mm-Wave Sensor and Communications Components at 60, 94, and 122 GHz in SiGe BiCMOS Technology

Workshop on “Wireless Multi-Gigabit-Systems”, Center for Informatics and Information Technology, TU Braunschweig, July 2st 2009

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Outline

• Silicon technology progress and mm-wave design

• 1 Gbps 60 GHz transceiver (WIGWAM, BMBF)

• 2 – 6 Gbps 60 GHz transceiver (Easy-A, BMBF)

• 94 and 122 GHz components for mm-wave sensing (ISM, ZIM)

• Towards 100 Gbps Wireless Short-Range Communications (TeraCom, Leibniz Excellence Project)
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Silicon Technologies for Wireless & Broadband

- Advanced silicon (SiGe, CMOS) technologies feature:
  - $f_T, f_{\text{max}}$ up to 200 ... 350 GHz,
  - $\text{NF}_{\text{min}} < 0.5 \text{ dB@1GHz}$,
  - $\text{NF}_{\text{min}} \sim 8 \text{ dB@100GHz}$

  Operating frequencies up to >100 GHz
  Digital & RF integration
  Simplified packaging
  Low die cost (< 0.2 USD / mm$^2$)

⇒ Low-cost, reliable, high-frequency & broadband systems
Silicon technology progress and mm-wave design

Johnson Limit

\[ \frac{E_{\text{max}} v_{\text{sat}}}{2\pi} = BV \times f_T = \text{const.} \]

- The product of transistor break voltage and \( f_T \) is constant
- It depends only on the semiconductor material (Si, SiGe, GaAs, InP)

⇒ Faster semiconductor technologies give higher RF gain but lower maximum PA power!

1 “Physical limitations on frequency and power parameters of transistors”, E. O. Johnson, RCA Review, June 1965; 163-177
Silicon technology progress and mm-wave design

**Link Budget Considerations**

- Free space loss is proportional to $1/f^2$
- From Johnson limit we could conclude that max. $P_{TX} \sim 1/f^2$

- Link budget

$$P_{RX} = P_{TX} G_{TX} G_{RX} \left( \frac{\lambda}{4\pi R} \right)^2$$

*RX power proportional to $\sim 1/f^4$!*  
*for given antenna gain, range, and Johnson limit.*

There are some good physical reasons for the THz gap!
What About the Receiver NF?

- \( \text{NF}_{\text{min}} \): Minimum achievable amplifier noise figure

\[
\text{NF}_{\text{min}} \approx 1 + \frac{1}{\beta} + \sqrt{2g_m r_b} \sqrt{\frac{1}{\beta} + \left(\frac{f}{f_T}\right)^2}
\]

- A mm-wave LNA can be designed at roughly NFmin + 2 dB

\textit{The receiver NF benefits from scaling.}
Silicon technology progress and mm-wave design

Preliminary Conclusions and Remarks

• Semiconductor technology scaling allows us to have gain $> 1$ at ever higher frequencies

• Due to Johnson limit and free space path loss received power is reduced by $1/f^4$

• There are some good news, too: Johnson limit is increasing (at least for SiGe)
  Beam-forming
  mm-wave short-range communication and sensing applications
  …
Comparison of mm-Wave SiGe Production Technologies

IHP „workhorse“ for mmWave / 60 GHz

<table>
<thead>
<tr>
<th>Feature</th>
<th>IHP SG25H1</th>
<th>IHP SG13</th>
<th>ST BiCMOS9MW</th>
<th>IBM 8HP</th>
<th>Jazz SBC18HX</th>
<th>Infineon B7HF200</th>
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<tbody>
<tr>
<td>Feature size</td>
<td>0.25 µm</td>
<td>0.13 µm</td>
<td>0.12 µm</td>
<td>0.13 µm</td>
<td>0.18 µm</td>
<td>0.35 µm</td>
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<tr>
<td>Trench Isolation</td>
<td>Shallow</td>
<td>Shallow</td>
<td>Deep</td>
<td>Deep</td>
<td>Deep</td>
<td>Deep</td>
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<tr>
<td>MIMs</td>
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<td>yes</td>
<td>yes</td>
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<td>yes</td>
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<td>Cu</td>
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<td>Cu</td>
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<td>200</td>
<td>500</td>
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<td>N.A.</td>
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<td>npn fT</td>
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<td>npn BVCE0</td>
<td>1.9 V</td>
<td>1.7 V</td>
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<td>2.2 V</td>
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<tr>
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<td>N.A.</td>
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1 N.A. = not available (published) parameter
## Comparison of mm-Wave SiGe Production Technologies

New, 1st designs in 2008/2009, for >100 GHz

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Why 60 GHz for Gbps communication?

- 3.5 to 7 GHz bandwidth world-wide => exceptionally high BW
- 40 dBm EIRP allowed in most regions => sufficient range
- Largely unused to date => low interference probability
- 60 GHz does not penetrate walls => security

60 GHz well suited for short-range (1…10 m) wireless communication
60 GHz Applications

- Standardization activities in IEEE 802.15, 802.11 & ECMA
- Applications
  - media streaming
  - data synchronisation
  - Wireless networking

Entertainment in aircrafts, buses, trains, cars

Unlicensed PtP microwave links
WIGWAM Project, Targets of IHP

- RF at 60 GHz
- Target data rate 1 Gbps
- 14*500 MHz channel scheme for realistic multi-user operation
- Eff. Channel BW ~400 MHz
- SiGe Frontend
- OFDM BB and Gbps MAC (FPGA)
60 GHz System

Wigwam System Demonstrator

60-GHz analog front-end
- 60-GHz RF Tx
- IF I/Q mod.
- 60-GHz RF Rx
- IF I/Q demod.

Digital baseband processor
- I/Q DAC
- OFDM Tx FPGA
- I/Q ADC
- OFDM Rx FPGA

MAC processor
- MAC FPGA (hardware accelerator)
- 32-bit MAC processor
- RAM + Flash
RF Frontend Architecture

- Super-Heterodyne
- IF at 5 GHz, LO at 56 GHz
- Image at 51 GHz (TX & RX)
60 GHz 1 Gbps RX

60 GHz RX IC¹

die area = 1.6 mm²

Prototype PCB w. integrated antenna

RX Figures

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>LNA Gain</td>
<td>18 dB</td>
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<tr>
<td>LNA NF</td>
<td>6.8 dB</td>
</tr>
<tr>
<td>56 GHz PLL PN</td>
<td>-90 dBC @ 1 MHz</td>
</tr>
<tr>
<td>RX 1dB CP</td>
<td>-5 dBm</td>
</tr>
<tr>
<td>RX NF</td>
<td>7.3 dB</td>
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<tr>
<td>RX Power</td>
<td>736 mW</td>
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</table>

56 GHz PLL IC

PLL Figures

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Phase noise</td>
<td>-90 dBc/Hz @ 1 MHz</td>
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<tr>
<td>BW</td>
<td>4.5 MHz</td>
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<tr>
<td>XTAL Freq.</td>
<td>109 MHz</td>
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<tr>
<td>PLL type</td>
<td>4th order, CP / passive LF</td>
</tr>
<tr>
<td>Power diss.</td>
<td>600 mW</td>
</tr>
</tbody>
</table>

“A Fully Integrated BiCMOS PLL for 60 GHz Wireless Applications“ W. Winkler, J. Borngräber, B. Heinemann, F. Herzel, ISSCC 2005

And: „60 GHz Transceiver System Design“ Y. Sun, Proc. of the European Microwave Week, 2007;
60 GHz PA w. Image Rejection

- PA is very critical component in 60 GHz WLAN
  - linear output power (P1dB)
  - gain vs. stability
- $BV_{CBO}$ limits saturated and lin. output power (P1dB)
  - => critical for OFDM
- Passives & substrate coupling endanger stability

Results:
- Fully diff. design
- Power gain: 20 ... 33 dB
- Psat: 19 dBm
- P1dB: 13.5 ... 17.2 dBm
- PAE: 9 ... 10%
- Power: 600 ... 800 mW
60 GHz PA w. Image Rejection

S. Glisic, C. Scheytt: „A 17 dBm 1dBCP Selective High-Gain PA for 60 GHz Applications in SiGe” BCTM 2008, Monterey

Highest P1dB w. SiGe reported so far (!)
60 GHz 1 Gbps TX w. PA and Image Reception Filter

**60 GHz Transmitter w. integrated PA and IR filter**

- **Mixer**
- **Preamplifier**
- **Image-rejection Filter**
- **Power Amplifier**

5GHz Input → Mixer → Preamplifier → Image-rejection Filter → Power Amplifier → 60GHz Output

**TX Figures**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
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<tbody>
<tr>
<td>Gain</td>
<td>40 dB</td>
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<tr>
<td>P1dB (single-ended)</td>
<td>10.5 dB</td>
</tr>
<tr>
<td>Psat (single-ended)</td>
<td>14.9 dBm</td>
</tr>
<tr>
<td>Image Rejection</td>
<td>better -40 dB @ 51 GHz</td>
</tr>
<tr>
<td>Power diss.</td>
<td>1.15 W</td>
</tr>
</tbody>
</table>

**Prototype PCB w. antenna**

- **1.8 x 1.4 mm²**

S. Glisic, C. Scheytt: „A Fully Integrated 60 GHz Transmitter Front-End with a PLL, an Image-rejection Filter and a PA in SiGe, ESSCIRC 2008, Edinburgh
60 GHz Transceiver in LTCC Package

- Package designed and fabricated by IMST and TU Ilmenau
- Integrated cavity antenna on backside
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Easy-A Project

- BMBF project
- 15 partners, 5 subcontractors, coordinated by IHP

- Two systems targeted
  - **VHR-E**: 2 to 6 Gbps data rate, up to 10m range (IEEE 802.15.3c)
  - **UHR-C**: Up to 10 Gbps, 1 m range

- Channel allocation for VHR-E:
  - 4 bands with each having BW of 2 GHz

---

![Diagram](image-url)
Easy-A RF Frontend Architecture

- 2 GHz BW -> higher IF required
- Sliding-IF transceiver (Atheros’ solution for 802.11a) chosen
- 48 GHz PLL, 12 GHz IF
- Image at 60GHz-24GHz = 36GHz is well suppressed by LNA / PA
- 1:4 division delivers accurate quadrature signals at 12GHz

Funded by BMBF
15 Partners, 5 Subcontractors
Start: 1.1.2008
Co-ordinated by IHP
Easy-A 48 GHz Synthesizer

- Fully-integrated PLL, tunable from 47.2 to 49.6 GHz
- Coarse and fine-tuning loop => reduced VCO input noise
- Novel resistive biasing => PLL dynamics invariant to tuning
- PN at 48 GHz: -98 dBc/Hz @ 1 MHz
- PN exceeds requirements for 16QAM OFDM mode in 802.15.3c

“A Fully Integrated 48-GHz Low-Noise PLL with a Constant Loop Bandwidth”,
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94 GHz LNA

Gain: 16.2 dB
NF: 10.6 dB
P1dB: -1 dB
Supply Volt.: 3.5 V
Pdiss: 61 mW
Technology: SG25H1

"94 GHz Amplifier in SiGe:C BiCMOS Technology", Wolfgang Winkler, Johannes Borngräber, Falk Korndörfer, Christoph Scheytt, European Microwave Week 2008
122 GHz Receiver in SiGe BiCMOS

122 GHz Radar Receiver in SiGe BiCMOS

- ISM band at 122.5 GHz w. BW of 1 GHz
- Radar-based distance, angle, speed, sensing
- Low-cost solutions in BiCMOS / CMOS possible with mm-Wave SoC approach
- Low-cost packaging
- Antenna in package

- Applications:
  - Commercial sensors (buildings, safety) (replacement of ultra-sonic, laser-based devices)
  - Industrial sensors (material characterisation, safety)
  - Security applications (body scanners)

Example of mm-wave package for 77 GHz radar (Source: HS Ulm)
122 GHz LNA in SiGe BiCMOS

122 GHz LNA\(^1\)

Transistor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter Area</td>
<td>0.17 x 0.53 μm</td>
</tr>
<tr>
<td>Peak f\text{max}</td>
<td>255 GHz</td>
</tr>
<tr>
<td>Peak f\text{T}</td>
<td>315 GHz</td>
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<tr>
<td>BV\text{CBO}</td>
<td>1.8 V</td>
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<tr>
<td>BV\text{CEO}</td>
<td>5.6</td>
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<tr>
<td>β</td>
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\(^1\)“122 GHz LNA in SiGe Technology“, Wolfgang Winkler et al., accepted at ESSCIRC 2009
### 122 GHz LNA Measurement Results

#### Performance Summary

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<th>Parameter</th>
<th>Value</th>
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<td>13.5 dB @ 122 GHz</td>
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<tr>
<td>NF</td>
<td>9.6 dB @ 122 GHz</td>
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<tr>
<td>Supply Volt.</td>
<td>3.5 V</td>
</tr>
<tr>
<td>ICC</td>
<td>15 mA</td>
</tr>
</tbody>
</table>

#### Graphs

**Gain vs. Frequency**
- **m1**
  - freq = 122.0 Hz
  - LNA120GHz_27..Gain = 13.500

**NF vs. Frequency**
- **m2**
  - freq = 122.0 Hz
  - LNA120GHz_27..corrNoise = 9.590
122 GHz Receiver in SiGe BiCMOS

122 GHz Receiver

- 122 GHz LNA
- Subharmonic mixer with poly-phase filter
- 60 GHz oscillator with integrated frequency divider
- Interstage coupling w. transformers

1“122 GHz Receiver in SiGe Technology”, K.Schmalz et al., accepted at IEEE BCTM 2009
122 GHz Receiver in SiGe BiCMOS

- Optimum operating frequency 127 GHz -> needs some tweaking due to VCO frequency and optimum matching between LO and mixer shifted to higher frequency
- Future work: RX redesign and TX design
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Wireless Short Range Roadmap

- Flash (NVM) scaling exponentially
- NVM is driver for mobile wireless short links
- Wireless short range data rates have to increase exponentially\(^1\) (!)
- Technical solution for 100 Gbps and ~1m needed by 2015

\(^1\) Flash read/write time bottleneck has to be overcome
**How Far Can We Get at 60 GHz?**

- 5 GHz of BW at 60 GHz will be good for ~10 Gbps (single-user)

- Higher data rates?
  
  => 60 GHz MIMO could be solution

  => Or go to higher frequencies / higher BW beyond 100 GHz

### Table: Modulation Formats and Data Rates

<table>
<thead>
<tr>
<th>Modulation Format</th>
<th>Spectral Efficiency [b/(s×Hz)]</th>
<th>FEC Code Rate</th>
<th>Bandwidth [GHz]</th>
<th>Decoded Data Rate [Gbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>2</td>
<td>0.75</td>
<td>5</td>
<td>7.5</td>
</tr>
<tr>
<td>8-PSK</td>
<td>3</td>
<td>0.75</td>
<td>5</td>
<td>11.3</td>
</tr>
<tr>
<td>16-QAM</td>
<td>4</td>
<td>0.75</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>64-QAM</td>
<td>6</td>
<td>0.75</td>
<td>5</td>
<td>22.5</td>
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### Spectral Efficiency for 50 to 100 Gbps Wireless

Using frequency band beyond 250 GHz for 100 Gbps ...

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<tr>
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<td>1</td>
<td>0,75</td>
<td>25 / 48</td>
<td>18.75 / 36</td>
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<td>75 / 144</td>
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... still spectral efficiency of > 3 ... 4 bits/s/Hz is needed.
ITRS $f_T$, $f_{\text{max}}$ Roadmap on SiGe HBTs

"Manufacturing solutions are NOT known"

"Manufacturing solutions are known"
DOTFIVE Project

- Partners: ST, Infineon, IHP, IMEC
- Target: SiGe technology with fmax of 500 GHz
- With DOTFIVE European companies and institutes are trying to get ahead of ITRS roadmap
SiGe HBT Critical Parameters for mm-Wave Design

- Johnson law ($BV_{CEO} \cdot f_T = \text{const.}$) not valid anymore!
- New interpretation needed.
$f_T$, $f_{\text{max}}$ vs. Operating Frequency

- Results beyond 60 GHz in 250 GHz SiGe Technology (IHP SG25H1):
  - 122 GHz RX Frontend w. NF 11 dB, gain >15 dB
  - 100 to 200 GHz fundamental frequency VCOs
  - 95 GHz Frequency Divider
  
  ⇒ RF Components demonstrated at >$f_{\text{max}}$/2

- 60 (and 77 GHz) Frontends implemented in SG25H1
  
  ⇒ Mature RF frontends demonstrated at $f_{\text{max}}$/3

- IHP & partners working towards 500 GHz SiGe HBT in DOTFIVE
- SiGe HBT $f_T$, $f_{\text{max}}$ performance of > 800, 1000 GHz predicted$^1$

250 to 300 GHz SiGe Frontend will be feasible!

$^1$ Y. Shi and Goufu Niu, “2-D Analysis of Device Parasitics for 800/1000 GHz $f_T$/f_{\text{max}}$ SiGe HBT”, in Proceedings BCTM, pp. 252-255, 2005
Challenges for 100 Gbps Wireless Communications

- Semiconductor technology challenges
  - 500 GHz HBTs & process integration
  - Breakdown-voltage optimization

- RF / analog design challenges
  - Component / Frontend design
  - Beam-forming
  - ADC, DAC
  - Mixed-signal processing

- System design challenges
  - Baseband complexity, power diss.
  - ADC, DAC, BW, ENOB, clock jitter
  - Novel modulation schemes
  - MAC issues

- Packaging challenges
  - Low-cost
  - Antenna integration
  - Beam forming
  - Chip interfaces
  - BB interfaces / integration

⇒ Concurrent research is required to enable low-cost, highly-integrated, energy-efficient 50-100 Gbps wireless communication devices
Conclusion

• 60 GHz band offers BW for up to 10 Gbps wireless short-range communication or more.

• SiGe BiCMOS (and CMOS) technology very well suited for 60 GHz wireless communication frontends.

• 50 to 100 Gbps wireless short-range communication is driven by NVM capacity and high-resolution media applications

• Beyond 250 GHz abundant BW is available which could be used for wireless short-range communication.

• Silicon technology will enable low-cost single-chip RF frontends for such applications
Acknowledgements

- Thanks to:

  IHP circuit design dept., specifically
  Yaoming Sun, Frank Herzel, Srdjan Glisic, Klaus Schmalz, Chang-Soon Choi, Johannes Borngräber

  IHP system design dept.

  IHP technology dept.

  BMBF for funding of Wigwam / Easy-A project

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  today's audience!