Silicon–Germanium Gives Semiconductors the Edge

FEATURE

by Jennifer Ouellette

Performance drives a boom in silicon–germanium chips

It is no secret that silicon devices dominate the microelectronics industry. Indeed, they account for more than 98% of sales in the global semiconductor market, largely because of their low manufacturing cost. However, the driving force behind today's growth in high-speed optical networking and inexpensive, lightweight personal-communications devices is not silicon but silicon–germanium (SiGe). This technology increases operating speed, reduces electronic noise, lowers power consumption, supports higher levels of integration, and, thus, enables the design of more functional components on a chip.

Thanks to SiGe's substantial performance benefits, it is quickly becoming the material of choice for both wireless integrated circuits (ICs) and low-power radio-frequency (RF) chips. And the number of SiGe applications is expected to explode over the next few years, with a concomitant increase in chip production. Strategies Unlimited (Mountain View, CA), a market research firm, predicts that sales of SiGe wireless and digital semiconductor devices will increase from $450 million in 2002—up from $15 million in 1999, an annual growth rate of 200%—to $1.8 billion by 2005. By then, SiGe ICs are expected to have captured nearly 10% of the total $19 billion market for high-speed devices in competition with silicon and gallium arsenide chips. Another firm, IC Insights (Scottsdale, AZ), takes an even more bullish view, estimating that the market will grow to about $2.7 billion by 2006.

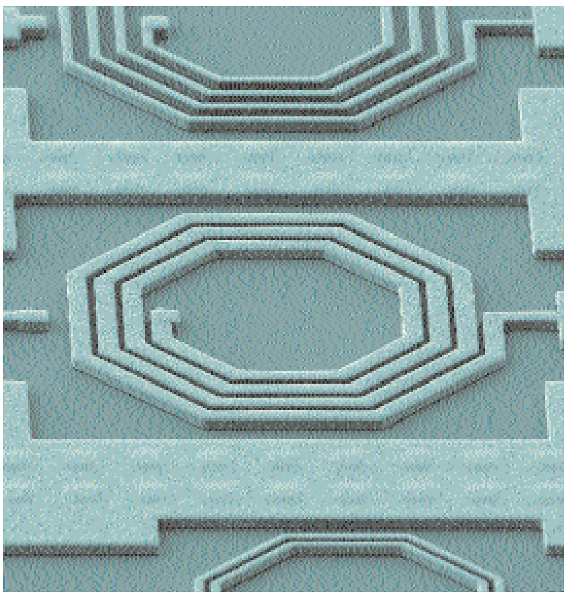


Figure 1. Scanning electron micrograph of electroplated copper spiral inductors, 10 µm thick, used with Motorola's 0.35- and 0.18-µm silicon–germanium–carbon bipolar complementary-metal-oxide-semiconductor technologies.

Applications such as wireless and satellite-based voice and data services are expected to drive 79% of the demand, with high-speed computer networking making up another 16% of the market, according to Strategies Unlimited. SiGe is already widely used in a range of high-speed and low-cost wireless gear, including RF components in cellular handsets, wireless local-area network chipsets, high-speed test and measurement equipment, and chipsets for optical data-transmission systems. "Wireless is such a huge volume of the market," says Cliff King, R&D technical manager at Agere Systems, which spun off from Lucent Technologies last year to focus on communications components. "That's the sweet spot for SiGe technology in terms of turning a profit." That volume will allow the technology to move into other market sectors in which its benefits outweigh the extra cost incurred in manufacturing.

Not surprisingly, telecommunications companies worldwide are taking note. More than 30 companies are developing SiGe ICs. In North America, IBM leads the industry, followed by other giants such as Lucent Technologies, Texas Instruments, National Semiconductor, Nortel, and SiGe Microsystems. A host of smaller component companies are interested in licensing the chips for their products. Overseas, the major players actively investigating SiGe applications are Alcatel, Daimler-Benz, Philips, and STMicroelectronics in Europe, as well as several Japanese corporations such as Hitachi, Toshiba, and NEC.

Advantages

SiGe (dubbed "Siggie" by industry insiders) involves a revolutionary process technology in which the electrical properties of silicon are augmented with germanium to make the chips operate more efficiently. Introducing germanium into the base layer of an otherwise all-silicon bipolar transistor improves operating frequency, current, noise, and power capabilities (see Figure 3). As such, SiGe offers a bridge between low-cost, low-power, low-frequency silicon chips and high-cost, high-power, high-frequency chips made from class III-V semiconductor materials such as gallium arsenide and indium phosphide. Scientists first became interested in the compound in the early 1980s, when researchers at Bell Laboratories discovered that SiGe has a smaller bandgap than conventional silicon, making it useful for building transistors. "That is what really got people excited about using this material for heterostructures, similar to what was being done at the time with III-V heterostructures," says King.

SiGe technology also maintains the key advantages of state-of-the-art silicon processing. Unlike the manufacture of other high-speed semiconductors made of two or more materials, SiGe processing is relatively simple because silicon and germanium have similar chemical and physical properties. Initially, SiGe was built using molecular-beam epitaxy, a labor-intensive process that has never been successfully transferred into silicon technology, according to King. But by the end of the 1980s, researchers had learned how to grow SiGe using chemical-vapor deposition. That feat proved a critical turning point for the material's commercial potential because it combines the two elements into high-quality thin films at relatively low temperatures and cost. And unlike chips created using more-expensive and less-reliable gallium arsenide, chip-makers can run SiGe on existing production lines with minimal changes and retooling.

Ordinary silicon does not operate at frequencies above a few gigahertz, which has hampered the development of higher-speed wireless telecommunications devices, and manufacturers are beginning to reach the physical limits of what they can do to improve the performance of ordinary silicon-based materials. In contrast to silicon-based chips, SiGe semiconductors have speeds of up to 120 GHz, increasing traditional current speeds by a factor between 2 and 4. "As the circuitry on chips was continually scaled down to achieve greater speeds, it became clear that the performance characteristics of bipolar silicon chips would eventually break down at very tiny dimensions," says Jack Hurt, director of semiconductor foundry relations at Tektronix (Beaverton, OR), a manufacturer of test, measurement, and monitoring equipment. "If bipolar silicon were to continue to advance in speed, an alternative technology was needed."

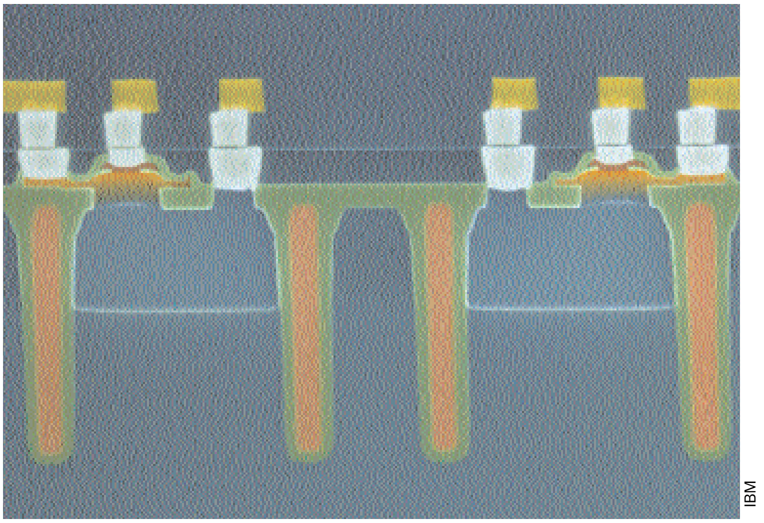


Figure 2. Two adjacent silicon–germanium heterojunction bipolar-technology devices with polysilicon-filled deep-trench isolation and base/emitter/collector aluminum metal interconnections.

SiGe gives IC manufacturers the ability to reengineer the bandgap of the silicon for higher performance, resulting in a two-material, or heterojunction system that is compatible with silicon technology. Although silicon and germanium have the same crystal structure, there is a greater than 4% difference in their lattice constants, according to David Leet, director of transparent modeling and technical strategic planning for Rudolph Technologies (Sunnyvale, CA), a metrology instruments company. Introducing the larger germanium atoms into a silicon lattice causes its structure to expand and become strained to create the alloy material. It is this stress that changes the bandgap.

Applications

In 1989, IBM became the first company to introduce the new technology into mainstream manufacturing and to produce the industry's first standard, high-volume SiGe chips. Since then, many companies have adopted IBM's technology, and the company is now introducing its fourth generation of SiGe chips, which have a linewidth of 0.18 μm. In February of this year, IBM announced the creation of the world's fastest semiconductor circuit using SiGe, which operates at more than 110 GHz and processes an electrical signal in 4.3 trillionths of a second. The first of the fourth-generation chips are expected to reach the market no later than the end of this year.

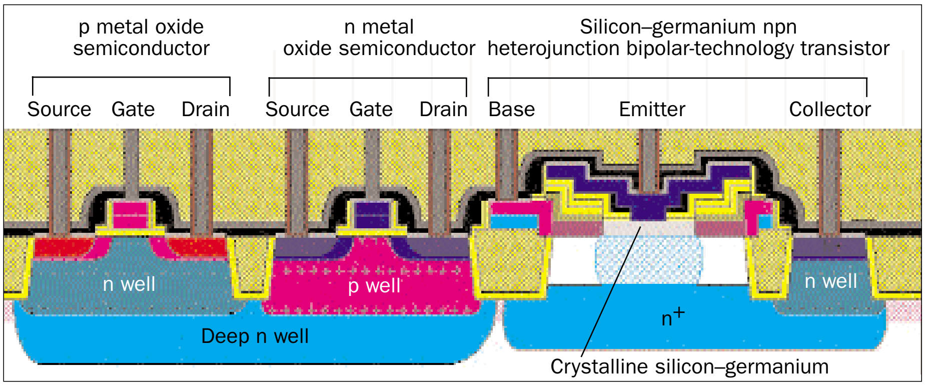
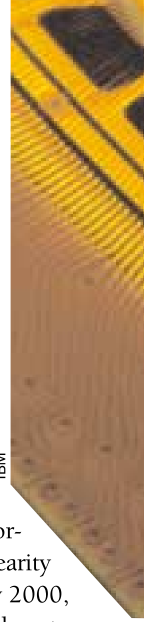


Figure 3. Cross section of the Texas Instruments silicon–germanium bipolar complementary-metal-oxide-semiconductor integrated circuit shows where the silicon–germanium is placed in the transistor.



IBM

Figure 4. Packaged 1.8-million-transistor application-specific integrated-circuit test chip fabricated with 0.5-μm silicon–germanium bipolar complementary-metal-oxide-semiconductor technology.

Tektronix recently signed an agreement with IBM to incorporate the 0.18-μm SiGe chips into its test instrumentation. Tektronix was the first test-and-measurement company to adopt IBM's 0.5-μm SiGe chip (Figure 4) for a digital phosphor oscilloscope, which it introduced in June 2000. The company has since used it in other products. These devices include a family of flexible, multiformat waveform monitors and, most recently, a jitter-analysis module introduced in January 2002. "SiGe provides the bandwidth necessary for next-generation, leading-edge test instrumentation," says Bob Woolhiser, director of microelectronics at Tektronix. "And its affordability makes it appropriate as an enabling technology for lower-cost products, such as probes and handheld measurement devices."

Agere Systems launched a 0.24-μm SiGe fabrication process in 1999. The company's initial products were used in 10-gigabyte (10-GB) optical networking, and last summer Agere created a strategic alliance with RF Micro Devices (Greensboro, NC) to jointly develop SiGe processes for wireless technology. Sirenza Microdevices (Sunnyvale, CA), formerly Stanford Microdevices, offers high-performance RF components, including a SiGe high-linearity active mixer for wireless applications. In January 2000, Texas Instruments announced its first SiGe technology to enhance its RF offerings for wireless telephony. STMicroelectronics (Geneva, Switzerland) followed suit in June 2001, targeting wireless products for which cost is critical, including handheld terminals, wireless home networking devices, and Bluetooth-equipped peripherals.

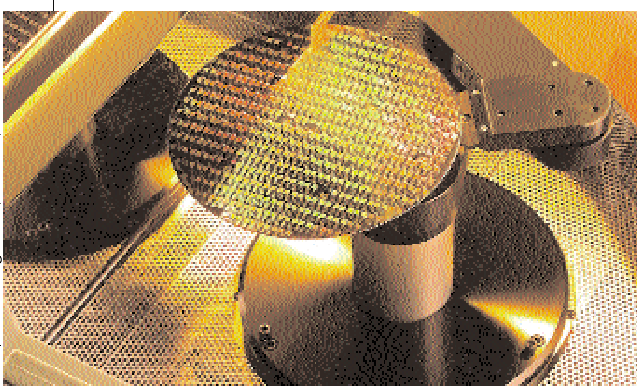
Canada's SiGe Semiconductor (Ottawa, ON) is also developing Bluetooth SiGe chips. Although SiGe had previously been considered too expensive for such a low-end application, the company believes that the combination of flip-chip packaging and the efficiency of its power amplifiers, as well as superior noise characteristics, can be exploited to create less expensive Bluetooth designs. Sirenza Microdevices provides high-performance RF components, including a SiGe high-linearity active mixer for wireless applications.

In early 2000, Motorola (Figure 1) became the first in the industry to qualify the SiGe heterojunction bipolar-technology (HBT) (Figure 2) bipolar complementary-metal-oxide-semiconductor (BiCMOS) process. A year later, it introduced a general-purpose, low-noise amplifier with selectable current. Other applications include Bluetooth technology, short-range wireless data transmission, and fiber-optic drivers in optical networking. Motorola also makes a series of SiGe clock drivers with a wide range of performance, power, and timing for various applications in telecommunications, networking, and instrumentation. Northrop Grumman is pursuing many applications for SiGe HBT, including microwave power transistors, small-signal application-specific ICs, materials growth, and cryogenics.

Characterizing silicon–germanium

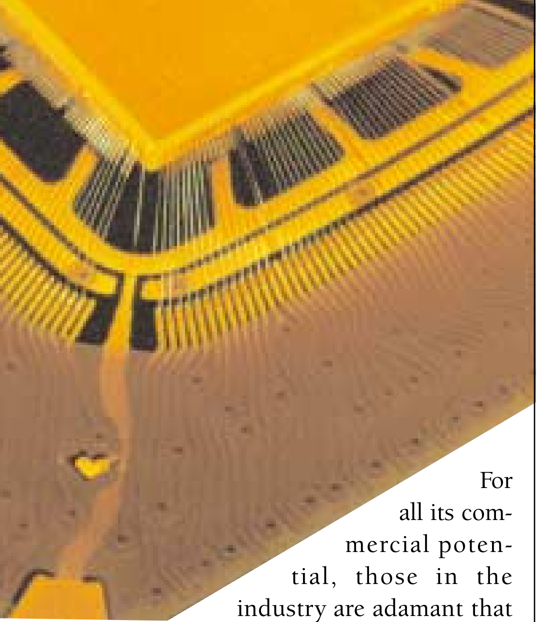
With the approaching advent of high-volume SiGe production, there is a corresponding need for metrology tools that can quickly and nondestructively characterize SiGe on product wafers. The desired SiGe device functionalities—such as high speed, low power consumption, high dynamic range, and low noise—are achieved by engineering the material's bandgap by controlling the amount of germanium added to the mix. According to David Leet of Rudolph Technologies (Sunnyvale, CA), the process must be carefully controlled, not only to obtain the desired bandgap but also to prevent lattice defects and unstable films. Spectroscopic ellipsometers (SEs) are often used in the industry to provide the process-control measurements of SiGe film thickness and germanium concentration.

SEs work well for very thin films. However, as the films become thicker than a few hundred angstroms, SE measurements become more challenging because of light absorption in the short-wavelength region. The data obtained from the long-wavelength region may contain errors because of the higher noise level of the xenon lamps used in the process, explains Vladimir Gavrilenko, senior system scientist at Rudolph. For more complex film stacks with graded SiGe layers, SE data measured at only one angle of incidence is insufficient for modeling purposes, and using the technique with multiple angles is too time-consuming for commercial manufacturing processes.



Rudolph Technologies Inc., Flanders, NJ

A new method that can simultaneously measure multiple angles of incidence has been developed at Rudolph. Microspot lenses focus the light from four laser sources onto the surface of the film, and the rays are then imaged onto an array detector, which allows data to be collected from more than 100 angles of incidence in one measurement. Gavrilenko reports that these measurements have the same advantages as those obtained with research-grade SEs, yet with a throughput rate high enough for the semiconductor industry's purposes. The company is currently developing modeling techniques to allow its instrument to measure thickness, maximum germanium concentration, and a full germanium profile of graded SiGe layers, which is one of the remaining challenges.



For all its commercial potential, those in the industry are adamant that SiGe will never displace traditional silicon in most market sectors. "If you can use CMOS for an application, you will use it because SiGe is more expensive due to the extra steps involved in manufacturing," says King. "What we will displace are III-V compounds such as gallium arsenide and indium phosphide. And as CMOS marches down its scaling curve, it is eventually going to displace us. But SiGe can buy you a generation or two in terms of products, and in this competitive marketplace, that is very useful."

Nonetheless, commercial potential abounds. True, the latest generations of CMOS technology are now capable of the processing speeds required for 10-GB optical networking. But SiGe also benefits from the industry learning curve. "We can take advantage of all the advances made in CMOS," says King. And SiGe is currently the only viable material for 40-GB optical networking—although the economic downturn has caused the telecommunications industry to put such upgrades on hold.

In the future, SiGe technology may lead to the creation of powerful new microcommunications devices such as single-chip, watch-sized cellular phones; collision-avoidance radar; and products combining the features of cell phones, the Global Positioning System, and Internet access in one package. Several companies, including IBM, envision such multifunction devices as a key element of future computing. "We certainly see the market for SiGe growing beyond just the high-speed transistors currently available," says Rudolph's Leet. "I think we are just beginning to see this material take off commercially." Ω