The Compound Semiconductor Roadmap Embedded in the ITRS: Implications for the MANTECH Community

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Outline

- Roadmap Tutorial
- Trends
- Lessons Learned from Existing Roadmaps
- Compound Semiconductors in the ITRS
  http://public.itrs.net/Files/2003ITRS/Home2003.htm
  http://www.itrs.net/Common/2004Update/2004_04_Wireless.pdf
- Implications for the MANTECH Community
- Conclusions

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What is a technology Roadmap?

A technology roadmap in the context of this talk

is an <u>industrial</u> consensus

with inputs from the
<u>research community</u> and

if appropriate with inputs
from <u>governments.</u>

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Technology Roadmaps

" A *roadmap* is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field."

"Roadmaps allow our industry leaders to communicate convincingly with those in government and business regarding their support of our goals."

"Roadmaps are working now in industry and they are beginning to gain a stronghold in science."

----- Robert Galvin, Chairman of the Executive Committee of Motorola, editorial in *Science* **280**, 8 May 1998, p. 803.

Why is a technology roadmap useful?

It increases the rates of both technology development and deployment.

A technology roadmap is an effective technique to

1) **Reduce uncertainties in investments**
2) **Use changes among competing technologies as opportunities**
3) **Increase the probability for more robust economic performance**
4) **Guide critical research**
5) **Assist in setting priorities for resource allocations**

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Why You Should Be Interested in Roadmaps?

- **Some compound semiconductors coexist/compete with Si and SiGe (i.e., with CMOS compatible processing).**

- **Smaller budgets place greater emphases on consensus-based planning for smarter investments.**

- **Participants identify what is common knowledge and what is truly intellectual property.**

- **Participants gain knowledge, broaden their industrial outlook and awareness, and become more valuable employees.**

When is a technology roadmap most effective?

When it:

1) Increases industrial cooperation and

2) Produces positive changes in how companies work together.

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Key Drivers for a Technology Roadmap

Key drivers that bring companies together to share common pre-competitive interests and goals include:

1) **Market share dynamics among competing technologies and**
2) **Costs of doing business and maintaining its infrastructure becoming too great for one company or one country to assume.**

Metrics for Success Include:

1. **Determine whether the compound semiconductor infrastructure permits going from tolerances in processing parameters (e.g., composition, thickness, and doping density) to acceptable costs, yields, reliabilities, and bit error rates in a system.**

2. **Determine whether sufficient knowledge exists to determine how the above examples of tolerances in processing parameters vary with time and with market application.**

Metrics for Success (continued)

3. **Assess whether the compound semiconductor market segment growth is greater than that projected today.**

4. **Measure the investments that commercial companies commit to the roadmap activities.**

5. **Document the number of roadmap citations by university, industry and government as a function of time.**

Trends

- Bigger wafers and smaller devices.
- Increased R & D and production facilities costs are becoming too great for any one company or country.
- Shorter process technology life cycles.
- Emphasis on faster characterization of manufacturing processes.
- All - global participants in the “Si CMOS ecosystem” now collaborate to develop and improve manufacturing technologies; e.g., ITRS and International SEMATECH.

Trends (continued)

- Competition among Si CMOS manufacturers is shifting from an emphasis on technology and fabrication to a much greater emphasis on product design, architecture, algorithm, and software; i.e., shift from technology-oriented R&D to product-oriented R&D.

- Many observers credit consensus-based planning and deliberate roadmapping efforts for the sustained average annual growth rate of 15% for the silicon semiconductor industry over this past decade.

- Users interested more in function and price than in process.

Trends (continued)

- **Communications products may replace computers as a key driver of volume manufacturing.**

- **Present and future volume products include:**
  - **cell phones and video phones**
  - **Bluetooth appliances**
  - **optoelectronics**
  - **automotive electronics that add functionality of home and office to cars and trucks.**

History – Where are compounds addressed?

- **NEMI (2004 Roadmaps)**
  - some material specificity in energy storage, RF components, and optoelectronics
  - numerous market applications

- **ITRS (2003 Edition and 2004 Update, and 2005 Edition in-progress)**
  - very material and process specific (limited primarily to crystalline Si CMOS; but now has RF and AMS compounds)
  - limited to a few very big market applications (microprocessor-logic, memory, and RF and analog/mixed-signal)
  - simple metrics for determining progress (e.g., line width, and density)

- **OIDA (Recent Reports)**
  - some material specificity in sensors and detectors
  - numerous market applications

Lessons Learned from Si CMOS Roadmaps

- Many technology barriers, once thought to be of concern to a few companies, are common through out the industry. Overcoming such barriers offers an appropriate focus for technology roadmaps.

- Prior to mid 1980's, most Si CMOS companies assumed that over 50% of what they knew was proprietary and not to be part of consensus-based planning and collaborations.

- From the late 1980's to today, most Si CMOS companies found that over 50% of what they know is not proprietary and may be shared with other companies for a globally more competitive industry.

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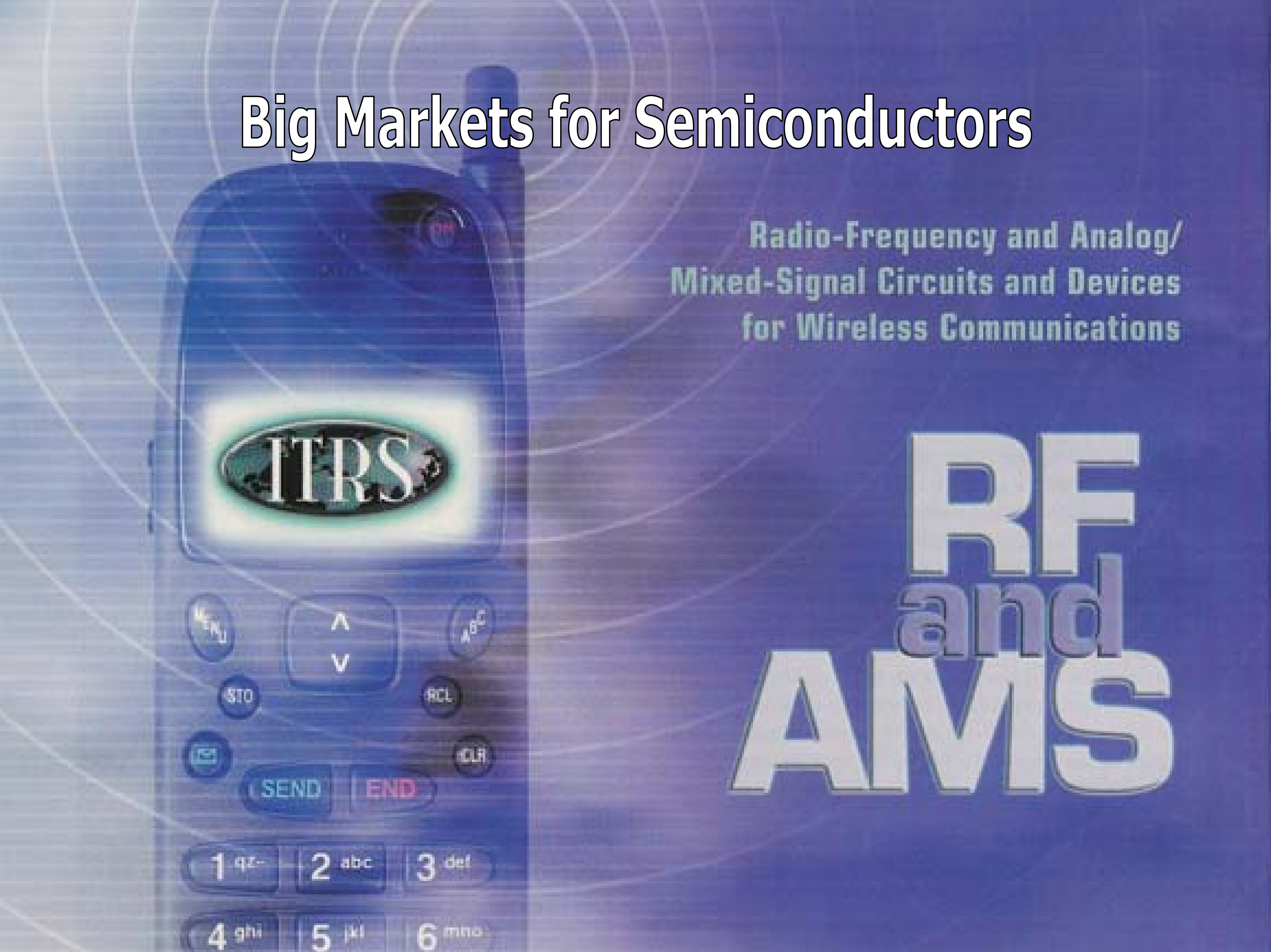
Lessons Learned from NEMI

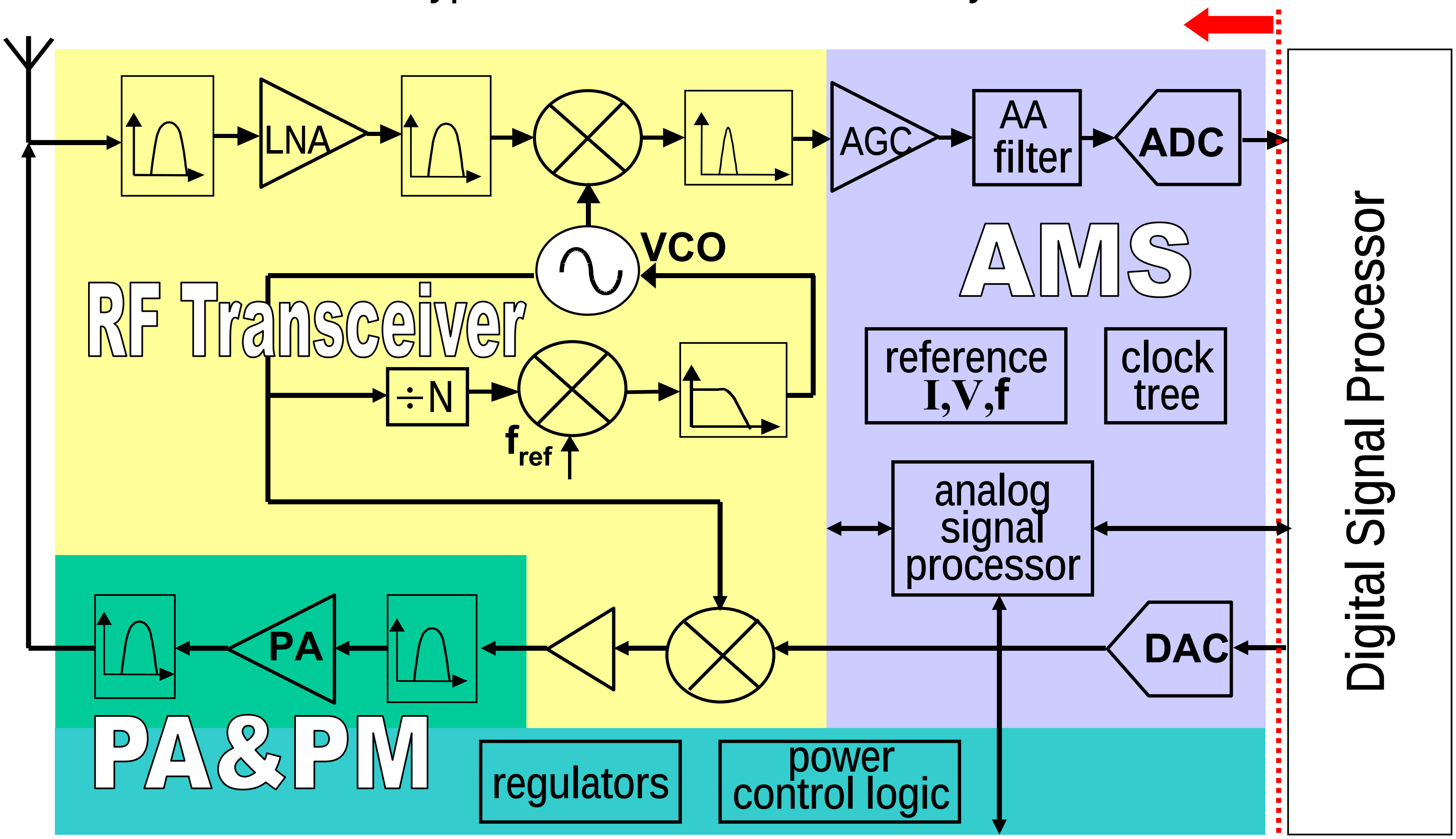
- Discussions with senior industrial managers for acceptance.
- Worked from a "virtual product" as basis for bringing all stakeholders together.
- Challenge was to have a large enough effort to be effective, but still focussed enough to have measurable progress.
- Everyone has similar problems. Much IP is common to everyone. Industry moves faster when these are recognized and common problems are solved.

Big Markets for Semiconductors



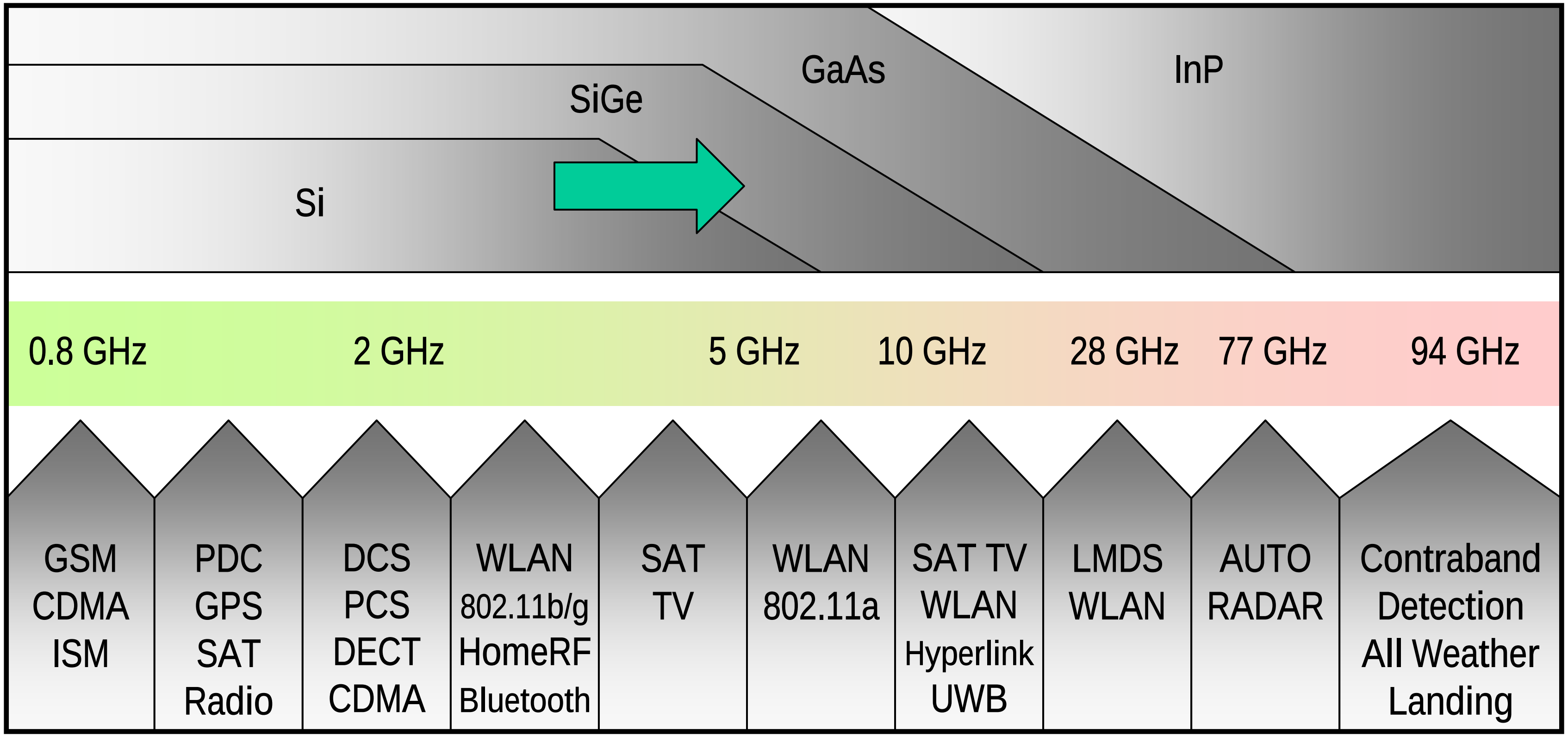
Scope of RF and AMS Technology Roadmap

Circuit functions of a typical mobile communication system 0.8 GHz -100GHz



2005 Application Spectrum

Today's Technology Options for Designers



What will be the technology options in 2011? Will frequency continue to be a technology differentiator or will it be noise, output power, efficiency, linearity, high voltage operation, and cost?

RF and AMS ITWG Objectives

- Use wireless IC as system / technology driver for ITRS
- Address intersection of Si-based technologies with III-V compound semiconductors and other potential technologies (MEMS, BAW, Passives, ..)
- Present technical challenges and requirements for AMS & RF IC technologies in wireless applications for cellular phones, WLAN/WPAN, automotive radar, and phased array RF systems, frequencies 0.8 GHz - 100GHz
- 34 members (22 US, 6 Europe, and 6 Asian Pacific
- Divide RF and AMS Working Group into 5 sub-groups
  - CMOS for RF and AMS (0.8 GHz - 10 GHz)
  - Bipolar for RF and AMS (0.8 GHz - 10 GHz)
  - Power Amplifiers and Power Management (0.8 GHz – 10 GHz)
  - Passives for RF&AMS and PA (0.8 GHz – 10 GHz)
  - Millimeter Wave (10 GHz – 100 GHz)

Working Strategy

- **Methodology**
  (1) Communication protocols/standards – governing requirements
  (2) Circuits: performance figure of merit – trends/requirements
  (3) Devices: performance trend – solutions/challenges

- **Divided into 2 frequecy bands**
  (1) 0.8 GHz - 10 GHz *(CMOS, Bipolar, Passives, Power Amplifiers)*
  (2) 10 GHz - 100 GHz (*mm-Wave*)

- **Generates roadmap tables in each of the 5 areas:**
  requirements, difficult challenges, potential solutions

- **Tables cover technologies**
  Si CMOS, SiGe HBT, Si LDMOS, GaAs, InP, SiC, GaN
  and device structures
  MOSFET, MESFET, PHEMT, MHEMT, HBT, LDMOS, on-chip passives

- **Outcome: RF & AMS technology roadmap**

Key Considerations

- Drivers for Wireless Communications
  - Cost (die size, part count)
  - Power consumption
  - Functionality
  - Device operating frequencies, channel bandwidth, transmit power, etc. – determined by wireless communication standards and protocols

- Non-traditional ITRS roadmap parameters
  - Regulations from governments determine system spectrum
  - Standards and protocols drive frequencies and performance
  - Production – may be initially specialty foundries and captive
  - applications

- Cost / Performance drives integration
  - Signal Isolation (technology, circuit/system, EDA)
  - Analog shrink (power supply, area, novel device structures)
  - Filters and T/R switches integration (MEMS)
  - Multi-band Multi-mode applications SOC vs. SIP / RF modules

Difficult Challenges

- Optimizing analog/RF CMOS devices with scaled technologies: mismatch, 1/f noise, and leakage with high-k gate dielectrics
- High density integrated passive element scaling and use of new materials: Q-factor value for inductors; matching and linearity for capacitors
- Reduced power supply voltages: degradation in SNR and signal distortion performance
- Reduced device breakdown voltage in scaled technologies
- High frequency devices with increased operating voltage for base station applications
- Difficulty and cost of integrating various analog/RF and digital functions on a chip or in a module

Implications for the MANTECH Community
Selected III-V Difficult Challenges

- Compound semiconductor substrate quality
- Signal isolation – a role for more optoelectronics
- Process equipment for fabrication at low cost
- Larger size compound substrates [GaAs, SiC and InP] for lower chip costs and compatibility with silicon processing equipment
- Epitaxial layers in compound semiconductors - engineering to relieve stress in heteroepitaxy
- Increased RF performance for III-Vs predominantly through materials and bandgap enginnering; not through scaling as in silicon technologies

RF and AMS Summary of Trends
Implications for the MANTECH Community

Power Amplifiers and Power Management

- **Highly integrated power amplifier modules will be realized on multilayer laminates or ceramics with embedded passive technologies.**
- **Plastic will become the dominant packaging format for base station semiconductor devices and will significantly reduce the component cost.**
- **The use of compound semiconductors and higher operating voltages will increase the RF power density of base station devices.**

Implications for the MANTECH Community

- **Millimeter Wave (10-100GHz)**
  - **Projections will go to near term [~2011] only, as in previous years, because**
    - **III-Vs do not have the decades of history for high volume production from which to extrapolate parameters as does silicon.**
    - **Industry is smaller and less mature and has lower investments than silicon.**
  - **Gate dimensions are not shrinking as fast as predicted in 2003-2004 roadmaps.**
    - **70 nm gate not in production until 2007 time frame**
    - **advances in performance tied more to material and device technologies**
      - **e.g., MHEMTS have higher performance than PHEMTs have at same lithographic dimensions**
  - **May see some technologies becoming obsolete over this decade**
    - **Low noise GaAs MESFETs are expected to have no new designs past 2006.**
    - **Foundries are likely to produce for legacy products/end of life buys only; same for low voltage power MESFETs.**
    - **PHEMTs and InP HEMTs may lose ground to MHEMTs late in decade.**
  - **GaN is advancing much faster than predicted in 2003/2004.**
    - **Some parameters colored “red” for 2007 have already been achieved; but materials quality and device reliability are still issues.**

RF and AMS "Production"

- **ITRS consensus for when Si CMOS "production" based on a new technology begins for ITRS Technology Requirements Tables**
  - **10K wafers per month by one company or foundry followed within 2 or 3 months by another company ore foundry**

- **ITRS consensus for RF and AMS "production" does not exist. RF and AMS companies have many more different business models**
  - **suggestions include:**
    a) 5K wafers per year
    b) 2% to 5 % of an existing market – total existing market (TAM)
    c) Insertion into volume products by a captive foundry

Implications for the MANTECH Community

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—FET							
GaAs MESFET (digital mixed-signal)							
Gate length—L physical (nm)	**250**	**250**	**150**	**150**	-	-	-
Minimum M1 pitch (nm)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F_t - enhancement mode (GHz)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F_t - depletion mode (GHz)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BV_{GD} (1mA/mm, V_g=0) (vol	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Power delay product at gate d	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Shortest DCFL gate delay (pS)	**10**	**10**	**6**	**6**	-	-	-
Interconnect metal layers	**4**	**4**	**5**	**5**	-	-	-
Interconnect metal	**Al**	**Al**	**Al**	**Al**	-	-	-
Inter line dielectric constant (effective)	**4.2**	**4.2**	**3.1**	**3.1**	-	-	-
Gain at 94 GHz, at P_{1dB} (dB)***	**6**	**6**	-	-	-	-	-

GaAs MESFETs for low voltage applications will tend to obsolescence; but high voltage applications below 10 GHz may remain.

Work-in-Progress DRAFT - Subject to change - Not for Publication.

Table 57 Millimeter Wave 10 GHz – 100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology — FET							
GaAs PHEMT (low noise)							
Gate length (nm)	**100**	**100**	**70**	**70**	**50**	**50**	**32**
F_t (GHz)	**130**	**130**	**150**	**150**	**170**	**170**	**200**
Breakdown (volts)							
I_{max} (mA/mm)							
G_m (S/mm)							
NF (dB) at 26 GHz, 18–20 dB associated							
NF (dB) at 94 GHz, 8–10 dB associated g							
GaAs PHEMT (power)							
Gate length (nm)							
F_{max} (GHz)							
Breakdown (volts)							
I_{max} (ma/mm)							
G_m (S/mm)							
P_{out} at 26 GHz and peak efficiency (mW/							
Peak efficiency at 26 GHz (%)							
Gain at 26 GHz, at P_{1dB} (dB)***							
P_{out} at 94 GHz and peak efficiency (mW/							
Peak efficiency at 94 GHz (%)	**15**	**15**	-	-	-	-	-
Gain at 94 GHz, at P_{1dB} (dB)***	**6**	**6**	-	-	-	-	-

III-Vs have technical edge for high performance at front end; e.g., LNAs and PAs.

HEMTs and PHEMTs provide lowest noise figures.

Frequency and power level determine technology choices for highest power, efficiency, and linearity. LDMOS acceptable below 3 GHz and III-Vs best above 3 GHz.

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued)
- excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—FET							
InP HEMT (low noise)							
Gate length (nm)	-	**100**	**70**	**70**	**50**	**50**	**32**
F_t (GHz)	-	**200**	**240**	**240**	**300**	**300**	**350**
Breakdown (volts)	-	**4**	**3.5**	**3.5**	**3**	**3**	**2.5**
I_{max} (ma/mm)	-	**700**	**700**	**700**	**650**	**650**	**600**
G_m (S/mm)	-	**1**	**1.2**	**1.2**	**1.5**	**1.5**	**1.8**
NF (dB) at 26 GHz, 20–23 dB associated gain	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
NF (dB) at 94 GHz, 10–13 dB associated gain	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
InP HEMT (power)							
Gate length (nm)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F_{max} (GHz)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Breakdown (volts)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
I_{max} (ma/mm)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
G_m (S/mm)	-	-	**0.8**	**0.9**	**0.9**	**0.9**	**0.9**
P_{out} at 26 GHz and peak efficiency (mW/mm)	-	-	**400**	**400**	**450**	**450**	**450**
Peak efficiency at 26 GHz (%)	-	-	**30**	**40**	**50**	**50**	**50**
Gain at 26 GHz, at P_{1dB} (dB)***	-	-	**12**	**15**	**15**	**16**	**16**
P_{out} at 94 GHz and peak efficiency (mW/mm)	-	-	**250**	**300**	**350**	**350**	**400**
Peak efficiency at 94 GHz (%)	-	-	**25**	**40**	**40**	**45**	**45**
Gain at 94 GHz, at P_{1dB} (dB)***	-	-	**6**	**8**	**10**	**10**	**12**

Although the gap between InP and SiGe is closing, InP has the advantage of higher breakdown voltages while SiGe BiCMOS has the advantage of higher integration densities.

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—FET							
GaAs MHEMT (low noise)							
Gate length (nm)							
F_t (GHz)							
Breakdown (volts)							
I_{max} (ma/mm)							
G_m (S/mm)							
NF (dB) at 26 GHz, 10–23 dB associate							
NF (dB) at 94 GHz, 10–13 dB associate							
GaAs MHEMT (Power)							
Gate length (nm)	-	-	-	**200**	**100**	**100**	**100**
F_{max} (GHz)	-	-	-	**200**	**250**	**275**	**300**
Breakdown (volts)	-	-	-	**8**	**8**	**8**	**9**
I_{max} (ma/mm)	-	-	-	**600**	**600**	**600**	**600**
G_m (S/mm)	-	-	-	**0.8**	**0.9**	**0.9**	**0.9**
P_{out} at 26 GHz and peak efficiency (mW/mm)	-	-	-	**350**	**500**	**600**	**750**
Peak efficiency at 26 GHz (%)	-	-	-	**45**	**55**	**55**	**60**
Gain at 26 GHz, at P_{1dB} (dB)***	-	-	-	**12**	**15**	**16**	**16**
P_{out} at 94 GHz and peak efficiency (mW/mm)	-	-	-	**200**	**350**	**400**	**450**
Peak efficiency at 94 GHz (%)	-	-	-	**25**	**40**	**45**	**45**
Gain at 94 GHz, at P_{1dB} (dB)***	-	-	-	**6**	**8**	**10**	**12**

GaAs MHEMT will supplant GaAs PHEMTs and InP HEMTs for low noise front end and power applications above 40 GHz.

III-Vs enable higher operating voltages and greater RF power densities for base stations.

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—FET							
GaN HEMT (low noise)							
Gate length (nm)	-	-	-	-	**150**	**100**	**100**
F_t (GHz)							
Breakdown (volts)							
I_{max} (ma/mm)							
G_m (S/mm)							
NF (dB) at 26 GHz, 14 dB g							
GaN HEMT (power)							
Gate length (nm)							
F_{max} (GHz)	-	-	-	-	**100**	**100**	**150**
Breakdown (volts)	-	-	-	-	**>40**	**60**	**60**
I_{max} (ma/mm)	-	-	-	-	**>1000**	**1200**	**1500**
G_m (S/mm)	-	-	-	-	**>0.3**	**0.4**	**0.5**
P_{out} at 26 GHz and peak efficiency (mW/mm)	-	-	-	-	**3000**	**5000**	**5000**
Peak efficiency at 26 GHz (%)	-	-	-	-	**35**	**40**	**50**
Gain at 26 GHz, at P_{1dB} (dB)***	-	-	-	-	**10**	**12**	**12**

When it becomes less costly, GaN offers competition for GaAs.

GaN is expected to make inroads up to 40 GHz near the end of the decade.

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—HBT							
InP HBT							
Emitter width (nm)	**1200**	**800**	**350**	**350**	**250**	**250**	**150**
F_t (GHz)	**170**	**170**	**300**	**300**	**350**	**350**	**400**
F_{max} (GHz)	**170**	**200**	**300**	**300**	**400**	**400**	**450**
Breakdown (BV_{CEO}) (volts)							
$I_{max}/\mu m^2$ ($mA/\mu m^2$)							
Beta							
3 sigma V_{BE} (mV)							
Interconnect metal layers							
Interconnect metal							
Interconnect metal							
Barrier	**PVD**	**PVD**	**PVD**	**PVD**	**IMP**	**IMP**	**IMP**
Wafer diameter (mm)	**100**	**100**	**100**	**100**	**150**	**150**	**150**

When efficiency and linearity are critical, InP and GaAs HBTs are best for low power applications.

InP will predominate in the near term for mixed signal applications up to 100 GHz.

Work-in-Progress DRAFT - Subject to change - Not for Publication.

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—HBT							
SiGe HBT							
Emitter Width	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F_t (GHz)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F_{max} (GHz)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Breakdown (B[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Breakdown (BV_{CEO}) (volts)	**2.3**	**2**	**2**	**2**	**1.8**	**1.8**	**1.8**
$I_{max}/\mu m^2$ ($mA/\mu m^2$)	**7**	**8**	**10**	**14**	**14**	**18**	**18**
Beta	**140**	**200**	**200**	**200**	**250**	**250**	**300**
Nf_{min} at 77 GHz (dB)	**6.6**	**6.1**	**5.5**	**5.1**	**4.6**	**4.3**	**3.9**

SiGe HBTs challenge InP HBTs for applications up to 40 GHz and will challenge InP HBTs for high volume applications such as auto radar.

Lessons from RF and AMS Roadmap

More inputs from the physics, chemistry, and metrology communities

- Understand electrical contacts well enough to control and reproduce in high volumes their RF and AMS properties

- Alternative isolation methods based on optoelectronics

- Improve RF and AMS metrology for 1/f noise, PAE, linearity, bandwidth, gain, reliability, and the like.

- Exploit additional degrees of freedom offered by emerging research devices (RTDs, spin transistors, CNTs, molecular electronics, planar double gate transistors, 3D structures including vertical transistors
  - e.g.,
    a) control independently the voltage on multiple-gated devices
    b) apply electric field perpendicular to the axis of CNT to alter the band structure

CONCLUSIONS

- International consensus-based planning offers a way to determine priorities in investing funds to support additional R & D and to remove technology gaps between what is available and what the markets require.

- In order to deliver its full potential, the compound semiconductor industry needs improved industry, university, and government collaborations.

RF and AMS

TECHNOLOGY ROADMAPS

“No one is big enough to drive the totality of the infrastructure and pre-competitive investments on their own.”

----- Avtar Oberai, formerly from IBM and a founding director of SEMATECH, in *Compound Semiconductor* **5**, 44 (April 1999).

RF and AMS

ITRS