High-speed Si/SiGe technology for next generation wireless system applications

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Si/SiGe integrated circuit technology represents a revolutionary opportunity to combine high-performance digital, analog, and rf circuits on a common substrate. The outstanding high-frequency performance of the Si/SiGe devices, combined with the high levels of integration of complementary metal–oxide–semiconductors will contribute to a long-term "paradigm shift" in the architectural partitioning of high-frequency high-performance wireless systems. This article outlines the key future systems applications for the technology. © *1998 American Vacuum Society.* [S0734-211X(98)05603-0]

I. INTRODUCTION

The revolution in wireless communications has been brought about by a combination of advances in digital integrated circuit technology, radio frequency components, digital communications, and networking techniques. Of all these factors, the first two have been most instrumental in bringing the cost of the technology within reach of the average consumer. A radio transceiver that would have required an entire rack of equipment and several hundred watts of power 15 years ago can now comfortably fit in the palm of a person's hand and operate from a single-cell battery for several hours.

But the relentless advance of applications and markets for these devices is still accelerating, and new technologies and new architectures will be required to address future system needs. Digital integrated circuit technology continues to double in complexity roughly every two years, thanks to Moore's law, and the attendant drop in power supply voltage and power dissipation will accelerate the trend towards higher levels of integration in digital wireless communications devices. The advance of digital integrated circuit technology will provide the required technology for digital signal processing in advanced wireless systems in the coming years.

However, the radio frequency portion of digital communications devices—roughly that portion of the system between the antenna and the digital signal processor—still remains a hodgepodge of components of differing technologies, each with its own peculiar level of integration and interface requirements. A revolution in radio frequency transceivers, comparable to the complementary metal–oxide–semiconductor (CMOS) revolution in digital integrated circuits, remains to be implemented. It is the author's contention that Si/SiGe heterojunction bipolar transistor (HBT) bipolar CMOS (BiCMOS) technology, combined with advanced packaging techniques, have the capability to effect that revolution. The technology may allow for the eventual realization of a "single-chip" multifunction low-cost wireless transceiver—the Holy Grail of radio frequency designers.

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In this article we will briefly summarize the high-frequency requirements of next generation wireless systems, and follow with a summary of the role that Si/SiGe technology can expect to play in these systems. It is clear that wireless systems can be segmented into either "low-tier" (pagers, cordless phones, RFID tags, etc.) or "high-tier" (PCS, GSM, IS-136, LMDS, etc.) markets, and that SiGe will find its greatest application in those high-tier applications where the best performance is essential. CMOS technology will probably dominate the low-tier applications in the near future.

II. WIRELESS SYSTEM REQUIREMENTS

Table I summarizes radio frequency requirements for wireless communications systems. It is clear from this summary that a variety of frequencies, modulation schemes, and output power requirements has proliferated on a worldwide basis, and that no one single standard or frequency can be expected to dominate wireless data systems for the foreseeable future. Instead, in order to address a broad market, radio transceivers must increasingly satisfy the competing constraints of flexibility and low cost.

The standard transceiver architecture for wireless systems—the venerable superheterodyne—is shown in Fig. 1. Since its initial development by Edwin Armstrong in the early 1900s, superheterodyne architecture has remained the preferred approach for the implementation of the vast majority of radio-frequency applications in the world. The word "heterodyne" is derived from the Greek words "heteros," meaning different, and "dynamis," meaning power.[1] Its perennial popularity is due to its ability to reproducibly pick out narrow-bandwidth high-frequency signals from the surrounding background clutter of signals outside the frequency range of interest.

In this design, the radio signal is sent from the receiving antenna to a low-noise amplifier (LNA), whose purpose is to boost the signal level without reducing the signal-to-noise ratio significantly. The signal level at the antenna can range between 1 μV to nearly 100 mV rms—over 100 dB variation! At the low end of the signal range, the low-noise amplifier performance is fundamentally limited by thermody-

TABLE I. Comparison of wireless communications standards.

Standard	System	Frequency band	Access method	Duplex method	Modulation format	Data carrier	Rate signal	Audio coding	Channel BW/SP	Max user average	Power peak
AMPS	Cellular	800 MHz	EDMA	FDD	FM	...	...	...	30 kHz	600 mW	600 mW
GSM	Cellular	900 MHz	TDMA (8:1)	FDD	GMSK(0.3)	270 kbit	13 kbit	RPE-LTP	200 kHz	250 mW	2 W
PCS-1900	PCS-TAG-5	1.9 GHz	TDMA(8:1)	FDD	GMSK(0.3)	270 kbit	13 kbit	RPE-LTP	200 kHz	125 mW	1 W
IS-136	PCS-TAG-4	1.9 GHz	TDMA(3:1)	FDD	pl/4 DOPSK	48 kbit	8 kbit	VSELP	30 kHz	200 mW	600 mW
IS-95	PCS-TAG-2	1.9 GHz	CDMA(20:1)	FDD	OQPSK /QPSK	1.23 MChip	8/13 kbit	QCELP	1.25 MHz	200 mW	200 mW
W-CDMA	PCS-TAG-7	1.9 GHz	CDMA(64:1)	FDD	QPSK	4.096 MChip	32 kbit	ADPCM	5 MHz	200 mW	200 mW
IS-661	PCS-TAG-1	1.9 GHz	TDMA(32:1)	TDD	SE-QAM	781 kbit/ 5.0 MChip	8/32 kbit	CELP /ADPCM	5 MHz	9 mW	600 mW
DCTU	PCS-TAG-6	1.9 GHz	TDMA(12:1)	TDD	GMSK(0.5)	1.15 Mbit	32 kbit	ADPCM	1.72 MHz	10 mW	250 mW
PACS	PCS-TAG-3	1.9 GHz	TDMA(8:1)	FDD	Pl/4 DQPSK	384 kbit	32 kbit	ADPCM	300 kHz	25 mW	200 mW
PHS/PHP	PCS-Japan	1.9 GHz	TDMA(4:1)	TDD	pl/4 DQPSK	384 kbit	32 kbit	ADPCM	300 kHz	10 mW	80 mW
PDC	Cell-Japan	800/900 MHz to 1.6 GHz	TDMA(3:1)	FDD	pl/4 dQPSK	42 kbit	8 kbit	VSELP	25 kHz	100 mW	300 mW
CT-2	CT-Europe	900 MHz	FDMA	TDD	GMSK(0.5)	72 kbit	32 kbit	ADPCM	100 kHz	5 mW	10 mW
15.323	PCS-Voice	1.9 GHz	TDMA	TDD	Any digital	...	...	Any	1.25 MHz	0.1×BW	...
15.321	PCS-Data	1.9 GHz	CSMA	TDD	Any	...	...	...	<10 MHz	0.1×BW	...
802.11-FH	WLAN	2.4 GHz	CSMA	TDD	GMSK(0.5)	1 to 2 Mbit	1 to 2 Mbit	...	1 MHz	...	1 W
802.11−DS	WLAN	2.4 GHz	CSMA	TDD	DBPSK /QPSK	11 to 22 MChip	1 to 2 Mbit	...	22 MHz	...	1 W
15.247-FH	CT-USA	900 MHz	FDMA	TDD	FSK	93 kbit	32 kbit	ADPCM	200 kHz	100 mW	200 mW
15.247-DS	CT-USA	900 MHz	FDMA/ CSMA	TDD	BPSK	1 mChip	64 kbit	ADPCM	5 MHz	100 mW	200 mW
CDPD	WAN	800 MHz	FDMA	FDD	GMSK(0.5)	19.2 kbit	19.2 kbit	...	30 kHz	...	600 mW

namic issues, while at the high end of the signal range, the challenge is to minimize the effects of nonlinearities on receiver performance. These diverse requirements are often referred to as the LNA bottleneck.[2] As a result, the high-frequency low-noise amplifier must exhibit excellent performance over both small-signal and large-signal conditions. SiGe is particularly well suited to this application because of its outstanding f_T and low base resistance.

In addition, the low-noise amplifier is typically "on" all the time—listening for transmitted signals of interest—so it is constantly draining power. The combination of extremely high performance and low-power requirements result in the low-noise amplifier being one of the most significant power drains in the system.

Following the low-noise amplifier, the signal is typically passed through a mixer, which essentially multiplies the input signal by a local oscillator signal of constant frequency, producing an output signal whose frequency is the difference between the two inputs—the so-called "intermediate frequency" (IF)—and whose amplitude is proportional to the original input signal. Preceding the mixer, an analog filter eliminates the response to an undesired input signal at $(2f_{lo}-f_{rf})$ that would also downconvert to the intermediate frequency. This "image reject" filter is typically implemented with a physically large surface acoustic wave (SAW) filter. In addition to their size, these filters have extremely unforgiving sensitivities to variations in source impedance, ground loops, etc. The dilemma of image rejection and its elimination in heterodyne receivers is one of the fundamental limitations on performance and power reduction in radio-frequency systems. A highly integrated Si/SiGe transceiver might allow these filters to be dispensed with, significantly reducing the power dissipation and physical size in the transceiver.

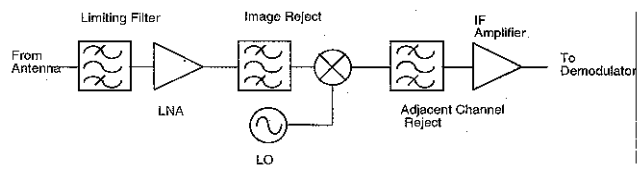

FIG. 1. Superheterodyne receiver architecture. This is the most commonly used architecture for wireless transceiver systems.

A second limitation of traditional frequency translating mixers and the heterodyne architecture is their sensitivity to a menagerie of "spurious responses" that result from nonlinearities in the amplifiers preceding the mixer, as well as in the mixer itself. These nonlinearities produce harmonics of the input and local oscillator frequencies that can themselves mix down to the IF frequency. The potential range of frequencies where this unfortunate set of circumstances can occur is nearly limitless, so very high linearity in the mixer is required, which is another potential advantage of SiGe technology since it can operate at higher levels of linearity for a given power dissipation compared to Si BJT or CMOS implementations.

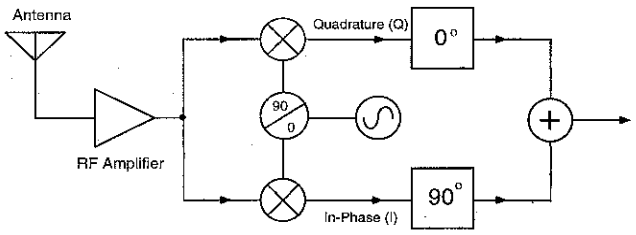

FIG. 2. Image reject downconversion using the Weaver phasing method. Note that this approach eliminates the need for image reject filtering.

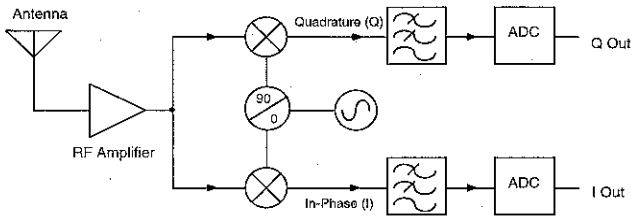

FIG. 3. Direct downconversion receiver. The IF frequency is now zero, eliminating the possibility of an image response.

The architecture of the superheterodyne also has a number of problems, which makes it very poorly suited for completely monolithic integration—the key to lower power operation. The major problems are the ubiquitous image and spurious responses, which must be carefully controlled through bulky and expensive off-chip filters. These filters represent the major impediment to raising the level of integration of wireless radios since they cannot be easily implemented monolithically. Therefore, alternative architectures that do not suffer from these limitations are being actively explored.

One example of a potential improvement in the area of receiver architectures is the use of quadrature signal processing techniques, also known as the Hartley phasing method, as a way of eliminating some of the image rejection filtering. In this case, the image rejection problem is solved geometrically through the use of two local oscillators and mixers operated at a 90° phase shift with respect to each other. Figure 2 is a block diagram of a typical image rejection mixer using the Hartley phasing approach. After downconversion, the two paths are again shifted 90° with respect to each other to produce the desired downconverted response.

Adding or subtracting the resulting signal can produce either the desired signal or the image. In this particular approach, the need for an image rejection filter is eliminated, but the image rejection of the system is highly dependent on the accuracy of the phase shift and the gain matching in the two legs of the downconverter.[3] Image rejection in excess of 60 dB requires a phase accuracy of less than 0.5°, which is very difficult to realize on a monolithic integrated circuit.

Substantial progress has made recently in the area of "direct downconversion," or homodyne, approaches for wireless receivers, which also eliminate the need for image rejection filters and are better suited to monolithic integration. A schematic diagram of a typical direct conversion receiver is shown in Fig. 3. Some excellent reviews of recent research in this field are presented in Refs. 4 and 5. In this case, the IF is at dc, and the in-phase and quadrature (I and Q) paths of the mixer contain the positive and negative frequency components of the desired signal. The advantages of this particular architecture are that it is uniquely well suited to monolithic integration due to its lack of complex filtering, and its architecture is intrinsically simple.

However, although it is being actively researched, the direct conversion receiver has not gained widespread acceptance to date, especially in high-performance wireless receivers, due to its intrinsic sensitivity to dc offset problems, even-order harmonics of the input signal that interfere with the desired signal, and local-oscillator leakage problems back to the antenna. These issues are all being actively pursued by a variety of worldwide research groups, and it is anticipated that they will gradually become solved with further design maturity.

An interesting variation on the superheterodyne/homodyne receiver architecture is the wide-band IF double conversion (WBIFDC) technique recently developed by researchers at the University of California–Berkeley.[6] In this case, a low-IF image reject downconverter, operating at a fixed local oscillator frequency, is followed by a second stage of direct downconversion, whose frequency is set by a tunable oscillator. The advantages of this architecture are that it greatly eases the generation of the first local oscillator, which is now at a fixed frequency, and that reradiation of the local oscillator back to the antenna is not a problem, as it would be if a direct downconversion technique were employed. This approach is highly desirable for monolithic integration, but suffers from the use of six mixers to perform the complete downconversion, thereby raising the dc power dissipation considerably.

All of these alternative architectures address the needs for higher levels of integration in next generation wireless systems. SiGe technology is ideally suited to implement these approaches due to its relatively low cost and outstanding performance. In Sec. III we will outline some of the features of SiGe technology that render it particularly attractive for next generation wireless transceiver designs.

III. Si/SiGe TECHNOLOGY FOR NEXT GENERATION RADIO TRANSCEIVERS

Si/SiGe technology promises to satisfy the simultaneous requirements of outstanding high-frequency performance and low-cost silicon manufacturing. These advantages can manifest themselves in several different ways, depending on the system requirements, and these trade-offs will now be examined.

A. Power dissipation advantages of Si/SiGe HBT technology

The outstanding high-frequency performance of Si/SiGe HBT technology has been well established by a variety of groups.[7,8] In many applications, this speed performance advantage can be "traded off" in a very satisfactory way for

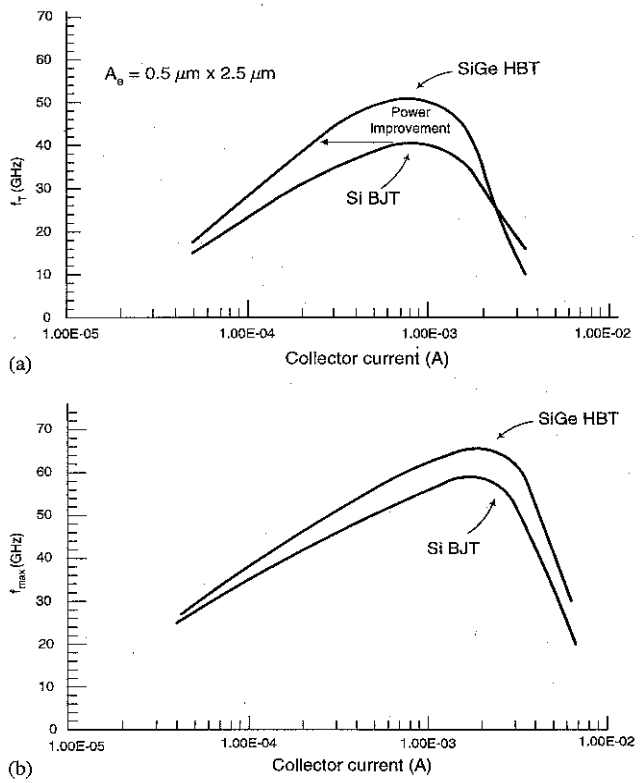

FIG. 4. Comparison of an epi-based Si/SiGe HBT and a Si BJT with comparable base resistivity and geometry: (a) f_T vs collector current and (b) f_{max} vs collector current (Ref. 9).

dramatically reduced power dissipation. It is at these low-power levels that Si/SiGe HBT technology has a distinct advantage compared to Si BJT or CMOS technology. The germanium content within the base of the SiGe HBT leads to a device of superior performance compared with a similarly structured silicon-only epitaxial-base transistor.

A good example of this improvement can be seen from the transistor data presented in Figs. 4(a) and 4(b), which compare transistor f_T and f_{max} as a function of collector current for epi-based SiGe HBTs and Si BJTs of comparable base resistance (approximately 12 kΩ/□).[9] The electrical characteristics of the two device types are compared in Table II. In this case, the peak f_T values for the Si BJT and the SiGe HBT are 38 and 50 GHz, respectively. The peak f_{max} values of the Si BJT and the SiGe HBT are 54 and 66 GHz, respectively. The epi-based SiGe HBT achieves higher f_T and f_{max} values than the epi-based Si BJT over its entire range of operation. In addition, for a given required f_T or f_{max} the SiGe HBT requires roughly one-third the collector current of an "equivalent" Si BJT for equivalently sized devices, dramatically lowering the power requirements in those circuits that are required to operate at very high frequencies.

As mentioned before, low-noise amplifiers are one of the key performance bottlenecks in a rf system. They are required to contend with a variety of signals coming from the antenna—ones often of larger amplitude than the desired

TABLE II. Electrical characteristics of wafers used to compare Si BJT and SiGe HBT performance (Ref. 9).

Parameter (A_E=0.5×2.5 μm^2)		
Type	Si BJT	SiGe HBT
R_{BI}(Ω/□)	12 121	12 099
β at V_{CE}=0.72 V	48	89
V_A(V)	20.3	33
$\beta \cdot V_A$(V)	974	2937
BV_{CEO}(V)	3.5	3.4
BV_{CBO}(V)	9.6	11
BV_{EBO}(V)	4.2	4.2
J_C at 300 K (A/cm^2)	7.2×10^{-11}	1.5×10^{-10}
J_{OE} at 300 K (A/cm^2)	2.0×10^{-12}	1.9×10^{-12}
R_E(Ω)	19.1	19.8
f_T(GHz)	38	50
f_{max}(GHz)	54	66
Low bias r_b(Ω)	130	130

signal—and so both low noise and high linearity are required simultaneously. These requirements are often at odds with an additional requirement for low-power dissipation.

Low-noise amplifiers are usually required to amplify a signal coming from the antenna whose lowest level is very close to the thermodynamic limit of background noise, given by kTB, where k is Boltzmann's constant, T is the ambient temperature, and B is the bandwidth. In the case of a 50 kHz signal, this corresponds to a background noise power level of only 10^{-15} W at room temperature! So the intrinsic noise of the amplifier when connected to the antenna should not be much larger than the noise due to the anenna itself. The ratio of these two quantities is known as the noise figure (NF) of the amplifier. The minimum noise figure of a transistor is roughly proportional to the device base resistance and inversely proportional to the f_T. This illustrates the importance of high transistor f_T at low dc currents for hand-held wireless applications. Unfortunately, a typical transistor's f_T peaks at a relatively high current, and so the device is often biased at as low a current as possible, consistent with acceptable noise figure performance, in order to realize its lowest power operation. In fact, this relationship implies that there is a relatively straightforward trade-off between LNA gain, the noise figure, and power dissipation for a given semiconductor technology. The higher the gain for a given power dissipation and noise figure, the better the performance.

Figure 5 plots amplifier gain/dc power dissipation (in dB/mW) as a function of the noise figure (in dB) for a variety of reported low-noise amplifiers in silicon and GaAs technologies at 2 GHz. Most of the recently reported LNA results, fabricated in Si CMOS[10] or bipolar technologies[11,12] fall along a gain/(Pdc*NF) line of approximately 0.4 (1/mW). By comparison, a recent SiGe HBT result[13] demonstrated a fully integrated LNA with a 0.95 dB noise figure, 2 mW power dissipation, and a 10.5 dB gain at 2.4 GHz, for a figure-of-merit of approximately 5.5 (1/mW). The best reported GaAs LNAs have figures-of-merit of approximately 3.0 (1/mW).[14–16] These results demonstrate the potential performance advantage of SiGe technologies at these frequencies

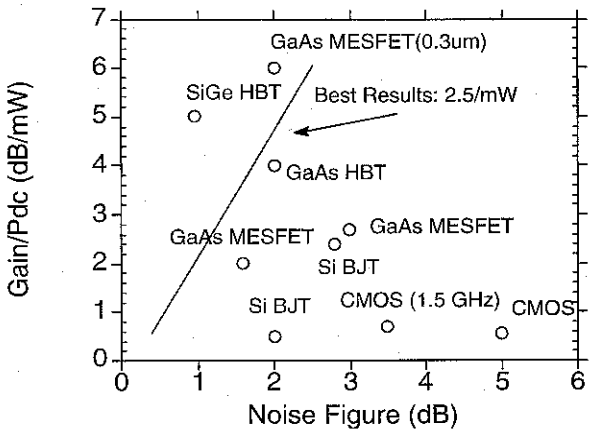

FIG. 5. Gain to dc power ratio plotted vs NF for state-of-the-art 2 GHz LNAs (Ref. 13). Note that the SiGe HBT circuit provides the best result when power dissipation is a critical factor.

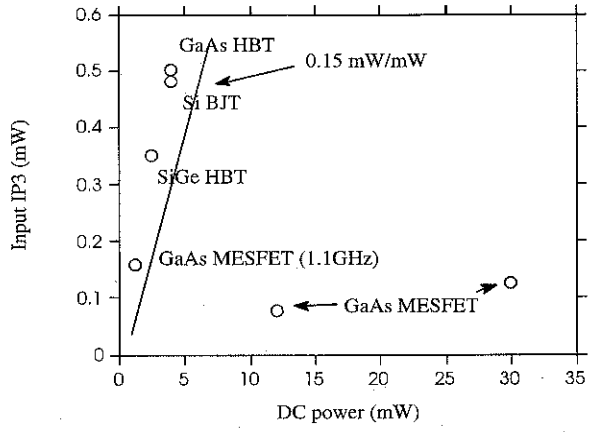

FIG. 6. Amplifier linearity figure-of-merit plotted for the same monolithic 2 GHz amplifiers of Fig. 5. The best results fall on a line of approximately 0.15 mW/mW (Ref. 13). Here, the advantages of SiGe HBT technology are not as dramatic.

where dc power dissipation is a major consideration.[17]

Linearity is an equally important figure of merit for front-end transistor amplifiers. In this case, an often-used linearity figure-of-merit is the ratio of the input third order intercept point (IIP3) to the dc power dissipation. The IIP3 point occurs when the extrapolated intermodulation products are equal in magnitude to those of the desired output signal. Field effect transistors (FETs) [MOSFETs as well as GaAs metal–semiconductor FETs (MESFETs) and psedomorphic high electron mobility transistors (PHEMT)] generally exhibit improved third order intermodulation distortion compared with bipolar devices due to their near square-law current versus voltage behavior. On the other hand, bipolar transistor amplifiers have recently demonstrated outstanding linearity performance as well, apparently due to the cancellation of the resistive and capacitive nonlinearities in the base–emitter junction at certain frequencies.[18] As with the case of the noise figure, the performance advantages of SiGe HBTs becomes significant if dc power dissipation is a critical parameter, although the improvement is less dramatic. The best low-noise amplifier results have a ratio of IIP3/dc power of approximately 0.15, as shown in Fig. 6.

B. Higher frequency operation

The high-frequency performance of Si/SiGe HBTs was demonstrated early in the development of the technology, with dramatic improvements in transistor f_T resulting from the improved transport properties in the base region. A particularly dramatic example of this improvement was demonstrated by Meyerson,[19] where the peak reported f_T of silicon bipolar devices nearly doubled in the late 1980s as a result of the fabrication of high-performance SiGe HBTs by a variety of laboratories. This dramatic increase is shown graphically in Fig. 7.[19]

The high-frequency systems applications of a technology capable of achieving f_T's in excess of 100 GHz are numerous, and extend well into the millimeter wave frequency region. They include automobile collision warning radar, wireless distribution of cable television, and millimeter wave point-to-point radios. Recent research results have demonstrated outstanding performance for Si/SiGe HBT circuits operating at frequencies above 10 GHz. They include frequency dividers operating to 28 GHz,[20] Gilbert mixers operating to 12 GHz,[21] power amplifiers with over 25 dB M of output power at 1.9 GHz,[22] VCOs with, -103 dBc/Hz of phase noise at 7.5 GHz.[23]

Advanced packaging techniques will also be required in order to fully utilize the technology in systems applications above 10 GHz. Typical bond-wire and lead-frame inductances limit the high-frequency performance of packaged devices to less than 5 GHz.[24] Flip-chip bonding of X-band and Ku-band Si/SiGe monolithic microwave integrated circuits MMICs was recently demonstrated,[25] with outstanding results, in a quasihybrid packaging environment.

One major potential limitation of silicon technology for very high-frequency applications is the availability of low-loss transmission line structures for impedance matching applications. Historically, transmission lines in silicon technology have suffered from extremely high losses resulting from

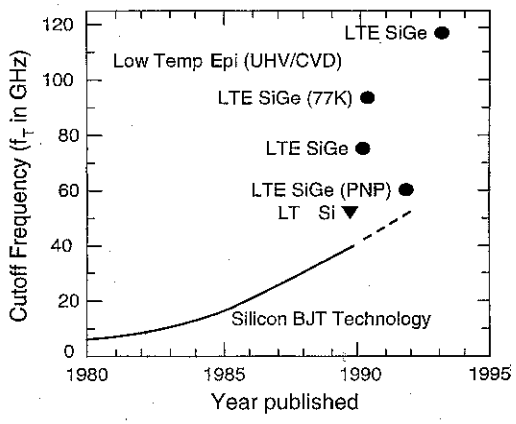

FIG. 7. f_T trend chart for silicon-based bipolar transistor performance over the past 15 years (Ref. 19).

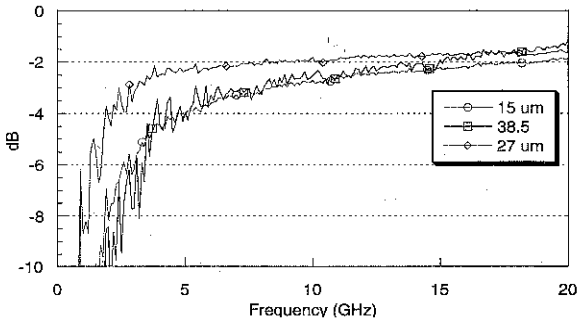

FIG. 8. Measured transmission line loss in dB/wavelength for Si/SiGe transmission line structures (Ref. 33).

the relatively high conductivity of typical silicon substrates. In addition, the ohmic losses of transmission lines implemented in silicon have tended to be high because of the relatively thin Al-based metallization employed in most very large scale integrated (VLSI) processes.

Despite these drawbacks, a number of approaches has been attempted to realize these structures in a monolithic silicon environment, including coplanar transmission lines on lightly doped substrates,[26,27] thickly deposited SiO_2 for realization of microstrip structures,[28] and thick polyimide layers to separate the transmission lines from the silicon substrate.[29] These existing approaches have a number of drawbacks. Lightly doped silicon substrates are known to have a high degree of residual internal stress, which makes subsequent high temperature processing very difficult.[30] The deposition of thick layers of high-quality SiO_2 is also limited by high levels of internal stress, limiting the critical thickness to less than 10 μm in most cases. Previous thick polyimide approaches have employed gold-based metallization,[31] which is often incompatible with high volume semiconductor processing. Recent results have demonstrated outstanding low-loss characteristics in silicon through bulk micromachining techniques.[32] All of these processes require an undesirable significant departure from standard silicon VLSI processing techniques.

Recent results have demonstrated a manufacturable, low-loss, transmission line process in silicon technology using thick spun-on polyimide dielectrics.[33] A plot of the measured transmission line losses, in dB/wavelength for a variety of microstrip transmission linewidths, is shown in Fig. 8, and a plot of the measured uniformity of the characteristic impedance and effective permittivity across a 200 mm wafer is shown in Fig. 9. Clearly these results are adequate for many high-frequency amplifier applications, although the losses are substantially higher than what can be achieved in GaAs or hybrid MIC technology.

C. Comparison to III–V technology

There is absolutely no question that III–V-based devices in GaAs or InP technology will exhibit superior f_T and f_{max} compared to a Si/SiGe device for a specified geometry. An excellent comparison of the technologies was presented in

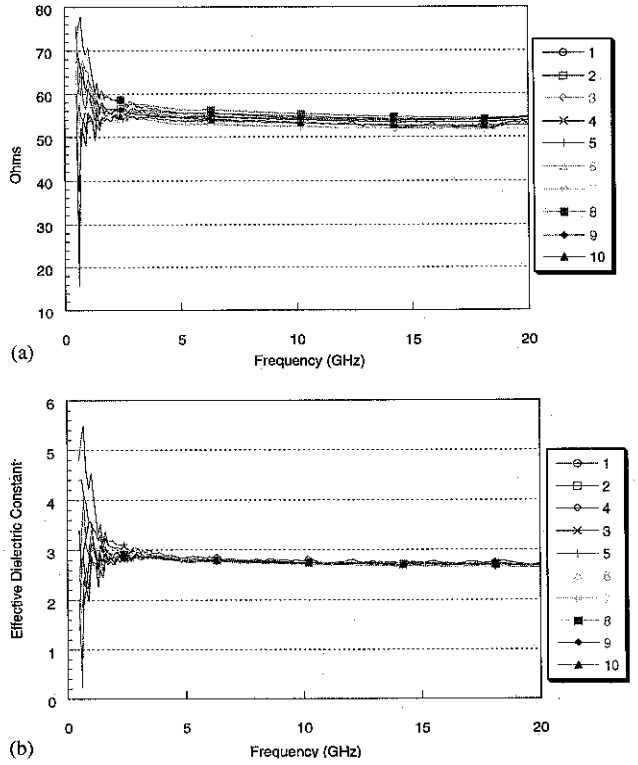

FIG. 9. Measured variation of Si/SiGe HBT transmission line parameters across a 200 mm wafer: (a) characteristic impedance and (b) effective dielectric constant (Ref. 33).

Ref. 34, and a plot from that paper of relative speed (both f_T and f_{max}) as a function of base width is shown in Figs. 10 and 11. Clearly, if maximum performance or speed is the only criterion, then III–V technology is the more superior option.

III–V-based devices will also exhibit superior breakdown voltage properties at a given speed due to their well-known

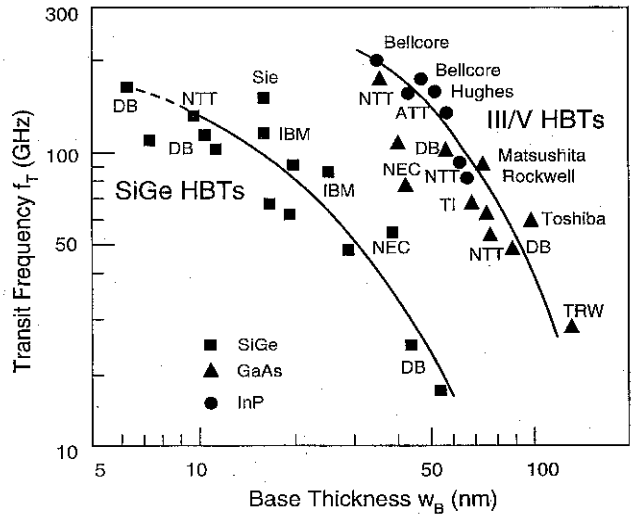

FIG. 10. Comparison of HBT f_T as a function of base width for Si/SiGe and III–V technologies (Ref. 34).

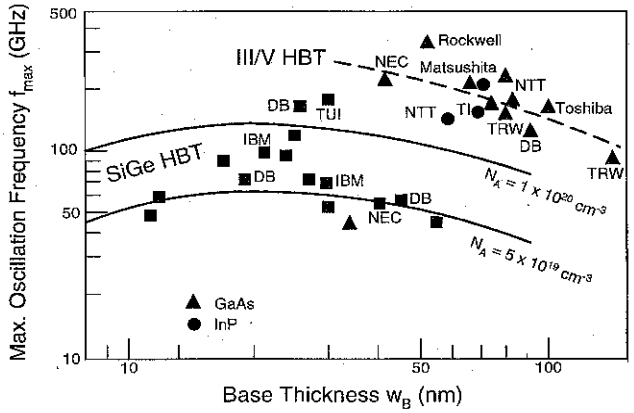

FIG. 11. Comparison of HBT f_{max} as a function of base width for Si/SiGe and III–V technologies (Ref. 34).

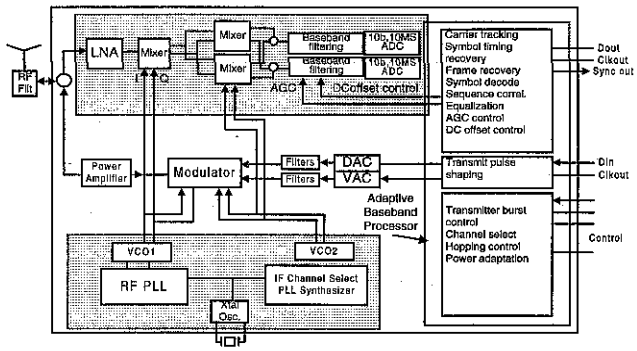

FIG. 12. Block diagram of a possible future highly integrated adaptive transceiver (Ref. 36).

higher band gap energies and mobilities. As with low-noise amplifiers, despite their high f_T, the performance of silicon-based power devices will lag behind that of GaAs-based power devices for the foreseeable future, even at lower power supply voltages. The well-known Johnson limit[35] for speed versus breakdown voltage in semiconductor devices results in much higher gain for the GaAs power devices, even at the lower operating voltage, due to the higher electron mobility. The higher gain translates into improved power-added efficiency, and potentially improved linearity at higher-frequencies of operation.

Clearly, in areas where the best performance is essential, III–V technology will demonstrate the best performance. However, its use may only be required at the critical antenna interfaces (the low-noise and power amplifiers), where the ultimate system performance is set, and relatively low levels of integration are necessary. The rest of the transceiver can plausibly be implemented in a highly integrated Si/SiGe BiCMOS circuit.

D. Si/SiGe technology for higher levels of integration

The silicon pedigree of Si/SiGe technology will provide a straightforward path for "up integration" of standard radio-frequency functions along with analog-to-digital conversion and digital signal processing onto a single high-performance integrated circuit. This migration of multiple functions onto a single die will have some profound implications for wireless transceiver architectures.

Gray and Meyer point out the multiple advantages of a highly integrated adaptive transceiver for future wireless communications systems.[36] There is no fundamental reason why a single transceiver architecture could not in principle accommodate all of the multiple worldwide wireless standards summarized in Table I. This would require an architecture where most of the IF signal processing is performed in the digital domain; this would also be the case for choice of carrier frequency, modulation formats, carrier recovery, symbol timing recovery, power control, dc offset removal, etc. A conceptual block diagram of such a highly integrated architecture is shown in Fig. 12.[36] Clearly, a highly integrated BiCMOS technology would be essential to the realization of this approach, and the use of SiGe will allow the performance of such a unit to be comparable to that of more specialized implementations.

IV. CONCLUSIONS

Si/SiGe HBT technology has the potential to revolutionize high-frequency transceiver design in a way comparable to the revolution in digital integrated circuit technology brought about by CMOS. Its unique combination of outstanding high-frequency performance, ultra low manufacturing cost, and high yield will provide abundant opportunities for new architectures and new systems in the near future.

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[1]R. S. Carson, *Radio Communications Concepts: Analog* (Wiley, New York, 1990).
[2]B. Gilbert, IEEE BCTM Short Course Notes, 1996.
[3]D. K. Weaver, Proc. IRE **44**, 1703 (1956).
[4]A. Abidi, IEEE J. Solid-State Circuits **30**, 1399 (1995).
[5]F. Aschwanden, IEEE Trans. Consumer Electron. **42**, 729 (1996).
[6]J. C. Rudell *et al.*, in Proc. 1997 IEEE ISSCC, Vol. 40, pp. 304–305.
[7]D. Harame *et al.*, IEEE Trans. Electron Devices , 455 (1995).
[8]D. Harame *et al.*, IEDM Tech. Dig. , 874 (1993).
[9]D. Harame, B. Meyerson, L. Larson, and P. Cunningham (private communication, 1995).
[10]A. Karanicolas, International Solid-State Circuits Conference, 1996, pp. 50–51.
[11]J. Long and M. Copeland, IEEE J. Solid-State Circuits **30**, 1438 (1995).
[12]H. Takeuchi *et al.*, J. Solid-State Circuits 1991 IEEE MTT Symp. Dig., pp. 1283–1284.
[13]J. Long *et al.*, International Solid-State Circuits Conference 1996, pp. 82–83.
[14]K. Cioffi, 1992 IEEE MMWMCS Dig., pp. 9–12.
[15]S. Hara *et al.*, in 1991 IEEE MTT Symp. Dig., Atlanta, GA, pp. 67–70.
[16]K. Kobayashi *et al.*, IEEE Trans. Microwave Theory Tech. **43**, 3055 (1995).
[17]L. Larson, Proc. 1997 IEEE CICC, pp. 169–176.
[18]S. Maas *et al.*, IEEE Trans. Microwave Theory Tech. **40**, 442 (1992).
[19]B. Meyerson, Proc. 1996 IEEE BCTM, pp. 499–503.
[20]M. Case *et al.*, Proc. 1995 IEEE BCTM, pp. 121–124.

[21]J. Glenn *et al.*, Proc. 1995 IEEE BCTM, pp. 186–189.
[22]G. Henderson *et al.*, 1997 IEEE MTT-S International Microwave Symposium Digest, pp. 1299–1302.
[23]L. Larson *et al.*, Proc. 1996 IEEE Int. Solid-State Circuits Conf., pp. 88–89.
[24]R. W. Jackson and S. Rakshit, in IEEE Electrical Performance of Electronic Packaging, 1996, pp. 199–201.
[25]M. Case, Microwave J. , 278 (1997).
[26]A. C. Reyes *et al.*, Proceedings of the 46th Electronic Components and Technology Conference, 1996, pp. 382–391.
[27]A. C. Reyes *et al.*, IEEE MTT-S **43**, 2016 (1995).
[28]H. Sakai *et al.*, IEEE MTT-S Int. Microwave Symposium Dig. **3**, 1763 (1994).
[29]Bon-Kee Kim *et al.*, International Electron Devices Meeting Technical Dig. 1995, pp. 717–720.
[30]S. R. Taub and P. Young, IEEE MTT-S Int. Microwave Symp. Dig. **2**, 1049 (1994).
[31]M. Case *et al.*, IEEE MTT-S Int. Microwave Symp. Dig. **2**, 655 (1996).
[32]J. Papapolymerou *et al.*, IEEE Microwave Guid. Wave Lett. **7**, 168 (1997).
[33]L. Larson *et al.*, IEEE Trans. Microwave Theory Tech. (submitted).
[34]U. Konig, A. Gruhle, and A. Schuppen, Proc. 1995 IEEE GaAs IC Symposium, pp. 14–18.
[35]E. O. Johnson, IEEE Int. Conv. Record **5**, 27 (1965).
[36]P. Gray and R. Meyer, Proc. 1995 IEEE CICC, pp. 83–90.