Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Current Status of Semiconductor Technologies and Circuits for THz applications

Date Submitted: July 2008
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Re:

Abstract: Current Status of Semiconductor Technologies and Circuits for THz applications

Purpose:

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Current Status of Semiconductor Technologies and Circuits for THz applications

2008. 7.16

Jae-Sung Rieh
School of Electrical Engineering
Korea University
Outline

- Introduction
- Components for THz Communication Systems
- Semiconductor Technologies for THz
- Circuit Examples for THz
- Summary
Introduction

- Two main approaches for THz system implementation
  - Optical approach
    - Challenge: lowering the operation frequency
  - Electrical approach
    - Challenge: raising the operation frequency

- Electrical approaches
  - Diode approach
    → Passive and no gain provided
  - Transistor approach
    → Operation frequency still not sufficient but growing
Traditional Diode-Based THz Receiver

- **Issues**
  - Absence of LNA
    - Noise from mixer and IF amp not suppressed
  - Passive nature of mixer
    - No gain provided. Noise from IF amp not suppressed
  - LO source
    - Typically not integration-ready

\[ F = F_{m \text{ixer}} + L_{M \text{ixer}} \left( F_{I \text{Famp}} - 1 \right) + \ldots \]
Transistor-Based THz Receiver

- Widely accepted architecture for low frequency receivers
  - Addition of LNA
  - Active mixer with gain or reduced loss
  - Integration-friendly LO

→ Enabled by transistor-based semiconductor technologies
→ Can this architecture be applied to THz receivers, too?

\[ F = F_{LNA} + \frac{(F_{Mixer} - 1)}{G_{LNA}} + \frac{(F_{IFamp} - 1)}{G_{LNA} G_{Mixer}} + \ldots \]
Semiconductor Technologies for THz

• III-V technologies
  – HBT (heterojunction bipolar transistor) technologies
  – HEMT (high electron mobility transistor) technologies

• Si-based technologies
  – SiGe HBT technologies
  – RFCMOS technologies
Technology Comparison

GaAs/InP HBT or HEMT
- Very high operation speed
- High cost
- Reliability issues

SiGe BiCMOS
- High operation speed
- CMOS-technology compatible
- High reliability
- Extra mask steps on base CMOS technology

CMOS
- Acceptable operation speed
- Low cost and high reliability
- Relatively low $g_m$
- Poor device matching
Operation Speed Trend of Technologies
III-V HBT Record Performance

- UIUC
- Peak $f_T = 765$ GHz at 25C
- Peak $f_T = 845$ GHz at -55C

Snodgrass et al IEDM 2006
III-V HBT Performance Issues

- Issues with increasing operation frequency
  - Reduction in breakdown voltage $\Rightarrow$ Limits safe operation region
  - Increase in collector current density $\Rightarrow$ Influences reliability

Snodgrass et al IEDM 2006
HEMT Record Performance

- Seoul National Univ.
- 15 nm gate length InP HEMT
- Peak $f_T / f_{max} = 610/305$ GHz

Yeon et al IEDM 2007
SiGe HBT Record Performance

- IBM
- 0.12 um SiGe HBT
- Peak $f_T / f_{max} = 375/210$ GHz

Rieh et al IPRM 2003
SiGe HBT Performance Trend

- Trend of IBM SiGe HBTs

<table>
<thead>
<tr>
<th></th>
<th>5HP</th>
<th>6HP</th>
<th>7HP</th>
<th>8HP</th>
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<td>$J_{C,P}$ [mA/µm²]</td>
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<td>300</td>
<td>650</td>
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SiGe HBT $f_T$ and $f_{\text{max}}$
RFCMOS Record Performance (I)

- 65 nm SOI NFET ($L_{\text{poly}}=29$ nm)
- Peak $f_T / f_{\text{max}} = 360/420$ GHz

- 65 nm SOI PFET
- Peak $f_T / f_{\text{max}} = 238/295$ GHz

Post et al IEDM 2006
RFCMOS Record Performance (II)

- **NFET:** 45 nm SOI ($L_{\text{poly}}=29$ nm)
  - Peak $f_T = 485$ GHz

- **PFET:** 45 nm SOI ($L_{\text{poly}}=31$ nm)
  - Peak $f_T = 345$ GHz

A: Relaxed poly pitch, B: Minimum poly pitch
# ITRS Roadmap 2007 for RFCMOS

## Near-term

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<tr>
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<td>50</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>32</td>
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### Performance RF/Analog [1]

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<td>1.3</td>
<td>1.2</td>
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<td>1.2</td>
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<td>Gate Length (nm) [2]</td>
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<td>37</td>
<td>32</td>
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<td>25</td>
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<td>$1/f$-noise ($\mu V^2 \cdot \mu m^2$/Hz) [4]</td>
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<td>140</td>
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<td>80</td>
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<tr>
<td>$I_{ds}$ ($\mu A/\mu m$) [6]</td>
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<td>11</td>
<td>9</td>
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<td>7</td>
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<td>240</td>
<td>280</td>
<td>320</td>
<td>360</td>
<td>400</td>
<td>440</td>
<td>490</td>
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<td>Peak $F_{max}$ (GHz) [8]</td>
<td>200</td>
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<td>390</td>
<td>440</td>
<td>510</td>
<td>560</td>
<td>630</td>
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## Long-term

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<th>Year of Production</th>
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<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
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<tr>
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<td>18</td>
<td>16</td>
<td>14</td>
<td>13</td>
<td>11</td>
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<tr>
<td>Supply voltage (V) [2]</td>
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<td>$T_{ox}$ (nm) [2]</td>
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<td>1</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
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<td>Gate Length (nm) [2]</td>
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<td>14</td>
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<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>$I_{ds}$ ($\mu A/\mu m$) [6]</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Peak $F_1$ (GHz) [7]</td>
<td>550</td>
<td>630</td>
<td>670</td>
<td>730</td>
<td>790</td>
<td>870</td>
<td>870</td>
</tr>
<tr>
<td>Peak $F_{max}$ (GHz) [8]</td>
<td>710</td>
<td>820</td>
<td>880</td>
<td>960</td>
<td>1050</td>
<td>1160</td>
<td>1160</td>
</tr>
<tr>
<td>$N_{F_{min}}$ (dB) [9]</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>
320 GHz InP HEMT Amplifier

- NGC
- 35 nm NGC InP HEMT
- 3 stage
- $P_{\text{Diss}} = 43 \text{ mW}$
- Gain = 13-15 dB for 295-340 GHz
324 GHz InP HBT Amplifier

- Teledyne
- 250 nm Teledyne InP HBT
- Single stage common base
- Gain = 4.8 dB at 324 GHz
- Saturated $P_{\text{out}} = 1.13$ dBm
220 GHz GaAs MHEMT LNA

- Franhofer
- 0.1 um Franhofer GaAs mHEMT
- 4 stage cascode
- Peak gain = ~20 dB
- NF = 9.4 dB up to 213 GHz

Pukala et al MWCL 2008
140 GHz SiGe HBT Amplifier

- Univ. of Toronto
- STM SiGe BiCMOS
- 5 stage cascode
- $P_{\text{Diss}} = 112$ mW
- Gain = 17 dB at 140 GHz

Laskin et al IMS 2007
Accumulated Performance: Amplifiers
346 GHz InP HEMT Fundamental Oscillator

- NGC
- 35 nm NGC InP HEMT
- DC power = 11.7 mW
- Output power = -16 dBm at 346 GHz

<table>
<thead>
<tr>
<th>Frequency of Oscillation (GHz)</th>
<th>Vds (V)</th>
<th>Ids (mA)</th>
<th>Measured Output Power (μW)</th>
<th>DC to RF Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>254</td>
<td>1.3</td>
<td>9</td>
<td>158</td>
<td>1.35</td>
</tr>
<tr>
<td>314</td>
<td>1.2</td>
<td>6</td>
<td>46</td>
<td>0.64</td>
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<tr>
<td>346</td>
<td>1.3</td>
<td>9</td>
<td>25</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Radisic et al MWCL 2007
278 GHz SiGe HBT Push-Push VCO

- Technische Univ. Munchen
- Infineon 200 GHz SiGe HBT Technology
- Tuning range: 275.5 - 279.6 GHz
- Output power = -30 dBm at 277 GHz
- DC power = 132 mW
410 GHz RFCMOS Push-Push VCO

- Univ. of Florida
- 45 nm RFCMOS
- Output power = -47 dBm at 410 GHz
- DC power = 16.5 mW

Seok et al ISSCC 2008
Accumulated Performance: Oscillators (I)

Partially adopted from Wanner et al IMS 2007
Accumulated Performance: Oscillators (II)

Partially adopted from Wanner et al IMS 2007
220 GHz MHEMT Active Mixer

- Chalmers University
- 0.1 um GaAs MHEMT
- Conversion loss = ~12 dB for resistive mixer mode
- Conversion loss = ~8 dB for drain mixer mode

Gunnarsson et al MWCL 2008
Accumulated Performance: Active Mixers

![Graph showing conversion loss vs. RF frequency]
Summary

• Current status of semiconductor technologies
  – III-V HBT: $f_T \sim 785$ GHz
  – III-V HEMT: $f_T \sim 610$ GHz
  – SiGe HBT: $f_T \sim 375$ GHz
  – RFCMOS: $f_T \sim 485$ GHz

• Current status of circuits
  – Amplifiers: up to 345 GHz (15 dB gain)
  – Oscillators: up to 410 GHz for push-push, 346 GHz for fundamental
  – Active mixers: up to $\sim 220$ GHz with conversion loss $\sim 8$ dB

→ Transistor-based THz front-end highly promising