SiGe HBT BiCMOS Technology as an Enabler for Next Generation Communications Systems

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Abstract — **The rapid deployment of next generation wireless communications systems creates a unique opportunity for the semiconductor industry. High-speed communications networks require massive digital computing power along with analog and radio frequency devices with wide dynamic range and bandwidth. CMOS technology increasingly forms the technological basis for these developments. This raises the question of the appropriate future role of "non-standard" technologies like Si/SiGe BiCMOS. This paper will summarize the unique advantages of Si/SiGe technology in future wireless communications systems.**

I. Introduction

Digital CMOS technology is the "tsunami," that created the technological impetus for the communication revolution. Traditional scaling of CMOS technology continues unabated, with production gate lengths now less than 0.09um. The digital VLSI portions of the communications system can "ride" the CMOS scaling wave for the foreseeable future. At the same time, the analog and RF portions of the communications system are also increasingly being implemented in CMOS.

The major issue with the implementation of next generation communications systems in "CMOS-only" technologies is the ultimate limit on scaling and the reduction in dynamic range of MOS devices. Many of the newer systems are actually increasing their dynamic range requirements – 3G and 4G wireless systems being good examples of wireless devices where dynamic range requirements are increasingly difficult to meet. So the challenge for an all-CMOS implementation will be to maintain the dynamic range of scaled CMOS technology while exploiting its digital capabilities. This is essentially dependent on the maximum operating voltage of the device, which is continuing to shrink as gate length is scaled.

Si/SiGe BiCMOS technology faces a different challenge in high volume commercial applications – how to justify the inevitably higher cost of the extra bipolar device if a "CMOS-only" implementation can satisfy system requirements. The answer to this question lies in the historic role of SiGe technology as a *technology leader*. This is roughly illustrated in Figure 1, where the f_T of SiGe and CMOS devices is plotted as a function of critical dimension. Due to the superior scaling properties of the HBT, its performance usually exceeds that of an NMOS device at a given lithographic generation.

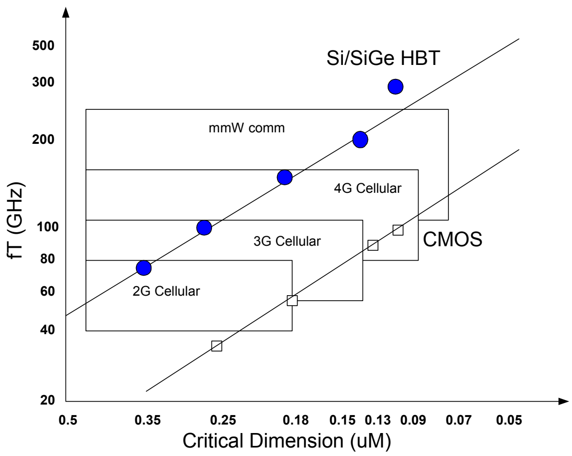

Figure 1: Unity gain cutoff frequency of Si/SiGe HBTs and CMOS devices as a function of critical dimension.

As the Figure shows, Si/SiGe HBT technology maintains its speed advantage for between one and two technological generations (3-5 years typically) over CMOS – enough time to demonstrate unique system capabilities. Therefore, we need to address the question of "what next" for SiGe HBT technology? The most promising applications today of Si/SiGe HBT technology is in the area of > 10 GHz wireless communications systems, particularly in the 30-60 GHz (millimeterwave) frequency region.

II. Millimeterwave Applications of SiGe Technology

Millimeterwave systems – operating from 30 GHz to 100 GHz - have enormous potential for the realization of ultra-wide bandwidth communications systems and position location. The applications of these systems include high data rate point-to-point communications links, Gb/sec personal area networks, and automotive collision warning radars. The widespread application of these systems has historically been limited by the high cost associated with their implementation.

The high implementation cost is due to many factors, including the challenges of packaging and test at very high frequencies, but the largest factor delaying implementation of these systems is the cost of the mmW semiconductor devices. Traditionally, the amplifiers, VCOs, mixers and other high-frequency components have been implemented in III-V technology – first GaAs-based, and now InP-based, and perhaps GaN in the near future. Although impressive gains have been made in the cost of these technologies (particularly wafer cost and yield), the economics of these technologies is still extremely unfavorable compared to silicon-based technologies.

The emergence of commercial SiGe BiCMOS technologies with SiGe HBT cutoff f_T and oscillation f_{MAX} frequencies exceeding 170 GHz [1-3] illustrates the real possibility of the use of silicon HBT technology for millimeterwave applications. 60-GHz radio receiver blocks were recently demonstrated in a 0.13 μm SiGe HBT technology with impressive performance [4]. SiGe HBT VCOs have demonstrated excellent output power and phase noise at millimeterwave frequencies [5], and a 60 GHz transceiver in a Si/SiGe:C technology [6]. A *silicon-based* millimeterwave technology has the potential to realize the low-cost goals required to reach high volumes for these next generation systems. So, the question is: as silicon-based technology continues to scale to higher performance - with f_T's exceeding 200 GHz - can it meet the stringent performance requirements required for mmW systems?

III. MILLIMETERWAVE SYSTEM CHALLENGES

Millimeterwave technology has historically been the province of high bandwidth communications and precise position location radar. A vast amount of spectrum is available in the 60 GHz range for communications applications. In the United States, the FCC has allocated 59-64 GHz for general unlicensed applications, and in Japan the 59-66 GHz range has been allocated. In Europe, various bands from 59-66 GHz have been allocated for fixed wireless and WLAN applications. In addition, wireless GigaBit Ethernet networks have been proposed in the newly licensed 70-80 GHz band [7]. Automotive radar applications are particularly attractive, and early implementations of these systems have been in the 24 GHz range [8], but are now moving to 77 GHz

Automotive radars employ a variety of waveforms, with FMCW modulation being the most common reported. A block diagram of a typical FMCW radar is shown in Figure 1 and the typical system requirements for a FMCW radar are listed in Table I [9].

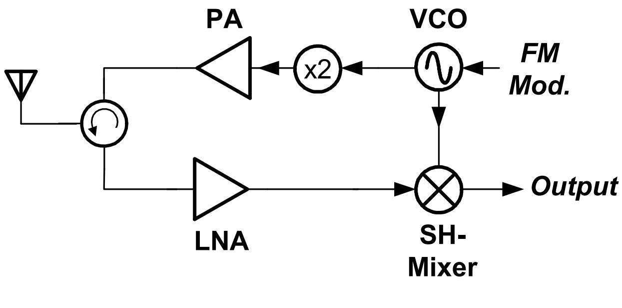

Figure 2: Simplified schematic of 77 GHz mmW radar front end [8].

Table I: Automotive FM CW 77 GHz Radar Transceiver Requirements [9]

	FM CW Radar
Power Out	>13 dBm
LO Power	>13 dBm
Phase Noise	-80dBc @100kHz
System Noise Figure	< 13 dB
Tuning Bandwidth	200MHz
Tuning Linearity	1%
Spurious and Harmonics	-50dbc
Temperature	-40 to +85C

Most mmW communications and radar systems are essentially *noise limited,* due to the attenuation of potential interferers in the mmW region, so the key performance parameters for a transceiver are Noise Figure, output power, and oscillator phase noise. For example, the typical specifications for a 77 GHz collision warning radar require a local oscillator producing roughly 100mW, a VCO with phase noise < -80dBc @ 100 kHz offset, and a system Noise Figure <8 dB as shown in Table I [9].

Of these specifications, the output power represents the greatest challenge for silicon technology, since a lower breakdown voltage is an inevitable consequence of scaling the devices for mmW operation. At the same time, the intrinsically high losses of mmW signal propagation on a conducting silicon substrate will make VCO design and power combining losses especially difficult.

The economics of a mmW transceiver for automotive applications are particularly challenging. Morenc reported in [9] that the target costs for an entire transceiver module are in the $40-$70 range, and IC costs must be a small fraction of that. Much like the market for 2.4 and 5 GHz WLAN products, highly integrated transceivers based on silicon VLSI technology are key to achieving these cost goals. At the same time, the annual volume requirements for automotive applications will be low compared to those of the WLAN or cellular market, making the use of "commercial" silicon technology even more important.

Communications systems in mmW technologies typically utilize low performance digital modulation schemes - such as ASK or FSK - in order to avoid the need for linear modulation of the carrier, and ease the demodulation of the carrier at high (Gb/sec.) data rates [10]. This is acceptable for point-to-point communications links, with minimal multi-path interference, but indoor WLAN uses of mmW technology will probably require sophisticated equalization techniques or the use of OFDM to overcome issues of multi-path interference while maintaining a high data rate. The use of constant envelope OFDM approaches [11] may allow the use of multipath insensitive techniques to be used consistent with the limited transmit power in the mmW environment. In this case, the bandwidth expansion of the signal is very significant, but this can easily be accommodated at mmW frequencies.

III. SIGE HBT TECHNOLOGY FOR MMW APPLICATIONS

As was pointed out earlier, SiGe HBT technology has historically played the role of technology leader in the high-frequency arena. What aspects of the device continue to provide it with a key advantage in the era of sub-100nm CMOS? Since these systems are essentially noise limited, transmit power becomes a key limitation in system performance in the mmW regime. As a result, the realization of high power amplifiers in this frequency range becomes a key aspect of the technology.

The well-known Johnson limit in semiconductor devices specifies the trade-off between device speed and breakdown voltage for any given material system, i.e.

$$f_T \times BV = \text{Constant} \quad (1)$$

where BV is the device breakdown voltage. Figure 2 illustrates this tradeoff for reported breakdown voltages and f_T's for SiGe HBTs and MOSFETs [12]. The breakdown voltage becomes especially low (sub-1V) for MOSFETs in the sub 100nm region due to hot electron effects, making the implementation of power amplifiers extremely difficult. Even SiGe HBT's operated at low base impedance (BVCBo) exhibit reduced operating swing of less than 3V at high f_T (>200GHz). However, this improved margin is quite significant when operated in a power limited regime, and provides a key performance advantage for SiGe HBT-based circuits. As a result of these limitations the practical output power will be limited to roughly 50 -100 mW per stage.

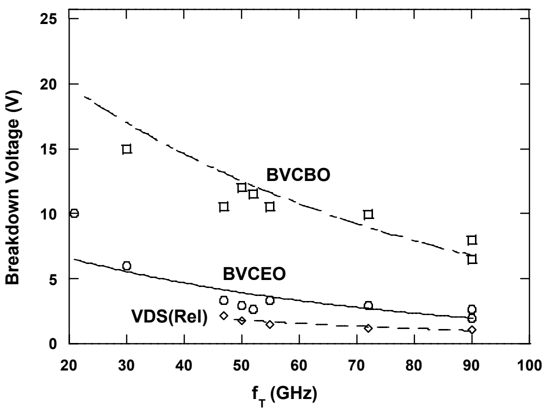

Figure 2. Reported breakdown voltage/reliable operating limits for SiGe HBTs (BVCEO and BVCBO) and Si MOSFETs (VDS(Rel)) as a function of f_T [3].

Monolithic power combining techniques must be employed in order to achieve output powers in the 20-25 dBm range. At mmW frequencies, promising approaches include stacked amplifier configurations [13], transformer-coupled approaches [14], and traditional Wilkinson combiner schemes [15]. The effectiveness of these approaches will depend on the transmission line performance at mmW frequencies on a silicon substrate.

IV. CONCLUSIONS

In order for Si/SiGe HBT technology to retain its vital role as technology leader for high frequency systems, it must extend its domain in the mmW region. Fortunately, recent improvements in device technology allow implementation of high performance mmW circuits in silicon technology for the first time. The future implementation of these circuits in a cost effective and robust manner will depend on advances in design techniques, packaging, and system-oriented approaches.

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