

INTERNATIONAL
TECHNOLOGY ROADMAP
FOR
SEMICONDUCTORS
2006 UPDATE

RADIO FREQUENCY
AND ANALOG/MIXED-SIGNAL TECHNOLOGIES
FOR WIRELESS COMMUNICATIONS

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RADIO FREQUENCY AND ANALOG/MIXED-SIGNAL TECHNOLOGIES FOR WIRELESS COMMUNICATIONS

SUMMARY—STATE OF WIRELESS TECHNOLOGIES 2006 - ITRS PERSPECTIVE

Radio frequency (RF) and analog mixed-signal technologies serve the rapidly growing wireless communications market and represent essential and critical technologies for the success of many semiconductor manufacturers. Communications products may replace computers as a key driver of volume manufacturing. Consumer products now account for over half of the demand for semiconductors.¹ For example, third generation (3G) cellular phones now have a much higher semiconductor content and now are 50 % of the cellular phone market compared to only 5 % of the market a few years ago. The consumer portions of wireless communications markets are very sensitive to cost. With different technologies capable of meeting technical requirements, time to market and overall system cost will govern technology selection.

The boundary between silicon-based and III-V semiconductors continues to move to higher frequencies with time. Frequency will be less important for defining the boundaries among technologies and other parameters such as noise figure, output power, power-added efficiency, linearity and ultimately cost will become more important. This shift in importance from frequency to parameters such as those listed in the previous sentence is already occurring for power amplifiers.

For CMOS, the long term prediction of device RF and noise performance becomes more uncertain with the introduction of metal gate electrodes (2009), high permittivity (high- κ) gate dielectrics (2009), and new device structures such as fully depleted and/or double-gated silicon-on-insulator (SOI) (2015). The trend of higher integration and performance levels for logic with mixed-signal circuitry leads to steadily increasing digital processing capabilities that enable more signal treatments to be done in the digital domain.

For bipolar, the key driving forces include speed, power consumption, noise, and breakdown.

For passive devices, the biggest challenges are integrating them into a digital CMOS process and the trade-off between processing cost and device performance.

For power amplifiers—mobile, the nearly fixed battery voltages and ruggedness requirements tend to slow technology evolution. Highly integrated modules with multi-layer laminates are dramatically reducing total RF front end area.

For power amplifiers—basestation, the device cost is projected to steadily decrease from about \$0.70/Watt today to less than \$0.50/Watt by 2008 and the applications space is moving from 2 GHz and below to higher frequencies, such as worldwide interoperability for microwave access (WiMAX) at 3.5 GHz and from saturated power amplifiers to more linear amplifiers to support code division multiple access (CDMA) and wideband CDMA (WCDMA).

For millimeter wave applications, InP-based RF transistors have demonstrated very high frequencies and GaN transistors have demonstrated record power densities at 40 GHz of 10W/mm with 40 Volts drain bias. GaN is advancing much more quickly than predicted in 2003 and 2004.

Future wireless challenges include signal isolation and the software defined radio (SDR). A signal isolation roadmap with quantitative technical requirements is very difficult because agreement on which figures of merit and measurements to use does not exist. The SDR presents many issues such as the analog-to-digital (ADC) performance, transmitter solutions, and cost.

¹ P. H. Singer, "Dramatic Gains in Performance on the Horizon," editorial in Semiconductor International, Vol. 29, No. 8, 29, July 2006, page 15.

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2006 UPDATE TECHNOLOGY REQUIREMENTS TABLES

Table 46a RF and Analog Mixed-Signal CMOS Technology Requirements—Near-term Years

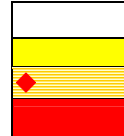
| Year of Production | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|------|------|------|------|------|------|------|------|------|
| DRAM ½ Pitch (nm) (contacted) | 80 | 70 | 65 | 57 | 50 | 45 | 40 | 35 | 32 |
| <i>Performance RF/Analog [1]</i> | | | | | | | | | |
| Supply voltage (V) [2] | 1.2 | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 | 1.1 | 1 | 1 |
| T _{ox} (nm) [2] | 2.2 | 2.1 | 2.0 | 1.9 | 1.6 | 1.5 | 1.4 | 1.4 | 1.3 |
| Gate Length (nm) [2] | 75 | 65 | 53 | 45 | 37 | 32 | 28 | 25 | 22 |
| g _m /g _{ds} at 5·L _{min-digital} [3] | 47 | 40 | 32 | 30 | 30 | 30 | 30 | 30 | 30 |
| 1/f-noise (μV ² ·μm ² /Hz) [4] | 190 | 180 | 160 | 140 | 100 | 90 | 80 | 80 | 70 |
| σ V _{th} matching (mV·μm) [5] | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 |
| I _{ds} (μA/μm) [6] | 19 | 15 | 13 | 11 | 9 | 8 | 7 | 6 | 6 |
| Peak F _t (GHz) [7] | 120 | 140 | 170 | 200 | 240 | 280 | 320 | 360 | 400 |
| Peak F _{max} (GHz) [8] | 200 | 220 | 270 | 310 | 370 | 420 | 480 | 530 | 590 |
| NF _{min} (dB) [9] | 0.33 | 0.3 | 0.25 | 0.22 | 0.2 | <0.2 | <0.2 | <0.2 | <0.2 |
| <i>Precision Analog/RF Driver [1]</i> | | | | | | | | | |
| Supply voltage (V) | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 1.8 | 1.8 | 1.8 | 1.8 |
| T _{ox} (nm) [10] | 5 | 5 | 5 | 5 | 5 | 3 | 3 | 3 | 3 |
| Gate Length (nm) [10] | 250 | 250 | 250 | 250 | 250 | 180 | 180 | 180 | 180 |
| g _m /g _{ds} at 10·L _{min-digital} [11] | 220 | 220 | 220 | 220 | 220 | 160 | 160 | 160 | 160 |
| 1/f Noise (μV ² ·μm ² /Hz) [4] | 500 | 500 | 500 | 500 | 500 | 180 | 180 | 180 | 180 |
| σ V _{th} matching (mV·μm) [5] | 9 | 9 | 9 | 9 | 9 | 6 | 6 | 6 | 6 |
| Peak F _t (GHz) [7] | 40 | 40 | 40 | 40 | 40 | 50 | 50 | 50 | 50 |
| Peak F _{max} (GHz) [8] | 70 | 70 | 70 | 70 | 70 | 90 | 90 | 90 | 90 |

Manufacturable solutions exist, and are being optimized

Manufacturable solutions are known

Interim solutions are known

Manufacturable solutions are NOT known



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[9] This is the minimum transistor noise figure at 5 GHz.

[10] This device is required to achieve direct modulation of the PA for applications from 2 to 5 GHz and to support precision analog applications. With continued scaling of logic devices alternate device structures may be required to support the required specifications.

[11] Measure for the low frequency amplification of a 10× minimum length, low-standby power CMOS transistor. Using different lengths is an extra degree of freedom in mixed signal designs. Long devices have better G_{ds} amplification (at low frequencies). Operation point taken at 200 mV above the threshold voltage, V_{th} , and at $V_{ds} = V_{dd}/2$.

Table 47a 0.8 GHz–10 GHz RF and Analog Mixed-Signal Bipolar Technology Requirements—Near-term Years **UPDATED**

| Year of Production | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|--|-------------|-------------|-------------|-------------|------------|----------------|----------------|----------------|----------------|
| DRAM ½ Pitch (nm) (contacted) | 80 | 70 | 65 | 57 | 50 | 45 | 40 | 36 | 32 |
| <i>General Analog NPN Parameters</i> | | | | | | | | | |
| Emitter width (um) | 0.15 | 0.14 | 0.13 | 0.12 | 0.1 | 0.1 | 0.1 | 0.09 | 0.09 |
| 1/f-noise ($\mu V^2 \cdot \mu m^2 / Hz$) | 3 | 3 | 2 | 2 | 2 | 1.5 | 1.5 | 1.5 | 1 |
| σ current matching (%· μm) | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| <i>High Speed NPN (should be common to mmWave)</i> | | | | | | | | | |
| Peak F_t (GHz) [$V_{bc}=1V$] | 200 | 230 | 265 | 300 | 350 | 370 | 385 | 400 | 420 |
| Peak F_{max} (GHz) | 240 | 260 | 300 | 330 | 390 | 410 | 425 | 440 | 460 |
| BV_{ceo} | 2 | 1.9 | 1.8 | 1.7 | 1.7 | 1.7 | 1.7 | 1.6 | 1.6 |
| Was J_c at Peak F_t (mA/ μm^2) | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| Is J_c at Peak F_t (mA/ μm^2) | 10 | 12 | 14 | 17 | 20 | 21 | 22 | 23 | 25 |
| <i>RF NPN</i> | | | | | | | | | |
| Peak F_t (GHz) [$V_{bc}=1V$] | 80 | 80 | 90 | 90 | 100 | 100 | 110 | 110 | 120 |
| Peak F_{max} (GHz) | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 |
| BV_{ceo} | 3.3 | 3.3 | 3.1 | 3.1 | 2.9 | 2.9 | 2.8 | 2.8 | 2.6 |
| NF_{min} (dB) at 5GHz | 0.3 | 0.28 | 0.26 | 0.24 | 0.2 | <0.2 | <0.2 | <0.2 | <0.2 |
| I_c ($\mu A/\mu m$) at 50GHz F_t | 43 | 37 | 28 | 22 | 16 | 15 | 14 | 13 | 12 |
| <i>High Voltage NPN (Should be common to PA)</i> | | | | | | | | | |
| Peak F_t (GHz) [$V_{bc}=1V$] | 30 | 32 | 34 | 36 | 38 | 40 | 42 | 44 | 46 |
| Peak F_{max} (GHz) | 100 | 110 | 120 | 130 | 140 | 150 | 160 | 170 | 180 |
| BV_{ceo} | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 |
| BV_{cbo} (V) | 18 | 18 | 18 | 18 | 16 | 16 | 16 | 16 | 16 |

Table 47b 0.8 GHz–10 GHz RF and Analog Mixed-Signal Bipolar Technology Requirements—Long-term Years **UPDATED**

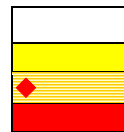
| Year of Production | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|------|------|------|------|------|------|------|
| DRAM ½ Pitch (nm) (contacted) | 28 | 25 | 22 | 20 | 18 | 16 | 14 |
| <i>General Analog NPN Parameters</i> | | | | | | | |
| Emitter width (um) | 0.09 | 0.08 | 0.08 | 0.08 | 0.07 | 0.07 | 0.07 |
| 1/f-noise ($\mu\text{V}^2\cdot\mu\text{m}^2/\text{Hz}$) | 1 | 1 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| σ current matching (%· μm) | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| <i>High Speed NPN (should be common to mmWave)</i> | | | | | | | |
| Peak F_t (GHz) [$V_{bc}=1\text{V}$] | 440 | 460 | 480 | 500 | 530 | 550 | 570 |
| Peak F_{max} (GHz) | 480 | 500 | 520 | 540 | 570 | 590 | 610 |
| BV_{ceo} | 1.5 | 1.5 | 1.4 | 1.4 | 1.3 | 1.3 | 1.3 |
| Was J_c at Peak F_t (mA/ μm^2) | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Is J_c at Peak F_t (mA/ μm^2) | 26 | 27 | 29 | 30 | 32 | 33 | 35 |
| <i>RF NPN</i> | | | | | | | |
| Peak F_t (GHz) [$V_{bc}=1\text{V}$] | 120 | 130 | 130 | 140 | 140 | 150 | 150 |
| Peak F_{max} (GHz) | 240 | 250 | 260 | 270 | 280 | 290 | 300 |
| BV_{ceo} | 2.6 | 2.5 | 2.5 | 2.4 | 2.4 | 2.4 | 2.4 |
| NF_{min} (dB) at 5GHz | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 |
| I_c ($\mu\text{A}/\mu\text{m}$) at 50GHz F_t | 11 | 10 | 9 | 8 | 7 | 6 | 5 |
| <i>High Voltage NPN (Should be common to PA)</i> | | | | | | | |
| Peak F_t (GHz) [$V_{bc}=1\text{V}$] | 48 | 50 | 52 | 54 | 56 | 58 | 60 |
| Peak F_{max} (GHz) | 190 | 200 | 210 | 220 | 230 | 240 | 250 |
| BV_{ceo} | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 |
| BV_{cbo} (V) | 16 | 16 | 16 | 16 | 16 | 16 | 16 |

Manufacturable solutions exist, and are being optimized

Manufacturable solutions are known

Interim solutions are known

Manufacturable solutions are NOT known



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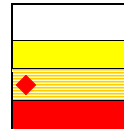
Table 48a Passives Technology Requirements—Near-term Years

| Year of Production | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|--|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| DRAM ½ Pitch (nm) (contacted) | 80 | 70 | 65 | 57 | 50 | 45 | 40 | 36 | 32 |
| ANALOG | | | | | | | | | |
| <i>MOS Capacitor</i> | | | | | | | | | |
| Density (fF/μm ²) [1] | 7 | 7 | 7 | 7 | 7 | 11 | 11 | 11 | 11 |
| Leakage (A/cm ²) | <1e-9 | <1e-9 | <1e-9 | <1e-9 | <1e-9 | <2e-6 | <2e-6 | <2e-6 | <2e-6 |
| <i>Resistor</i> | | | | | | | | | |
| <i>Thin Film BEOL</i> | | | | | | | | | |
| Parasitic capacitance (fF/μm ²) | 0.03 | 0.03 | 0.03 | 0.03 | 0.05 | 0.05 | 0.05 | 0.05 | 0.08 |
| Temp. linearity (ppm/°C) | <100 | <100 | <100 | <100 | 40-80 | 40-80 | 40-80 | 40-80 | 30 |
| 1σ Matching (% μm) | 0.2 | 0.2 | 0.2 | 0.2 | 0.15 | 0.15 | 0.15 | 0.15 | 0.1 |
| Sheet resistance, Rs (Ohm/sq) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| <i>P+ Polysilicon</i> | | | | | | | | | |
| Parasitic capacitance (fF/μm ²) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Temp. linearity (ppm/°C) | <100 | <100 | <100 | <100 | 40-80 | 40-80 | 40-80 | 40-80 | 30 |
| 1σ Matching (% μm) | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1 |
| Sheet resistance, Rs (Ohm/sq) | 200-300 | 200-300 | 200-300 | 200-300 | 200-300 | 200-300 | 200-300 | 200-300 | 200-300 |
| RF | | | | | | | | | |
| <i>Metal-Insulator-Metal Capacitor</i> | | | | | | | | | |
| Density (fF/μm ²) [2] | 2 | 2 | 2 | 4 | 4 | 5 | 5 | 5 | 7 |
| Voltage linearity (ppm/V ²) | <100 | <100 | <100 | <100 | <100 | < 100 | < 100 | < 100 | < 100 |
| Leakage (A/cm ²) | <1e-8 | <1e-8 | <1e-8 | <1e-8 | <1e-8 | <1e-8 | <1e-8 | <1e-8 | <1e-8 |
| σ Matching (% μm) | 0.7 | 0.7 | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.3 |
| Q (5 GHz for 1pF) | >50 | >50 | >50 | >50 | >50 | >50 | >50 | >50 | >50 |
| <i>Inductor</i> | | | | | | | | | |
| Q (5 GHz, 1nH) [3] | 25 | 27 | 29 | 30 | 32 | 34 | 36 | 38 | 40 |
| <i>MOS Varactor</i> | | | | | | | | | |
| Tuning Range [4] | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |
| Q (5 GHz, 0 V) | 30 | 30 | 35 | 35 | 40 | 40 | 45 | 45 | 50 |
| PA | | | | | | | | | |
| <i>PA III-V Passives</i> | | | | | | | | | |
| Inductors Q (1GHz, 5nH) [5] | 15 | 25 | 25 | 25 | 25 | 25 | 25 | 30 | 30 |
| Capacitor Q [6] | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| RF capacitor density (fF/μm ²) [7] | 0.6 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| <i>PA Silicon/SiGe Passives [Table 49 a&b]</i> | | | | | | | | | |
| Inductors Q (1GHz, 5nH) [5] | 10 | 14 | 14 | 14 | 14 | 14 | 14 | 18 | 18 |
| Capacitor Q [6] | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| RF capacitor density (fF/μm ²) [7] | 2 | 2 | 2 | 4 | 4 | 5 | 5 | 5 | 7 |

Table 48b Passives Technology Requirements—Long-term Years

| Year of Production | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|--|---------|---------|---------|---------|---------|---------|---------|
| DRAM ½ Pitch (nm) (contacted) | 28 | 25 | 22 | 20 | 18 | 16 | 14 |
| ANALOG | | | | | | | |
| <i>MOS Capacitor</i> | | | | | | | |
| Density (fF/μm ²) [1] | 11 | 11 | 11 | 11 | 11 | 13 | 13 |
| Leakage (A/cm ²) [8] | <2e-6 | <2e-6 | <2e-6 | <2e-6 | <2e-6 | <2e-5 | <2e-5 |
| <i>Resistor</i> | | | | | | | |
| <i>Thin Film BEOL</i> | | | | | | | |
| Parasitic capacitance (fF/μm ²) | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| Temp. linearity (ppm/°C) | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| 1σ Matching (% μm) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Sheet resistance, Rs (Ohm/sq) | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| <i>P+ Polysilicon</i> | | | | | | | |
| Parasitic capacitance (fF/μm ²) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Temp. linearity (ppm/°C) | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| 1σ Matching (% μm) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Sheet resistance, Rs (Ohm/sq) | 200–300 | 200–300 | 200–300 | 200–300 | 200–300 | 200–300 | 200–300 |
| RF | | | | | | | |
| <i>Metal-Insulator-Metal Capacitor</i> | | | | | | | |
| Density (fF/μm ²) [2] | 7 | 7 | 10 | 10 | 10 | 12 | 12 |
| Voltage linearity (ppm/V ²) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Leakage (A/cm ²) [9] | <1e-8 | <1e-8 | <1e-8 | <1e-8 | <1e-8 | <1e-8 | <1e-8 |
| σ Matching (% μm) | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Q (5 GHz for 1pF) | >50 | >50 | >50 | >50 | >50 | >50 | >50 |
| <i>Inductor</i> | | | | | | | |
| Q (5 GHz, 1nH) [3] | 42 | 44 | 46 | 48 | 50 | 52 | 54 |
| <i>MOS Varactor</i> | | | | | | | |
| Tuning Range [4] | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |
| Q (5 GHz, 0 V) | 50 | 55 | 55 | 60 | 60 | 60 | 60 |
| PA | | | | | | | |
| <i>PA III-V Passives</i> | | | | | | | |
| Inductors Q (1GHz, 5nH) [5] | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| Capacitor Q [6] | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| RF capacitor density (fF/μm ²) [7] | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| <i>PA Silicon/SiGe Passives [Table 49 a&b]</i> | | | | | | | |
| Inductors Q (1GHz, 5nH) [5] | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| Capacitor Q [6] | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| RF capacitor density (fF/μm ²) [7] | 7 | 7 | 10 | 10 | 10 | 10 | 12 |

Manufacturable solutions exist, and are being optimized
 Manufacturable solutions are known
 Interim solutions are known
 Manufacturable solutions are NOT known



8 Radio Frequency and Analog/Mixed-signal Technologies for Wireless Communications

Notes for Tables 48 and b:

- [1] This capacitance density corresponds to the highest end of the gate oxide thickness for precision analog device in the CMOS table.
- [2] No stacking (two capacitors on top of each other) is included. Coloring reflected MIM capacitor meeting all requirements including density, voltage linearity, leakage and matching on copper metallization.
- [3] Q at 5 GHz for a single-ended 1nH inductor with a dedicated thick metal (analog metal).
- [4] Defined as C_{max}/C_{min} in C-V curve of the varactor. Varactor align with performance RF device in the CMOS table.
- [5] Inductor Q —quality factor of a 5nH inductor at 1 GHz achievable with the technology with a metallization suitable for handling the power requirements of the PA.
- [6] Capacitor Q —quality factor of a 10 pF capacitor at 1 GHz achievable with the technology. Capacitor breakdown voltage must be rated for appropriate power amplification function.
- [7] RF capacitor density—capacitor used for all other functions (matching, harmonic filtering, coupling, etc). Capacitor must have adequate breakdown for the given application. No stacking.
- [8] Leakage current is defined at room temperature and for the highest end of the supply voltage range and thickness end of the gate oxide thickness for precision analog device in the CMOS table.
- [9] Leakage current is defined at room temperature and for the highest end of the supply voltage range for precision analog device in the CMOS table.

Table 49a Power Amplifier Technology Requirements—Near-term Years

| Year of Production | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|-----------------------------------|----------------------|---------|---------|------------------------|---------|---------|---------|------------------------|---------|
| DRAM ½ Pitch (nm) (contacted) | 80 | 70 | 65 | 57 | 50 | 45 | 40 | 36 | 32 |
| Nominal Battery Voltage | 3.2 | 3.2 | 3.2 | 3.2 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 |
| PA Product Solutions | Single Radio SIP [1] | | | Radio/Baseband SIP [2] | | | | Radio/Baseband SIP [2] | |
| PA Frequency (GHz) | 0.8–6 | | | 0.8-6 | | | | 0.8-6 | |
| III-V HBT Transistor | | | | | | | | | |
| F_{max} (at V_{cc}) (GHz) | 45 | 45 | 45 | 45 | 55 | 55 | 55 | 65 | 65 |
| BV_{CBO} (V) | 25 | 25 | 25 | 25 | 18 | 18 | 18 | 18 | 18 |
| Linear efficiency (%) [1] | 52 | 52 | 52 | 52 | 55 | 55 | 55 | 55 | 55 |
| Area (mm^2) [2] | 2.5 | 2.5 | 2.5 | 2.5 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |
| Cost/ mm^2 (US\$) [3] | 0.4 | 0.35 | 0.32 | 0.3 | 0.28 | 0.28 | 0.28 | 0.25 | 0.25 |
| III-V HBT Integration | | | | | | | | | |
| Power management [4] | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Switch [5] | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT |
| Filter [6] | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| III-V PHEMT Transistor | | | | | | | | | |
| F_{max} (at V_{dd}) (GHz) | 45 | 45 | 45 | 45 | 75 | 75 | 75 | 75 | 75 |
| BV_{DGO} (V) | 20 | 20 | 20 | 20 | 16 | 16 | 16 | 16 | 16 |
| Linear Efficiency (%) [1] | 55 | 55 | 55 | 55 | 58 | 58 | 58 | 58 | 58 |
| PA Area (mm^2) [2] | 4 | 4 | 4 | 4 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Cost/ mm^2 (US\$) [3] | 0.4 | 0.28 | 0.28 | 0.25 | 0.24 | 0.24 | 0.24 | 0.22 | 0.22 |
| III-V PHEMT Integration | | | | | | | | | |
| Power management [6] | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Switch [5] | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Filter [6] | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Silicon MOSFET Transistor | | | | | | | | | |
| T_{ox} (PA) (Å) [7] | 60 | 60 | 60 | 60 | 35 | 35 | 35 | 35 | 35 |
| F_{max} (at V_{dd}) | 45 | 45 | 45 | 45 | 60 | 60 | 60 | 60 | 60 |
| BV_{DSS} (V) | 12 | 12 | 12 | 12 | 10 | 10 | 10 | 10 | 10 |
| Linear efficiency (%) [1] | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| PA Area (mm^2) [2] | 6 | 6 | 6 | 6 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Cost/ mm^2 (US\$) [3] | 0.08 | 0.08 | 0.08 | 0.08 | 0.06 | 0.06 | 0.06 | 0.05 | 0.05 |
| Silicon MOSFET Integration | | | | | | | | | |
| Power management [4] | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Switch [5] | NO | NO | NO | NO | MEMS | MEMS | MEMS | MEMS | MEMS |
| Filter [6] | NO | NO | NO | NO | NO | NO | MEMS | MEMS | MEMS |
| SiGe HBT Transistor | | | | | | | | | |
| F_{max} (GHz) | 60 | 60 | 60 | 60 | 80 | 80 | 80 | 80 | 80 |
| BV_{CBO} (V) | 18 | 18 | 18 | 18 | 16 | 16 | 16 | 16 | 16 |
| Linear efficiency (%) [1] | 50 | 50 | 50 | 50 | 55 | 55 | 55 | 55 | 55 |
| PA Area (mm^2) [2] | 2.5 | 2.5 | 2.5 | 2.5 | 2 | 2 | 2 | 2 | 2 |
| Cost/ mm^2 (US\$) [3] | 0.12 | 0.12 | 0.12 | 0.12 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 |
| SiGe Integration | | | | | | | | | |
| Power management | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Switch | NO | NO | NO | NO | MEMS | MEMS | MEMS | MEMS | MEMS |
| Filter | NO | NO | NO | NO | NO | NO | MEMS | MEMS | MEMS |

10 Radio Frequency and Analog/Mixed-signal Technologies for Wireless Communications

Table 49b Power Amplifier Technology Requirements—Long-term Years

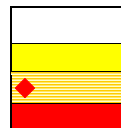
| Year of Production | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|--------------------------------|------------------------|---------|---------|---------|---------|---------|---------|
| DRAM ½ Pitch (nm) (contacted) | 28 | 25 | 22 | 20 | 18 | 16 | 14 |
| Nominal Battery Voltage | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 |
| PA Product Solutions | Radio/Baseband SIP [2] | | | | | | |
| PA Frequency (GHz) | 0.8-6 | | | | | | |
| III-V HBT Transistor | | | | | | | |
| F_{max} (at V_{cc}) (GHz) | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| BV_{CBO} (V) | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| Linear efficiency (%) [1] | 55 | 55 | 55 | 55 | 55 | 55 | 55 |
| Area (mm^2) [2] | 2.2 | 2.2 | 2.2 | 2 | 2 | 2 | 2 |
| Cost/ mm^2 (US\$) [3] | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| III-V HBT Integration | | | | | | | |
| Power management [4] | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Switch [5] | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT | E-PHEMT |
| Filter [6] | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| III-V PHEMT Transistor | | | | | | | |
| F_{max} (at V_{dd}) (GHz) | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| BV_{DGO} (V) | 16 | 16 | 16 | 16 | 16 | 16 | 16 |
| Linear Efficiency (%) [1] | 58 | 58 | 58 | 58 | 58 | 58 | 58 |
| PA Area (mm^2) [2] | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Cost/ mm^2 (US\$) [3] | 0.22 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| III-V PHEMT Integration | | | | | | | |
| Power management [4] | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Switch [5] | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Filter [6] | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Silicon MOSFET Transistor | | | | | | | |
| T_{ox} (PA) (Å) [7] | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| F_{max} (at V_{dd}) | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| BV_{DSS} (V) | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Linear efficiency (%) [1] | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| PA Area (mm^2) [2] | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Cost/ mm^2 (US\$) [3] | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Silicon MOSFET Integration | | | | | | | |
| Power management [4] | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Switch [5] | MEMS | MEMS | MEMS | MEMS | MEMS | MEMS | MEMS |
| Filter [6] | MEMS | MEMS | MEMS | MEMS | MEMS | MEMS | MEMS |
| SiGe HBT Transistor | | | | | | | |
| F_{max} (GHz) | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| BV_{CBO} (V) | 16 | 16 | 16 | 16 | 16 | 16 | 16 |
| Linear efficiency (%) [1] | 55 | 55 | 55 | 55 | 55 | 55 | 55 |
| PA Area (mm^2) [2] | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Cost/ mm^2 (US\$) [3] | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 |
| SiGe Integration | | | | | | | |
| Power management | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Switch | MEMS | MEMS | MEMS | MEMS | MEMS | MEMS | MEMS |
| Filter | MEMS | MEMS | MEMS | MEMS | MEMS | MEMS | MEMS |

Manufacturable solutions exist, and are being optimized

Manufacturable solutions are known

Interim solutions are known

Manufacturable solutions are NOT known



Notes for Table 49a and b:

[1] Linear efficiency—power added efficiency of the final PA stage under personal communication service (PCS) CDMA (IS-95) modulation.

[2] Area—total semiconductor area necessary for the implementation of the quad-band GSM/general packet radio service (GPRS)/ Enhanced Data rates for GSM Evolution (EDGE) PA function, including matching/filtering.

[3] Cost/mm²—approximate commercial foundry cost of the area mentioned in [4].

[4] Power management—capability of the technology to provide RF power detection/DC power management for the PA.

[5] Switch—capability of the technology to integrate cost-effectively a transmit/receive switch into the PA active die.

[6] Filter—capability of the technology to integrate high-quality band selection filters needed for the assumed PA solution; currently performed with surface acoustic wave (SAW) filter technology.

[7] $T_{ox}(PA)$ —thickness of the MOSFET transistor in the RF power amplifier function.

12 Radio Frequency and Analog/Mixed-signal Technologies for Wireless Communications

Table 50a Base Station Devices Technology Requirements—Near-term Years

| Year of Production | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|----------------------------------|---------|---------|---------|------|------|-------|------|------|------|
| DRAM ½ Pitch (nm) (contacted) | 80 | 70 | 65 | 57 | 50 | 45 | 40 | 36 | 32 |
| Application frequency (GHz) [1] | 0.8–2.7 | | 0.8–3.5 | | | 0.8–5 | | | |
| Cost (\$\$/Watt) | 0.7 | 0.6 | 0.5 | 0.4 | | 0.3 | | | 0.25 |
| Packaging (C-Ceramic, P-Plastic) | C/P | Plastic | | | | | | | |
| <i>Si LDMOS</i> | | | | | | | | | |
| Operating voltage (V) | <40 | <40 | <50 | <50 | <50 | <50 | <50 | <50 | <50 |
| Saturated power (Watt) | 240 | 240 | 240 | 240 | 240 | 240 | 240 | 240 | 240 |
| Saturated power density (W/mm) | 1 | 1.2 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 |
| Saturated PAE (%) | 65 | 68 | 65 | 68 | 70 | 65 | 65 | 65 | 70 |
| Linear power (Watt) | <120 | <120 | <120 | <120 | <120 | <120 | <120 | <120 | <120 |
| Linear PAE (%) | 50 | 52 | 50 | 52 | 54 | 50 | 50 | 50 | 52 |
| <i>GaAs FET</i> | | | | | | | | | |
| Operating voltage (V) | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 |
| Saturated power (Watt) | 180 | 180 | 180 | 180 | 180 | 180 | 180 | 240 | 240 |
| Saturated power density (W/mm) | 1 | 1.2 | 1.5 | 1.5 | 1.5 | 1.8 | 1.8 | 1.8 | 1.8 |
| Saturated PAE (%) | 68 | 70 | 72 | 68 | 70 | 72 | 72 | 68 | 68 |
| Linear power (Watt) | <60 | <60 | <60 | <90 | <90 | <90 | <90 | <120 | <120 |
| Linear PAE (%) | 52 | 55 | 57 | 52 | 54 | 56 | 57 | 52 | 52 |
| <i>SiC FET</i> | | | | | | | | | |
| Operating voltage (V) | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| Saturated power (Watt) | 60 | 60 | 60 | 120 | 120 | 120 | 120 | 180 | 180 |
| Saturated power density (W/mm) | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 |
| Saturated PAE (%) | 45 | 45 | 47 | 42 | 45 | 45 | 47 | 42 | 42 |
| <i>GaN FET</i> | | | | | | | | | |
| Operating voltage (V) | 28 | 28 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| Saturated power (Watt) | 60 | 60 | 120 | 120 | 120 | 180 | 180 | 180 | 180 |
| Saturated power density (W/mm) | 3 | 3 | 4 | 4 | 5 | 5 | 5 | 5 | 5 |
| Saturated PAE (%) | 52 | 55 | 55 | 60 | 55 | 60 | 60 | 55 | 60 |

Manufacturable solutions exist, and are being optimized

Manufacturable solutions are known

Interim solutions are known

Manufacturable solutions are NOT known

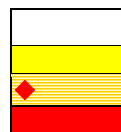


Table 50b Base Station Devices Technology Requirements—Long-term Years

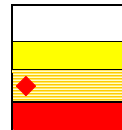
| <i>Year of Production</i> | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|----------------|------|------|------|------|------|------|
| <i>DRAM ½ Pitch (nm) (contacted)</i> | 28 | 25 | 22 | 20 | 18 | 16 | 14 |
| <i>Application frequency (GHz) [1]</i> | 0.8–5 | | | | | | |
| <i>Cost (\$\$/Watt)</i> | 0.25 | | | | | | |
| <i>Packaging (C-Ceramic, P-Plastic)</i> | Plastic | | | | | | |
| <i>Si LDMOS</i> | | | | | | | |
| Operating voltage (V) | <50 | <50 | <50 | <50 | <50 | <50 | <50 |
| Saturated power (Watt) | 240 | 240 | 240 | 240 | 240 | 240 | 240 |
| Saturated power density (W/mm) | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 |
| Saturated PAE (%) | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| Linear power (Watt) | <120 | <120 | <120 | <120 | <120 | <120 | <120 |
| Linear PAE (%) | 52 | 52 | 52 | 52 | 52 | 52 | 52 |
| <i>GaAs FET</i> | | | | | | | |
| Operating voltage (V) | 28 | 28 | 28 | 28 | 28 | 28 | 28 |
| Saturated power (Watt) | 240 | 240 | 240 | 240 | 240 | 240 | 240 |
| Saturated power density (W/mm) | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |
| Saturated PAE (%) | 70 | 70 | 70 | 72 | 72 | 72 | 72 |
| Linear power (Watt) | <120 | <120 | <120 | <120 | <120 | <120 | <120 |
| Linear PAE (%) | 55 | 55 | 55 | 57 | 57 | 57 | 57 |
| <i>SiC FET</i> | | | | | | | |
| Operating voltage (V) | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| Saturated power (Watt) | 180 | 180 | 180 | 180 | 180 | 180 | 180 |
| Saturated power density (W/mm) | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Saturated PAE (%) | 42 | 42 | 42 | 42 | 42 | 42 | 42 |
| <i>GaN FET</i> | | | | | | | |
| Operating voltage (V) | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| Saturated power (Watt) | 240 | 240 | 240 | 240 | 240 | 240 | 240 |
| Saturated power density (W/mm) | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Saturated PAE (%) | 55 | 60 | 60 | 60 | 60 | 60 | 60 |

Manufacturable solutions exist, and are being optimized

Manufacturable solutions are known

Interim solutions are known

Manufacturable solutions are NOT known



Notes for Table 50:

[1] Application frequencies affected device saturated PAE scaling.

14 Radio Frequency and Analog/Mixed-signal Technologies for Wireless Communications

*Table 51 Millimeter Wave 10 GHz–100 GHz Technology Requirements—Near-term Years **UPDATED***

| <i>Year of Production</i> | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|--------------|--------------|------|------|------|------|------|------|------|
| <i>DRAM ½ Pitch (nm) (contacted)</i> | 80 | 70 | 65 | 57 | 50 | 45 | 40 | 36 | 32 |
| <i>Device Technology—FET *</i> | | | | | | | | | |
| <i>GaAs MESFET (digital mixed-signal)</i> | | | | | | | | | |
| Gate length—L physical (nm) | 150 | 150 | - | - | - | | | | |
| Minimum M1 pitch (nm) | 680 | 680 | - | - | - | | | | |
| F _t – enhancement mode (GHz) | 120 | 120 | - | - | - | | | | |
| F _t – depletion mode (GHz) | 100 | 100 | - | - | - | | | | |
| BV _{GD} (1 mA/mm, V _g =0) (volts) | 5 to 10 | 5 to 10 | - | - | - | | | | |
| Power delay product at gate delay- FO=1 (fJ at pS) | 1.2 at 18 | 1.2 at 18 | - | - | - | | | | |
| Shortest DCFL gate delay (pS) | 6 | 6 | - | - | - | | | | |
| Interconnect metal layers | 5 | 5 | - | - | - | | | | |
| Interconnect metal | Al | Al | - | - | - | | | | |
| Inter line dielectric constant (effective) | 3.1 | 3.1 | - | - | - | | | | |
| <i>GaAs PHEMT (low noise)</i> | | | | | | | | | |
| Gate length (nm) | 100 | 100 | 70 | 70 | 70 | 50 | 50 | | |
| F _t (GHz) | 130 | 130 | 150 | 150 | 170 | 170 | 200 | | |
| Breakdown (volts) | 7.5 | 7.5 | 7 | 7 | 6 | 5 | 5 | | |
| I _{max} (mA/mm) | 700 | 700 | 600 | 600 | 600 | 550 | 550 | | |
| G _m (S/mm) | 0.72 | 0.72 | 0.8 | 0.8 | 0.8 | 0.85 | 0.85 | | |
| NF (dB) at 26 GHz, 18–20 dB associated gain | 2.5 | 2.5 | 2 | 2 | 2 | 1.8 | 1.8 | | |
| NF (dB) at 94 GHz, 8–10 dB associated gain | 4 | 4 | 3.5 | 3.5 | 3.5 | 3.2 | 3.2 | | |
| <i>GaAs PHEMT (power)</i> | | | | | | | | | |
| Gate length (nm) | 100 | 100 | 100 | 100 | 70 | 70 | 70 | | |
| F _{max} (GHz) | 150 | 150 | 200 | 200 | 250 | 250 | 250 | | |
| Breakdown (volts) | 11 | 11 | 9 | 9 | 7 | 7 | 7 | | |
| I _{max} (ma/mm) | 750 | 750 | 850 | 850 | 900 | 900 | 900 | | |
| G _m (S/mm) | 0.67 | 0.67 | 0.85 | 0.85 | 0.95 | 0.95 | 0.95 | | |
| P _{out} at 26 GHz and peak efficiency (mW/mm) | 550 | 550 | 600 | 600 | 750 | 750 | 750 | | |
| Peak efficiency at 26 GHz (%) | 30 | 30 | 40 | 40 | 45 | 45 | 45 | | |
| Gain at 26 GHz, at P _{1dB} (dB)*** | 12 | 12 | 14 | 14 | 16 | 16 | 16 | | |
| P _{out} at 94 GHz and peak efficiency (mW/mm) | 300 | 300 | 350 | 350 | 350 | 350 | 350 | | |
| Peak efficiency at 94 GHz (%) | 15 | 15 | 20 | 20 | 25 | 30 | 30 | | |
| Gain at 94 GHz, at P _{1dB} (dB)*** | 5 | 5 | 6 | 6 | 6 | 7 | 7 | | |
| <i>Device Technology—FET *</i> | | | | | | | | | |
| <i>InP HEMT (low noise)</i> | | | | | | | | | |
| Gate length (nm) | 100 | 100 | 70 | 70 | 70 | 50 | 50 | | |
| F _t (GHz) | 210 | 210 | 240 | 240 | 240 | 260 | 260 | | |
| Breakdown (volts) | 3.5 | 3.5 | 3 | 3 | 3 | 2.5 | 2.5 | | |
| I _{max} (ma/mm) | 700 | 700 | 650 | 650 | 650 | 600 | 600 | | |
| G _m (S/mm) | 1 | 1 | 1.2 | 1.2 | 1.2 | 1.3 | 1.3 | | |
| NF (dB) at 26 GHz, 20–23 dB associated gain | 1.8 | 1.8 | 1.5 | 1.5 | 1.5 | 1.3 | 1.3 | | |
| NF (dB) at 94 GHz, 10–13 dB associated gain | 2.5 | 2.5 | 2 | 2 | 2 | 1.8 | 1.8 | | |
| <i>InP HEMT (power)</i> | | | | | | | | | |
| Gate length (nm) | 150 | 100 | 100 | 100 | 70 | 70 | 70 | | |
| F _{max} (GHz) | 200 | 220 | 260 | 260 | 260 | 300 | 300 | | |
| Breakdown (volts) | 5 | 5 | 6 | 6 | 6 | 7 | 7 | | |
| I _{max} (ma/mm) | 750 | 700 | 650 | 650 | 650 | 650 | 650 | | |
| G _m (S/mm) | 0.8 | 0.9 | 0.9 | 0.9 | 1 | 1 | 1 | | |

| Year of Production | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|--|------|------|------|------|------|------|------|------|------|
| <i>DRAM ½ Pitch (nm) (contacted)</i> | 80 | 70 | 65 | 57 | 50 | 45 | 40 | 36 | 32 |
| P _{out} at 26 GHz and peak efficiency (mW/mm) | 400 | 400 | 450 | 450 | 450 | 500 | 500 | | |
| Peak efficiency at 26 GHz (%) | 30 | 40 | 50 | 50 | 50 | 55 | 55 | | |
| Gain at 26 GHz, at P _{1dB} (dB)** | 12 | 14 | 15 | 15 | 16 | 16 | 16 | | |
| P _{out} at 94 GHz and peak efficiency (mW/mm) | 250 | 300 | 350 | 350 | 400 | 400 | 400 | | |
| Peak efficiency at 94 GHz (%) | 25 | 40 | 40 | 45 | 45 | 45 | 45 | | |
| Gain at 94 GHz, at P _{1dB} (dB)** | 6 | 8 | 10 | 10 | 12 | 12 | 12 | | |
| <i>GaAs MHEMT (low noise)</i> | | | | | | | | | |
| Gate length (nm) | 100 | 100 | 100 | 70 | 70 | 50 | 50 | | |
| F _t (GHz) | 200 | 250 | 300 | 300 | 400 | 400 | 450 | | |
| Breakdown (volts) | 5 | 5 | 5 | 4 | 4 | 3 | 3 | | |
| I _{max} (ma/mm) | 680 | 680 | 680 | 680 | 680 | 680 | 680 | | |
| G _m (S/mm) | 1 | 1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 | | |
| NF (dB) at 26 GHz, 10–23 dB associated gain | 1.6 | 1.6 | 1.2 | 1.2 | 1 | 1 | 0.8 | | |
| NF (dB) at 94 GHz, 10–13 dB associated gain | 2.5 | 2.3 | 2.3 | 2 | 2 | 1.8 | 1.8 | | |
| <i>Device Technology—FET *</i> | | | | | | | | | |
| <i>GaAs MHEMT (Power)</i> | | | | | | | | | |
| Gate length (nm) | | 150 | 150 | 100 | 100 | 70 | 70 | | |
| Was F _{max} (GHz) | | 200 | 250 | 275 | 300 | 300 | 300 | | |
| Is F _{max} (GHz) | | 200 | 250 | 275 | 300 | 300 | 300 | | |
| Was Breakdown (volts) | | 8 | 8 | 9 | 9 | 10 | 10 | | |
| Is Breakdown (volts) | | 9 | 9 | 11 | 11 | 12 | 12 | | |
| Was I _{max} (ma/mm) | | 650 | 700 | 750 | 800 | 800 | 850 | | |
| Is I _{max} (ma/mm) | | 700 | 700 | 750 | 750 | 750 | 800 | | |
| G _m (S/mm) | | 0.75 | 0.8 | 0.85 | 0.9 | 0.95 | 1 | | |
| P _{out} at 26 GHz and peak efficiency (mW/mm) | | 600 | 650 | 700 | 750 | 800 | 850 | | |
| Peak efficiency at 26 GHz (%) | | 45 | 55 | 55 | 60 | 60 | 65 | | |
| Gain at 26 GHz, at P _{1dB} (dB)** | | 12 | 15 | 16 | 16 | 16 | 17 | | |
| P _{out} at 94 GHz and peak efficiency (mW/mm) | | 250 | 300 | 325 | 350 | 400 | 450 | | |
| Peak efficiency at 94 GHz (%) | | 25 | 30 | 35 | 40 | 45 | 45 | | |
| Gain at 94 GHz, at P _{1dB} (dB)** | | 7 | 8 | 10 | 10 | 11 | 12 | | |
| <i>GaN HEMT (low noise)</i> | | | | | | | | | |
| Was Gate length (nm) | | | 150 | 100 | 100 | 70 | 70 | | |
| Is Gate Length (nm) | | | 150 | 150 | 100 | 100 | 70 | | |
| Was F _t (GHz) | | | 100 | 100 | 120 | 150 | 200 | | |
| Is F _t (GHz) | | | 100 | 100 | 120 | 150 | 200 | | |
| Was Breakdown (volts) | | | 40 | 40 | 40 | 40 | 40 | | |
| Is Breakdown (volts) | | | 40 | 40 | 40 | 40 | 40 | | |
| Was I _{max} (ma/mm) | | | 1000 | 1200 | 1500 | 1500 | 1500 | | |
| Is I _{max} (ma/mm) | | | 1000 | 1000 | 1200 | 1500 | 1500 | | |
| Was G _m (S/mm) | | | 0.3 | 0.4 | 0.5 | 0.5 | 0.5 | | |
| Is G _m (S/mm) | | | 0.3 | 0.4 | 0.4 | 0.5 | 0.6 | | |
| Was NF (dB) at 26 GHz, 14 dB gain | | | 2 | 2 | 1.5 | 1 | 0.8 | | |
| Is NF (dB) at 26 GHz, 14 dB gain | | | 2 | 2 | 1.5 | 1.5 | 1 | | |
| <i>GaN HEMT (power)</i> | | | | | | | | | |
| Was Gate length (nm) | | | 150 | 100 | 100 | 70 | 70 | | |
| Is Gate length (nm) | | | 150 | 150 | 100 | 100 | 70 | | |
| Was F _{max} (GHz) | | | 100 | 100 | 150 | 200 | 200 | | |
| Is F _{max} (GHz) | | | 100 | 80 | 100 | 125 | 200 | | |
| Was Breakdown (volts) | | | 40 | 60 | 80 | 100 | 100 | | |

16 Radio Frequency and Analog/Mixed-signal Technologies for Wireless Communications

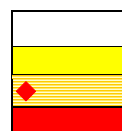
| Year of Production | | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|-------------------------------|---|--------|--------|-----------------|------------|------------|------------|------------|------|------|
| DRAM ½ Pitch (nm) (contacted) | | 80 | 70 | 65 | 57 | 50 | 45 | 40 | 36 | 32 |
| Is | Breakdown (volts) | | | 40 | 40 | 60 | 75 | 100 | | |
| Was | I _{max} (ma/mm) | | | 1000 | 1000 | 1000 | 1500 | 1500 | | |
| Is | I _{max} (ma/mm) | | | 1000 | 1000 | 1200 | 1500 | 1500 | | |
| Was | G _m (S/mm) | | | 0.3 | 0.4 | 0.5 | 0.5 | 0.5 | | |
| Is | G _m (S/mm) | | | 0.3 | 0.4 | 0.5 | 0.5 | 0.6 | | |
| Was | P _{out} at 26 GHz and peak efficiency (mW/mm) | | | 5000 | 6000 | 7000 | 8000 | 10000 | | |
| Is | P _{out} at 26 GHz and peak efficiency (mW/mm) | | | 5000 | 5000 | 6000 | 7500 | 10000 | | |
| Was | Peak efficiency at 26 GHz (%) | | | 35 | 40 | 50 | 60 | 60 | | |
| Is | Peak efficiency at 26 GHz (%) | | | 35 | 35 | 40 | 50 | 60 | | |
| Was | Gain at 26 GHz, at P _{1dB} (dB)*** | | | 10 | 12 | 12 | 13 | 14 | | |
| Is | Gain at 26 GHz, at P _{1dB} (dB)*** | | | 10 | 10 | 12 | 13 | 14 | | |
| Was | P _{out} at 44 GHz and peak efficiency (mW/mm) | | | 2000 | 2000 | 2000 | 2500 | 2500 | | |
| Is | P _{out} at 44 GHz and peak efficiency (mW/mm) | | | 2000 | 2000 | 2500 | 3000 | 3500 | | |
| Was | Peak efficiency at 44 GHz (%) | | | 35 | 35 | 35 | 40 | 40 | | |
| Is | Peak efficiency at 44 GHz (%) | | | 35 | 35 | 40 | 50 | 50 | | |
| Was | Gain at 44 GHz, at P _{1dB} (dB)*** | | | 8 | 8 | 8 | 9 | 9 | | |
| Is | Gain at 44 GHz, at P _{1dB} (dB)*** | | | 8 | 6 | 8 | 9 | 10 | | |
| Device Technology—HBT * | | | | | | | | | | |
| InP HBT | | | | | | | | | | |
| Was | Emitter width (nm) | 350 | 350 | 250 | 250 | 150 | 150 | 150 | | |
| Is | Emitter Area (square microns) | 1 | 0.75 | 0.75 | 0.5 | 0.5 | 0.4 | 0.4 | | |
| Was | F _t (GHz) | 300 | 300 | 350 | 350 | 400 | 400 | 400 | | |
| Is | F _t (GHz) | 300 | 300 | 350 | 350 | 400 | 400 | 400 | | |
| Was | F _{max} (GHz) | 300 | 300 | 400 | 400 | 450 | 450 | 450 | | |
| Is | F _{max} (GHz) | 300 | 300 | 400 | 400 | 450 | 450 | 450 | | |
| | Breakdown (BV _{CEO}) (volts) | 4 | 4 | 4 | 4 | 3 | 3 | 3 | | |
| | I _{max} /μm ² (mA/μm ²) | 4 | 5 | 5 | 5 | 7 | 7 | 7 | | |
| | Beta | 50 | 50 | 50 | 50 | 50 | 50 | 50 | | |
| | 3 sigma V _{BE} (mV) | 40 | 30 | 30 | 25 | 25 | 20 | 20 | | |
| | Interconnect metal layers | 4 | 4 | 5 | 5 | 5 | | | | |
| | Interconnect metal | Al, Au | Al, Au | Al, Au, Cu | Al, Au, Cu | Al, Au, Cu | Al, Au, Cu | Al, Au, Cu | | |
| | Barrier | PVD | PVD | IMP | IMP | IMP | IMP | IMP | | |
| | Wafer diameter (mm) | 100 | 100 | 150 | 150 | 150 | 150 | 150 | | |
| SiGe HBT | | | | | | | | | | |
| | Emitter Width (nm) | 150 | 140 | 130 | 120 | 100 | 100 | 100 | | |
| | Peak F _t (GHz) B _{bc} =1V | 200 | 230 | 265 | 300 | 350 | 370 | 385 | | |
| | Peak F _{max} (GHz) | 240 | 260 | 300 | 330 | 390 | 410 | 425 | | |
| | Breakdown (BV _{CBO}) (volts) | 5.3 | 5 | 5 | 4.5 | 4.5 | 4.3 | 4.3 | | |
| | Breakdown (BV _{CEO}) (volts) | 2 | 1.9 | 1.8 | 1.7 | 1.7 | 1.7 | 1.7 | | |
| | I _{max} /μm ² (mA/μm ²) | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | |
| | Beta | 200 | 200 | 250 | 250 | 300 | 325 | 350 | | |
| | Nf _{min} at 77 GHz (dB) | 5.5 | 5.1 | 4.6 | 4.3 | 3.9 | 3.8 | 3.7 | | |

Manufacturable solutions exist, and are being optimized

Manufacturable solutions are known

Interim solutions are known

Manufacturable solutions are NOT known



* Lithography dimensions are drawn dimensions.

** Output power at peak efficiency is generally at 2 to 3 dB into compression; P_{out} is normalized to total gate periphery.

*** P_{1dB} (dB) is the point at which the device gain is 1 dB less than the linear gain, i.e., the gain is compressed by 1 dB.

REFERENCES

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