Si:Ge DEVICES AND TECHNOLOGY FOR TELECOMMUNICATIONS IC APPLICATIONS

Stanley Wolf Ph.D.

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There is a rapidly growing market for wide-bandwidth and wireless telecommunications. That is, consumer demand for data from the Internet, for digital audio and video, and for video-on-demand is on the rise. In general, data is delivered to the consumer in two ways: *guided-wave propagation* and *free-space transmission*. Guided-wave propagation occurs along optical-fiber links and coaxial cables. Free-space transmission is the territory of radio, television broadcasting, satellite links, local multi-point distribution systems, and wireless local-area networks. (For example, such wireless applications as cellular phones currently operate in the 2.5-10-GHz range.) For free-space propagation, expensive installations are not necessarily required, but governments do regulate the use of bandwidth and frequency with a firm hand.

Since most of the *wireless* part of the frequency spectrum has been allocated, new or large bandwidth applications will be forced to resort to unallocated higher carrier frequencies. For example, a new wireless local-area network may have to operate at 60 GHz. Besides possible economy, a second attraction of higher frequencies is that they use smaller antennas. Because antenna efficiency is proportional to carrier frequency, receivers of higher carrier frequencies need only compact antennas. For instance, an antenna just 10-cm in length suffices for collision-avoidance automotive radar at 77-GHz.

As for *guided-wave systems*, cable has been deployed, and once it is in place, bandwidth is relatively unregulated. In this kind of system (such as an optical-fiber data-link), the development of high-frequency components is mainly a response to the call for higher data rates. As optical-fiber trunk lines are more fully exploited, the next generation of communications channels will come to operate at 40, 80, or 100 Gb/s, well above the current 2.5-10 Gb/s. In fact, 100 Gb/s links could be in production as soon as 2010.

These data rates raise another obstacle. The signals must be received and processed at high speed and then eventually slowed down to match silicon CMOS processing speeds of, at best, 1.5-Gb/s. Such a receiving circuit requires complexity of at least the LSI level.

There is also a trend to higher operation frequencies in mobile communications and high-speed data-links. Future optical communications systems will also operate at over 10-Gb/sec and microwave/millimeter-wave systems will be used for mobile communication and intelligent traffic-control. The diverse range of applications in the broadband space includes *local multi-*

point distribution systems (LMDS) that distribute information within major metropolitan centers via microwave transmission; *global-positioning systems* (GPS); *wide-* and *local-area networks*; *cellular base stations* and *handsets*, including *cellular, 3rd-generation* (3G) *personal-communications systems* (PCS) for wireless telephony; *asynchronous transfer mode* (ATM) *switching and multiplexing for information transfer*; and the *synchronous optical network* (SONET) protocols and systems for optical communication.

Table 1 Performance Characteristic Comparison of GaAs and Si:Ge-HBTs

Characteristic	GaAs HBT	Si:Ge HBT
GAIN		
f_t, GHz	50	30
f_{max}, GHz	70	62
G_{max} @ 2 GHz, dB	20	23
NOISE		
F_{min} @ 2 GHz	1.5	0.5
G_{assoc}	> 20	> 0.5
1/f corner	1-10	0.1-1
POWER		
V_{be}, V	1.4	0.85
V_{knee}, V	0.5	0.25
FEATURE SIZE (μm)	2.0	0.5

In 1990, conventional wisdom predicted that devices built using silicon-based technology could operate only at high frequencies below 2-GHz. As noted above, there are many applications in telecommunications, radar, and data transmission that need higher frequencies. It was felt that all of these applications would require devices built using the more expensive III-V-based materials. In fact, since that time such wireless and high-performance (wide bandwidth) applications have turned increasingly to gallium arsenide (GaAs) and other III-V compound-semiconductor technologies to fabricate the high-frequency devices that such applications require. However, in the wireless personal communications systems that use GaAs devices, designers have had to use many technologies for one system (such as GaAs technology for the power amplifier [PA], low-noise amplifier [LNA] and other rf components), and CMOS-silicon-VLSI-technology for the baseband operations. To overcome this issue, in 1992 IBM decided to develop a competitive, commercially-acceptable analog technology for such applications based entirely on silicon (that is to say, strictly speaking, on silicon devices fabricated with some added *silicon-germanium* [Si:Ge] layers).

The premise for this technical and commercial breakthrough was to transform standard Si into a heterojunction semiconductor material by doping the Si lattice with germanium (Ge). Such a film can be created by epitaxially depositing such a Si:Ge layer onto a Si substrate. This epitaxial Si:Ge layer can be used as the base region of a *heterojunction bipolar transistor* (HBT). Table 1 compares the performance of such Si:Ge-HBTs to those made with GaAs. It can be seen that the maximum operating frequency of operation of Si:Ge-HBTs is close to those made from GaAs.

When IBM decided to pursue this path, they realized that there were many process integration challenges that would have to be met. However, if the venture was successful, it would become possible for silicon-based devices to compete with III-V semiconductor performance while simultaneously maintaining the low-cost advantages traditionally associated with Si. Furthermore, the intent was to make the ultra-high-speed Si:Ge-HBTs fully compatible with existing CMOS technologies. This would enable ICs to be designed with a BiCMOS process that integrated these ultra-high-frequency (bipolar) HBTs with CMOS on the same chip. In this fashion, a technology would be created that combines the radio-frequency (rf) front-end circuits with CMOS signal-processing circuitry. Since such a BiCMOS technology would offer both high-speed HBTs and CMOS on the same chip, it would be ideally suited for providing the high-performance and low-power characteristics required by wireless applications. In addition, it would be possible to manufacture the products on 200-mm wafers, with low defect densities, and in mature silicon-IC production facilities.

The overall approach to establishing such a technology was to develop a process in which the fabrication sequence of the Si:Ge-HBT became a module that could be integrated into a state-of-the-art CMOS process with no change to the CMOS flow or parameters. If this could be possible, it would represent an attractive route to cost-effective, single-chip solutions for the wireless market. That is, the cost of manufacturing Si:Ge-ICs is only marginally higher than for ICs in Si alone, while the fabrication of ICs made of GaAs or InP is considerably higher. In addition, such an approach would also pave the way for achieving high levels of integration not possible with GaAs technologies.

The first Si:Ge-IC that IBM offered commercially was built using 0.25-μm geometries and combined 1200 Si:Ge-bipolar-transistors with over million CMOS-transistors. This IC was the highest-performance, lowest-noise *data-channel-circuit* in the world. It is used to read data from high-speed hard-drives. The IBM fab at Burlington VT was processing 75 wafers per day of this device (starting in 1999), with yields above 75%.

In 1998 IBM described the characteristics of a 1.8-million-transistor ASIC chip, fabricated using a Si:Ge-BiCMOS technology. Neither the HBT nor the CMOS parameters were adversely impacted by the additional thermal budget of the complete BiCMOS process. The technology is low-cost, has high-performance, and allows re-use of existing CMOS designs. The Si/Si:Ge-HBTs in this technology are able to perform at very high speeds; f_{max} = 65-GHz. Because such high device-switching-speeds are not necessary for most wireless circuits operating at 900-MHz and 2.4-GHz, the Si:Ge leverage comes from being able to trade the excess speed for improvement in other device attributes; most notably, low-power operation. Another example of integrating Si:Ge-HBTs into a CMOS process was described by King of IBM at the 1999 IEEM. In this process four additional masking steps were needed to create this BiCMOS process. The result is a BiCMOS technology that includes a super self-aligned (SSA) Si:Ge-HBT with a peak f_T of 52-GHz and a peak f_{max} of 70-GHz. A 0.18-μm rf-BiCMOS technology with a 73-GHz f_T Si:Ge-HBT was described at the 2000 IEDM by Hahimoto. A two-step annealing technique is used to solve the thermal budget tradeoff between Si:Ge HBTs and CMOS. IBM has also devoted significant effort to develop high-quality capacitors and inductors, which can be integrated into the Si:Ge-process. These passive components allow IBM to build the world's only single chip Global Positioning Satellite (GPS) receiver.