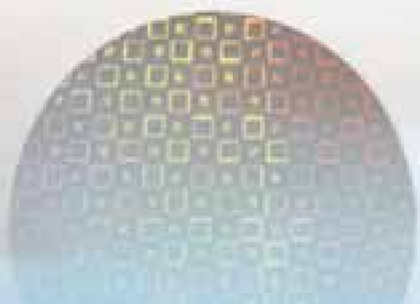
 By Bill Schweber, Technical Editor

SiGe *gets* real

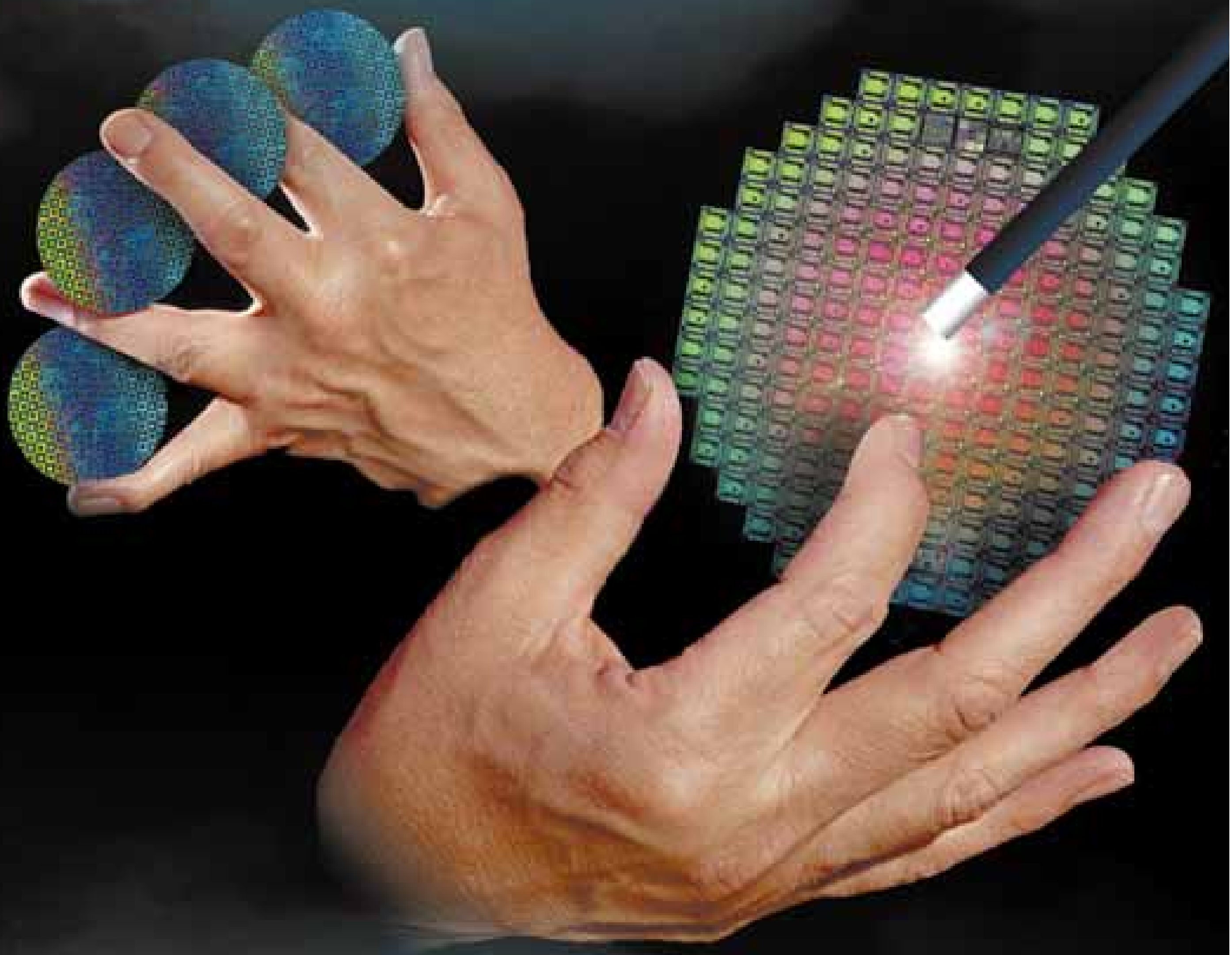
LONG-HERALDED AS THE NEXT GREAT PROCESS FOR RF ICs, INNOVATIVE SiGe PARTS ARE NOW AVAILABLE, BUT ESTABLISHED PROCESSES, SUCH AS GaAs, STILL HAVE A LOT OF LIFE IN THEM.



Mention IC-process technology to engineers, and you usually get a bipolar reaction. Those engineers who design ICs get misty-eyed when they talk about process, because it is an important tool that they need to create leading-edge devices. Conversely, engineers who design ICs into circuits roll their eyes when they hear about process, because they want to know about features and benefits of the final, shippable product and don't care much about line width, double-poly structures, metallization, deep-trench isolation, or similar apparently esoteric features.

Enter silicon germanium (SiGe), a process that IBM (White Plains, NY, www.chips.ibm.com or www.research.ibm.com/sigetech) has been developing over the last 10 years and that it licenses to other IC vendors. By combining silicon with germanium, the process in theory offers IC designers the best of both worlds. They get the well-known and established attributes and process flow of silicon, along with a performance edge that a little added germanium provides and that either germanium or silicon alone does not. This amalgamation is difficult to achieve (see **sidebar** "What's so hard about combining semiconductors?"). (Proponents pronounce "SiGe" as both "Siggy" and "See-Gee.")

In the last year, some SiGe parts from a variety of vendors finally reached the shelves. These parts exclusively target RF and gigabit-per-second applications because SiGe excels in those areas. The parts include both basic building blocks and highly integrated devices. They offer some interesting combinations of performance, speed, noise, and power consumption. Meanwhile, these SiGe offerings don't obsolete existing



high-performance RF parts, such as those fabricated in gallium arsenide (GaAs).

WHY GO TO ALL THIS TROUBLE?

The road to improved performance of ICs comprises fundamental process improvement of the transistors within the ICs—via new underlying structures and doping strategies—and shrinking, or scaling, the transistor's features, which increases its speed and reduces power consumption.

But such scaling can't continue indefinitely, because you eventually encounter some fundamental constraints of the laws of physics. As feature dimensions shrink, for example, the density of the dopants in the base region of transistors in the silicon must increase to keep overall charge constant. Eventually, this localized density is so high that the transistor leaks current even when it should be off.

AT A GLANCE

- ▷ Vendors are finally offering long-awaited ICs based on silicon-germanium (SiGe) process technology.
- ▷ SiGe ICs offer a new set of performance, power, and price parameters.
- ▷ SiGe won't displace GaAs, which still offers the performance edge in targeted applications and has a manufacturing track record.

In simplified terms, SiGe uses a new composition of the semiconducting material—traditionally, silicon—at the transistor junctions to change the electric field gradient, which in turn induces the electrons to travel more quickly through the material than a silicon-only material can travel. Proponents theorize that such SiGe-based devices will increase transistor speed. For example, if optimized all-silicon devices switch at 50 to 70 GHz, the corresponding SiGe device switches at approximately two to three times that speed.

SiGe's virtues, in principle, are increased speed and lower power using mask and process steps that are similar to those in widespread use for conventional silicon-only ICs. IC vendors could use the same equipment, the same size wafers, and even the same process flow—but with extra steps—they already use and have refined. The additional manufacturing investment and uncertainty for vendors would be low.

SiGe vendors and proponents make some strong arguments for the process (see **sidebar** "Process is element(ary)"). Compared with GaAs, they say, SiGe operates on lower voltages, uses less power, has improved input third-order intercept-point performance, develops less low-frequency noise (good for lower jit-

WHAT'S SO HARD ABOUT COMBINING SEMICONDUCTORS?

It's ironic that germanium is the added element that gives silicon-only ICs that extra performance buzz. When John Bardeen, Walter Houser Brattain, and William Shockley at Bell Labs invented the transistor in 1947, it was a germanium-only device (**references A** and **B**). Silicon did not come into use for solid-state devices until a few years later, when researchers overcame some crystal-growing and processing issues with the material as well as other technical challenges. Now, designers use silicon only, virtually excluding germanium except for some specialty devices. Engineers even use the word "silicon" as synonymous with "IC"—a slight to the vendors of gallium-arsenide devices.

All IC processes have some magic associated with them, and silicon germanium (SiGe) is no exception. Unfortunately, you can't simply mix the raw, molten silicon and germanium and then grow a composite crystal, and you can't directly grow germanium on top of a silicon substrate. The crystal structures of each element are incompatible in their dimensions or thermal characteristics, and this incompatibility results in a composite wafer with voids, stress cracks, and other unacceptable characteristics.

Beginning in 1989, Bernard Meyerson, PhD, led other researchers at IBM (www.chips.ibm.com) to develop a sophisticated way to build a germanium layer on a silicon layer using ultrahigh-vacuum/chemical-vapor deposition. They started with a low-temperature epitaxy and built a pure silicon *homojunction*—the interface between two regions of semiconductor made of the same substrate crystal, such as silicon, but with opposing doping polarities. They then fabricated a graded *heterojunction*—an interface between two regions of semiconductor but made of different substrate materials—between the silicon and SiGe-alloy layer on top of the silicon. The resulting heterojunction-bipolar transistor was the first step toward larger SiGe devices with full, useful functions (**Figure A**). **References C** and **D** provide a better understanding of the challenges and how they were overcome.

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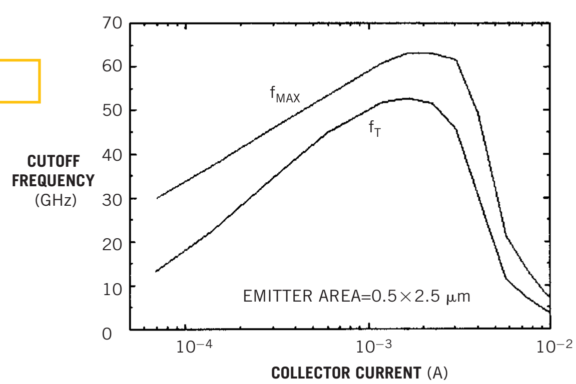
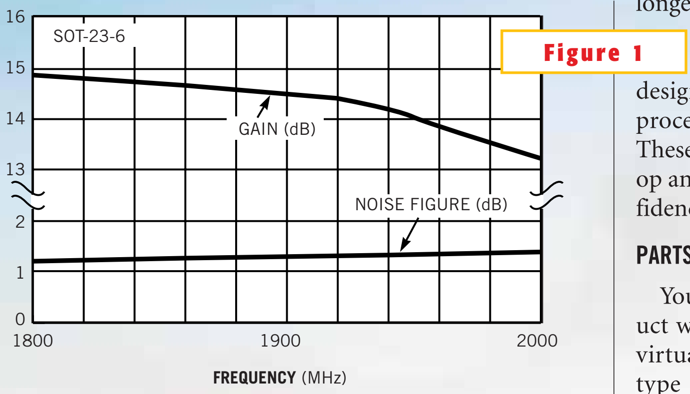
Figure A



For a basic SiGe heterojunction-bipolar transistor, IBM provides a representative f_{MAX} and f_T graph.

ter), and offers greater potential for functional integration. Most of today's high-performance systems use GaAs for RF front-end low-noise amplifiers and power amplifiers but bipolar silicon for the IF and other RF stages. In contrast, you could theoretically use SiGe for all these functions. Furthermore, like silicon, SiGe requires no negative bias for its power amplifier, so you need neither an external dc/dc bias source nor a power amplifier with a built-in bias generator. With deep-trench structures for isolation, you can build good passive devices on the IC or integrate several signal-processing functions that have acceptably low crosstalk.



Maxim's MAX2641 low-noise amplifier has a 1.3-dB noise figure and 14.4-dB gain at 1900 MHz. The input and output circuits are matched to that frequency.

In addition, SiGe could eventually replace the CMOS silicon for baseband and lower frequency IF functions. IC designers should be able to take advantage of a long-standing attribute of silicon ICs: that you can economically and reliably design an increasing number of devices onto the IC. This ability leads to higher levels of integration per device with subsequent reductions in overall power, cost, system size, interconnection problems, and unreliability.

IBM-owned CommQuest Technologies' (Encinitas, CA, www.commquest.com) Web site provides an interesting discussion of the apparent virtues (and some vices) of SiGe, but note that this presentation is from the perspective of a leading SiGe proponent. GaAs-device vendors have a different view of the competitive position and viability of SiGe (see **sidebar** "Will SiGe step on the GaAs?").

The history of semiconductor devices shows that an attractive process in the lab, even though some products substantiate that allure, does not necessarily translate to a dominant manufacturing reality. The SiGe devices require some additional process steps, and every new IC process is fickle at first. Some stay fickle longer than others do. Second, IC designers need the right tools to model, design, and characterize the process and its structures. These tools take time to develop and qualify with high confidence.

PARTS HIT THE SHELVES

You can't build a real product with just data sheets and virtual- or laboratory-prototype components; you need real components. In the past year, several vendors have released standard SiGe parts, and others have announced parts for this year. These components range from basic amplifiers to more complex, multifunction devices.

Maxim (Sunnyvale, CA, www.maxim-ic.com), for example, has transimpedance amplifiers, low-noise amplifiers, and mixers using the SiGe process. The MAX2640 and similar MAX2641 low-noise amplifiers operate at 400 to 2500 MHz and need a 2.7 to 5.5V supply at less than 3.4 mA. These 80-cent (1000) units have an internal bias circuit that eliminates the need for bias resistors or an external negative bias supply. The MAX2640 primarily targets applications requiring 400 to 1500 MHz; it offers typical gain of 15.1 dB and a noise figure of

PROCESS IS ELEMENT(ARY)

Remember the periodic table from chemistry class labeling the 18 columns IA through VIIIB? (Note, there's potential for confusion here. Approximately 20 years ago, the International Union of Pure and Applied Chemistry Convention, an international standards-setting body, renumbered the columns as simply 1 through 18, but many older versions of the chart still exist, and many people still refer to the columns by their earlier designations.) Using the original designations, silicon and germanium are in Group IVA of the table, whereas alternate semiconductor-element pair gallium and arsenic are in groups IIIA and VA, respectively. Until about 10 years ago, industry participants viewed gallium-arsenide (GaAs) devices as exotic, expensive, and low-yield. In the past few years, however, these devices have matured and achieved competitive pricing and high yields by supplying high-volume low-noise-amplifier and power-amplifier applications, such as cell phones, cable set-top boxes, and global-positioning-system receivers.

Why use GaAs at all? Compared with conventional silicon—not silicon-germanium (SiGe)—devices, GaAs is faster and better for several reasons. For one thing, its low-field electron mobility is higher. Also, it has a lower saturation field, and it can be semi-insulating (like a semiconductor, but toward the insulation end of the range) because its energy gap is much larger. This large gap in turn allows designers to build good passive components, including inductors, directly onto the substrate. GaAs has less parasitic capacitance, yielding further speed advantages, than silicon and is a direct-bandgap material, so you can use it for light emission and microwave emitters. Further, GaAs operates at higher voltages, which is especially useful for RF power amplifiers.

Because GaAs offers these advantages, why not just migrate from silicon to GaAs and skip SiGe, assuming that either GaAs or SiGe provides the necessary speed? Again, the issue is complex, but silicon has some strong virtues. The oxide of silicon, SiO_2, is an insulator, so you can use silicon to form its own protective mask. Silicon conducts heat nearly three times better than GaAs, so you can build devices with higher power densities, and raw silicon wafers are much cheaper than those for GaAs, because silicon is so abundant whereas gallium is relatively scarce.

0.9 dB at 900 MHz. The companion MAX2641 targets the higher range of 1400 to 2500 MHz; at 1900 MHz, its typical gain is 14.4 dB with a 1.3-dB noise figure (**Figure 1**).

When you need to downconvert 400- to 2.5-GHz RF to 10- to 500-MHz IF, you may want to consider the MAX2680, MAX2681, and MAX2682 mixers. These single-supply, double-balanced mixers use a 2.7 to 5.5V supply with a noise figure of less than 7 dB at 900 MHz. The three 92-cent (1000) parts differ in their typical supply current and input third-order intercept-point level pairings; this parameter ranges from −6.9 to +3.2 dBm at 2450 MHz, depending on the part.

Focusing on fiber-optic-receiver applications, the 2.5-Gbps MAX3267 and 1.25-Gbps MAX3266 transimpedance amplifiers operate at 3.3V and typically consume 86 mW. The $5 (100,000) MAX3267 has 485-nA input-referred noise, 1900-MHz bandwidth, and 1900Ω transimpedance. This amplifier can handle signals with dynamic range spanning −21 to 0 dBm at an 850-nm wavelength and −24 to −3 dBm at a 1300-nm wavelength.

Figure 2

Three of the four ICs, including the HFA389 power amplifier and detector, in Harris' upgraded 2.4-GHz Prism chip set use SiGe.

Harris Semiconductor (www.semi.harris. com) is using SiGe to upgrade its 2.4-GHz Prism wireless-LAN chip set to a top data rate of 11 Mbps using direct-sequence spread-spectrum (DSSS) techniques. The original Prism chip set used eight ICs, whereas this reengineered chip set, which complies with the high-speed IEEE802.11 standard, has half that number of ICs and also incorporates several functions that external discrete components previously handled.

The four ICs include the $3.59 (10,000) HFA3983 power amplifier and detector (**Figure 2**), the $8.66 (10,000) HFA3683 RF-to-IF converter, the $9.76 (10,000) HFA3783 I/Q modulator/demodulator and synthesizer, and the $14.02 (10,000) HFA3861 DSSS baseband processor of the ICs. The power amplifier, converter, and I/Q modulator/demodulator use SiGe. Harris cites fewer parts, reduced power consumption, and higher speed as the virtues of this improved chip set.

SiGe is not limited solely to analog or analog-dominant ICs. American Micro

WILL SiGe STEP ON THE GaAs?

In the battle among silicon, silicon-germanium (SiGe), and gallium-arsenide (GaAs) processes and devices, vendors take a variety of positions. Some are striving to make conventional silicon devices better and faster to take advantage of regular silicon's low cost and are holding off on SiGe. Others are actively extending their silicon technology and designs to SiGe by licensing the process from IBM (www.chips.ibm.com).

In contrast, GaAs-only vendors Anadigics Corp (Warren, NJ, www.anadigics.com), TriQuint Semiconductor (Hillsboro, OR, www.tqs.com), and Vitesse Semiconductor Corp (Camarillo, CA, www.vitesse.com) are staying with GaAs for the foreseeable future. Officials at the companies believe that the system-level benefits and performance of GaAs keep it far ahead of highest performance silicon-only devices and that GaAs will remain superior to SiGe components at the system level. (Note that TriQuint takes its name from the Latin roots for III (tri) and V (quint), the columns of the periodic chart to which gallium and arsenic belong.)

They point to several factors in their favor: that GaAs lets IC designers incorporate high-performance passives into ICs; that GaAs' cost differential is less significant, now that high-volume GaAs products are on the market; and that the process has high yields. They also note that the additional steps for SiGe, although they hope those steps are just an extension of the standard silicon-only recipe, add cost and process uncertainty. If you look solely at cost per square millimeter, conventional silicon is the cheapest technology, GaAs is the most expensive, and SiGe should land between them. But, the GaAs vendors say you have to look at total system implementation cost for a design that also meets your power, performance, passive-component, and architectural requirements.

Even some vendors that offer silicon (non-SiGe) and GaAs devices are holding off on SiGe for now. Motorola Semiconductor (Phoenix, www.motorola.com/sps), for example, is using GaAs in the 900-MHz MRFIC1817 Global System for Mobile (GSM) communications power amplifier, which produces 34.5-dBm output power from a 3.6V supply with 43% efficiency. The company's MRFIC1819 and MRFIC0919 GaAs power-amplifier ICs for digital-communication-system 1800/personal-communication-system 1900 and GSM designs, respectively, each include an integral negative-voltage generator so they look like single-supply devices to your design. The GSM part boasts 35.3-dBm typical output for 3-dBm RF input and 53% efficiency.

GaAs is the only technology with available parts for high gigabit and gigahertz applications. Oki Semiconductor (Sunnyvale, CA, www.okisemi.com) has announced a set of GaAs devices—a postamplifier, an automatic-gain-control amplifier, a rectifier, a limiting amplifier, and a modulation driver—all for 10-Gbps OC-192 optical fiber systems. And Hewlett-Packard (Palo Alto, CA, www.hp.com) has no plans for SiGe, although the company is producing the HMMC-5034 medium-power GaAs amplifier, which provides 23-dBm output and 8-dB small-signal gain at 40 GHz.

The world of high-performance components can be an alphabet soup of structures such as HBT (heterojunction-bipolar-transistor), MESFET, and BJT (bipolar-junction-transistor) devices in silicon, GaAs, and SiGe. **Reference B** provides a brief, readable overview of the features and attributes of each.

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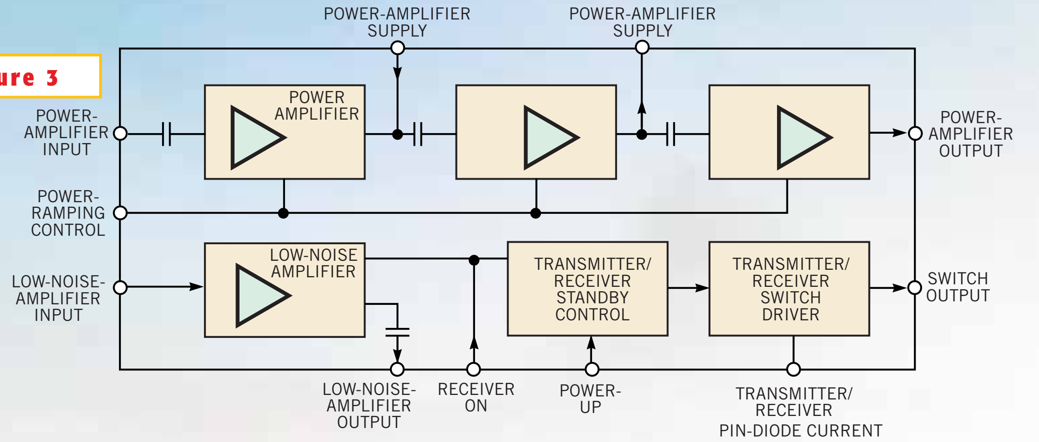
Circuits (San Diego, www.amcc.com) has applied the process to a family of synchronous-optical-network/synchronous-digital-hierarchy parts. The S3056 clock-recovery unit provides high-speed timing signals from the received data stream for 155.52- to 2488.32-Mbps OC-3 and through OC-48 as well as 1.250-Gbps Gigabit Ethernet. The 3.3V device typically consumes 1W, which is a little more than half its non-SiGe predecessor. The S3057 transceiver IC for the same bit-rate span provides the serial-to-parallel and the complementary function and interfaces to low-voltage positive-ECL and TTL; it provides similar power savings.

Figure 3



Temic uses SiGe for the front-end IC of a three-IC DECT chip set. The U7004B has a power amplifier, a low-noise amplifier, and a transmitter/receiver switch driver.

The company does not neglect functions with largely analog issues, although any IC operating faster than 1 Gbps has inherent analog issues even if the signal is digital. The S3058 limiter-amplifier and clock-recovery unit quantizes an input signal and produces a voltage-limited waveform over a 62-dB dynamic range. It has 1-mV input sensitivity and 43-dB gain distributed over three gain stages, plus a loss-of-signal output that you can set to trigger at any input level from 4 to 50 mV p-p. It also includes an offset-correction function to reduce pulse-width distortion, and a user-settable decision threshold lets you compensate for certain types of errors resulting from asymmetric noise.

The Temic Semiconductor (Heil-

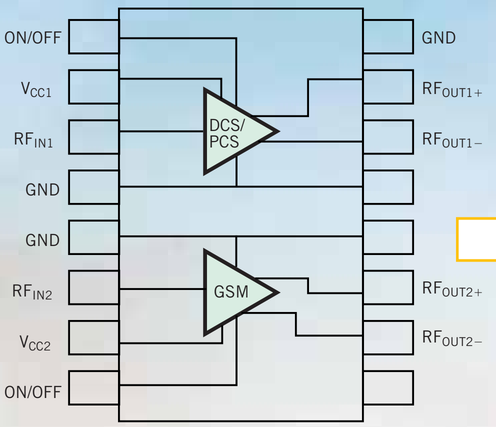


Figure 4

Supporting RF bands at 900, 1800, and 1900 MHz for GSM, PCS, and DCS systems, the SiGe CQT2240 from CommQuest has two independent low-noise amplifiers in a 16-pin package.

bronn, Germany, www.temic-semi.de) subsidiary of Atmel Corp has put its initial SiGe efforts toward an RF IC that is part of a Digital European Cordless Telephone chip set. The three-IC chip set spans antenna to baseband and comprises the U7004B front end plus the U2761B receiver and U2785B transmitter PLL. The U7004B, which is the SiGe IC in the set, integrates a low-noise amplifier, a power amplifier, and a transmitter/receiver switch driver into a 20-pin, 3V, 350-mA device (**Figure 3**). Typical noise figure for the $1.45 (500,000) preamp is 1.8 dB, and the power-amplifier stage has 26.5-dBm typical output level.

CommQuest offers two parts that are the start of more highly integrated, multiband building-block ICs for universal mobile phones. The triband CQT-2240 low-noise amplifier handles 900-, 1800-, and 1900-MHz channels (**Figure 4**). Its 16-pin package has two separate amplifiers for Global System for Mobile (GSM) communications and digital-communication-system (DCS)/ personal-communication-system (PCS) operation, each with 15-dB power gain and a 1.5-dB noise figure. Similarly, the triband CQT2250 has dual power amplifiers plus a VCO and divider that allow it to reach both GSM and DCS/PCS bands. Output power is 34 dBm at 900 MHz and 31 dBm at 1800/1900 MHz.

No discussion of SiGe would be complete without looking at IBM's parts, because the company started the SiGe process and brought it to practical implementation. In addition to a device library that the company licenses, IBM offers a packaged transistor and other devices. The IBM43RF0100 HBT (heterojunction-bipolar transistor) has input third-order intercept point of more than 10 dBm at a current of 7 mA and supply of 3V, which is about 5 to 10% the power that GaAs metal-semiconductor FETs and PHEMTs (pseudomorphic high-electron-mobility transistors) need for comparable third-order intercept performance.

IBM has also announced a family of building blocks. These building blocks include the 800- to 2000-MHz IBM43-RF1111 low-noise amplifier; the 900-

MHz IBMSGRF1112 low-noise amplifier, which operates at power as low as 1V; the triband IBMSGRF1113 low-noise amplifier for 945/1900-MHz operation; a 940-MHz power amplifier; and an 880/1850-MHz VCO.

Other vendors also expect to have parts available soon. For example, Philsar Electronics (Ottawa, ON, Canada, www.philsar.com) has signed a licensing agreement with IBM and plans to use the technology to design highly integrated, low-power radio ICs. RF Micro Devices (Greensboro, NC, www.rfmd.com), currently a vendor of a line of BiCMOS and GaAs devices, has signed an agreement with IBM to use the SiGe process for a line of RF building blocks.

Is SiGe the ultimate high-speed process for the future? No. It adds another set of tools to the kit that IC designers can use to juggle speed, power, noise, and cost for their application priorities. It lets IC designers choose another combination of trade-offs as they strive for parts that target application priorities.

Skeptics and detractors of any highly touted new technology sometimes quip derisively, “This new technology is the wave of the future...and always will be.” Will this be the tale of SiGe? For the foreseeable future, which I believe is two years at most, SiGe complements but doesn’t replace GaAs and high-performance silicon. IC vendors can use the process to meet certain combinations of requirements in noise, speed, power, and cost for specific applications. After that, who knows?

Realize that, while IBM and others were developing and commercializing SiGe over the last 10 years, those other non-SiGe processes were changing, too. Nearly all IC vendors have advanced their own technologies, enhanced their yields, and improved their development tools to make conventional silicon, as well as GaAs, faster, cheaper, and better. Check back in a few years, and see which technology paths succeeded and how. □

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