Recent NGST HEMT Device & MMIC Development

MMIC Array Receivers and Spectrographs Workshop

Richard Lai and Xiao-Bing (Gerry) Mei
Northrop Grumman Corporation, Redondo Beach CA, 90278

July 21, 2008
HEMT Technology Development Applicable towards Radiometric Applications at NGST

- **NGST Internal R&D**
  - Yearly budget > $2M for last 10 years
  - First LNAs at various frequencies including 90, 140, 150, 180, 240 GHz
  - First 30 dB gain 160-190 GHz amplifier block and full radiometer

- **DARPA**
  - MIMIC Phase II W-band GaAs HEMT LNA
  - TRP W-band MMW Camera
  - MAFET MMW InP HEMT MMIC production
  - SWIFT – 340 GHz Transceiver
  - Hi-Five – 220 GHz Driver

- **JPL CHOP** – focused development of InP HEMT cryogenic LNAs
  - FCRAO 94 GHz LNA UMass Amherst
  - European Space Agency – ground telescopes MMW LNAs, PINs
  - GEOSTAR, 183 GHz SAR
  - Deep Space Network, Paul Allen Telescope, Hawaii MMW LNAs

- **Projects**
  - Jason (TOPEX/Poseidon) Ka-band LNAs
  - ODIN, IMAS, MLS (120 GHz flight)
  - Cloudsat (W-band)
  - PLANCK and Herschel (MMW, W-band power)
  - ALMA (NRAO, X-band LNAs, W-band power)
  - CSIRO (Australia): Narrabri telescopes, VLA (MMW to 200 GHz)
  - NOAA (ATMS, CMIS) development (**MMW to 200 GHz**)
  - LRR (Goddard – X-band)
  - **NRL G-band MMICs**
**InP HEMT**

- **Features**
  - Pseudomorphic growth of InP HEMT layers with MBE
  - Mobility, $f_T$ improve with higher Indium composition
  - Single recess, semi-selective etch process
  - SiNx passivation
  - 2-level interconnect metal process with airbridges, TFR and MIMCAP
  - 50 um thick chips with through via process
InP HEMT Device Structure

Process commonality between different InP HEMT technologies shortens development cycle
Cryogenic InP HEMT

Cryo-4 300K

Key to achieving best cryogenic LNA NFmin is highest Gm for lowest Id

Ref. T. Gaier et. al. 2005

Cryo-4 60K
Cryogenic InP HEMT

- Shot noise due to forward $I_g$ can impact overall $NF_{\text{min}}$

Ref. M. Pospieszalski et al. 2005
**InP HEMT: Ohmic contact improvement**

- Ohmic contact process has been optimized
  - Composite n+ cap
  - Non-alloyed Ohmic metal
- Improved Ohmic contact resistance by over 60%
- Good on-wafer uniformity.
- Good lot-to-lot repeatability
DC characteristics of 0.1um InP HEMT with improved Ohmic process

- 20% improvement in Gmp
- Low V-knee: good for low power performance
- Well controled output conductance
- Good pinch-off characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rc (Ω-mm)</td>
<td>0.04 (Ω-mm)</td>
</tr>
<tr>
<td>BVgd</td>
<td>3.5V</td>
</tr>
<tr>
<td>Gmp, Vds=1V</td>
<td>1400 (mS/mm)</td>
</tr>
<tr>
<td>fT, Vds=1V</td>
<td>230 GHz</td>
</tr>
<tr>
<td>MSG @ 26GHz, Vds=1V</td>
<td>17 dB</td>
</tr>
</tbody>
</table>
Low DC Power InP HEMT

- Peak Gm>900mS/mm at Vds=0.2V
- Ft >140 GHz at a DC power of 20mW/mm
- Good choice for low DC power applications
InP HEMT Production W-band MMIC Performance

- 100 mm InP HEMT
- 60 wafers/20 sites per wafer
- On-wafer testing
- Fixture testing NF is better than on-wafer data by 0.5 dB

Average Gain = 12.5

Average NF = 3.3
Noise figure of a 3-stage W-band LNA MMIC

- $V_{ds}=1V$, $I_{ds}=18mA$
- 2.5 dB noise figure at 94GHz
- 19.4dB associate gain
**W-Band (94 GHz) ABCS HEMT LNA**

- **Broadband Three-Stage Amplifier**
  - Grounded Coplanar Waveguide (GCPW), with 100-µm substrate

- **Low Power, Low-Noise Results**
  - 5.4 dB Noise Figure with 11.1 dB Associated Gain at 94 GHz
  - Total DC Power only 1.8 mW
  - 0.6 mW per stage

---

**Graph**

- Associated Gain (Left Axis)
- Noise Figure (Right Axis)

---

**Image**

- RF_IN
- RF_OUT
- Gate Bypass (Large C)
- Drain Bypass (Small C, 25-Ω R)
- Substrate Mode Suppression Vias
- 2-Finger, 40-µm Devices
InAs channel Design

- Composite channel with InAs/InGaAs
- Hall mobility of 16,000 cm²/V-sec and 3.5 x 10¹²/cm² sheet charge
- Highly doped cap layer for low ohmic contact/access resistance
- Layer structure scaled for 35 nm gate length
Sub 50 nm T-gate

• >5:1 ratio gate top to gate length for low $R_g$
• Single recess, 100 nm length typical
• 20 KeV exposure, two layer resist scheme
THz InP HEMT

- 2 and 4 finger devices
- Typical d.c. Gm > 2 S/mm @1V Vds
- Low on-resistance and knee voltage
- Good pinchoff & output resistance
THz Fmax

- 2f 20 um InP HEMT
- SOLT calibration
- Vd = 1V, Id = 6 mA
- U@100 GHz ~ 22 dB
- MSG@100 GHz ~ 14 dB
- Model predicts even higher performance

![Graph showing THz Fmax performance](image)
## InP HEMT Small-Signal Model

<table>
<thead>
<tr>
<th>Param.</th>
<th>Unit</th>
<th>100 nm</th>
<th>70 nm*</th>
<th>35 nm</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_m$</td>
<td>mS/mm</td>
<td>1125</td>
<td>1500</td>
<td><strong>2600</strong></td>
<td>Epitaxy; threshold voltage</td>
</tr>
<tr>
<td>$C_{gs}$</td>
<td>pF/mm</td>
<td>0.90</td>
<td>0.83</td>
<td><strong>0.80</strong></td>
<td>Lg reduction; higher Cgs due to shorter gate to channel design</td>
</tr>
<tr>
<td>$C_{ds}$</td>
<td>pF/mm</td>
<td>0.63</td>
<td>0.60</td>
<td><strong>0.30</strong></td>
<td></td>
</tr>
<tr>
<td>$C_{dg}$</td>
<td>pF/mm</td>
<td>0.16</td>
<td>0.18</td>
<td><strong>0.13</strong></td>
<td>Improved Cdg</td>
</tr>
<tr>
<td>$R_{ds}$</td>
<td>Ω-mm</td>
<td>10.4</td>
<td>7.2</td>
<td><strong>6.0</strong></td>
<td>Epitaxy; threshold voltage</td>
</tr>
<tr>
<td>$R_g$</td>
<td>Ω-mm</td>
<td>120</td>
<td>150</td>
<td><strong>250</strong></td>
<td></td>
</tr>
<tr>
<td>$f_T$</td>
<td>THz</td>
<td>0.2</td>
<td>0.35</td>
<td><strong>0.45</strong></td>
<td>Simulated from model</td>
</tr>
<tr>
<td>$f_{max}$</td>
<td>THz</td>
<td>0.4</td>
<td>0.7</td>
<td><strong>1.4</strong></td>
<td>Simulated from model</td>
</tr>
<tr>
<td>MSG@340 GHz</td>
<td>dB</td>
<td>1</td>
<td>4</td>
<td><strong>10</strong></td>
<td>Simulated from model</td>
</tr>
</tbody>
</table>

- Sub 50 nm InP HEMT
- $V_d = 1V$, $I_d = 300$ mA/mm
- Derived from measurements on 2f10 um, 2f20 um, 2f30 um devices for 340 GHz s-MMIC amplifiers

*reported IEDM 2000
New InP HEMT transistors within this performance region.

Future development for THz systems.

Reported transistor results state-of-art courtesy DARPA and M. Feng, UIUC
- InP and MHEMT FETs, InP HBT,
- SiGe HBT, Si CMOS
- GaN HEMT, ABCS HEMT, HBT
ABCS compared with 35 nm InP HEMT (SWIFT)
Bias dependance

2-finger 40um InP HEMT.
Peak $F_{\text{max}} = 1.1$ THz; $f_T = 550$ GHz
Challenging Interconnects and Passives for Sub MMW Integrated Circuits (S-MMICs)

- TFR, MIMCAP, 2 interconnect metal layers with airbridges
- Interconnections scaled down by factor of 5
- Slot via development to 50 um thick InP substrate
- Overall S-MMIC size is ~10x smaller than MMW MMICs
Highest Frequency Circuits

Features

- 35 nm InP HEMT
- 50 um InP with vias
- 3-stage s-MMIC LNA
  - 2f 20 um per stage; 1V, 300 mA/mm
  - 21 dB gain @280 GHz (7 dB/stage)
  - 15 dB gain @340 GHz (5 dB/stage)
  - Best LNAs 18 dB gain@340 GHz
  - NF ~ 7 dB@330 GHz

- Highest frequency s-MMIC amplifier ever demonstrated
- Excellent match to simulation validates model
- Validates THz fmax Transistor
G-band LNA performance

• Legacy 3-stage 70 nm InP HEMT G-band LNA MMIC achieved 12 dB gain from 175-210 GHz
  • Singled ended MMIC LNA
  • 2f20 um devices on each of 3 stages

• Same MMIC fabricated on the new sub 50 nm InP HEMT process

• 21 dB gain has been achieved from 175-210 GHz at Vds = 1V and Id = 9 mA

• 18 dB gain was achieved at 220 GHz

• The gain shape with new device is preserved
  • 9 dB higher total gain achieved
  • 3 dB higher gain per stage achieved
Going Forward – HEMT Technology For Radiometers

Understand fundamentals towards cryogenic NF performance
- device stability
- role and reduction of shot noise in cooled devices
- continue to study next generation materials including ABCS HEMT, InAs channels
- apply and continue to push HEMT improvements towards cryogenic performance
- optimization of device technologies for specific frequency bands
  - X-band cryogenic device needs to be different than than W, G-band device

Continue to push the frequency envelope for amplifier technology
- shorter gates, reduced parasitics, InAs channels
- 140 GHz, 220 GHz window for MMW cameras
- 180 GHz for atmospheric sensing
- push 220, 260, 340 GHz and beyond – 1 THz one day?
- advanced packaging concepts

Next generation insertions – larger arrays, cameras, high frequency sensors
- 35, 94 GHz imaging solutions being introduced in commercial market
- 140, 220 GHz active radiometers for next generation cameras
- 180 GHz SAR concepts are being explored
- size, weight, power reduction with wider bandwidth and lower noise figure desired
Going Forward – Proposed Topics of Research for Keck program in next 2-3 years

Characterize, analysis, optimize InP HEMT device for cryogenic applications
- No systematic study has been conducted on InP HEMT devices to date
- At NGST, InP HEMTs are optimized for room temperature operation and have generally proven to translate to good cryogenic performance
- Several questions have been identified
  - measure and analyze devices to develop correlations to MMIC amplifier results
  - cryogenic leakage current shot noise is significant at lower frequencies
  - device stability with high Indium content channels
  - what gate length and device size is ideal at lower frequencies?
  - 35 nm device improvements at higher frequencies translate to lower freq?
  - do ohmic improvements at room temperature translate to cryogenic advantages?
  - how do recent isolation, gate metal, gate recess and passivation improvements impact cryogenic performance?
  - is there a more ideal device design/process target for cryogenic devices
    – threshold voltage
    – gate length
    – recess process
    – epitaxial design
    – device topologies
Going Forward – Proposed Topics of Research for Keck program in next 2-3 years

Characterize, analysis, optimize InP HEMT device for cryogenic applications (cont.)
- Systematic cryogenic study of existing samples and device/process splits both through MIC amplifiers and cryogenic on-wafer probing measurements
- Study next generation materials including ABCS, InAs channels, new metals and passivation layers
- Update models to set goals and metrics to meet 3x quantum limit noise performance
  - develop correlations to current device and MMIC amplifier results
  - evaluate proposed improvements to these goals

Apply improvements to update latest SOA InP HEMT designs
- develop and adapt new device models towards updated cryogenic LNA designs based on device improvements
- develop new designs to take advantage of performance improvements
  – example – lower Vds, Ids at equivalent gain
- consider splitting device technologies used for specific frequency ranges
- new designs to push higher frequency, wider bandwidth