Cost-effective Semiconductor Technologies for RF and Microwave Applications

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RF Markets & Applications

Communications

Security and Defence

Transport

Health

Community/monitoring

Education and

Entertainment

wireless, wired, mobile services

national, commercial, business, personal

integrated road systems, road safety, ACA

telemedicine, real time diagnostics, body sensors

Smart utility networks, pervasive networks

learning anywhere/anytime

Mobile Phones

Security

Wireless Infrastructure

Radar

Telemedicine

RFID

Femtocells

Automotive Radar

Mobile WLAN

WLAN

WPAN

Semiconductors for RF

- **Silicon (Si):** Bipolar, CMOS, BiCMOS, LDMOS
- **Gallium Arsenide (GaAs):** pHEMT, MESFET HBT, mHemt, BiFET
- **Indium Phosphide (InP):** pHEMT, HBT
- **Silicon-Germanium (SiGe):** HBT
- **Gallium Nitride (GaN):** HEMT, MOSFET
- **Superior mixed signal integration capabilities in Si.**
- **Supplied by IDMs or Foundries – mostly to OEMs.**
 - Integrated device manufacturers supplying components and modules
 - Foundry services providing finished wafers
- **\$255 Billion market for semiconductors in 2008¹**
 - \$3Bn GaAs MMIC Market with \$220M in Foundry Business²
- **Technology drivers for lower cost, higher functionality and higher speed/frequencies of operation**
 - Millimetre-wave opportunities for compound semiconductors and SiGe.

“Junction for the Function*”

The choice of semiconductor is based on:

- **Cost** – design & production
- **Performance** – electronic, reliability
- **Process yield and consistency**
- **Integration** – power and functionality/\$
- **Availability, capacity and delivery time**

The final choice of semiconductor technology will depend on the application but only the right combination of all parameters will provide the optimum solution at the right cost.

Cost/function & Performance

RF Semiconductor Technologies

Technology Cost Drivers

- Increasing design cost for decreasing gate length in Si.
- Mask set costs in silicon vary from \$100k to \$1m as the gate length shrinks from 0.18 μm down to 65 nm.
- RF Si CMOS and SiGe are cost-efficient in very high volumes.
- Mask sets for GaAs typically cost \$25k to \$50k.
- Design Iterations take typically longer in silicon (8 weeks).
 - GaAs hot-lot cycle times typically 4 weeks
- GaAs is still the technology of choice for RF power and switching in cellular and WLAN markets
 - GaAs offers better power efficiency
 - GaAs costs continue to fall and yields are high in 150mm.
 - GaAs offers high levels of integration with E/D pHEMT, BiHEMT
- Wafer Cost: \$1000 (CMOS) \$2500 (SiGe); GaAs \$1000 to \$2500
..... + design + masks.

Si RF CMOS

- RF CMOS is well suited to high levels of integration and System on Chip solutions (SoC) using 200mm wafer technology for high volume markets.
- High volume CMOS transceiver circuits, low-Noise amplifiers, PLL, prescalers, VCOs and synthesizers – typically to 3 GHz (demonstrated up to 104 GHz).
- RF switches, including SP6T and SP9T for cellular handsets, with insertion loss of <0.6 dB and isolation of better than 39 dB.
- Bluetooth can be fabricated and implemented using CMOS because of the low powers involved and well suited to very high volumes.

RF CMOS transceiver, over 500 million shipped 1.9 to 2.4 GHz (Plextek + National Semiconductor)

Bluetooth (Ferret)

Quadband RF CMOS transceiver (Infineon)

Flip-Chip SP6T and SP7T RF switches (Peregrine Semiconductor)

Peregrine Semiconductor RF switches and attenuators

RF CMOS for Wireless PAs

- Biggest issue with CMOS for RF applications is the low breakdown voltage, requiring very challenging impedance transformation for high output power levels and careful handling of mismatch (e.g. from cellular phone antennas).
- Until recently, CMOS power amplifiers were not suitable for cellular phones PAs (GaAs domination).
 - New developments in device and circuit technologies show the potential for CMOS power amplifiers for mass-market applications.
- The largest challenges faced by CMOS for PA design remain in terms of output power, mismatch handling, and thermal management.
- IBM have 50V breakdown voltage 180 nm RF process.

*Silicon Laboratories
Si4300 GSM/GPRS PA*

**5.8 GHz 1V CMOS PA (2007
RFIC Best Student Paper),
Haldi, Berkeley**

Workshop: WSA (RFIC 2009) “Advances in CMOS
RF Power Amplifiers for Cellular”

SiGe BiCMOS Technology

- SiGe established as a low voltage high performance technology for RF through to millimetre-wave with f_T 's as high as 200 GHz.
- Mask set costs make this best suited to high volume applications.
- 0.13 μm , 0.18 μm & 0.35 μm CMOS gate lengths and SiGe bipolar transistor (SiGe BiCMOS) with supply voltages of 1.8 or 3.3 V.
- Suitable for RF to mm-wave applications.
- Normally PA's and LNA/PA filters off-chip

SiGe TRF6302 Dual Band WCDMA Transceiver
(Texas Instruments and Jazz)

RF Silicon on Insulator (SOI)

- RF antenna switches on SOI: keys for SOI are isolation and power handling. Isolation of 32 dB achieved and insertion loss better than 1dB up to at least 26 dBm (STM's SP6T).
- RF amplifier examples:
- 1.8 GHz Handset PA+RF Switch, 11 dB gain, 50% PAE, V_{DD} 3.5V (Costa et al, IEEE-MTT-S 2007)
- 5 GHz WLAN LNA, 14 dB gain, 1.4 dB NF, V_{DD} 1.2 V, (STMicroelectronics 130 nm)
- 80 GHz LNA, 7.2 dB gain, 5.7 dB NF (STM 65 nm 2007)
- VCO : 5 GHz, -130 dBc 1 MHz from carrier

5 GHz LNA: Giancesello, ISIC 2007

Integrated Power MOS x-section showing Soitec TF-SOI substrate

Integrated Power Amplifier- T/R Switch (RFMD)

Five layer metal SOI CMOS
www.surrey.ac.uk

Compound Semiconductor Technologies

Despite the scale of Si industry, compound semiconductors still dominate some markets:

- Handset & WLAN Front End Modules
- Higher frequency applications above 8 GHz
- Defence

GaAs 150mm wafer diameter, stepper based technology:

- Very cost effective for production quantities into millions.
- GaAs is capable of providing both high volume and high performance technologies:
 - MESFET D and E/D, HFET, BiFET, pHEMT D and E/D, HBT, BiHEMT, mHEMT.
 - Integration of GaAs HBT and E/D mode pHEMT = BiFET (WIN, Triquint, Skyworks, Anadigics)
 - Allows single chip PA, switch, LNA, control.

0.25μm T-gate (WIN)

GaAs MMIC Market Growth

GaAs MMIC Market by Application 2006-2011

Source: Strategy Analytics Feb 2008

- Cellular 2.5/3G
- WLAN
- 4G (WiMAX, LTE)
- Base stations
- Pt to Pt Radio
- Satellite (VSAT)
- Military – phased array radar
- Automotive
- Other

- 85% of the GaAs market is in MMICs
- Growth driven by wireless comm's and notably cellular handsets – TAM expected to be \$5 Bn by 2011
- 2.5/3G Cellular comm's dominant > \$2.5 Bn.
- Wireless LAN > \$ 1Bn in 2011

GaAs Foundry Business

- **Success in the GaAs foundry business depends on:**
 - Having the right technology – a range of technologies is needed today.
 - Strong customer support & ability to identify new customers/markets
 - Establishing trusting relationships and excellent product support
 - Financial viability for capacity expansion as demand grows and varies.
 - Sufficient volume to ensure lower production costs and material costs
 - High quality, high reliability and high yield.
- **Consolidation has occurred even though market continues to grow:**
 - Filtronic fab' acquired by RFMD, Suntek exited, GCTC acquired by WIN
 - Leaving only four major GaAs foundries in the market today:
 - TriQuint Semiconductor, Win Semiconductor, AWSC, GCS
- **Successful foundries offer customers a wide range of process technologies and the ability to manufacture wafers in high volume**
 - High volume means capacity for 10,000 to 100,000 wafer starts per year

GaAs for Cellular and WLAN

GaAs pHEMT technology is widely used for high performance cellular and WLAN RF switches – Compact, Low Loss, High Isolation RF Switch for quad band applications

GaAs-based HBT and MESFET technology is used extensively for RF PA's, achieving high efficiencies, good linearity and compact solutions.

Relatively easy designs and tolerance of wide range of VSWR's from antenna.

Flip-chip technology widely used.

Normally integrated using module technology.

SP6T Filtronic switches

3G PA Duplexer Module (Triquint)

RFMD PowerStar HBT
PA Module

Anadigics CDMA PA
HBT+FET on same die

Skyworks Chip Sets

Microwave and Millimetre-Wave Multi-function GaAs MMICs

- High performance microwave and millimetre-wave MMICs – cost-effective solutions from 1 to 60 GHz.
- Cost reduction and performance improvement in point-point and other demanding RF systems.
- Multi-function MMICs used in Filtronic point-point system reduced part-count 20-fold, with faster assembly, less tuning and higher reliability.

Courtesy Filtronic plc

Complete microwave point-point Transceiver – 15 parts (Filtronic).

Increasing Scale - 150mm Wafer Compound Semiconductor Fabs

Hwaya Technology Park Taiwan

Hwaya Technology Park Taiwan

Newton Aycliffe, UK

Hillsboro, Oregon

Richardson, Texas

- **Modern, 150mm GaAs facilities, with high volume, high yield and low finished wafer costs.**
- **Success of foundry model now in GaAs, as in Si and SiGe.**

Integration Trends – On-Chip PAs

- PA is the most expensive RF element.
- TX power range below 1W is the target of PA integrated SOC.
- PA IC/module: ~ \$1. On-chip PA: 1.5 mm x 2 mm = ~\$0.15
- Below 1W output power can be delivered using an on-chip PA 2-6GHz

Increasing function/area – On-Chip PA

- Reducing inference in MMICs

Unwanted Coupling through surface or near surface of IC can occur.

Improving on-chip isolation:

- Reduction by Circuitry
 - Use differential configuration/elements.
- Reduction of Leakage through Surface
 - Use multi-well / deep trench isolation.
 - Use wider on-chip shielding GND metal.
- Reduction of Leakage through Bulk
 - Use GND VIA, but expensive
 - Use thinner Si-substrate.
Thinning from 300 to 125 microns (5 mil) gives a 12 dB improvement in isolation..
- Design of differential PA without current source improves P_{sat} . Consideration of imbalanced operation is important for reactive inter-stage matching PA.

Noriharu Suematsu

Integration - SiGe 5.8 GHz TRX-MMIC

Tx output power	15.5dBm
Tx ACPR	-33.5dBc
Rx NF (DSB)	11.2dB
Rx conversion gain	22.0dB
Rx phase noise	-106.7dBc/Hz at 1MHz offset
Current consumption	366 mA

Low Cost RF GaAs Integration

Die Level Integration

- E/D pHEMT
- BiHEMT
- GaAs passives
- Copper Flip Chip

WLAN / Bluetooth

Module Integration

- Power Amplifiers
- Switches
- BAW/SAW Filters
- Embedded passives

GPS: SAW-LNA-SAW

Integration - Flip Chip Modules

- Flip-chip technology based on Cu bumps allows cost-effective module assembly.
- Triquint produced first Flip-Chip based GSM PA Module in volume in Feb 2005.
 - Very compact GSM PAM ($5 \times 5 \times 1.1 \text{ mm}^3$)
 - Excellent RF Performance
 - Low cost, high-volume production
- Flip chip technology widely used now.

Copper Bump Images

Courtesy of

TriQuint
SEMICONDUCTOR

Multi-Chip Assemblies and Packaging for High Volume Cost-sensitive RF applications

PiP/PoP Wire Bonding

PiP: Package in Package
PoP: Package on Package

Multi-Chip Assemblies and Packaging for High Volume Cost-sensitive RF applications

Chip on Chip

SONY

Advanced LSI packaging

Chip on Chip packaged
cross-section

Wire Bond

RF Power Transistor Market

- RF Power transistors used in:
 - Wireless infrastructure, >50% of the market
 - Broadcast
 - ISM
 - Military
 - Commercial avionics and non-cellular communications
- Total accessible market for Power Transistors below 3GHz currently \$750m and will exceed \$800m by 2011
- Volume for W.I. market growing but price pressure causing slight decline in overall revenues – other markets show good growth in the next 5 years.
- Key technologies: LDMOS, GaAs FET and emerging GaN HEMT.

RF Power Semiconductors - LDMOS

- **LDMOS**

- Dominant in cellular infrastructure space
- LDMOS is the leading RF PA device technology for the cellular infrastructure market - beats all others on cost.
- Proven reliability
- 50V technologies now being introduced ($\eta > 73\%$ with 23 dB gain)
- Maximum frequency of operation currently at 3.8 GHz – likely to rise to 5 GHz (currently $f_T > 11$ GHz)
- Challenged by III-V technology in applications above 4 GHz.
 - GaAs and GaN have higher f_T , current/mm and power densities.
- LDMOS has demonstrated excellent Doherty PA performance, and is being developed for other architectures (Class F, Drain Mod, etc)

Cost drivers in RF HPAs

- Power Amplifier devices are major contributors to system BOM cost
- Device level cost drivers include packaging & semiconductor
- Integration and low cost over-molded plastic packaging are innovative ways to effectively respond to price pressures

1.8-1.9 GHz GSM Edge Chipset

OM Plastic GPA +

OM Plastic 100W LDMOS IC

- 47dB Gain
- 100W GMSK / 40W Edge
- 40% PAE @ 48.5dBm
- Fixture size 70 x 50 mm²

Also: 900 MHz version of this 100W for GSM

Courtesy of Freescale Semiconductor, Inc

www.surrey.ac.uk

High efficiency HPAs based on LDMOS power ICs

- A Linear 250 Watt Doherty Power Amplifier
 - Based on Two-Stage Power ICs for 1.8 GHz Single and Multi-Carrier GSM Applications using 2 x MW7IC18100
- A 900 MHz, 200 W Silicon LDMOS Power Amplifier using Integrated Passive Devices in a New Over-Molded Plastic Package
 - *highest reported RF power in a plastic package*
 - Input match with integrated passive IC, output match with MOSCAP & bond wires

MRF8S9200

Papers on these amplifiers will be presented at IMS on Thursday, Session TH3A

GaAs Power Transistor Technologies

- Low cost base, mature and established technology.
 - pHEMT or MESFET technologies on 150mm o
 - Very good gain and power up to 60 GHz
 - Can compete at ~ \$1/Watt up to 5 GHz.
- Large devices up to 100W per die ~ 200 mm gate periphery
 - 3W/mm, 65% PAE at 3.5 GHz (Triquint)
 - 800 mW/mm, 53% PAE at 29 GHz (WIN)
- Substrates can be thinned to 50 μm thickness
 - low inductance via and low thermal resistance
- High breakdown Voltage of typ. 35V (up to 80V).
- Outstanding reliability – $>10^{10}$ hours at 125 $^{\circ}\text{C}$
- Outstanding production yield possible
 - eg: 96% KGD for an X-Band 5W MMIC

Triquint 8W S-Band PA

100W FET
RFMD (UK)

Triquint PA

X-Band 19W CW 40% efficiency

www.surrey.ac.uk

Gallium Nitride Power Transistors

- GaN – on SiC or on Si substrates.
 - 10x higher breakdown electric field than GaAs or Si.
 - High saturated velocity than GaAs or Si
- Advantages
 - Higher voltage operation (50V or higher)
 - High current capability (1 A/mm) and high power densities.
 - Higher frequency operation up to 80 GHz
 - High temperature compatibility (excellent thermally)
 - Higher impedance levels for a given power – attractive.
- Challenges
 - Cost is likely to remain a challenge compared to GaAs or LDMOS.
 - Material quality/defect density concerns (yield, performance anomalies)
 - Reliability data improving. Infrastructure applications are very demanding.
- Applications from RF to millimeter-wave including LNAs and PAs.

Triquint 100 Watt
GaN on SiC (20mm)

GaN High Power Transistors

- RFMD demonstrated a 400W, 48% PAE, 10 dB gain HPA at 3.5 GHz, using 2 x 22.2 mm devices operated at $V_{DD} = 65V$ (10% duty cycle)
- Eudyna has achieved breakdown voltages of 350 V from their GaN commercial range with 53 dBm, 57% PAE at 2.6 GHz at $V_{DD} = 50V$
- Triquint have 100 Watt GaN single die on SiC single achieving 46% PAE with 15 dB gain, at 3.5 GHz operated at $V_{DD} = 40V$.
- Nitronex launched a 200W packaged part in January 2009 achieving 63% efficiency with 18.3dB gain at 900MHz, operating from 28V.
- GaN power FETs are well suited to switching designs such as Class E and pre-distortion designs.
- GaN HEMTs allow LNAs to have very high intercepts – ideal for radar applications.

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400W HPA , K. Krishnamurthy, et al,
IMS2008 (RFMD)

77 GHz Technology for Automotive Radar

- The 77 GHz automotive radar market is highly cost-sensitive
 - Compact designs are essential
 - High performance, reliable technology is essential
- GaAs pHEMT technology capable of delivering 77GHz MMIC technology for automotive radar since 1995
 - Die size shrinkage 7 fold in area in 10 years.
 - Multichip and multi-technology solutions.
- SiGe 77 GHz solutions available (incl. single chip):
 - Jazz 180nm SiGe BiCMOS with VCO, tripler, PA, pre-scaler.
 - Hajimri's single chip phased-array radar transceiver in IBM8HP SiGe (Caltech)

SiGe 77GHz VCO

77GHz GaAs Power Amplifier

77GHz Flip-Chip Low Noise Amplifier

77 GHz GaAs Switch Triquint

Si and polySiGe MEMS Switches

Radant MEMS Switch

Memtronics RF switch
(Capacitive)

- RF MEMs now available in volume and suitable for chip-on-chip assembly.
- RF MEMs switches have high linearity.
- MEMs market expected to grow to over \$200m by 2011, in test and instrumentation, wireless infrastructure, defence.
- Electrostatic MEMS switches have been shown to have 100 billion switching cycles (Radant).
- MEMS switches have been incorporated at wafer level.
 - Insertion loss <0.5 dB up to 38 GHz (~ 0.3dB at 2 GHz).
 - Isolation 20 dB at 10 GHz, >23 dB at 2 GHz
 - On-response time 5 μ s. 40-120V actuating voltage.

Future ICT Technology Drivers

Personal Mobile

Smart Utility Networks

Wearable electronics
Snowboard jacket with MP3-Bluetooth module

- **High-end snowboard jacket with integrated docking station for MP3-Bluetooth module**

Wearable health and comfort monitoring

C. Claeys, H. De Man IMEC & W. Weber, Infineon and Upkar Dhalilwal

Conclusions and Observations

- RF technologies must provide RF performance at the lowest cost for today's volume markets.
- Si RF CMOS and SiGe are displacing GaAs from some high volume market segments from 800 MHz through to 100 GHz.
- Mask & design costs remain significant for RF CMOS and SiGe
 - these technologies are more suited to very high volume applications, such as WLAN, where they can be highly cost-effective. GaAs remains competitive in lower volumes.
- RF SOI is well suited to low power RF and provides easy mixed signal integration at lower cost.
- Trend towards higher levels of integration continues with reduced cost/function at both chip level and module assembly:
 - Multi-level RFIC Chip, multi-chip, chip on chip, PoP, PiP.

Conclusions and Observations

- **GaAs remains competitive for power, switching, high performance and millimetre-wave applications**
 - high yields and falling costs have increased its competitive position
 - ideal for product areas with rapid churn or limited volume runs.
- ... and GaAs will remain the most cost effective solution for high power, high frequency applications.
- LDMOS continues to dominate wireless infrastructure with costs falling below \$1/W.
- Impressive GaN performance will compete with lower cost GaAs power FETs and with LDMOS for WI in due course
- The potential for integrating compound semiconductors and silicon technologies on Si substrates has already been demonstrated - this could delivery the optimal solution!

Acknowledgments

- **WIN Semiconductors**, John Atherton, Bob Donahue
- **Triquint**, Glen Riley, Mike Peters
- **Freescale**, John Wood, Wayne Burger
- **Sony Semiconductor**, Chris Clifton and Kamegaya-san
- **Mitsubishi Electric Corp.**, Noriharu Suematsu
- **ADI**, Wolfgang Bösch
- **IMEC**, Cor Claeys
- **Filtronic**, Hemant Mardia
- Upkar Dhaliwal