The Silicon-Germanium Heterojunction Bipolar Transistor

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Seventy-five years of the transistor (shortened from "transresistance amplifier" to "transresistor" to "transistor"). Time flies. A remarkable little piece of quantum physics in action. In 2022, transistors are viral-sized, nearly as fast as a speed of light, and importantly, cleverly possess that unique golden attribute of amplification, making tiny voltages and currents larger. There are over 10^{24} transistors on Earth in 2022, made possible by the jaw-dropping exponential growth patterns embodied in Moore's law. Transistors are ubiquitous to modern life, whether seen or unseen by both purveyors and consumers of technology. Surely the word "transistor" should be added to the vocabulary of every single person on Earth. In sort, all of modern technology, without exception, from smartphones to automobiles to planes to internet to GPS, would instantly cease to function if they were subtracted from the planet. In fact, in terms of its impact on the trajectory of human civilization, one could fairly argue that the invention of the transistor is the single most important discovery in human history. Bold words, but defensible [1].

Transistor action was first observed by Bardeen and Brattain at Bell Labs in late 1947 using a point contact device. This demonstration of a solid-state amplifying object is also unique in the historical record for the precision with which we can locate it—December 23, 1947, at around 5:00 pm. The precise moment the world changed irrevocably. Snow was falling in Murray Hill, NJ. Not to be outdone, by February of 1948, Shockley, the third member of the "transistor three," developed the theory for how this clever little object did its remarkable thing, and importantly, could be further improved, leading three years later to the first bipolar junction transistor (BJT) on April 12, 1950. That first BJT was made, ironically, from Ge, not Si.

The concept of the heterojunction (a junction built from two different semiconductors) bipolar transistor (HBT) is a surprisingly old one, dating in fact to the fundamental BJT patent filed by Shockley in 1948. Given that the first bipolar transistor was built from Ge, and III-V semiconductors were not yet on the scene, it seems clear that Shockley envisioned the combination of Si (wider bandgap emitter) and Ge (narrower bandgap base) to form a SiGe HBT that would yield useful properties. The basic formulation and operational theory of the HBT, for both the traditional wide bandgap emitter plus narrow bandgap base approach found in most modern III-V HBTs, as well as the drift-base (graded) approach used in SiGe HBTs today, was pioneered by Kroemer, and was largely in place by 1957. It is noteworthy that Kroemer in fact worked hard early on to realize a SiGe HBT, without success, ultimately pushing him towards the III-V material systems for his heterostructure studies, a path that proved, in the end, to be quite fruitful for him, since he shared the Nobel Prize in physics in 2000 for his work in (III-V) bandgap engineering for electronic and photonic applications. While III-V HBTs (e.g., AlGaAs/GaAs) began appearing in the 1970s, driven largely by the needs for active microwave components in the defense industry, reducing the SiGe/Si HBT to practical reality took 30 years after the basic theory was in place, due primarily to material growth limitations.

The achievement of practical SiGe/Si heterostructures, the key to building SiGe HBTs, solidly rests on the shoulders of material scientists and crystal growers, those purveyors of the semiconductor "black arts" associated with the deposition of pristine SiGe alloys of nanoscale dimensionality onto enormous Si wafers, with near-infinite precision. Once device-quality SiGe alloys were finally achieved in the mid-1980s, progress was quite rapid.

The first functional SiGe HBT was demonstrated in December of 1987, 40 years, nearly to the day, after the first transistor. That pioneering result showed a SiGe HBT with functional, albeit leaky, DC I-V characteristics; but it was a SiGe HBT, it worked, and it was the first. It is an often-overlooked historical point, however, that at least four independent groups were simultaneously racing to demonstrate the first functional SiGe HBT. Worldwide attention became squarely focused on SiGe HBT technology in June of 1990, with the eyebrow-lifting demonstration of a SiGe HBT with a peak cutoff frequency of 75 GHz by IBM, at the time twice the performance of state-of-the-art Si BJTs, clearly demonstrating the future potential of the Si-processing-compatible SiGe technology. The pursuit of SiGe HBTs for practical circuit applications began in earnest at a large number of industrial and university laboratories around the world, a trend that has not let up since and likely never will [2]–[3].

While it may be tempting to assume that CMOS is the only transistor game in town, SiGe HBTs are alive and well, and growing rapidly in both sophistication and diversity of utilization. SiGe HBT (Fig. 1) frequency response since that pivotal 1990 unveiling has grown by 10x in only thirty years! Quite a feat. SiGe HBTs are now approaching THz levels of performance in 100% Si manufacturing compatible commercial platforms (>700 GHz and counting at 300K in 2022), something unimaginable at the field's inception.

Now universally practiced as a BiCMOS technology platform (SiGe HBT + CMOS together on die), SiGe technology (Fig. 2) offers an ideal division of labor between bipolars and FETs, which each have their own respective attributes, clearly, and remains in wide use globally in performance-constrained analog, RF through mm-wave, and even digital applications (Fig. 3). SiGe HBTs also possess a natural affinity for robust operation in so-called "extreme environments," which include exposure to intense space radiation and at deep cryogenic temperatures [4].

There you have it—the SiGe HBT. A remarkable product of human ingenuity and hard work. Happy anniversary to the transistor, and its remarkable SiGe HBT progeny!

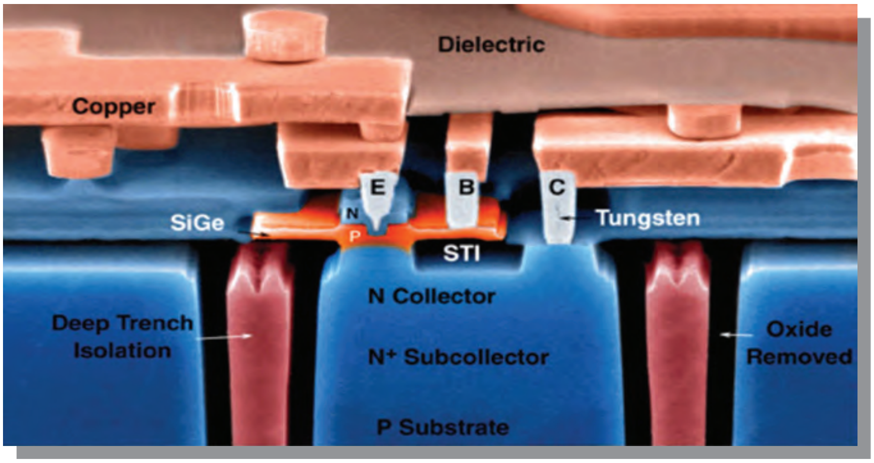

Figure 1. Decorated cross-sectional scanning electron micrograph of a SiGe HBT. The epitaxial SiGe alloy is shown in orange. (Courtesy of IBM Corporation.)

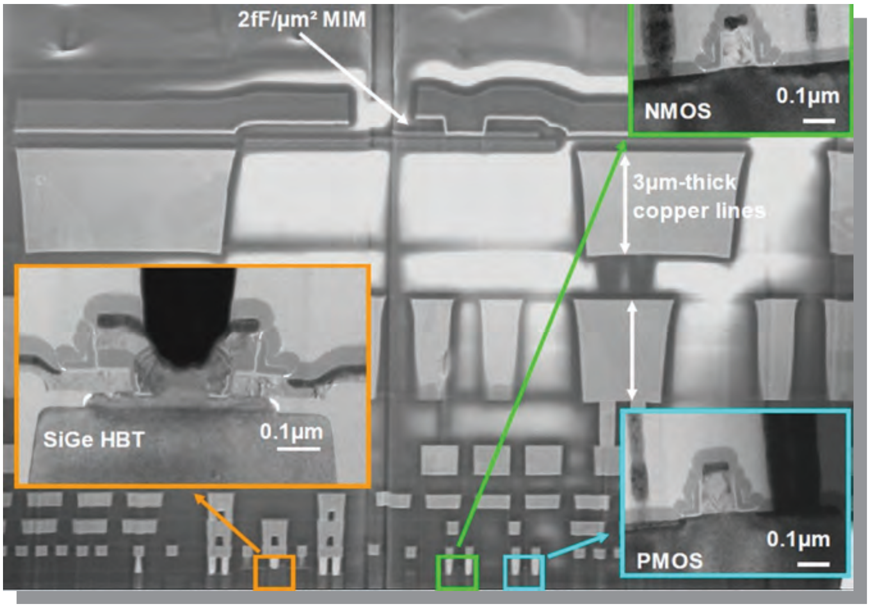

Figure 2. Cross-sectional scanning electron micrograph of a modern SiGe BiCMOS platform, showing SiGe HBT, CMOS devices (n-channel and p-channel), and the back-end-of-the-line metallization layers and passive elements. (Courtesy of P. Chevalier and ST Microelectronics.)

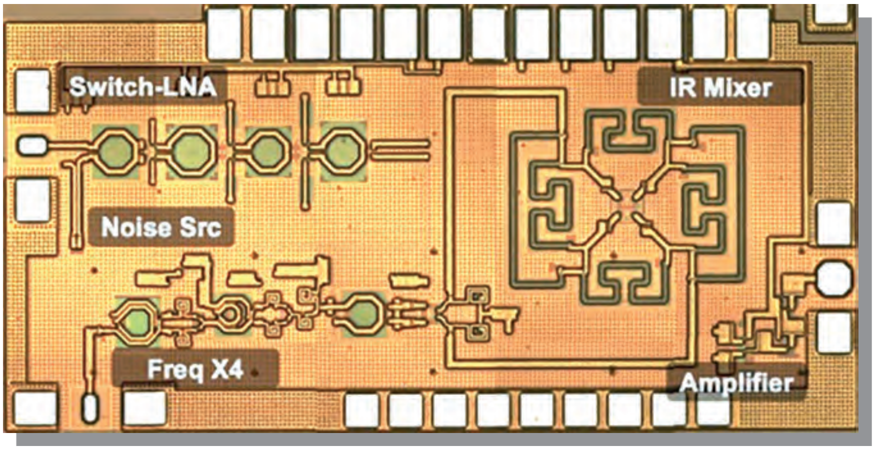

Figure 3. Example of a SiGe BiCMOS mm-wave integrated circuit, a 60 GHz SiGe radiometer for space-based remote sensing designed for use on a CubeSat. The die size is less than $2\ mm^2$.

Biography

John D. Cressler received his B.S. from Georgia Tech in 1984, and his Ph.D. from Columbia University in 1990. From 1984 to 1992, he was on the research staff at the IBM Thomas J. Watson Research Center, and from 1992 to 2002 he served on the faculty at Auburn University. In 2002, he joined the faculty at Georgia Tech, and is currently Regents Professor and Schlumberger Chair Professor in Electronics in the School of Electrical and Computer Engineering, as well as the Ken Byers Teaching Fellow in Science and Religion. The basic thrust of Cressler's research is to develop Si/SiGe-based micro/nanoelectronic and photonic devices, circuits, and systems for next-generation applications within the global terrestrial and space-based electronics/

photonics infrastructure. His research interests include: Si-based (SiGe/strained-Si) heterostructure devices and technology, mixed-signal circuits (analog, digital, RF to mm-wave) built from these devices, integrated Si/SiGe photonic devices and circuits, novel scientific instruments for space-systems, radiation effects in electronic and photonic devices and circuits, cryogenic electronics for quantum systems, device-to-circuit interactions, reliability physics, device-level simulation (TCAD), and compact circuit modeling. He and his students have published over 750 scientific papers in this field, and he has graduated 66 Ph.D. students during his 30-year academic career. He was elected Fellow of the Institute of Electrical and Electronics Engineers (IEEE) in 2001 for his research contributions, and was awarded the 2010 *Class of 1940 W. Howard Ector Outstanding Teacher Award* (Georgia Tech's top teaching award), the 2011 *IEEE Leon Kirchmayer Graduate Teaching Award* (the IEEE's top graduate teaching award), the *Class of 1934 Distinguished Professor Award* (the highest honor Georgia Tech bestows on its faculty), and the 2021 *IEEE James H. Mulligan, Jr. Education Medal* (the highest award IEEE gives in teaching and mentoring). He has served the Electron Devices Society in a number of roles, including as Editor-in-Chief of *IEEE Transactions on Electron Devices*, from 2012-2015. Cressler's books include *Silicon-Germanium Heterojunction Bipolar Transistors*, *Reinventing Teenagers: the Gentle Art of Instilling Character in Our Young People*, *Silicon Heterostructure Handbook*, *Silicon Earth: Introduction to Microelectronics and Nanotechnology*, *Extreme Environment Electronics*, and the historical novels *Emeralds of the Alhambra*, *Shadows in the Shining City*, and *Fortune's Lament*, love stories set in medieval Muslim Spain.

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