5G Enhanced Mobile Broadband Radio interface on mmWave – Hardware Architecture and role of Silicon Technologies

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Outline

1. Introduction to 5G
2. mmWave 5G Radio Access Technology Overview
3. mmWave 5G Radio Interface Architecture
4. Differentiated Silicon Technologies for mmWave 5G
5. Summary & references
What is 5G?

5G is the next Generation cellular standard to support faster data rate, lower latency & more number of connected devices.
5G is a superset in terms of usage scenarios, not backward compatible with 4G.

**5G Usage Scenario**

- **eMBB**: enhanced Mobile BroadBand
  - > 10Gb/s peak rate
  - 100 Mb/s whenever needed
  - 10000x data traffic
  - < 1ms latency
  - Ultra low cost
  - Ultra reliability
  - 10-100x devices
  - 10 years of battery

- **uRLLC**: Ultra Reliable Low Latency Communication
  - Remote operation
  - Smart grid
  - ITS
  - Factory automation

- **mMTC**: massive Machine Type Communication
  - Connected city/home
  - Smart logistics
  - Smart sensors

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*5G is a superset in terms of usage scenarios, not backward compatible with 4G*
Do we really need 5G?

Key Problems faced by current 4G connections

- Cell edge coverage
- Peak & average data rate / throughput

Concept of always being connected remains a myth

“I got so fed up with dropped calls and no service, I bought my own cell tower and take it where ever I go.”

Source: IWPC presentation, 2017

Data traffic density and higher data rate demand will always be on the rise
## 4G Frequency Bands

<table>
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<th>E-UTRA Band</th>
<th>Duplex Mode</th>
<th>f (MHz)</th>
<th>Common name</th>
<th>Included in (sub-set) Band</th>
<th>Uplink (MHz) BS receive UE transmit</th>
<th>Downlink (MHz) BS transmit UE receive</th>
<th>Duplex spacing (MHz)</th>
<th>Channel bandwidths (MHz)</th>
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<td>900</td>
<td>IMT</td>
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<td>1920 - 1880</td>
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<td>Lower PDC</td>
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<td>Japan upper 800</td>
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<td>3500</td>
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<td>1503.0 - 1519</td>
<td>80</td>
<td>5, 10</td>
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Bands are very fragmented with passband 20-200 MHz allocated among many carriers. Max Channel Bandwidth 20MHz.
Further enhancement in capacity/peak data rate needs larger channel BW and/or higher Spectral Efficiency

How good 4G can be?
- Max. 20MHz Channel BW
- Carrier Aggregation (2X – 5X)
  - Downlink 100MHz (5 x 20MHz)
  - Uplink 40MHz (2 x 20MHz)
- Higher Modulation level (16 QAM → 256QAM)
- Multiple Input Multiple Output (MIMO) Antenna
- Downlink up to 256 QAM, 4x4 MIMO
  - Theoretical max data rate ~2 Gb/s (using 5X CA, 256 QAM & 4x4 MIMO)
- Uplink up to 64 QAM, 2x2 MIMO

Network Capacity Improvement

Larger Channel Bandwidth \times\text{Higher Spectral Efficiency} = \text{Higher Capacity/Higher Peak Speeds}
5G will have both sub 6GHz & mmWave Bands

Enhanced Mobile Broadband

Sub 6 GHz 5G

4x4 DL MIMO

Conventional + mMIMO BTS

mmWave 5G

mMIMO + Phased Arrays BTS

New Bands + Re-farmed 4G Bands

FR1 Sub 6GHz & FR2 24 – 52 GHz defined so far (3GPP Rel 15)

Rel 16 will define bands > 52GHz
Why mmWave?

- **Contiguous Spectrum availability**
  - much more than sub 6GHz
  - Higher Channel bandwidth (defined up to 400MHz, can be more) and hence data rate

- **High frequency / small wavelength**
  - Smaller antenna, makes large arrays possible
  - Highly directive beam enables spatial multiplexing (spectral efficiency)
  - Less interference and more efficient use of Tx/Rx power

- **High link loss**
  - Atmospheric, Rain, foliage, building material absorption
  - Distance between Access point & User Equipment (UE) has to be small (<100-200m)
5G mmWave Spectrum Candidates

The 24.25-29.5 & 37.0-43.5 GHz are the most promising high frequency ranges for 5G early commercialization globally.

Source: GSA, June, 2018
By locking each beam to an UE, a spatial multiplexing is achieved to increase Spectral efficiency and improve Signal-to-Interference Ratio.
mmWave enables excellent spatial selectivity and hence high spectral efficiency & low interference.
Capacity Improvement using mmWave 5G

Channel BW 50-400MHz (4G max. 100MHz using 5X CA)

Spatial Multiplexing using Beamforming (8-16 Beams)
(4G 4x4 MIMO provides 4 data streams)

At least 5-10X of 4G ~10-20Gb/s

Might use lesser order Modulation to start with (64QAM instead of 4G 256QAM)
mmWave-based enhanced mobile broadband in UE will be widespread during phase 2 of 5G launch.
Current Cellular Radio Interface Architecture

• Today’s most high tier LTE handsets have LNA’s in RFFE to increase Rx sensitivity
• Transceiver is a single-chip solution currently most system on 28nm, QTI has 14FF based transceiver for higher CAT (16+) 4G handsets
• CAT 16+ 4G (and sub 6GHz 5G) Handsets will need many LO generators to support 4x4 MIMO, high order CA

Source: based on block diagram from http://www.anandtech.com/show/6541/
Different Beamforming Architectures

**Analog Beamforming**
- Smallest # components
- Lowest power dissipation
- Complexity in phase shifting
- Interference rejection (signal synthesized in power combiner before mixer)

**Digital Beamforming**
- Large # components
- Higher power dissipation
- Rx chains see spatial interference (requires high dynamic range)
- Simple to implement

**Hybrid Beamforming**
For large arrays where analog & digital beamforming are inefficient and complex

**EIRP, Rx sensitivity, available form factor, power budget determine array size and beamforming architecture for a particular mmWave application**
Transmission Lines Loss: Distance to Ground Plane

- Transmission line loss increases with frequency
  - Skin effect
  - Eddy current loss in substrate

- Thick Top metals (more than skin depth)
- Ground plane in BEOL prevents fields from entering substrate
- Distance from Ground Plane helps
- Higher substrate resistivity up to a level (~200Ohm-cm) helps

Source: Prof. Gabriel Rebeiz, UCSD on 90nm SiGe
Chip Partitioning for Beamforming (BF)

- For large 2D, linear array or where Transceiver is several cm away from FEM, the mmWave signal should be converted to IF / baseband in the nearest proximity of BF chip to avoid huge loss due to long interconnect.

- In case of monolithic analog BF + Up/down converter, the on-chip interconnect loss is a key parameter.
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EIRP Definition

Equivalent Isotropic Radiated Power (EIRP) is the product of transmitter power and the antenna gain in a given direction relative to an isotropic antenna of a radio transmitter.

It is the power that an isotropic (omnidirectional) antenna would have to transmit to match the directional reception.

Normally the EIRP is given in dBi, or decibels over isotropic.

\[ EIRP = P_T - L_C + G_a \]

Where,

- \( EIRP \) (Effective Isotropic Radiated Power) = Output power of a signal when it is concentrated into a smaller area by the antenna
- \( P_T \) = Output power of the transmitter (dBm)
- \( L_C \) = Cable Loss (dB)
- \( G_a \) = Antenna Gain (dBi)
Technology with better Rx noise figure and higher per element Tx power output will need fewer array elements for a target Rx antenna G/T and Tx antenna EIRP, respectively.

Technology with better FOM ⇒ smaller array ⇒ LOWER COST & AREA

Source: Anokiwave webinar
EIRP Example
IBM/Ericsson 28GHz 64-Element Phased Array in 130nm SiGe (8HP)

Measured saturated EIRP in one polarization = 54dBm
## Silicon Technologies for mmWave 5G Radio Interface

<table>
<thead>
<tr>
<th>Technology</th>
<th>Key Features</th>
<th>Device Cross-Section</th>
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</thead>
</table>
| **RF CMOS**     | • High-volume logic process technology base with multiple foundries  
                    • Comprehensive IP offerings for System-on-Chip (SOC)  
                    • Traction in mmWave markets: WiGig 802.11ad (60GHz), 77GHz auto radar                                                                 |                      |
| **PD-SOI**      | **PD-SOI = Partially Depleted Silicon on Insulator**  
                    • High-speed w/ lower junction capacitance, isolation & stacking  
                    • 180nm RF SOI extensively used in cellular & Wi-Fi FEM  
                    • Early adoption in 5G & Sat Comm for 45nm PDSOI with highest Ft/Fmax & optimum BEOL stack                                           |                      |
| **FD-SOI**      | **FD-SOI = Fully Depleted Silicon-on-Insulator**  
                    • Delivers FinFET-like performance and power-efficiency at 28/22nm cost  
                    • **Transistor body-biasing for flexible trade-off between performance and power**  
                    • Enables applications across mobile, IoT and mmWave markets                       |                      |
| **SiGe**        | **SiGe = Silicon Germanium**  
                    • Based on higher performance & power tolerant HBT (vs FET)  
                    • **Technology optimized for micro and mmWave applications:** backhaul, E-band links, Sat Comm, automotive radar, A&D           |                      |
Bulk, PDSOI & FDSOI FET Devices

-2.0V to +2.0V Body-Biasing

- Depending on thickness above Buried Oxide, Silicon under the Gate can be partially or fully depleted of carriers
- Both PDSOI & FDSOI enable stacking of FET for high voltage (Power) tolerance
Essential Elements for a Silicon Technology for mmWave

• High-performance technology
  - Higher performance enables design flexibility & techniques for a more robust design
  - $f_t / f_{\text{MAX}}$ should be at a minimum 3x and preferably > 5x application frequency
  - RF FOMs (Self Gain, Gain efficiency, $F_t/F_{\text{max}}$, $N_{\text{fmin}}$, 1/f noise) appropriate for target mmWave applications

• Low loss BEOL (metal and dielectric stack)
  - Thick top metal(s)
  - Distance to substrate
  - Substrate resistivity

• Well-modeled (including EM simulation) mmWave technology
  - mmWave model-to-hardware correlation is key to minimize design iterations

• Reliability and Ruggedness
  - Devices and components proven reliable and rugged over the voltage, temperature ranges
- PA Efficiency increases with Input power level
- PA linearity requirement and signal PAPR for the application determine the operating point back off from saturation
- PA Efficiency at operating point matters
45RF SOI BEOL Is Optimized to Provide Benefits for Millimeter Wave Operation

1. Raised thick Cu levels:
   - High Q inductors and transformers
   - Low loss transmission lines
   - High Q MIMs; high density MIMs or APMOMs
   - Dual thick Cu levels provide design flexibility

2. High resistivity trap rich substrate:
   - Improves back-end-of-line (BEOL) losses due to parasitics (~0.8dB reduction in TL IL per mm @ 28 GHz)
   - Reduces harmonics due to trap rich substrate for improved linearity

Increased 'd' to substrate reduces parasitics / coupling

BEOL IL comparison with different substrates
45RFSOI : High Performance mmWave Switches

- RonCoff ~90 fS
- 28 GHz SPDT 3 stack
  - IL 0.76 dB
  - Iso: 23 dB
  - Pmax: 23 dBm
  - One tone IIP3 49.5 dBm
- HR substrate provides improved parasitics over bulk

<table>
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<tr>
<th>Number of</th>
<th>IL @ 28/50 GHz (dB) W/Open</th>
<th>Iso @ 28/50 GHz (dB) W/Open</th>
<th>IP1dB (dBm) at 14 GHz</th>
<th>IIP3 (dBm) at 14 GHz</th>
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<tr>
<td>3</td>
<td>0.76/1.17</td>
<td>23.91/17.06</td>
<td>30</td>
<td>49.5</td>
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<td>4</td>
<td>0.91/1.18</td>
<td>24.14/17.94</td>
<td>32</td>
<td>48.7</td>
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<td>5</td>
<td>0.98/1.13</td>
<td>24.81/19.16</td>
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<td>48.4</td>
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Source: Globalfoundries test results
45RFSOI differentiated silicon results: 23dBm Psat@42% PAEmax

28 GHz LNA/PA/switch silicon results

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<th>PA</th>
<th>PAE at Psat</th>
<th>Psat</th>
<th>Gain</th>
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<td>GF Single ended PA</td>
<td>41.5%</td>
<td>16.2 dBm</td>
<td>13 dB</td>
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<td>Differential PA** (26 GHz)</td>
<td>42%</td>
<td>23 dBm</td>
<td>21 dB</td>
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<tr>
<td>Differential PA** (26 GHz)</td>
<td>37%</td>
<td>22.2 dBm</td>
<td>21 dB</td>
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LNA

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<th>NF</th>
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<td>GF Reference 45RFSOI designs</td>
<td>13 dB</td>
<td>4.3 dBm</td>
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Switch

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<th>Insertion Loss</th>
<th>Isolation</th>
<th>OIP3</th>
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<tr>
<td>GF Reference 45RFSOI designs (RonCoff = 90 fs, 1 V)</td>
<td>0.65 dB</td>
<td>26 dB</td>
</tr>
</tbody>
</table>

** Georgia Tech
22FDX® Technology: Optimized for mmWave SoC

- High $F_{\text{max}}$
  - 1.2X > 28 nm
- High mmWave self gain
  - 2.5x > 28 nm
- Low mmWave noise
  - $\text{NF}_{\text{min}} < 28\text{nm}$
- “mmWave FET stacking” enables single chip mmWave integration
  - Single stage PA
  - $P_{\text{out}}$ >> 28 nm or much smaller die area for same EIRP

Low Power, High Density Logic Integration (Forward & Reverse Body Bias)

- 2V to +2V Body-Biasing
22FDX Enables Lowest Power Consumption for mmWave Applications

For mmWave LNA, mixer circuits, 22FDX has 30% higher performance and 16% lower current than 28nm.

For mmWave PA circuits, 22FDX far outperforms any other CMOS node.

Source: Globalfoundries test results
22FDX® based 5G 28 GHz differential PA

High efficiency, high gain amplification

MPW2217 PA (2-Stack) Schematic

- All designs metal stack #11
- Ruggedness stress tested at VSWR 5:1; Tests ongoing

<table>
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<tr>
<th>Parameters</th>
<th>Measured 1</th>
<th>Measured 2</th>
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<tr>
<td>Stacking</td>
<td>3-Stack PA</td>
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<td>29</td>
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<tr>
<td>IDDQ (mA)</td>
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<td>15.8</td>
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<td>Gain (dB)</td>
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<td>P1dB (dBm)</td>
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<td>Psat/P3dB (dBm)</td>
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<td>S22</td>
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<td>Ruggedness Passed</td>
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<td>15 dBm</td>
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</table>

Source: Globalfoundries test results

PA is the fulcrum around which 5G architecture revolves and 22FDX enables BIC PA performance for Integrated RF SOC
Measured switch & LNA performance on 22FDX®

<table>
<thead>
<tr>
<th>Freq.</th>
<th>28 GHz</th>
<th>40 GHz</th>
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<tbody>
<tr>
<td>S21 (dB)</td>
<td>-0.95</td>
<td>-1.25</td>
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<tr>
<td>S11 (dB)</td>
<td>-13</td>
<td>-11</td>
</tr>
<tr>
<td>S21 (dB) OFF</td>
<td>-25.3</td>
<td>-21.5</td>
</tr>
<tr>
<td>IIP3 (dBm)</td>
<td>45</td>
<td>44</td>
</tr>
</tbody>
</table>

3-stacked switch architecture with power handling up to 23 dBm @ 4:1 VSWR

22FDX® mmWave FETs
- <10 mW power consumption
- NF 2.6 dB @ 28 GHz in 1st generation
- NF <2 dB @ 28 GHz in 2nd gen

5G mmWave switches based on mmWave layouts with increased gate pitch are targeted to have ~ 0.6-0.7 dB insertion loss at 28 GHz and better power handling due to low capacitances

“Beats Best GaAs pHEMT LNAs”
Prof. Gabriel Rebeiz, UCSD

Source: Globalfoundries test results
SiGe HBT Breakdown ($BV_{cbo}$) Saturating at 4 V for $F_t > 500$ GHz

- GF continues to push scaling of SiGe HBTs
- Optimizing vertical (intrinsic) & lateral (extrinsic) profiles allows one to gain $F_t$ – BV margin

Avoids the need for multi-stacking approach used for FETs $\Rightarrow$ improves PAE for PA

Source: GLOBALFOUNDRIES
130nm & 90nm SiGe Technologies - HBT’s offer High $F_t/F_{\text{max}}$ at low power

- SiGe (8XP) offers $F_{\text{max}}$ of 350 GHz; SiGe (9HP) offers $F_{\text{max}}$ of 370 GHz
- CMOS logic supporting thin and thick oxide for 1.2 V / 1.5 V, 1.8 V / 2.5 V / 3.3 V
- Thick top level metals for improved transmission line loss

- **High $F_{\text{max}}$ and breakdown voltage of SiGe makes it an ideal technology for high $P_{\text{sat}}$, Gain, PAE, & linearity of PA with high reliability.**
Paving the way to 5G/mmWave: 45RFSOI & 22FDX®

FEM-Centric Designs: highest performance with architecture flexibility

45RFSOI*
- High Ft/Fmax
- Hi-Res substrate for high power handling (>20 dBm) and low loss
- Low-loss BEOL
- Low density, medium leakage logic

Integration-Centric Designs: low system cost and low SOC power consumption

22FDX
- High Ft/Fmax and high GM/I
- Power handling (< 20 dBm)
- Low-loss BEOL
- Low power and high density logic

SiGe8HP/8XP PA for Psat > 23dBm
Generic architecture: mmWave 5G radio interface for UE—chip partitioning options

Chip partitioning & technology adoption will depend on Tx power, power efficiency, cost and available form factor

Possible chip partitioning options:
- 45RF SOI up to IF
- 14/12/10 nm FinFET
- 45RF SOI up to IF
- 28/22 nm bulk
- 28/22 nm bulk CMOS w/ SiGe/III-V PA & RF SOI switch if needed
- 14/10/7 nm FinFET
- 22FDX®
- 14/10/7 nm FinFET
- 14/10/7 nm FinFET
- 14/10/7 nm FinFET

Example of digital beamforming shown, can be analog beamforming as well.
Chip partitioning option: radio interface for mmWave 5G infrastructure

Technology solution will be determined by TX power, #arrays (system cost) & system power dissipation
### Comparison of 22FDX® and 28 nm for beamforming

**Analysis for 16QAM UL/DL, 100MHz RF BW**

#### Analog Beamforming (ABF) vs. Digital Beamforming (DBF)

- **5G FE**
- **PLL**
- **LO1 (Low-Side Injection)**
- **I/Q BB RX**
- **I/Q BB TX**
- **RF Transceiver**

#### Technology Comparison

<table>
<thead>
<tr>
<th>Technology</th>
<th>28 nm HKM</th>
<th>22 nm FD-SOI</th>
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<tbody>
<tr>
<td>Architecture</td>
<td>ABF, High IF, N=8</td>
<td>ABF, High IF, N=8</td>
</tr>
<tr>
<td>PA Pout (dBm)</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Pdc (mW) (Tx/RX 0.3/0.7)</td>
<td>506</td>
<td>415</td>
</tr>
</tbody>
</table>

All 22 nm FD-SOI power consumption results based on measured results of silicon blocks.

Source: Globalfoundries presentation at IMS 2018 workshop

~20% reduction in power dissipation w.r.t. 28 nm bulk for analog high IF beamforming,

The power advantage of 22FDX is even better for digital beamforming.
We have covered the enhanced Mobile Broadband (eMBB) usage scenario of 5G.

The use of mmWave carrier frequency will enable large channel bandwidth and high spectral efficiency.

The phased array technique to be used for mmWave 5G will enable Silicon technologies to play key roles in mmWave 5G systems.

We highlighted partially depleted (PD) and fully depleted (FD) SOI technologies along with SiGe BiCMOS technologies as differentiated Silicon technology choices for mmWave 5G radio interface.
References

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