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:** 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.
This ACT project targets developing the GaN MMICs to enable the Scanning Array Tile Technology. The GaN MMICs are used in the Cylindrical Parabolic Reflector Scanning Array Tile. The Micro-Machined All-Metal Patch Radiator is also used in the system. The 3CPR Tri-band radar concept is illustrated, along with an example cloud profile. More information can be found at http://www.nasa.gov/mission_pages/hurricanes/features/east-pacific.html.
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**

- **PA:**
  - 12 dB gain @ 1W Pout
  - 20% PAE
  - 15 dB small signal gain
  - Area: 4x1mm²

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

- **LNA:**
  - NF < 6 dB
  - 17 dB gain
  - Area < 2.6x1mm²
  - 250 mW Pin Off-Safe Handling

Center Frequency = 94 GHz
# 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>
</tr>
</thead>
<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>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td><strong>Dielectric Constant</strong></td>
<td>εr</td>
<td>9</td>
<td>10</td>
<td>12.5</td>
<td>12.8</td>
</tr>
</tbody>
</table>

• **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 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

1 GaN PA ≈ 8.5 GaAs PA

8.5x power density, 2.4x efficiency
4 Inch Diameter Wafer

Reticle layout

Reticle print is repeated over the wafer

Reticle print pattern

4 inch wafer
Partial reticle print will fill edges
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

Simulated 94 GHz Design Performance

Post Fabrication Measured On-Wafer S-Parameters
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
JPL LNA Design

- JPL 4-stage tuned low noise amplifier
- Simulated design: 94 GHz gain $S_{21}$ is 20.2 dB, $S_{11}$ is -9 dB, $S_{22}$ 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
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)

![Graph showing comparison of GaN, InP, and GaAs HEMT amplifier output power versus frequency with data points and trend lines.]

**GaAs/InP Data**
- Organization and Year
  - University of Bologna 2008
  - National Key Lab China 2006
  - TRW 1997
  - COMSAT Lab 1990
  - TRW 1998
  - NGC 2012
  - NGC 2010
  - NGC 2010

**GaN Data**
- Organization and Year
  - TriQuint 2012
  - Mitsubishi 2007
  - University of Roma 2013
  - HRL 2013
  - Fraunhofer 2008
  - HRL 2004
  - ARL/Rockwell 2006
  - Fujitsu 2010
  - HRL 2010
  - Raytheon 2011
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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