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Abstract: The implementation of circuits at frequencies above 100GHz poses significant challenges. Many circuits have been proposed using either heterogenous bipolar transistors (HBT) or high electron mobility transistors (HEMT) in III-V compound material. However, when price is an issue and large digital circuits are needed, CMOS technologies are preferred but they perform poorly at frequencies well above 100GHz. This presentation describes the capabilities of these technologies and discusses several approaches to reach high power at RF together with large digital circuits.

Purpose: Information for the IG THz

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Semiconductor technologies for THz Communications

Date: 2018-05-07

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Abstract

The implementation of circuits at frequencies above 100GHz poses significant challenges. Many circuits have been proposed using either heterogenous bipolar transistors (HBT) or high electron mobility transistors (HEMT) in III-V compound material. These are performant but specialty expensive implementations.

When price is an issue and large digital circuits are needed, CMOS technologies are preferred. They, however, perform poorly at frequencies well above 100GHz.

This presentation describes the capabilities of these technologies and discusses several approaches to reach high power at RF together with large digital circuits.
Outline

Application needs

The active device scene

Circuits >100GHz implemented in bulk CMOS

Conclusions
Application needs
5G: increasing complexity for the RF front-end
Going to mm-wave

Increasing integration level reduces overall cost, form factor, power:
- combination of power amplifier with its controlling circuitry
- bringing as much as possible into one IC or module (3D integration)
Wireless communication: 5G and beyond

Source: Nokia

• 5G will provide a total solution for a wide range of requirements
  Contains existing sub-6 GHz bands of 4G and new bands at mm-wave up to 90GHz
  Increased back- and fronthauling requirements towards 100s Gb/s

• 6G: wireless data rates > 100 Gb/s
  Carrier frequencies > 100 GHz: optical & wireless communication will meet
  See e.g.
    European projects in ICT-09 cluster: operation > 90 GHz, up to 1Tb/s
    IEEE802.15.3d
Sensing: mm-wave offers several advantages

Radar:
Range resolution = c/(2*bandwidth) → larger bandwidth easier to realize at higher frequencies
Better resolution of velocity and angle with smaller wavelength
Automotive radar 76-81 GHz: maturing market using Si technologies BiCMOS and single-chip CMOS
Future >100 GHz?
Smart home/office/building/city, e-health, ... : numerous applications from sub-10 GHz to >100GHz, potentially large market, pressure on form factor, power consumption

Mm-wave imaging
Spectroscopy

Source: P. de Maagt et al.,
Key requirements for >100GHz implementations

Efficient circuits @ frequency > 100GHz:
- PA: high output power for link budget (range)
- VCO/PLL: low phase noise for good EVM (spectral efficiency)

Highly integrated solution including
- RF
- Digital (digital calibration, PHY processing)
- Memory

Relatively large volumes
Key requirements for >100GHz implementations

Efficient circuits @ frequency > 100GHz:
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Relatively large volumes
The active device scene
Evolution for logic

$f_T$ of Si-based FETs will not increase (much) with further scaling
High-speed applications need fast device with good power handling capabilities ... which can be combined with CMOS

- CMOS cannot do it alone anymore
- $f_T$ of Si-based FETs will not increase (much) with further scaling
- FinFET delivers intrinsically lower speed than planar
- III-V HEMT offers $>500$GHz $f_T$ at relaxed gate length
- GaN similar to planar bulk but stronger driving capabilities
SiGe HBT beating CMOS in speed/power handling

1. Superiority evidenced by published designs

2. Long-term predictions for SiGe

3. SiGe technology developments

SiGe HBT with $f_T/f_{max}$ of 505 GHz/720 GHz


IHP, Frankfurt (Oder), Germany, email: heinemann@ihp-microelectronics.com

4. Maturing results in EU project

Physical and Electrical Performance Limits of High-Speed SiGeC HBTs—Part I: Vertical Scaling

Michael Schröter, Senior Member, IEEE, Gerald Wedel, Bernd Heinemann, Christoph Jungemann, Senior Member, IEEE, Julia Krause, Pascal Chevalier, Member, IEEE, and Alain Chantre, Senior Member, IEEE

cases on the vertically scaled structure. According to isothermal device simulation, the “ultimate” doping profile yields a peak transit frequency $f_T$ of almost 1.5 THz, a $BV_{CEO}$ above 1 V (dependent on BE bias) and a zero-bias internal base sheet resistance of about 3 kΩ/sq. The reasons for achieving a higher product $f_T BV_{CEO} (> 1.5$ THz V) than anticipated from the classical Johnson limit are explained. Finally, it is found that $f_T$ is
GaN and GaAs devices yield high output power and efficiency at high frequencies
The trend continues @ >100GHz

<table>
<thead>
<tr>
<th></th>
<th>Bandgap (eV)</th>
<th>Breakdown field (MV/cm)</th>
<th>Thermal conductivity (W/cm-K)</th>
<th>Johnson FOM (E_{br} \times v_{sat}/2\pi) (10^{12} V/s)</th>
<th>Saturation velocity (10^7\ cm/s)</th>
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<td>0.5</td>
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<tr>
<td>GaAs</td>
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<td>0.5</td>
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<tr>
<td>GaN</td>
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<td>3.5</td>
<td>1.5</td>
<td>8</td>
<td>2.7</td>
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All-silicon versus III-V co-integration

**FinFET → lateral nanowires**
- Best for complex logic
- Speed limited by 3D parasitics
- Poor driving capabilities

**BiCMOS**
- Logic usually lags few generations behind
- Compatible with FD-SOI
  - [ST Microelectronics, BJT + 28nm FD-SOI, BCTM 2016]
- Stronger driving capabilities than FinFET
- Highest $f_T$ of silicon devices
- $f_T > 1$ THz possible at $BV_{CEO} > 1$ V

**III-V**
- Higher $f_T$ than Si possible
- Better power handling
- Growth on 300mm Si complex but feasible

**RF-SOI**
- Higher $f_T$ than FinFET
- Body bias is extra feature
- Allows for device stacking in PAs
- Switches with very low $Ron*Coff$

several research groups in the world are considering co-integration of III-V materials on silicon
Circuits >100GHz implemented in bulk CMOS
140GHz PA in bulk CMOS

- 28 nm HPM
- $V_{DD} = 0.9$ V
- PA area = 0.11 mm$^2$
- PA $P_{dc} = 81$ mW
140GHz FMCW radar in bulk CMOS with on-chip antennas

TX
- EIRP with 2 PA’s active: 9 dBm
- 3 dB Bandwidth: 141 GHz – 156 GHz

RX
- 47 dB programmable Baseband gain
- 3 dB RF Bandwidth: 139.5 GHz – 151.2 GHz
- 3 dB baseband Bandwidth: 750 kHz – 18 MHz
Conclusions
Conclusions

• Need for high(er) speed and high power at a small factor
  Higher degree of integration, packaging challenges
• Scaling roadmap slowing down, CMOS not going faster anymore
• Will market embrace other devices co-integrated with CMOS?
  Or will design tricks in CMOS and digital compensation techniques rule out non-CMOS?
  Which device will win? SiGe HBT, III-V HBT, HEMT, MOSFET, ...?
  300 mm wafers are a must
  Affordable?
References for slide 13

2. Dae-Hyun Kim et al., “fT = 688 GHz and fmax = 800 GHz in Lg = 40 nm In0.7Ga0.3As MHEMTs with gm_max > 2.7 mS/μm”, IEDM Tech. Digest, pp. 319-322, 2011.
5. S.-J. Yeon et al., “610 GHz InAlAs/In0.75GaAs Metamorphic HEMTs with an Ultra-Short 15-mm-Gate”, IEDM Tech. Digest, pp. 48-51, 2007.
What are III-V semiconductors?

Typical III-V compounds:
- Ga-As
- Al-Ga-As
- Ga-N
- Al-Ga-N
- In-P

[Source: sciencenotes.org]