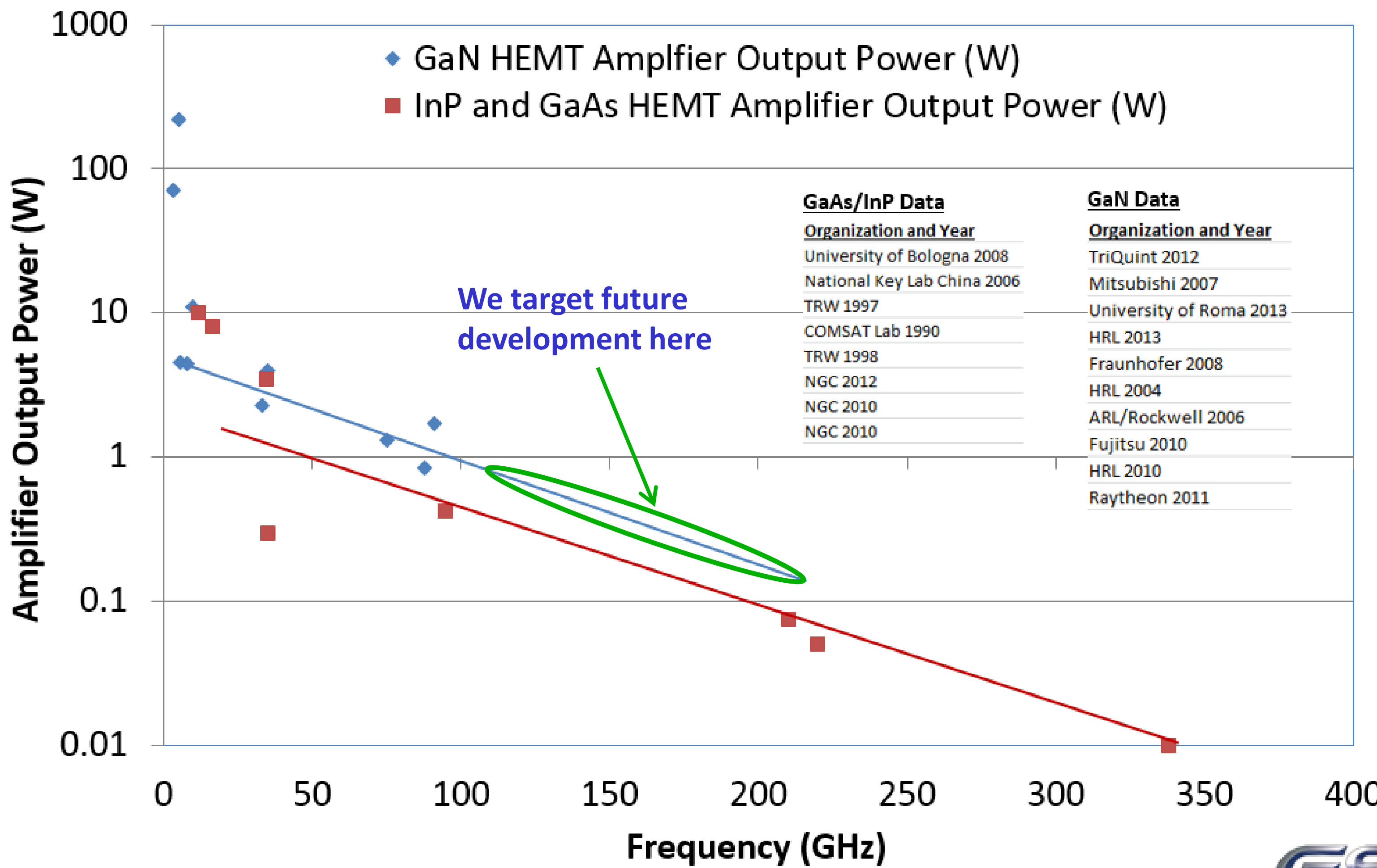
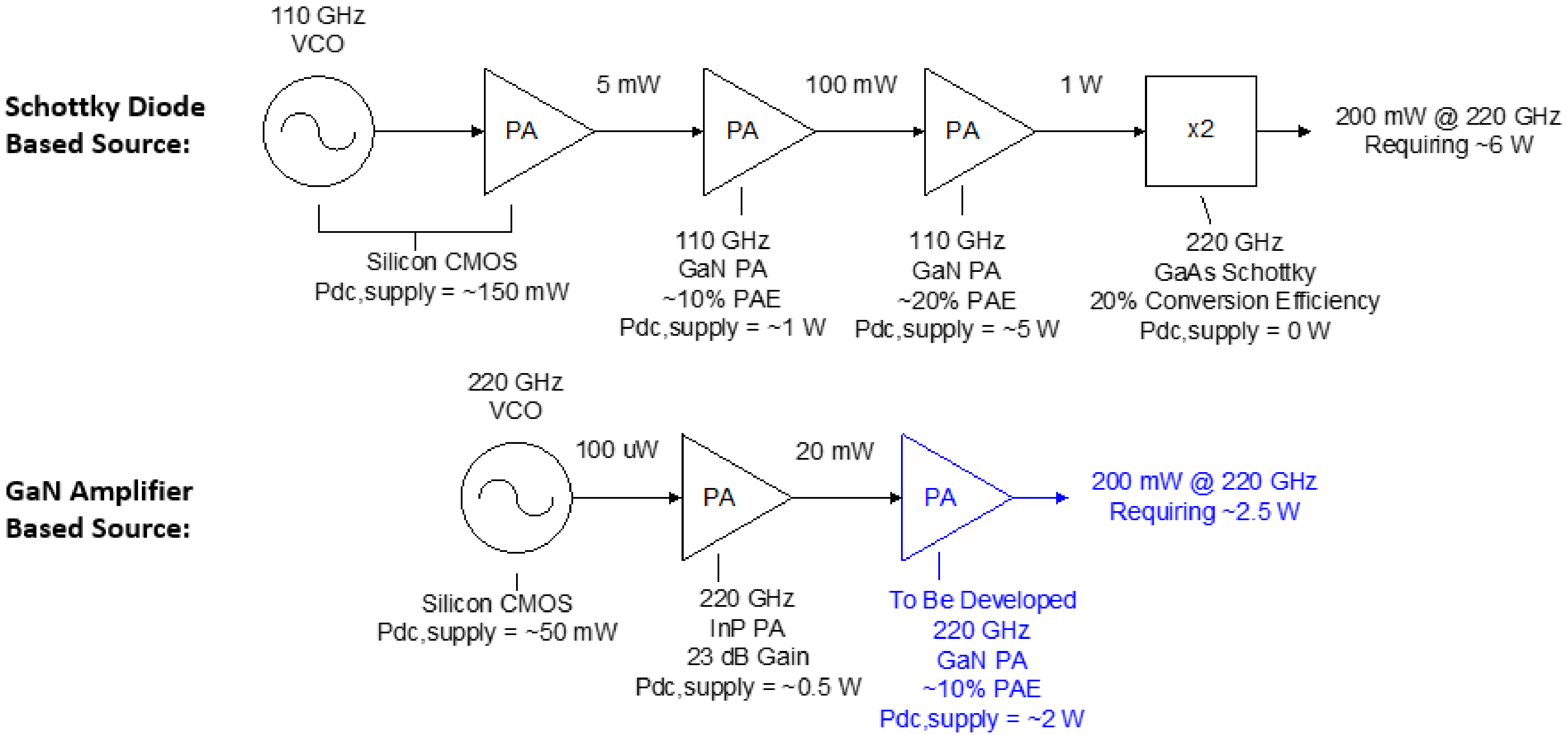
Future GaN Development

- **We target a 4x output power improvement with GaN MMICs over GaAs and Indium Phosphide (InP) semiconductors in D & G-Band (110-220 GHz)**



Future GaN Development

- **New 220 GHz GaN amplifiers will enable more efficient millimeter wave sources using less components**



Summary

- The Aerosol/Cloud/Ecosystem (ACE) Decadal Survey Mission, and the Cloud and Precipitation Processes Mission (CaPPM) can benefit from new 94 GHz array scanning radar capability
- New W-band GaN amplifiers that have been development under ESTO ACT can enable the most compact electronically steerable transceiver arrays for cloud Doppler radar, which can significantly 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, fabricated and now characterizing 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

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