The Compound Semiconductor Technology Roadmap Embedded in the 2003 ITRS: Implications for the MANTECH Community

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Abstract
Wireless applications have grown quickly to become significant markets for compound semiconductor device manufacturers. As a result, the 2003 ITRS recognizes wireless applications enabled by RF and analog/ mixed-signal (AMS) devices as a separate new system and technology driver. A technology roadmap for RF and AMS applications of compound semiconductors now exists in the 2003 International Technology Roadmap for Semiconductors (ITRS). Past ITRS roadmaps focused on mainstream CMOS and BiCMOS processes and applications. For the first time, the current 2003 ITRS Roadmap includes III-V compound semiconductors in the context of CMOS technology nodes. We present selected highlights from the 2003 ITRS that concern compound semiconductors and suggest possible implications for the Compound Semiconductor MANufacturing TECHnology community.

I. Introduction

The purpose of this paper is to present selected highlights on compound semiconductors from the perspective of the 2003 International Technology Roadmap for Semiconductors (ITRS) [1]. A technology roadmap represents an industrial consensus with inputs from the research community. It is an effective way to: 1) reduce uncertainties in investments, 2) view changes among technologies as opportunities, 3) increase the probability for more robust economic performance, 4) guide critical research, 5) assist in setting priorities for resource allocations, and 6) accelerate the rates of both technology development and deployment. It is most effective when it serves to increase industrial cooperation and produce positive changes in how companies work together. 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.

Some of the lessons learned from the Si CMOS technology roadmaps are relevant to the compound semiconductor industry. These lessons include: 1) many technology barriers, once thought to concern only a few companies, are common through out the industry and overcoming such barriers offers an appropriate focus for technology roadmaps; 2) The roadmapping effort must be large enough to be effective but must still remain focused enough to have measurable progress; and 3) from the late 1980s to today, most Si CMOS companies found that a large percentage of what they know is not proprietary and may be shared with other companies for a globally stronger industry.

II. Implications For Compound Semiconductors

The competitiveness among Si CMOS manufacturers is shifting from an emphasis on fabrication technology to a much greater emphasis on product design and architecture. A similar shift may be beginning for one or two major applications of compound semiconductors; particularly, in applications for which compound semiconductors and silicon co-exist. After considering 1) the foregoing changes, 2) compound semiconductors as the key enablers for very large markets that use Si CMOS and SiGe, 3) the large and rapidly growing markets for compound semiconductors themselves, 4) the success of consensus-based planning in the Si CMOS industry, and 5) the co-existence of Si, SiGe, and compound semiconductors for some applications such as RF and analog/mixed-signal (AMS) devices and circuits, the ITRS organizers decided in July 2001 to add for the 2003 ITRS edition a new chapter on RF and AMS technologies for wireless communications. Past ITRS roadmaps focused on mainstream CMOS and BiCMOS processes and applications. The ITRS is perhaps unique because unlike many other technology roadmaps, it has support from extensive R & D efforts that include the SRC, MARCO, and SEMATECH. For the first time, the current 2003 ITRS Roadmap includes III-V compound semiconductors in the context of CMOS technology nodes. We address here the intersection of III-V compound semiconductor based technologies and Si/SiGe based technologies and present major trends in RF and AMS technologies for their successful deployment in wireless applications that span the frequency range from 0.8 GHz to 100 GHz.

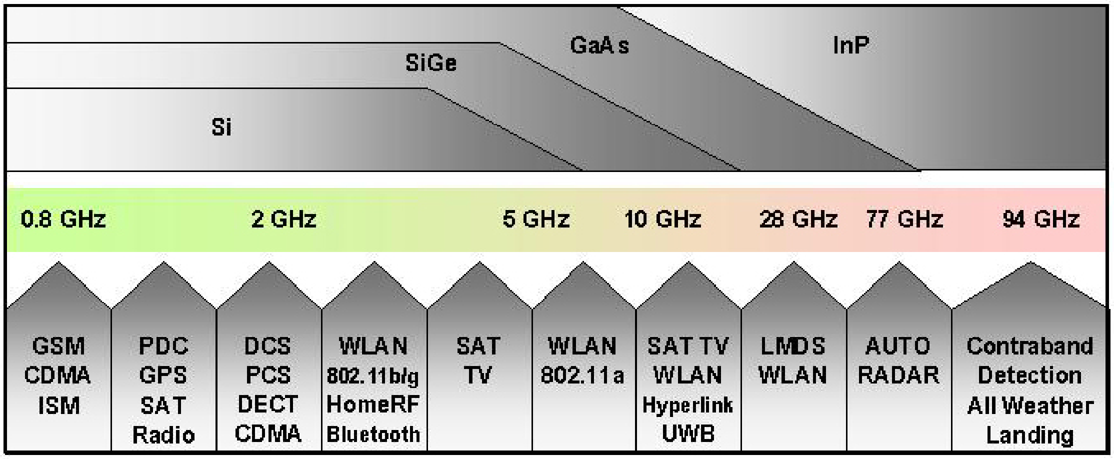

Figure 1. Wireless frequency spectrum showing RF semiconductor technologies and applications.

The locations of boundaries, shown schematically in Figure 1, between the RF semiconductors are diffuse, change with time, and depend very much on cost and other non-technical aspects that are beyond the scope of this presentation. The boundaries between the group IV semiconductors and the III-V semiconductor GaAs have been moving to higher frequencies with time. For other applications, the boundary between GaAs and InP is tending to shift to lower frequencies. When high volume products appear, silicon and more recently SiGe replace the III-Vs in those markets for which group IVs can deliver acceptable and/or appropriate performance at low cost. Carrier frequency is expected to lose its significance in defining the boundaries among technologies for some applications, because most of the RF technologies can provide very high operating frequencies. Future boundaries will be dominated more by such critical parameters as noise figure, output power, efficiency, linearity, high voltage operation, and cost.

III. Major Trends

Future system architectures will use a mix of the most optimum technologies that are consistent with cost and performance. Because analog is expensive and prone to or impacted unfavorably by noise, it will be tolerated only at the very front end of systems. Designers will move from the analog to digital domain as close to the antenna as technologies will permit. In special situations, optical fiber may be used to connect the front end to the digital signal processors so that the latter may be located in a safe environment and so that system maintenance will be less costly.

AMS functions tend now to be integrated together with other digital CMOS functions or sometimes alternatively with RF or power management (PM) ICs on the same die because cost is the most important driver. Process choices may either be BiCMOS or CMOS technology.

RF transceivers are migrating from heterodyne to direct conversion or low-IF architectures. These architectures directly convert the carrier frequency to a low frequency that feeds the AMS functions and thereby simplify frequency conversion by eliminating intermediate steps and by reducing the number of external components. Many RF transceivers are built today in RF CMOS and Si or SiGe BiCMOS. Both CMOS and BiCMOS transceivers will co-exist for the foreseeable future to address the varied market needs of wireless communication devices. Technology choices are dominated by tradeoffs that include: 1) required performance of the standard, 2) market being addressed - SiGe BiCMOS typically has higher performance, 3) level of integration - RF CMOS enables integration with more digital functions while SiGe enables integration with more PM or power amplifier (PA) functions, and 4) cost - RF CMOS is less expensive than SiGe BiCMOS at the same generation node.

Compound semiconductors will always have a technical edge for high performance at the front end, especially in low noise power amplifiers (LNAs) and PAs. HEMTs and/or PHEMT provide the lowest noise figures (NF). The frequency and power level influence technology choices for highest power, efficiency, and linearity. In general, LDMOS is acceptable below 3 GHz and GaAs is best above 3 GHz .

The appearance of GaN will offer competition for GaAs, but only when GaN becomes more cost competitive. When efficiency and linearity are critical, then GaAs and InP HBTs are the best choices for low power applications. The use of compound semiconductors and higher operating voltages will increase the RF power densities of base-station devices.

Applications in the mm-wave part of the spectrum will be dominated primarily by compound semiconductors. SiGe will challenge InP HBT for applications up to 40 GHz. InP will predominate for mixed signal applications up to 100 GHz in the near term. But in the future, SiGe HBTs will challenge InP for high volume applications such as 77 GHz auto radar. MHEMT will supplant GaAs PHEMTs and InP HEMTs through out the spectrum for low noise/front end and power applications above 40 GHz. GaN will make inroads up to 40 GHz by the close of the decade.

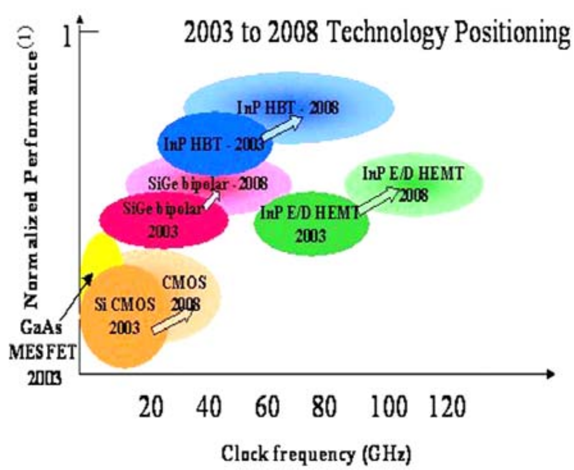

Figure 2. Evolution of mixed-signal and ultra high-speed digital technologies

Figure 2 shows the evolution of mixed-signal technology for mm-wave applications [2] that are driven by high center frequency, precise transistor matching, low-noise operation, and high linearity in the underlying technology. We expect CMOS technology with continuous scaling to address low-resolution circuits up to 20 GHz. SiGe bipolar extends the region of silicon performance to about 50 GHz, but it will likely be limited in dynamic range because its breakdown voltage (BVCEO) is less than 2 V. InP HBTs are the ultimate performance technology once the core transistor technology is aggressively scaled. InP HBTs will be limited by substrate size that now is typically at 100 mm, but 150 mm substrates are being sampled. InP enhancement/depletion (E/D) HEMTs offer higher frequency operation than InP HBTs when scaled to less than 100 nanometers.

E/D technology is also lower power than the HBT alternative, but the threshold voltage control of the HEMT is not as good. The HEMT also does not have as good 1/f noise performance as the HBT. E/D technology should operate at lower power than similar HBT circuits.

Bipolar devices are often preferred for applications where high dynamic range is required (e.g., intelligent cruise control radar) because they exhibit high linearity and low 1/f noise. The market force for advanced mixed-signal circuits will most likely drive increased wireless communications bandwidth through the real-time correction and synthesis of analog signals that rely on digital technologies. Doing this requires that the associated digital and mixed-signal circuits run 3 to 10 times faster than the analog carrier frequency. Additional opportunities exist for performing the control and routing in optical networks.

Compound semiconductors must take advantage of the advances in lithography and processing equipment that are evolving now in the digital silicon industry. In order to accomplish this, wafer diameter needs to be within one or two generations of the silicon industry. Six-inch semi-insulating GaAs wafers are in production now with InP not far behind. However, the III-V industry needs to continue to push to larger wafer sizes as silicon transitions from 8 inch to 12 inch diameter wafers. While significant advances are being made in optical lithography tools, the cost of masks is prohibitive for most of the relatively low volume III-V applications. Direct-write electron beam is a solution to the mask cost, but wafer through-put [measured in hours per wafer, as opposed to wafers per hour] needs to be improved with high-current electron sources and fast alignment systems.

Substrate quality is still problematic for the emerging wide bandgap devices. Research on GaN templates is continuing, but, in the interim, SiC substrates will become more viable as the defect density is improved. If SiGe is to challenge the mm-wave spectrum, high-resistivity low-loss silicon needs to be addressed.

High voltage breakdown is desirable for both mixed-signal as well as high-power devices. As dimensions are scaled downward for higher frequency performance, the operating voltage suffers. This is particularly troublesome for mixed-signal devices that require more headroom for the analog functions than for the digital functions. In this regard, InP HBTs offer a distinct advantage over SiGe HBTs, although the integration level offered by SiGe will be orders of magnitude greater. Continued improvement of passivation and hot carrier effects is also needed.

Finally, high frequency performance in III-Vs is driven as much by epitaxy (vertical scaling) as by lithography (horizontal scaling). Carrier velocity and mobility in the transport layer can be tailored by proper engineering of the epitaxial layer stack. Continued improvement in all of the III-V devices can be expected through bandgap engineering.

IV. Conclusions

RF and AMS technologies now represent essential and critical technologies for the success of many semiconductor products. There is increased demand for high-end electronic products and products involved with the convergence of computing, digital video, and communications. Such products serve the rapidly growing wireless communications market. They depend on many materials systems, some of which are compatible with CMOS processing, such as SiGe, and others of which are not compatible with CMOS processing, such as III-V compound semiconductors.

The frequency range between about 10 GHz and 40 GHz is the region in which the interplay and competition among elemental and compound semiconductors is expected to occur. Today, group IV semiconductors (Si and SiGe) dominate below 10 GHz, and III-V compound semiconductors dominate above 40 GHz. This range in frequencies for competition amongst elemental and compound semiconductors changes with time and is expected to move to high frequencies. Nevertheless, while SiGe has shown capability in the 10 GHz to 40 GHz range, it is an open question whether it will be able to replace III-Vs in applications where combinations of high power gain, ultra-low noise, and high linearity are required.

Performance tends to increase in the following order: Si CMOS, SiGe, GaAs, and InP metamorphic. Increased RF performance for silicon is predominantly achieved by geometrical scaling. Increased RF performance for III-V compound semiconductors is achieved by optimizing carrier transport properties through materials and bandgap engineering. Two or more technologies may coexist with one another for certain applications such as cellular transceivers, modules for terminal power amplifiers, and millimeter wave (mm-wave) receivers. Today, BiCMOS in cellular transceivers has the biggest share in terms of volume compared to CMOS. But, the opposite may occur in the future. Today, both GaAs HBT and discrete LDMOS devices in modules for terminal power amplifiers have big market shares compared to GaAs PHEMT and GaAs MESFET devices. In the future, silicon based technologies having higher integration capabilities will gain importance. Today, we see GaAs PHEMT and InP HEMT in mm-wave receivers. In the future, we may see competition from SiGe HBT, GaAs MHEMT, and InP HEMT.

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Acronyms

AMS: analog-mixed signal
BiCMOS: bipolar-complementary metal oxide semiconductor
CMOS: complementary metal oxide semiconductor;
DSP: digital signal processor
HBT: hetero bipolar transistor
HEMT: high electron mobility transistor
LDMOS: laterally diffused metal oxide semiconductor
LNA: low noise amplifier
MARCO: Microelectronics Advanced Research Corporation
MESFET: metal semiconductor field effect transistor
MHEMT: metamorphic high electron mobility transistor
mm-wave: millimeter wave
NF: noise figure
PA: power amplifier
PHEMT: pseudomorphic high electron mobility transistor
PM: power management
RF: radio frequency
SRC: Semiconductor Research Corporation