The Impact of Silicon Technology on Future Microwave Systems (Invited Paper)

Lawrence E. Larson – University of California – San Diego
Leo C.N. de Vreede – Technical University – Delft

Abstract: Silicon technology has made rapid progress in the field of microwave technology in the last decade, and is now poised to be the dominant microwave semiconductor technology for the next ten years. This paper summarizes the key recent developments in this field, and suggest possibilities for future technological improvements.

I. INTRODUCTION:

The potential application of silicon technology for microwave applications has a long pedigree, dating back to the earliest days of the technology. As an example, a Special Issue of the Proceedings of the IRE in 1959 on the tenth anniversary of the invention of the transistor [1] pointed to the utility of silicon transistor technology for communications applications, including low-noise amplifiers, mixers, and power amplifiers [2]. This was still many years before the invention of the integrated circuit!

However, rapid developments in III-V technology in the 1970's and 1980's eclipsed the development of silicon for microwave applications, and until recently, its performance was so inferior to that of III-V-based technologies that it was not considered viable except for the lowest performance applications. However, in the 1990's, the relentless improvements in lithography and processing, resulting essentially from "Moore's Law," have once again created new possibilities for the technology in the 0.3 to 30 GHz range. The improvements in processing, combined with the explosion in consumer demand for microwave systems – cellular phones, pagers and the like – have created a fertile field for the development of low-cost silicon solutions to microwave system needs.

This paper will summarize the technological developments that have contributed to this renaissance of silicon technology for microwave applications, as well as point to emerging technologies in silicon that promise further dramatic improvements.

II. SILICON BIPOLAR TRANSISTOR TECHNOLOGY FOR MICROWAVE APPLICATIONS

Silicon bipolar transistor technology has been used for many years in the lower regions of the microwave spectrum for a variety of applications, from gain blocks to pulsed power amplifiers to digital pre-scalers [3]. The ubiquitous Avantek wideband amplifiers were a classic example of the technology in the 1970's and 80's. They naturally provided a low-cost building-block for simple microwave applications.

However, the intrinsic speed of silicon bipolar transistors – and in fact all silicon device technologies - has risen dramatically in recent years, as evidenced by Fig. 1 [4]. This has opened the door to higher frequency applications of Si technology – in the 3-30 GHz range [5]. In particular, the application of epitaxial growth techniques to the addition of alloys of silicon and germanium in the base of the transistor has led to dramatic improvements in device speed – the Si/SiGe HBT. The peak reported f_T of silicon bipolar devices nearly doubled in the late 1980's as a result of the fabrication of high-performance Si/SiGe HBTs by a variety of laboratories [6, 7]. Today, silicon bipolar transistors with f_T's of over 100 GHz have been fabricated. In many applications, this speed performance advantage can be sacrificed in a very satisfactory way for dramatically reduced power dissipation. At very low power levels (<1 mA/ transistor) 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. Roughly speaking, for a given required f_T or f_{max}, the SiGe HBT requires approximately 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.

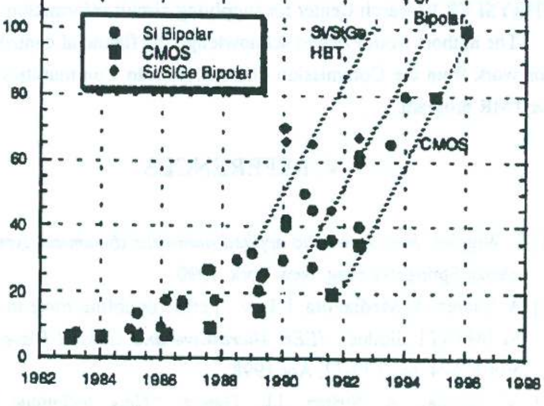

Fig. 1. Evolution of silicon transistor cutoff frequency [4].

The high-frequency systems applications of a *silicon* technology capable of achieving f_T 's in excess of 100 GHz are numerous, and extend well into the millimeterwave frequency region. They include automobile collision warning radar, wireless distribution of cable television, and millimeterwave point-to-point radios. These functions have yet to be demonstrated in this technology, but they will almost certainly be developed in the next century. 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 [8], Gilbert mixers operating to 12 GHz [9], power amplifiers with over 25 dBM of output power at 1.9 GHz [10], VCOs with, -103 dBc/Hz of phase noise at 7.5 GHz. [11].

Having stated the advantages of a silicon-based microwave technology, it is nevertheless clear 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 given lithographic limit. An excellent comparison of III-V and Si technologies was presented in [12], and a plot from that paper of the relative speeds (f_T) as a function of base width is shown in Fig. 2. The improved transport properties of III-V materials – both GaAs and InP – present a fundamental barrier that is difficult for silicon to overcome. Also, the well-known Johnson limit [13] for speed vs. breakdown voltage in semiconductor devices results in much higher gain for III-V *power* devices at a given breakdown voltage, due to the wider band gap. The higher gain translates into improved power-added efficiency, and improved linearity, at higher-frequencies of operation. Clearly, if achieving the best performance is the *only* criteria, then III-V technology is the superior option. However, in most applications, performance is rarely the only, or even the most important, criterion. It is in other areas, such as cost and time-to-market, where Si-based technologies have a distinct advantage.

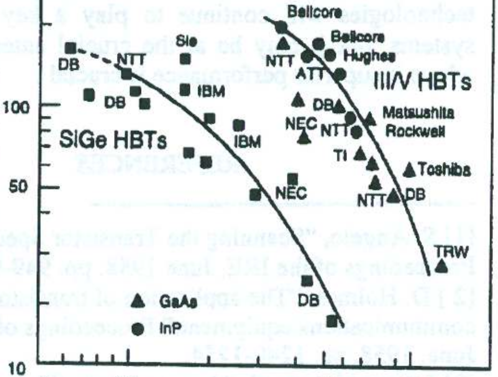

Fig. 2. Comparison of HBT f_T as a function of base width for Si/SiGe and III-V technologies [12].

III. CMOS TECHNOLOGY FOR MICROWAVE APPLICATIONS

CMOS technology is another emerging force in the field of microwave communications systems. The speed of the devices, as illustrated in Fig. 1, is certainly compatible with microwave applications. Several recent papers have demonstrated impressive results in highly integrated transceivers in the lower microwave frequency range [14]. CMOS transistors have certain advantages compared to bipolar transistors, including a somewhat lower Noise Figure, and an intrinsically very low third-order distortion, making them attractive for front-end applications. The ubiquitous LDMOS power amplifiers in many cellular handsets testify to its ability to realize low-cost microwave power amplifiers.

These advantages have to be balanced against the somewhat higher power dissipation of an NMOS device at a given f_T compared to a bipolar transistor of comparable lithography. An example of this comparison is shown in Fig. 3 [15] for a 20 GHz bipolar process and a 0.5μm CMOS process. These devices exhibit comparable *peak* f_T's, but the peak occurs at a higher voltage for the NMOS device. This will become less and less of a problem for each succeeding generation of CMOS devices. However, as gate length and oxide thickness scale, the dynamic range of the devices is inevitably decreasing, removing some of the advantages of the intrinsic device. Counterintuitively, for low-power high dynamic range applications, bipolar technology may have the best performance. This presents a powerful case for the use of BiCMOS technology in highly integrated radio transceivers, where the bipolar devices can be used for critical interface applications, and CMOS can be used for the back-end baseband and DSP functions.

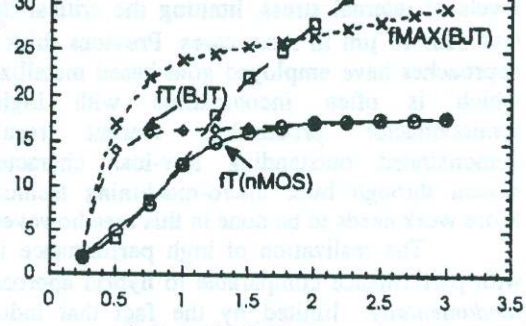

Fig. 3. Measured device cutoff frequency as a function of bias voltage for MOS and bipolar transistors. From [15].

One approach to circumvent some of the drawbacks of silicon technology for microwave applications (lossy substrate, poor high-frequency isolation) is the use of a sapphire substrate in a CMOS/SOS configuration [16, 17]. Substantial progress has been made recently in the development of this technology for wireless transceiver applications. N-channel MOSFETs with 0.5 µm T-gate structures exhibit f_T values in excess of 22 GHz and f_{MAX} values in excess of 60 GHz [18]. Comparable P-Channel devices exhibit f_T values in excess of 10 GHz and f_{MAX} values in excess of 50 GHz. A 2.4 GHz monolithic LNA fabricated in this technology exhibited 10 dB of gain, with a 2.8 dB noise figure and input referred intercept point of 4 dBm, while dissipating 14 mW of dc power [17].

IV. PASSIVE ELEMENTS IN SILICON TECHNOLOGY FOR MICROWAVE APPLICATIONS

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 the relatively high conductivity of typical silicon substrates. This high conductivity also leads to a high degree of coupling between adjacent high-frequency circuits. Finally, the ohmic loss of transmission lines implemented in silicon have tended to be high, because of the relatively thin Al-based metallization employed in most VLSI processes.

Despite these drawbacks, a number of approaches have been pursued for low-loss transmission lines in a monolithic silicon environment, including coplanar transmission lines on lightly-doped substrates [19,20], thick deposited SiO_2 for realization of microstrip structures [21], and thick polyimide layers to separate the transmission lines from the silicon substrate [22]. 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 [23]. 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[24] , which is often incompatible with high volume semiconductor processing. Recent results have demonstrated outstanding low-loss characteristics in silicon through bulk micro-machining techniques [25]. More work needs to be done in this area however.

The realization of high performance inductors - with performance comparable to hybrid approaches - is *fundamentally* limited by the fact that inductor Q is roughly proportional to the *area* of the inductor [26]; the inevitable area limitations of a monolithic integrated circuit render dramatic improvements in Q nearly impossible. Silicon technology is doubly burdened because of the additional issues of the resistive aluminum metallization and the lossy substrate. Most current efforts at Q enhancement involve modest reductions in series resistance, or elimination of substrate loss effects. These efforts include the use of thick gold metallization [27], multiple metal layers in parallel [28], bulk micromachining techniques for the removal of resistive material underneath the inductor [29], and spun-on thick dielectrics [30] to physically separate the inductor from the lossy silicon substrate. A further improvement in the Q of monolithic inductors was recently demonstrated by researchers, who employed “porous silicon” processing techniques to increase the resistivity of the bulk substrate underneath a spiral inductor [31]. Peak values of monolithic inductor Q in the 5-20 range have been achieved to date, but this is still well below what is achievable using off-chip hybrid components.

At mmW frequencies, there has recently been substantial progress in the area of bulk-micromachining techniques for the realization of monolithic suspended stripline filters in silicon technology, from 20 - 100 GHz [32]. These structures exhibit negligible dielectric losses, and very little dispersion or radiative losses. A 95 GHz bandpass filter was realized in this technology, and achieved a 3.4 dB insertion loss, with a 6% bandwidth [33]. The prospects of combining these structures with very advanced silicon transistors is an exciting prospect.

V. CONCLUSIONS

The digital CMOS origins of the emerging advanced silicon microwave technologies will provide a straightforward path of “up-integration” of traditional microwave systems onto single-chip or “couple-chip” implementations in the coming years. This will clearly have some profound implications for microwave systems, and particularly the appropriate interface between III-V-based technologies and silicon technologies. Clearly III-V technologies will continue to play a key role in these systems, but it may be at the crucial antenna interfaces, where it superior performance is crucial .

REFERENCES

[1] S. Angelo, “Scanning the Transistor Special Issue,” Proceedings of the IRE, June 1958. pp. 949-951.
[2] D. Holmes, “The application of transistors in communications equipment,” Proceedings of the IRE, June, 1958, pp. 1240-1254.
[3] J. Coughlin, et. al, “A monolithic silicon wide-band amplifier from dc to1 GHz,” IEEE Journal of Solid-State Circuits, vol. SC-8, no. 6, Dec. 1973, pp. 414-420.

[4] L.C.N. De Vreede, "HF Silicon ICs for Wide-Band Communications Systems, Ph.D. Thesis, TU Delft, 1996, pp. 1-8.

[5] L. Larson, et. al., "A low-cost monolithic microwave integrated circuit technology in Si/SiGe HBT technology," Proc. 1996 IEEE Intl. Solid-state Circuits Conf. Pp. 88-89.

[6] D. Harame, et. al., "Si/SiGe epitaxial-base transistors – part I: materials, physics, and circuits," IEEE Trans. on Electron Devices, March, 1995, pp. 455-468.

[7] D. Harame, et. al., "Optimization of SiGe HBT technology for analog and mixed-signal applications," IEDM Tech. Dig., Dec. 1993, pp. 874-876.

[8] M. Case, et. al, "A 26 GHz digital frequency divider implemented in a manufacturable Si/SiGe HBT technology," Proc. 1995 IEEE BCTM, 1995.

[9]J. Glenn, et. al, "12-Ghz Gilbert mixers using a manufacturable Si/SiGe epitaxial-base bipolar technology," Proc. 1995 IEEE BCTM, pp. 186-189.

[10] G. Henderson, et. al, "SiGe bipolar transistors for microwave power applications," 1997 IEEE MTT-S International Microwave Symposium digest, pp. 1299-1302.

[11]L. Larson, et. al., "A low-cost monolithic microwave integrated circuit technology in Si/SiGe HBT technology," Proc. 1996 IEEE Intl. Solid-state Circuits Conf. Pp. 88-89.

[12] U. Konig, A. Gruhle, and A. Schuppen, "SiGe devices and circuits: where are the advantages over III-V/," Proc. 1995 IEEE GaAs IC Symposium, pp. 14-18

[13] E.O. Johnson, "Physical limitation on frequency and power parameters of transistors," IEEE Intern. Conv. record, pt. 5, p. 27, 1965.

[14]A. Abidi, "CMOS-only RF and baseband circuits for a monolithic 900 MHz wireless transceiver," 1996 IEEE BCTM Dig. , Minneapolis, Minn., pp. 35-42.

[15]S. Voinigescu, S. Tarasewicz, T. Macalwee, and J. Ilowski, " An assessment of state-of-the-art 0.5um bulk CMOS technology for RF applications," in 1995 IEEE IEDM Dig., Wash, DC., pp. 721-724.

[16] A. E. Schmitz, R. H. Walden, L. E. Larson, S. E. Rosenbaum, R. A. Metzger, J. R. Behnke, and P. A. MacDonald, "A Deep Submicrometer Microwave/Digital CMOS/SOS Technology", *IEEE Electron Device Letters*, **12** (1), 16-17 (1991).

[17] C. Chang, R. Johnson, I. Lagnado and P. Asbeck., "Microwave characterization of sub-micron n- and p-channel MOSFETs fabricated with thin-film silicon-on-sapphire," 1994 MTT-S Digest.

[18] R. Johnson, C. Chang, P. Asbeck, and I. Lagnado "Microwave characterization of high f_{MAX} low-noise thin-film silicon-on-sapphire MOSFETs," 1995 International SOI conference, Oct. 1995.

[19] A. C. Reyes, *et al.*, "High resistivity Si as a microwave substrate", *Proc. 46th Electronic Components and Technology Conf.*, pp. 382-391, 1996.

[20] A. C. Reyes, *et al.*, Coplanar waveguides and microwave inductors on silicon substrates", *IEEE MTT-S*, vol. 43, no. 9, pt. 1, pp. 2016-2022, 1995.

[21] H. Sakai, et. al, "A novel millimeterwave IC on Si substrate using flip-chip bonding technology," IEEE MTT-S Intl. Microwave Symposium Digest, vol. 3, pp. 1763-1766, 1994.

[22] Bon-Kee Kim, *et al.*, "Monolithic planar RF inductor and waveguide structures on silicon with performance comparable to those in GaAs MMIC", *International Electron Devices Meeting Technical Digest*, pp. 717-720, 1995

[23] S.R. Taub and P. Young, "Temperature dependent performance on coplanar waveguide (CPW) on substrates of various materials", *IEEE MTT-S International Microwave Symposium Digest*, vol. 2, pp. 1049-51, 1994.

[24] M. Case, S.A. Maas, L. Larson, D. Rensch, et. al, "An X-band monolithic active mixer in SiGe HBT technology", *IEEE MTT-S Intl. Microwave Symposium Digest*, vol. 2, pp. 655-8, 1996.

[25] J. Papapolymerou, et. al., "A micromachined high-Q X-band resonator," IEEE Microwave and Guided Wave Letters, vol. 7, no. 6, pp. 168-170, 1997.

[26] G.Temes, and J. LaPatra, *Introduction to Circuit Synthesis and Design*, McGraw-Hill, 1977, see Chpt. 7.

[27] K. Ashby, I. Koullias, W. Finley, J. Bastek, and S. Moinian., "High-Q inductors for wireless applications in a complementary silicon bipolar process," IEEE JSSC, vol. 31, no. 1, 1996, pp. 4-9.

[28] J. Burghartz, "RF components implemented in an analog SiGe bipolar technology," 1996 IEEE BCTM Dig. , Minneapolis, Minn., pp. 138-141.

[29] J. Chang and A. Abidi, " Large suspended inductors on silicon and their use in a 2-um CMOS RF amplifier ," IEEE JSSC, vol. 14, no. 5, 1993, pp. 246-248.

[30] L. Larson, M. Case, S. Rosenbaum, B. Meyerson, and D. Harame, "Si/SiGe HBT technology for low-cost monolithic microwave integrated circuits," *Int. Solid-State Circuits Conf.* , San Francisco, CA, 1996, pp. 80-81.

[31] N. Choong and K. Young, "High-performance planar inductor on thin oxidized porous silicon (OPS) substrate," IEEE Microwave and Guided Wave Letters, vol. 7, no. 8, Aug., 1997, pp. 236-238.

[32] C. Chi, and G. Rebeiz, "Planar microwave and millimeterwave lumped elements and coupled line filters using micro-machining techniques," IEEE Transactions on Microwave Theory and Techniques, vol. 43, no. 4, pp. 730-738, April, 1995.

[33]S. Robertson, L. Katehi, and G. Rebeiz, "Micromachined W-band filters," IEEE Transactions on Microwave Theory and Techniques, vol. 44, no. 4, pp. 598-606, April, 1996.