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

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Outline

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3) New GaN MMIC amplifiers
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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.
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:

- **3CPR Tri-band radar concept**
- **Example cloud profile**
- **Micro-Machined All-Metal Patch Radiator**
- **Cylindrical Parabolic Reflector**
- **Active Array Linear Feed**
- **GaN MMICs**
GaN MMICs best satisfy the RF output transmit power, input receive power handling, and physical size requirements for the Scanning Array Tile design.

**ACT Project: GaN MMIC Target Specifications**

- **Transmit and Receive Frontend**
  - **PA:**
    - 12 dB gain @ 1W Pout
    - 20% PAE
    - 15 dB small signal gain
    - Area: 4x1mm²
  - **LNA:**
    - NF < 6 dB
    - 17 dB gain
    - Area < 2.6x1mm²
    - 250 mW Pin Off-Sate Handling

- **Driver PA:**
  - 17 dB small signal gain
  - Area: 2.6x1mm²

- **Center Frequency = 94 GHz**

- **2.5 mm critical dimension**
- Width of 1 PA must fit within
- Width of 2 LNA must fit within
### Material Properties of Common Semiconductors

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Gallium Nitride</th>
<th>Silicon Carbide</th>
<th>Indium Phosphide</th>
<th>Gallium Arsenide</th>
<th>Silicon</th>
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<tbody>
<tr>
<td><strong>Bandgap</strong></td>
<td>eV</td>
<td>3.49</td>
<td>3.25</td>
<td>1.35</td>
<td>1.42</td>
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<tr>
<td><strong>Breakdown Field</strong></td>
<td>MV/cm</td>
<td>3.3</td>
<td>3</td>
<td>0.5</td>
<td>0.4</td>
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<tr>
<td><strong>Electron Mobility</strong></td>
<td>cm²/V*s</td>
<td>1,000-2,000</td>
<td>700</td>
<td>5,400</td>
<td>8,500</td>
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<tr>
<td><strong>Thermal Conductivity</strong></td>
<td>W/(cm*K)</td>
<td>2.0</td>
<td>4.5</td>
<td>0.68</td>
<td>0.54</td>
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<tr>
<td><strong>Dielectric Constant</strong></td>
<td>εr</td>
<td>9</td>
<td>10</td>
<td>12.5</td>
<td>12.8</td>
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</tbody>
</table>

Example HRL GaN Transistor Cross Sectional Structure and Energy Band Diagram

- **High electric field breakdown** GaN semiconductor
  => 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)

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

Example Raytheon 91 GHz GaN MMIC

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

GaN improvement over GaAs

Can be reduced in size

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

GaN improvement over GaAs
• 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

- 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

PA Layout Size
ACT10: New GaN Amplifier Designs
Driver Amplifier Simulations

- JPL 3-stage 4x35 um HEMT driver amplifier
- Most goals satisfied: Gain $S_{21}$ 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](image)

**Gain versus Frequency**
- Gain $> 17$ dB

**Return Loss versus Frequency**
- RL $< -10$ dB

**Stability versus Frequency**
- Stability Factor $> 1$
• 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
Reticle Layout
Reticle size ~19.45 mm x 19.52 mm

4 Inch Diameter Wafer
Reticle print is repeated over the wafer

Reticle print pattern

4 inch wafer
Partial reticle print will fill edges
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
• 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

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