SiGe-based Power Amplifier for CDMA Handset Circuitry

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Outline

- Introduction
- Literature review and discussion
  - Device design and performance
  - Circuit design and performance
- Commercial application
- Conclusion

Introduction

For CDMA power amplifier, we need to consider

- Gain
- Breakdown voltage
- High maximum oscillation frequency f_{max}
- Linearity (important for CDMA)
- Heat dissipation (require good thermal conductivity)

Introduction

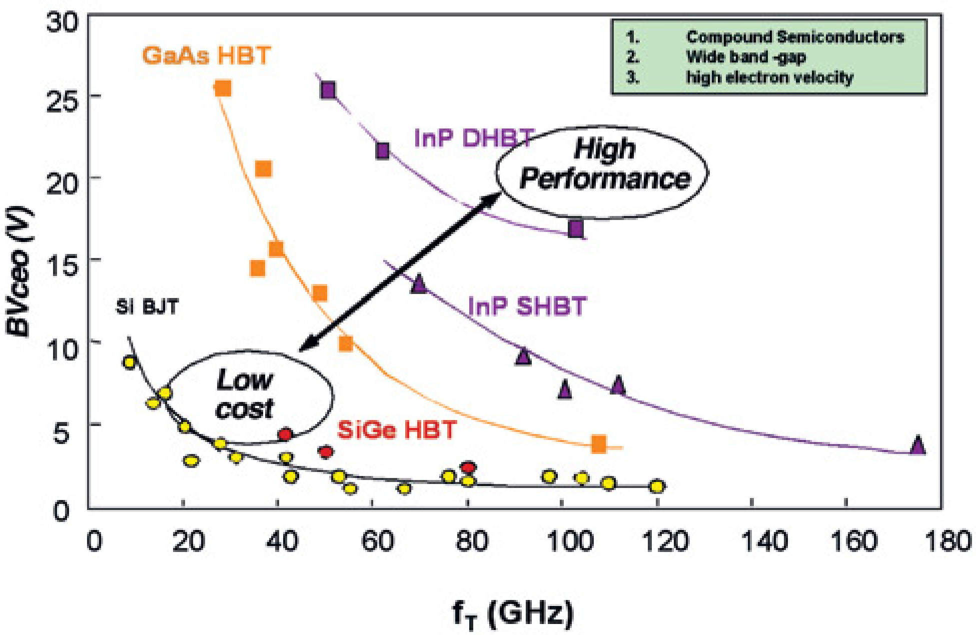


Fig. 1. Breakdown versus f_T for various Bipolar Technologies

Why SiGe?

- Low cost: maturity of process technology
- Superior thermal conductivity
- Compatible with CMOS technology: ease of high level integration
- Mechanical stability of substrate

Introduction

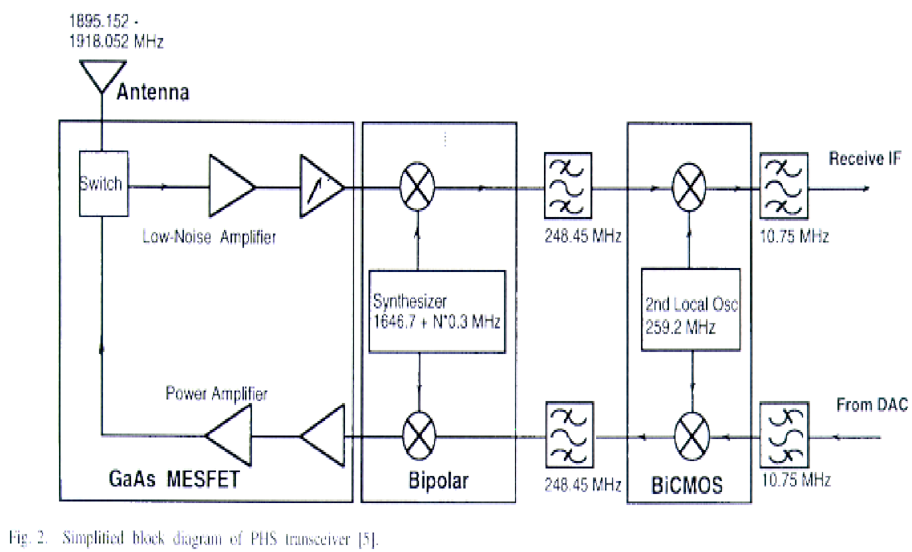


Fig. 2. Simplified block diagram of PHS transceiver

Design Consideration:

- Breakdown voltage V_{CE0}
- Linearity ACPR (adjacent channel power response)
- Maximum oscillation

  Frequency f_{max}
- Thermal conductivity
- Power gain and f_T

Literature review and discussion

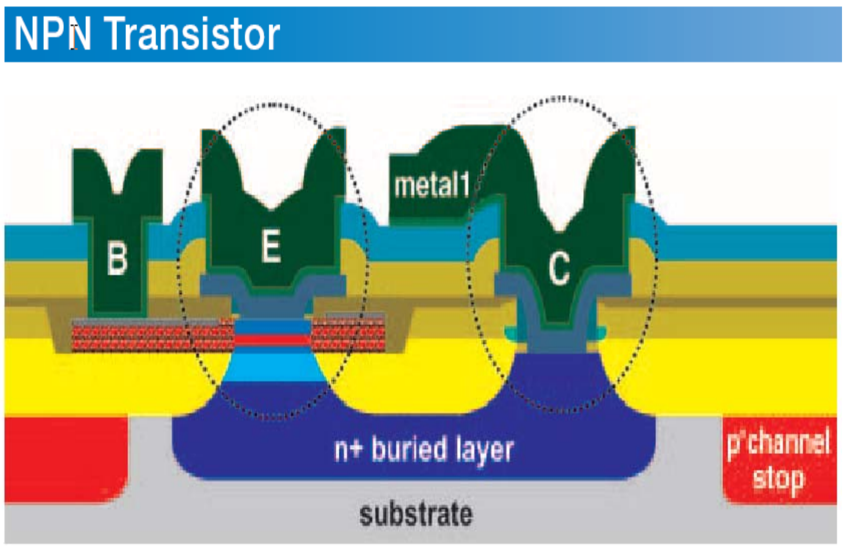


Fig. 3. Schematic cross section of an NPN HBT

- Self-aligned structure
- polysilicon emitter contact
- Silicided extrinsic base
- Deep- and shallow-trench isolation
- W-stud AlCu CMOS metallization scheme
- Parasitic resistor and capacitor consideration

Device design and performance

Device structure:

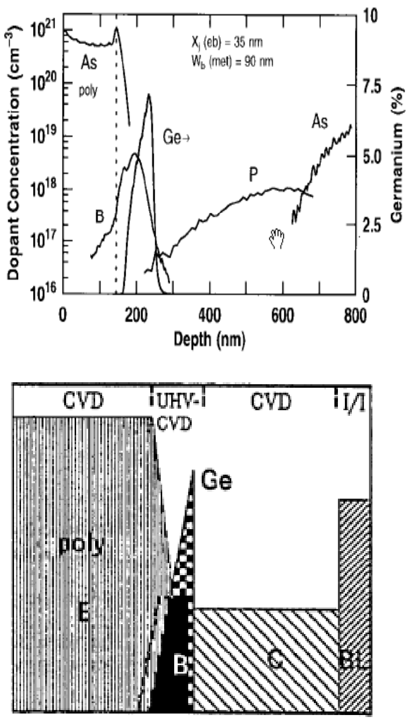


Fig. 4. IBM SiGe HBT doping profile

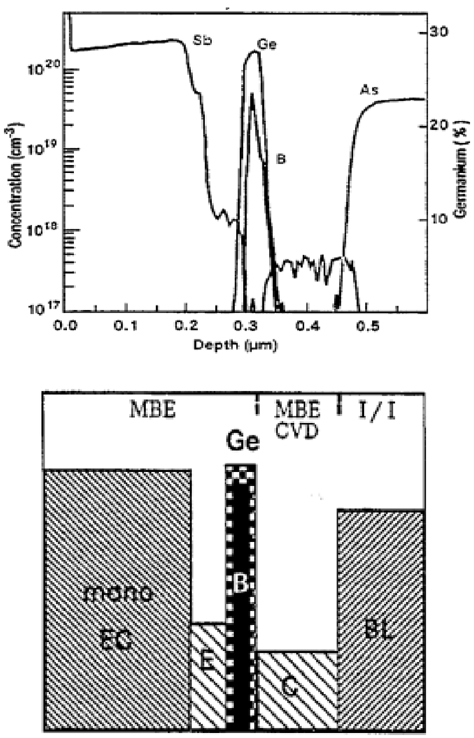


Fig. 5. Atmel SiGe HBT doping profile

IBM

- Graded SiGe base, peak content 8%~15%
- High emitter doping
- Lower base doping
- UHV/CVD grown SiGe
- No heterojunction at emitter-base junction
- Polycrystalline Si emitter

Atmel

- Uniform Ge concentration up to 28%
- Reduced emitter doping
- Higher base doping, low base sheet resistance ~1.5 kΩ/□
- MBE grown structure
- Heterojunction at emitter-base junction

Device design and performance

Device performance characteristics of Atmel SiGe HBT

Devices	SiGe1-RF		SiGe1-Power	SiGe2-Basic		*Sige2-RF*		*SiGe2-Power*	
Types of NPN-HBT	2		1	2		*2*		*2*	
Min. pitch [µm]	5		5	5		*3*		*3*	
Min. emitter width [µm]	0.8		0.8	0.5		*0.5*		*0.5*	
Base sheet resistance [Ohm]	1500		1500	2000		*2000*		*1400*	
Current gain	180		180	180		*250*		*150*	
V_{CB0} [V]	15	12	20	11.5	9,5	*11.5*	*9.5*	*17*	*16.5*
V_{CE0} [V]	6	3	7.3	4	2.5	*4*	*2.5*	*6*	*4*
F_T [GHz]	30	50	25	50	80	*50*	*80*	*35*	*45*
F_{max} [GHz]	50	50	50	90	90	*90*	*90*	*90*	*90*
Metal layers	3		3	3		*3*		*3*	

Table 1. Key SiGe Performance Parameters

Parameter	**With SIC**	**No SIC**
f_T	**50 GHz**	**30 GHz**
f_{max}	**50 GHz**	**50 GHz**
BV_{CE0}	**3.0 V**	**6.0 V**
Nf_{min}@2GHz	**1 dB**	**1 dB**
1/f corner-frq.	**1 KHz**	**1 KHz**

Table 2. Key Performance Parameters of SiGe1-RF

Device design and performance

Device performance characteristics of IBM BICMOS 5PA

Specifications

SiGe HBT NPNs	*High-Speed Device*	**High-Breakdown Device*
Gain (beta)	100	80
f_t (@ Vcb = 1V)	47 GHz	23 GHz
f_{max}	65 GHz	55 GHz
V_{early}	65 V	124 V
BV_{cbo}	10.5	20 V
BV_{ceo}	3.3 V	7.0 V
FETs	*NFET*	*PFET*
T_{ox}	7.8 nm	7.8 nm
L_{eff}	0.39 µm	0.39 µm
Capacitors		
MOS Cap	1.5 fF/µm^2	
* HB MIM Cap	0.3 fF/µm^2	
MIM Cap	0.7 fF/µm^2	
Diodes		
SBD (Schottky)	Vf = 355 mV @ 0.1 mA	
ESD	2000 VHBM	
Analog Metal Spiral Inductors: Inductance values range from 0.28 nH to 83 nH with outer dimensions between 100 µm and 450 µm. Peak Q value of 28 @ 5.5 GHz for a 1.3 nH inductor.		

* Unique to BiCMOS 5PA

Table 3. Key Performance Parameters of BICMOS 5PA

Device design and performance

Vertical design consideration

$$\tau_{EC} = \tau_E + \tau_B + \tau_C + \tau_{CSCL}$$

$$\tau_C = C_{BC}\left(\frac{KT}{qI_C} + R_E + R_C\right) \approx \frac{\varepsilon_{Si} A_{BC}}{W_C}\left(\frac{KT}{qI_C} + R_E + R_C\right)$$

$$\tau_{CSCL} = \frac{W_{CSCL}}{2\upsilon_s} \approx \frac{W_C}{2\upsilon_s} \qquad f_T = \frac{1}{2\pi\tau_{EC}}$$

$$f_{\max} = \left(\frac{f_T}{8\pi R_B C_{BC}}\right)^{1/2}$$

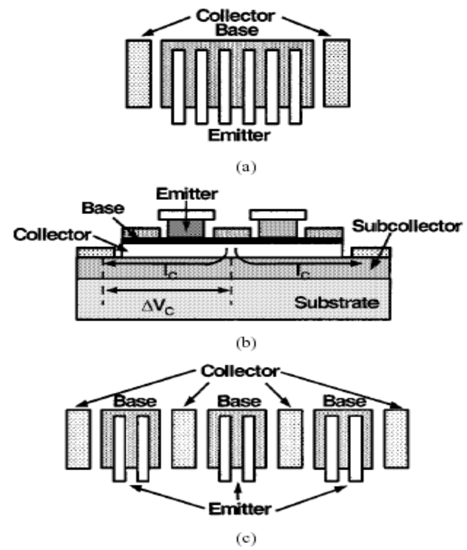
$$= \left(16\pi^2 R_B \varepsilon_{Si} A_{BC}\left(\frac{\tau_E + \tau_B}{W_C} + \frac{\varepsilon_{Si} A_{BC}}{W_C^2} \times \left(\frac{KT}{qI_C} + R_E + R_C\right) + \frac{1}{2\upsilon_s}\right)\right)^{-(1/}$$

W_c -- fully depleted collector thickness

A_{BC} – base-collector junction area

✓ A thicker and fully depleted collector layer is favorable for high breakdown voltage and large f_{max}

Lateral design consideration



- Minimize lateral current crowding effects
- Reduce thermal effects without increasing C_{BC}
- Decreased collector spreading resistance

Fig. 6. (a) Compact layout in which all emitter fingers are bound together. (b) Significant voltage drop for many finger devices due to the high spreading collector resistance. (c) Noncompact layout with two emitter fingers bound together in a subcell.

Circuit design and performance

An amplifier IC design in CDMA application using Atmel's SiGe1 HBT

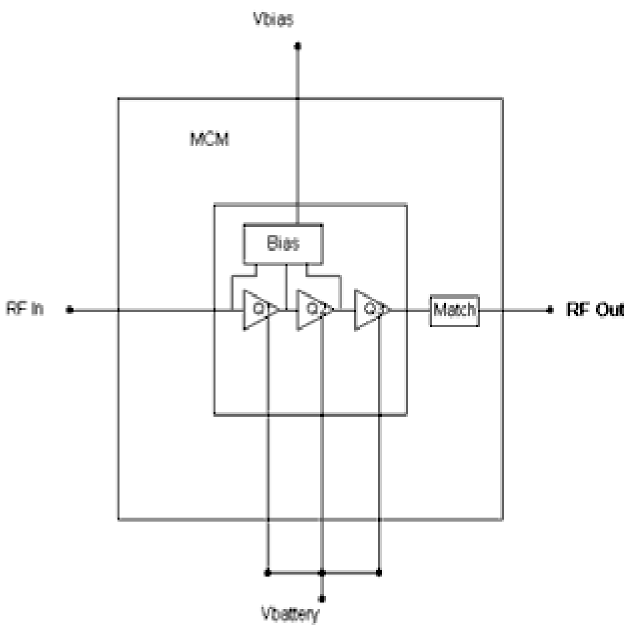


Fig. 7. Block Diagram (6 X 6 mm MCM)

Key Feature	Parameter	Units	Notes
Small size	6 x 6	mm	
Input/Output Impedance	50	Ohm	
Supply Voltage (Battery)	3.5	V	
Supply Voltage (Bias)	0.5 to 2.5	V	
Low Leakage	<1	uA	Off state
Quiescent Current	<90	mA	No RF
Operating Frequency	824-849	MHz	
Pout	27	dBm	
Efficiency	30	%	@ Pout=27 dBm
Low Power Efficiency	7	%	@ Pout=16 dBm
Power Gain	25	dB	@ Pout=27 dBm
ACPR	42	dBc	@ Pout=27 dBm

Table 4. MCM Design Targets

- All necessary RF circuitry components are included, providing 50 ohm RF connections in and out
- The goal of the module was to have a package outline of 6x6 mm and a height less than 2mm
- DC connections are required for Vbattery and Vbias connections

Circuit design and performance

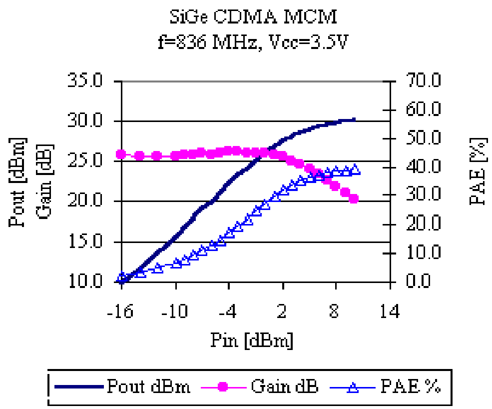


Fig. 8. Pout, Gain and PAE vs. Pin

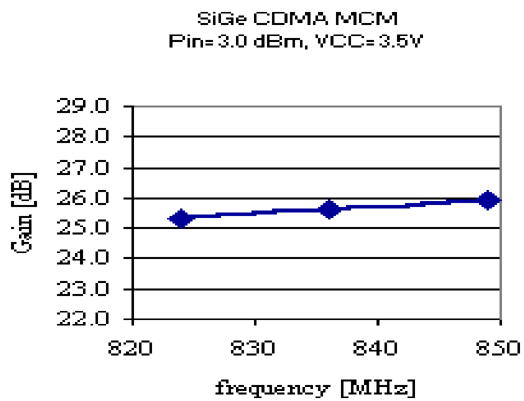


Fig. 9. Large Signal Gain vs. Frequency

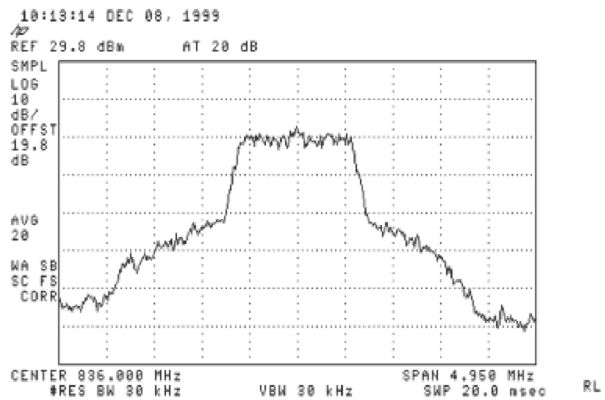


Fig. 10. Amplifier Spectral Output,
f= 836 MHz, Pout=27 dBm

- Module performance under IS-95 CDMA modulation conditions
- Saturation output power Pout over 30 dBm
- Power gain over 25 dB at Pout = 27 dBm
- PAE over 30% at Pout = 27 dBm and around 7% at Pout = 16 dBm
- Performance objectives for gain, Pout and PAE were either met or exceeded
- acceptable linearity (ACP ~ 42 dBc)

Circuit design and performance

An amplifier IC design in CDMA application using IBM's SiGe HBT technology

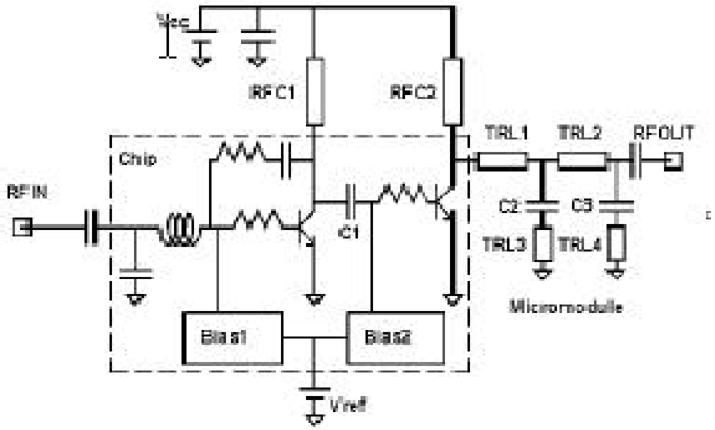


Fig. 11. Simplified schematic circuit diagram of a cellular handset PA

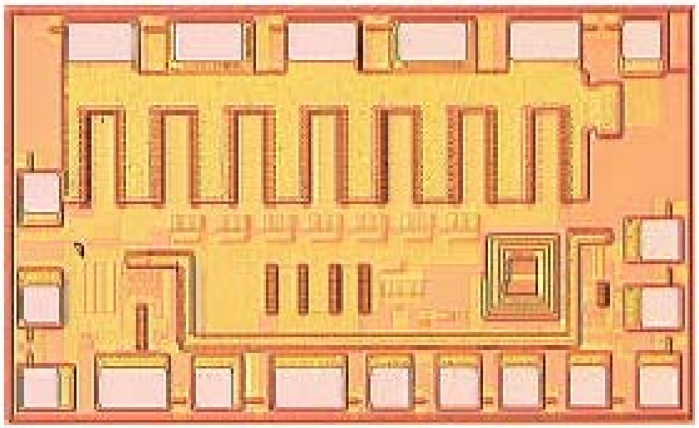


Fig. 12. Microphotograph of a fabricated PA

- 3V monolithic dual-mode CDMA/AMPS power amplifier IC
- Meets all linearity and output power requirements down to 2.7V

- RC feedback network to linearize the 1st stage and bias the 2nd stage to trade for high PAE
- Very compact (2.0x1.0mm2) in size

Circuit design and performance

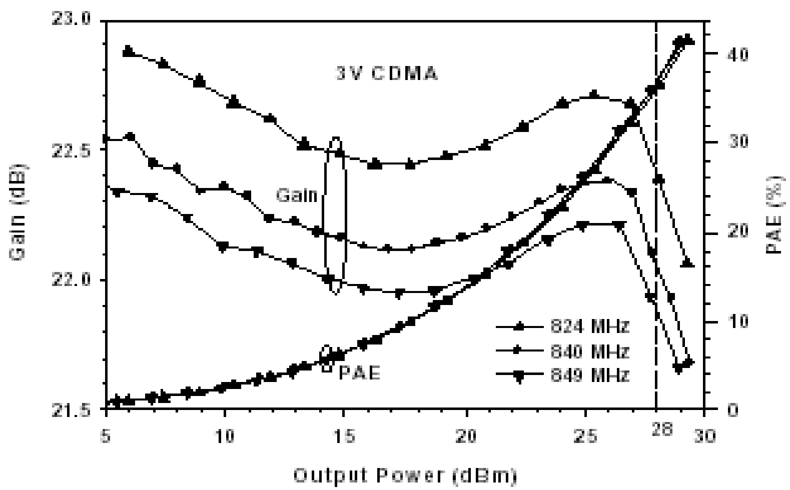


Fig. 13. Gain and Power Added Efficiency versus CDMA power amplifier output power as a function of operating frequency

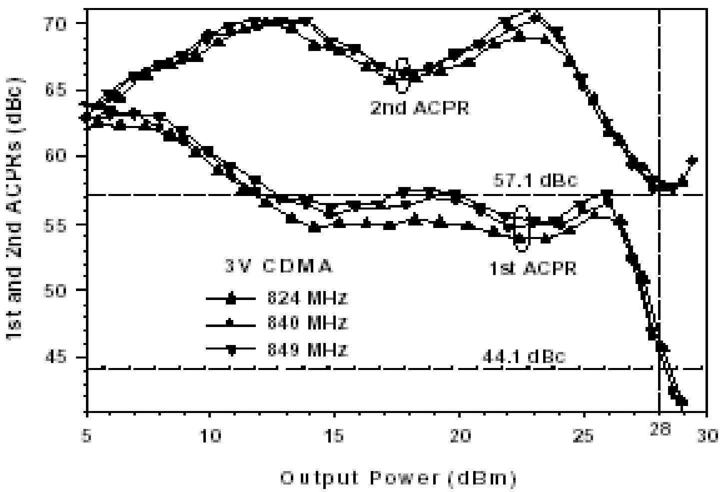


Fig. 14. The 1st and 2nd ACPRs versus CDMA power amplifier output power as a function of operating frequency

- satisfies linearity requirements at Vcc = 3V with 1st ACPR better than -44.1 dBc and 2nd ACPR better than –57.1 dBc with output power up to 28 dBm
- Gain varies between 22 to 23 dB with PAE of 36 to 37 % at 28 dBm output power

Circuit design and performance

- At 1 Watt output power, the maximum chip temperature is measured to be 40ºC above the ambient.
- The peak temperature of individual SiGe HBT cells varies only within 5ºC from the center to the edge of the power HBT.

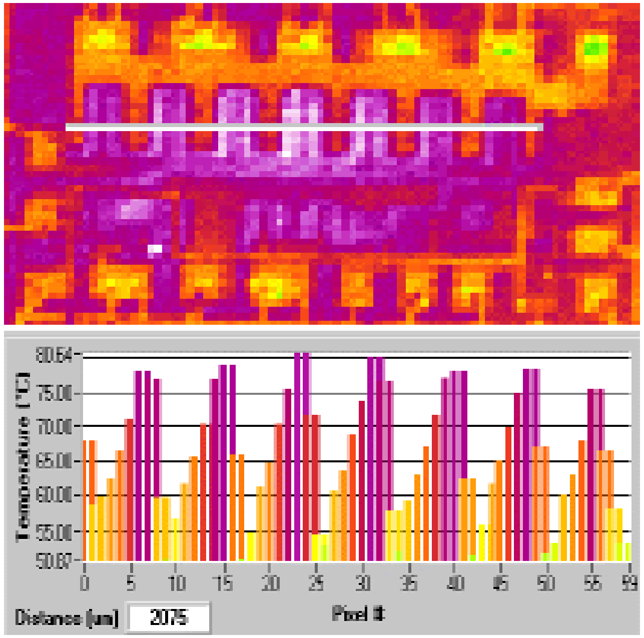


Fig. 15. Infrared Image and temperature distribution of a multi-cell SiGe HBT PA under 1W output power operation (the ambient temperature is set at 40 ºC)

Commercial application

Atmel's T0372 3-V CDMA/AMPS cell-band PA module

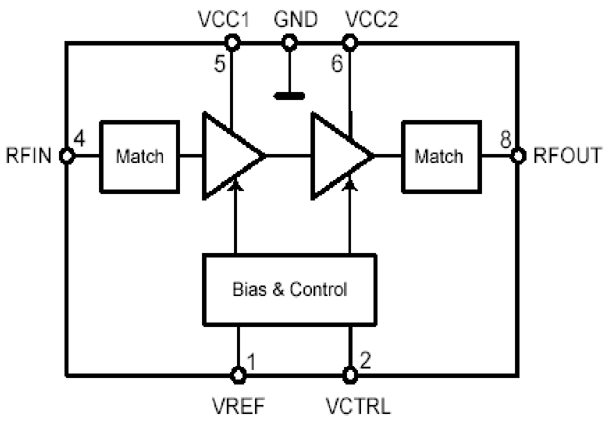


Fig. 16. Block diagram of T0372 PA module

Pin	Symbol	Function
1	VREF	Regulated supply for setting bias, reference voltage input
2	VCTRL	CMOS-compatible logic level used to set bias
3	GND	Ground recommended
4	RFIN	RF input, the RF circuit is DC-grounded internally, 50-Ω RF impedance
5	VCC1	Collector supply for input stage
6	VCC2	Collector supply for output stage
7	GND	Ground recommended
8	RFOUT	RF output, the RF circuit is DC-blocked internally, 50-Ω RF impedance
9	GND	Ground recommended
10	GND	Ground recommended
-	Paddle	Device ground and heat sink, requires good thermal path

Table 5. Pin description of T0372 PA module

- 4mm×4mm 3-V CDMA/AMPS cell-band PA module
- Supports the IS-95 and IS-98 standards
- Provides excellent RF performance with low current consumption
- The heart of the module is a two stage PA manufactured in Atmel's SiGe technology

Commercial application

Test conditions: $V_{CC1, CC2}$ = 3.4 VDC, V_{REF} = 2.85 VDC, V_{CTRL} = 0.5 VDC, RF = 836 MHz, Tc = 25°C, P_{out} = 28 dBm, Minimum/maximum limits are at +25°C ambient temperature, unless otherwise specified

No.	Parameters	Test Conditions	Pin	Symbol	Min.	Typ.	Max.	Unit	Type*
	Frequency		4, 8	f_o	824	836	849	MHz	A; D
	Output power		8	P_{out}		28		dBm	A
	Large signal gain	P_{out} = 28 dBm, V_{CTRL} = low	4, 8	G_{high}	26.0	29.0		dB	A
		P_{out} = 16 dBm, V_{CTRL} = high	4, 8	G_{low}	25.0	28.0		dB	A
	Gain variation versus temperature	-30°C to +85°C	4, 8			±1.4		dB	C
	Quiescent current (high-gain mode)	V_{CTRL} = low	1, 5, 6	I_{CQ}_hi		110		mA	A
	Quiescent current (low-gain mode)	V_{CTRL} = high	1, 5, 6	I_{CQ}_low		60		mA	A
	Current consumption	P_{out} = 28 dBm, V_{CTRL} = low	1, 5, 6	I_{cc}		503		mA	A
	Output power (low)	ACPR = -49 dBc, IS-95/98 standard, V_{CTRL} = high	8	P_{out}		16		dBm	B
	Power added efficiency	P_{out} = 28 dBm V_{CTRL} = low		PAE	33	36		%	A
	Adjacent channel power	P_{out} = 28 dBm, IS-95/98 standard, V_{CTRL} = low	8	ACP		-49	-44	dBc	A

*) Type means: A = 100% tested, B = 100% correlation tested, C = Characterized on samples, D = Design parameter

Table 6. Electrical characteristics of T0372 PA module

Commercial application

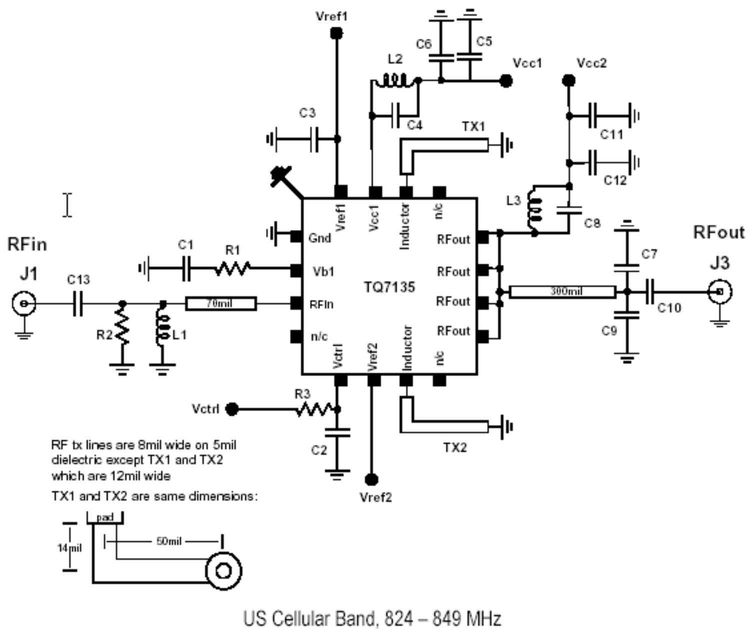
TriQuint Semiconductor's 3-V CDMA/AMPS cell-band PA module

Part	Description	P_{out} (dBm)	Efficiency (%)
TQ7135	824-849 MHz Cellular AMPS/CDMA Power Amp IC-SiGe	28.0	40%
TQM7136	824-849 MHz 2 Stage Cellular CDMA/AMPS SiGe HBT Power Amplifier Module	28/31.5	35% CDMA, 51% AMPS
TQM7138	824-849 MHz, 2 Stage Cellular CDMA/AMPS SiGe HBT Power Amplifier Module	28/31.5	35% CDMA, 51% AMPS

Table 7. TQO-Driver Amps, PAs, PA Modules

Commercial application

TQ7135 PA Module



Pin Name	Pin #	Description and Usage
GND	Paddle	Device Ground and Heat Sink. Needs good thermal path to remove heat.
Vc1	1	Recommend Ground Connection
Bypass	2	External bypassing.
RFIN	3	RF Input Pin, DC Blocked
N/C	4	
VCTRL	5	Output stage biasing control.
VREF2	6	Second stage bias reference. (Nominally set to 2.8VDC)
Inter-stage inductor	7	Node connected to inter-stage matching inductor.
N/C	8	
RFOUT	9,10,11,12	RF Output Pin, VCC2 input to the output stage of the PA.
N/C		
Inter-stage Inductor	14	Node connected to inter-stage matching transmission line.
VCC1	15	First stage collector supply.
VREF1	16	First stage bias reference. (Nominally set to 2.8VDC)

Fig. 17. The application/test circuit diagram of TQ7135 PA module

Table 8. Pin description of TQ7135 PA module

- 3V, 2 stage SiGe HBT PA
- RF performance meets IS-95/98 standards

Commercial application

Parameter	Conditions	Min.	Typ/Nom	Max.	Units
RF Frequency		824		849	MHz
Pout, I_{CQ}-hi			28		dBm
Large Signal Gain, I_{CQ}-hi	Pout = +28dBm, V_{CTRL}=2.8VDC	26	29.1		dB
Large Signal Gain, I_{CQ}-low	Pout = +15dBm, V_{CTRL}=0.25VDC		27.4		dB
Gain Variation vs. Temp.	-30 to 85 °C		+/-1.6		dB
Quiescent Current, I_{CQ}-hi			98	106	mA
Quiescent Current, I_{CQ}-low			66	84	mA
Power Added Efficiency	Pout = +28dBm	36	40.1		%
Adjacent Channel Power (ACP)	Pout = +28dBm, IS-95 Standard		-48	-44	dBc
Alternate Channel Power (ALT)	Pout = +28dBm, IS-95 Standard		-56		dBc
Noise Power in Rx band	Pout = +28dBm, RBW=30KHz		-93		dBm
Input VSWR	Both I_{CQ}-hi & I_{CQ}-low		1.5:1		

Table 9. Electrical characteristics of TQ7135 PA module

Commercial application

TQM7138 PA Module

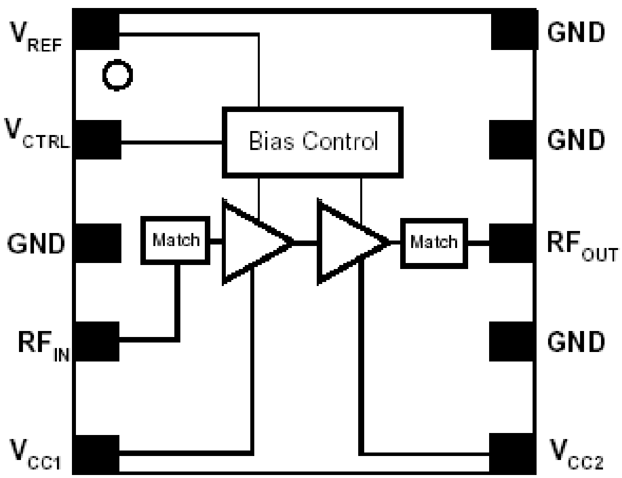
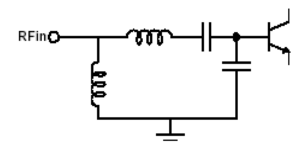


Fig. 18. Block diagram of TQM7138 PA

Pin Name	Pin #	Description and Usage (Equivalent Circuit)
GND	Paddle	Device Ground and Heat Sink. Needs good thermal path to remove heat.
V_{REF}	1	Regulated supply for setting bias. Vref is set to 0VDC to power-off the TQM7138
V_{CTRL}	2	CMOS compatible logic level to set bias level
RF_{IN}	4	RF input. The RF circuit is DC ground. 50 Ohm RF impedance. 
V_{CC1}	5	Collector supply for input stage.
V_{CC2}	6	Collector supply for output stage.
RF_{OUT}	8	RF output. The RF circuit is DC blocked internally. 50 ohm RF impedance.
GND	3, 7, 9, 10	Ground

TriQuint recommends use of several via holes to the backside ground under the Paddle.

Table 10. Electrical characteristics of TQM7138 PA module

- 3V, 2 stage SiGe HBT PA Module
- Small 4x4mm package
- RF performance meets IS-95/98 standards.
- Excellent RF performance with low current consumption
- Ideal for new generation small and light phones

Commercial application

Parameter	Conditions	Min.	Typ/Nom	Max.	Units
RF Frequency		824		849	MHz
Pout, I_{CQ}-hi	V_{CTRL} = low		28		dBm
Large Signal Gain, I_{CQ}-hi	Pout = 28dBm, V_{CTRL}= low		30		dB
Large Signal Gain, I_{CQ}-low	Pout = 16dBm, V_{CTRL} = high		28		dB
Gain Variation vs. Temp.	-30 to 85 °C, Pout=28dBm		+0.7/-1.6		dB
Quiescent Current, I_{CQ}-hi	V_{CTRL}= low		120		mA
Quiescent Current, I_{CQ}-low	V_{CTRL} = low		69		mA
Icc	Pout = 28dBm, V_{CTRL} = low		525		mA
Power Added Efficiency	Pout = 28dBm, V_{CTRL} = low		35		%
Adjacent Channel Power (ACP)	Pout = 28dBm, V_{CTRL} = low, IS-95 Standard		-49		dBc
Adjacent Channel Power (ACP-1xRTT)	Pout-=27.5dBm, V_{CTRL} = low, IS-98 Standard, 4.5 dB Peak to Average Ratio, CCDF=1%		-49		dBc
Alternate Channel Power (ALT)	Pout = 28dBm, V_{CTRL} = low, IS-95 Standard		-57		dBc
Alternate Channel Power (ALT-1xRTT)	Pout-=27.5dBm, V_{CTRL} = low, IS-98 Standard, 4.5 dB Peak to Average Ratio, CCDF=1%		-57		dBc
Output Power Low -Power Icq state	ACPR = -51dBc, V_{CTRL} = high, IS-95 Standard		16		dBm

Table 11. CDMA mode electrical characteristics of TQM7138 PA

Commercial application

IBM developed SiGe-base PA in wireless communication application in 2002

- Three SiGe PA modules: IBM 2022, IBM 2018, and IBM 2017
- 0.5-µm process
- The 2018 PA is designed for US CDMA/AMPS designs. In CDMA mode, it
  - features +28.5 dBm output power
  - 35% power added efficiency (PAE).
  - sports on-chip VSWR protection, a less than 1µA standby current
  - 6 x 6-mm package.

Conclusions

1. SiGe HBT technology combines transistor performance competitive with III–V technologies with the processing maturity, integration levels, yield, and cost. It has emerged from the research laboratory, entered manufacturing on 200-mm wafers, and is ready commercial RF and microwave market.
2. Power HBT design targeting high breakdown voltage with low current density can be obtained by designing a thick and lightly doped collector laye. A multifinger emitter configuration is required for high current density to reduce thermal effects

Conclusions

3. Specially designed SiGe HBTs used in CDMA handset PAs can have a breakdown voltage BV_{CE0} as high as 7.3 Vand 7 V, f_{max} of 50 GHz and 55 GHz , current gain of 180 and 80 for Atmel SiGe technology and IBM SiGe technology respectively
4. Commercially available SiGe based CDMA PAs can have an output power of 28 dBm, and power PAE over 35%. The acceptable linearity for specially designed circuitry can be as low as ACP~ 42dBc
5. Future SiGe PA designs should target linearity improvement at higher power levels typically required in today's handsets. Ongoing development efforts by the semiconductor industry should continue to improve device capability and performance levels of SiGe leading to it's increased use and new opportunities in RF analog products

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