mm-Wave Silicon Transistor and Benchmark

Circuit Scaling Through the 2030 ITRS Horizon

S.P. Voinigescu, S. Shopov, P. Chevalier*, J. Bateman, H. Farooq, A. Ye, Y. Xu, K. Vasilakopoulos, and M. Dadash

University of Toronto

*) STMicroelectronics, Crolles, France
Agenda

- Applications of mm-wave silicon technology
- HF Performance of State-of-the-Art Si Technology
- SiGe HBT Device and Circuit Scaling
- MOSFET scaling to 2nm
- Conclusions
Applications of mm-wave technology

- Tb/s wireless and fiberoptic ICs

http://www.digitaljournal.com/pr/2557832

- mm-wave and THz active sensors

mm-Wave Sensor and Tag Applications

- Autonomous cars
- Autonomous robots
- Autonomous drones
- Autonomous lawn-mower
- Autonomous snow-blower?

IEEE Spectrum
Why mm-wave sensors?

- Work in hostile and poor visibility environments where optical sensors fail
  - smoke, toxic gases, fire
  - night, fog, rain, heavy snow, mud
- Higher resolution (compared to cellular/WiFi)
  - < 5mm
- Can penetrate through clothes, wood, low-water content materials
150-GHz monostatic single-chip sensor with BIST

2.6mmx2.3mm

890 mW. 1.8/1.2V

130nm SiGe BiCMOS 230/280GHz

[I. Sarkas et al. CSICS 2012]
13-15 dB gain, 23 dB of gain control in LNA

Low noise figure: 8.5-10.5dB
Transmitter gain/Pout control

- TX output power states measured *without* external mm-wave equipment
65-GHz multi-channel range sensor

- 2-IQ receivers with differential transmitter
- 55-nm SiGe BiCMOS $f_T = 320$ GHz, $f_{\text{MAX}} = 350$ GHz
- 1.1/1.2/1.8V supplies, 24 mW
Mm-Wave Active Tag

- Reflect signal from base station back to base station with ID
- Link budget similar to radar

Requirements
- Low-power, ideally self-sufficient
- Very small form factor
- Long range operation (d > few meters)
mm-Wave active tag

- Frequency: 77-81 GHz
- $G > 30$ dB
- $NF < 7$ dB
- $S_i < -62$ dBm
- $P_D < 5$ mW
- Range > 10m when polled by +10dBm base station
- Wake-up detector
- 55nm SiGe BiCMOS
- Funded by Robert Bosch GmbH.
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28nm FDSOI Technology Cross-section

• Unlike CMOS and FinFET processes, the body is floating
• Can control $V_T$, $I_{ON}$, as well as, the $f_T$ and $f_{MAX}$ characteristics
$V_T$ linearly dependent on back gate bias
$f_T$, $f_{\text{MAX}}$ vs. $V_{\text{GS}}$, $V_{\text{BG}}$ Measurements

V$_{\text{BGN}}$ and -V$_{\text{BGP}}$ are swept from -0.5V to 6V
$f_T$, $f_{\text{MAX}}$ vs. $I_{DS}$

- **n-MOSFET**
- **p-MOSFET**

$V_{\text{BGN}}$ and $-V_{\text{BGP}}$ are swept from -0.5V to 6V.
On-die Measurements: SiGe HBT MAG

- 0.1x4.5um HBTHS122 wafer 5, fast

\[ V_{CB} = 0.5V \]
On-die Measurements: SiGe HBT U, H$_{21}$
BiCMOS55/28nm FDSOI: $f_t$

M. Schroeter et al. SiRF 2014
BiCMOS55/28nm FDSOI: $f_{\text{MAX}}$
SiGe HBT & n-MOSFET MAG: J-Band

MAXIMUM AVAILABLE GAIN (dB)

FREQUENCY (GHz)
Cascodes and Series Stacking

S. Pornpromlikit et al, JSSC 2010

I. Sarkas et al, ISSC 2012
BiCMOS55 Cascode MAG

![Graph showing the maximum available gain (dB) vs. frequency (GHz) for different cascode configurations. The graph includes data for HBT-HBT cascode, SG nMOSFET-HBT cascode, and SiGe HBT with $V_{CB}=0.5\text{V}$. The voltage $V_{DD}=2.5\text{V}$.](image)
4 n-MOS Series-Stacked 45nm SOI Cascode MAG

128x45nmx1.25um

MAG

S_{21}

Frequency (GHz)

0  25  50  75  100  125  150  175  200

MAG Meas.
MAG Sim.
S_{21} Meas.
S_{21} Sim.

[Balteanu et al, JSSC Oct.2014]
138GHz Power DAC in 45nm SOI

[S. Shopov, CSICS 2014]
Output Power vs. Input Power at D-Band

The graph shows the relationship between output power (in dBm) and input power (in dBm) at D-Band. Various curves represent different frequencies, with markers indicating specific values for each curve.
3x40Gb/s SiPh Transceiver Array in 28nm FDSOI

[S. Shopov, ESSCIRC 2015]
Transmitter: Output Eye Diagrams

4.0V_{pp} \text{ at } 40 \text{ Gb/s}
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SiGe HBT Scaling: $f_T$, $f_{\text{MAX}}$

M. Schroeter et al. SiRF 2014

1D

2D with parasitics
SiGe HBT Scaling: $NF_{\text{MIN}}$, MAG

M. Schroeter et al. SiRF 2014

$NF_{\text{MIN}}$ @ 60 GHz
Noise Correlation
SiGe HBT PA & VCO Scaling

M. Schroeter et al. SiRF 2014
S21 meas
S21 sim
S11 meas
S11 sim
S22 meas
S22 sim
NF sim
NF meas

BW_{3dB} = 93GHz
NF<5.5dB

[K. Vasilakopoulos, Submitted to BCTM 2015]
SiGe HBT TIA in Node 5

- $S_{21}$
- $NF_{50}$
- $NF_{MIN}$

FREQUENCY (GHz)

$S_{21}$, $NF_{50}$, $NF_{MIN}$ (dB)
SiGe HBT 220GHz PA in Node 5

\[
\text{PAE} \quad \text{P_{OUT}}
\]

\[
P_{\text{IN}} \quad (\text{dBm})
\]

\[
P_{\text{OUT}} \quad (\text{dBm})
\]
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Atomic Scale FETs: 2030 Time Horizon

- Traditional semiconductor channel
- CNT
- Graphene
- Metal channel
- 3x3(4x4) atoms channel

- Classical simulation with Sentaurus
- Atomic level simulations using Atomistix from QuantumWise
Double-gate Si MOSFET scaling simulation

Sentaurus Models

Parameters:
- Un-doped Channel
- S/D Dopant Charge = $5 \cdot 10^{20} cm^{-3}$
- $t_{ox} = 1 nm$, $\kappa = 25$
- $t_{Si} = 0.6 nm$
- $L_G = 3.5 nm$
Ideal $I_{on}$, $g'_m$, $f_T$ scaling from 28nm to 2nm

Sentaurus simulation
Impact of Contact Region Resistance

- 5nm p-MOSFET, Sentaurus simulation
Ultra-Scaled GAA SiNW-FET Model

Parameters:
- 384 atoms H-terminated Si
- Un-doped Channel
- S/D Dopant Charge = $4.6 \cdot 10^{20} \text{cm}^{-3}$
- Equivalent to $HfO_2$ with $t_{ox} = 2\text{nm}$, $\kappa = 25$.
  (Model uses $t_{ox} = 0.35\text{nm}$, $\kappa = 4.375$)
- Calculators: DFT GGA.PBE, NEGF

Cross-section

Side:

Source | Gate | Drain

$1.08\text{nm}$ $1.5\text{nm}$ $L_G = 3.5\text{nm}$ $1.5\text{nm}$ $1.08\text{nm}$

Total Length = $8.69\text{nm}$
Comparison: Subthreshold Characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sentaurus</th>
<th>Atomistix</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDS (V)</td>
<td>0.005</td>
<td>0.2</td>
</tr>
<tr>
<td>SS (mV/dec)</td>
<td>62.1</td>
<td>61.5</td>
</tr>
<tr>
<td>ION/IOFF</td>
<td>(\sim 5 \cdot 10^{-9})</td>
<td>(\sim 5 \cdot 10^{-9})</td>
</tr>
</tbody>
</table>

Parameters:
- Un-doped Channel
- S/D Dopant Charge = \(5 \cdot 10^{20} \text{ cm}^{-3}\)
- \(t_{ox} = 1 \text{ nm}, \kappa = 25\)
- \(t_{Si} = 0.6 \text{ nm}\)
- \(L_G = 3.5 \text{ nm}\)
Metallic Channels

3nm long channels
Conclusions

- State-of-the-art SiGe BiCMOS and 28nm FDSOI have both $f_T$ and $f_{MAX}$ > 325 GHz
- SiGe HBT circuit performance continues to scale
- Atomistix shows MOSFET theoretically scalable to 2nm
- CMOS performance scaling uncertain due to quantum effects
  - Ballistic transport
  - Bandgap increase
  - Surface scattering
- $Q$ of passives critical for low-power mm-wave IoT circuits
Acknowledgments

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- Bernard Sautreuil and Andreia Cathelin (ST)
- Jaro Pristupa and CMC for CAD and support
- Integrant for EMX software
145-GHz Transceiver die: VCO range

- 143-152 GHz tuning range
- PN = -103 dBc/Hz @ 10 MHz
- \( P_{DC} = 72 \) mW

Coarse = 1.4V
Coarse = 0.8V
Coarse = 0V