Introduction To The Transistor- A New Semiconductor Amplifier

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Introduction to "The Transistor—A New Semiconductor Amplifier"

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Invited Paper

It was a great pleasure to revisit one of the papers written during the dawn of the transistor age. This paper was first presented at the Winter General Meeting of the American Institute of Electrical Engineers (AIEE) in New York in early February 1949, the same month as the launching of the first U.S. rocket to enter space, loaded with transistorless telemetry. Recent publications [1], [2] are helping us to see more clearly how this semiconductor device came into being, how it was characterized, and how it was nicely named [3], albeit on the basis of a questionable rationale.

The pregnant title, "The Transistor—A New Semiconductor Amplifier," was arresting while at the same time curiously modest. The use of the indefinite article might have suggested that this frail and tentative device was merely one of a broad portfolio of contemporary developments related to amplifiers—"new" in the sense of "another." In fact, there were no other contenders; the "crystal triode" was special. Nevertheless, at its publication, this paper would scarcely be recognized as one of the strident notes in the brilliant fanfare that was about to usher in profound changes for all human endeavor and shape life on Earth so powerfully and irreversibly. At the time of this paper's publication, both Becker and Shive (Fig. 1) were at Bell Labs.

Being a part of this history, the paper has more than clinical interest to me. Sometime during 1954, while working at my first job at the carefully hidden Signals Research and Development Establishment (SRDE), perched on the chalk cliffs of the English Channel, I lapsed into a reckless love affair. I suppose it was inevitable. I was young and impressionable, and these things happen, as they say.

The object of my devotion was petite, black, with three legs, and had a heart of germanium. Though the decades have slipped by, I still hold her captive, with many of her kin, in the museum drawers of my home laboratory. From time to time, I will gently take her out and show my grandchildren some of her graceful curve-tracer characteristics, benevolently noting: "Kids, this humble device led to the compact disc, computers, and the Internet," being met only with respectful wide-eyed tolerance tinged with quiet disbelief.

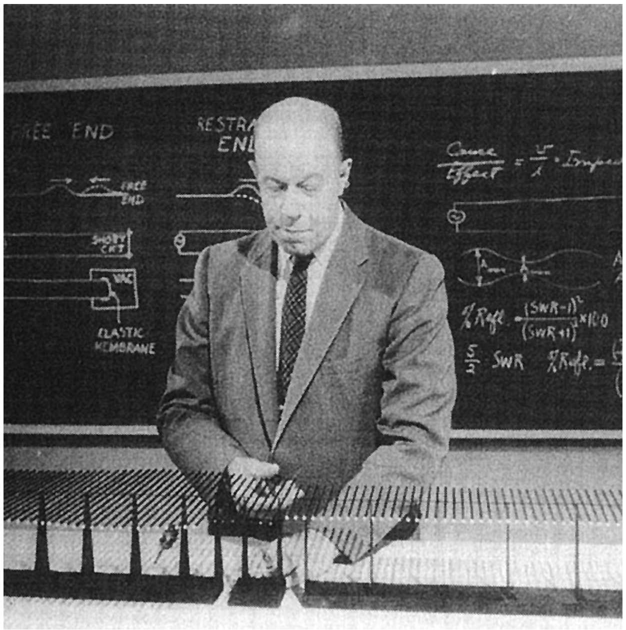

Fig. 1. J. N. Shive.

However, back then in the 1950's, I was almost as ill informed about this treasure as they and quite oblivious of the revolution that the transistor was about to unleash on the world. She was simply a fascinating creature: a young, fresh, and cheeky contender to the throne imperiously occupied by the vacuum tube family, an interesting alternative way to make amplifiers and perhaps, with luck, a few other things (Fig. 2).

This still-mysterious device bore some similarity to the "cat's-whisker" detectors that I had used as a kid to pull in the stronger local stations on headphones, but which used

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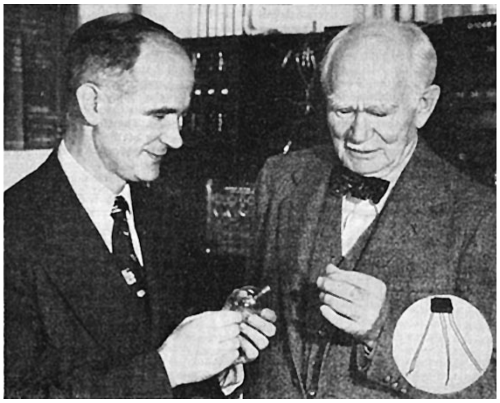

Fig. 2. The symbolic torch is passed from the age of vacuum tube amplifiers to the new solid-state creations in this remarkable photograph taken about 1952. On the left is Shockley, who directed the Bell Labs research program that led to the invention of the transistor. He is seen holding an audion, the forerunner of the modern vacuum tube. On the right is the audion's inventor, deForest, who inquisitively ponders the relatively tiny transistor. The insert shows a close-up view of the transistor. (From the PROCEEDINGS OF THE IRE, vol. 40, p. 1613, Nov. 1952.)

two closely positioned point contacts instead of one. My practical interest in it was muted by its strictly limited availability. I recall the day I finally acquired a solitary junction transistor, for a king's ransom, and put it through its paces in my bedroom-*cum*-home-workshop. Certainly, at that time, questions of epic proportions never occurred to me, but now that my perspective on the drama of electronics has matured, it is almost as exciting to explore this history in retrospect as it was to experience it in progress.

This paper, providing details of the construction, describing small- and large-signal operating regimes, touching briefly on noise performance and with a brave stab at modeling the device, served as a nostalgic reminder of how electronics used to be. It was very much a specialist world, distinctly separate from the everyday one, essential but not yet ubiquitous. What a shaky start the semiconductor industry had! Indeed, the transistor, while fascinating and alluring, did not seriously address the application I was later working on at SRDE—speech encoders and scramblers—which employed dozens of shift registers and logic using 12AT7 tubes in abundance. For that project, the slow, costly, unpredictable, and unreliable transistor was not even in the running; the next generation of equipment again used trusted and proven tube technologies, though of a miniaturized and wire-ended sort.

To enjoy this paper, we must try to see the world through the eyes of Becker and Shive, pioneers in crafting earlier semiconductor devices, i.e., crystal detectors, working at the famous Bell Telephone Laboratories in Murray Hill, NJ. The records clearly show they were operating in conditions and pursuing a style of invention much more reminiscent of one of Edison's laboratories than anything remotely connected with this vast industry today—this brave new world of automated, microclean, yellow-lit temples. In their time, progress was made at the bench, by painstaking experimentation, the "what if, cut-and-try" approach to discovery, rather than by a systematic methodology with large-scale production in mind. In his recollections on this invention [4] written in 1973, Shockley later used the expression "creative-failure methodology" to describe this.

Without yet having a deep understanding of the materials and, of course, lacking any kind of simulation tools or even a handheld calculator, these pioneers were groping in the dark. (Parenthetically, that would often be literally true of transistor experiments, where photon-induced conduction often masked the effect of injected carriers.) They could hardly be blamed for having only a vague notion of the potential of this new structure, a close cousin of crude galena and cat's-whisker detectors, or a clear grasp of how it worked. In this particular respect, what I had been doing as an ardent teenage experimentalist, before meeting Miss Germanium, was not so very different. The sense of being a participant through almost all of this still-unfolding drama has been a constant anchor in my outlook on the art and science of electronics.

The transistor's invention (or was it a discovery?) had been announced earlier, in 1948, at a June 30 press conference in New York, and the key principles were laid out in the seminal paper by Bardeen and Brattain entitled "The Transistor: A Semiconductor Triode" [5]. No one at that time was bold enough to predict the demise of the vacuum tube, then being manufactured in numerous forms by the hundreds of millions per year, and itself still revolutionizing the nature of electronics. In the late 1940's, most designs were based on the bedrock of wired and wireless communications, bringing television (with color transmissions almost ready), radar (itself described as "The Invention that Changed the World" [6]—though surely that claim must go to the transistor), dramatic advances in electronic instrumentation and medical applications, and blossoming in the stored-program computer, all laying down the pretransistor foundations of the information age.

With their brown-bag lunches on the workbench, besides a muddle of batteries, voltmeters, perhaps an early General Electric or Hewlett-Packard oscillator, and a blue-trace oscilloscope, coworkers Joe and John must have wondered, as they struggled to replicate yesterday's results, whether this newly discovered device could ever meet the stringent performance and reliability demands of repeaters for telephony. Their specific emphasis on amplifiers in this paper, as important as it was to be for telephony, did not nearly suggest the immense potential for the transistor. Maybe they had talked it over and decided that their backup title, "The Transistor—Harbinger of a Human Revolution of Epic Proportions," might be a bit over the top.

But it would have been closer to the truth. It would have been impossible, of course, for Becker and Shive, indeed, even for the most visionary, to have foreseen that their humble solid-state amplifier, this crudely assembled chunk of impure germanium would, with the later switch to silicon and the realization that this newer semiconductor material can grow a stable insulating oxide, lead rather quickly to the monolithic integration of a complete logic gate, then 100, 100 000, and eventually more than a billion transistors in a material volume less than that of the base slab of the experimental devices described in their modest paper.

Looking at this paper more closely, it is striking at the outset that there is no mention of the polarity type of the basic material. It was in fact n-type germanium, with the welded phosphor–bronze metal whiskers acting as p-type material, forming something more akin to a Schottky barrier than a true p–n junction; that came later. The device described here, having the emitter and collector on the same surface, was later called the "A-transistor," and it was a pnp type. Hypotheses about the conduction mechanism were highly tentative, and because this structure was the progeny of earlier experiments in search of what we would now call a field-effect transistor, the explanations focused on surface effects. Later, the discovery [7] of the double-surface transistor—a wedge of germanium contacted by similar whiskers on opposing sides where the tapered thickness was about 100 μm—would confirm Shockley's predictions that conduction can occur in the bulk crystal through minority-carrier injection, transport, and collection. That realization was the critical breakthrough that led to the bipolar junction transistor, and it heralded a hiatus in the quest for field-effect devices.

The emitter-to-collector current gain (called alpha then, and to this day) was often higher than unity; for a modern device it is always less. That property appears to have been seen as a useful feature and might have been necessary to support amplification and oscillation in some of the simple circuits developed at the time, in which the base terminal was the node common to input and output and was usually grounded. It seems that the idea of using the base as a more sensitive control electrode, in the common-emitter configuration, came somewhat later. The high alpha may have been due to ionization in the collector junction, that is, a single carrier arriving at the field in the collector depletion layer may cause secondary carriers to be generated by impacts with the lattice.

It is interesting that the transistor was from the start regarded as a current-mode device, a perspective which may be called the "beta-view." Pierce (Fig. 3), who proposed the name [3], has been at pains to point out that it was not at all like the vacuum tube, which had transconductance. Rather, he said, it was a "transresistance device." This is an odd distinction, since the former is an element that generates a current when driven by voltage [that is, a voltage-controlled current-source (VCCS)], while the latter is an element that generates a voltage when driven by a current [a current-controlled voltage-source (CCVS)]. But the transistor was no more one or the other. It was in no essential way different to a vacuum tube embedded in comparable biasing and loading means, except that what would have been the "grid," now the "base," required a current flow. (Even tubes, however, may have considerable grid current if "forward-biased" like a base-emitter junction.)

Fig. 3. J. R. Pierce.

Indeed, the modern view of the bipolar junction transistor (BJT) can afford to neglect its small base current (which is in no way a useful feature and is invariably just a troublemaker—another nonideality, like ohmic resistances and parasitic capacitances) and treat it as a pure transconductance (g_m) element, in which the applied base-emitter voltage V_{BE} generates a precisely corresponding current I_C bearing an exponential relationship to this voltage: $I_C = I_S$ exp(V_{BE}/V_T). This equation is almost the same as Shockley's famous junction equation, and it leads to the remarkable result that g_m is not only proportional to I_C, but related simply by the thermal voltage, $V_T = kT/q$. That is, $g_m = I_C/V_T$, regardless of the semiconductor material (Ge, Si, SiGe, GaAs, etc.), the polarity type, and the size of the device. Even temperature can be eliminated to achieve a constant g_m simply by making I_C proportional to temperature (PTAT), a common ruse today.

This fundamental property of the BJT is utterly astonishing, but it would need decades of refinement, both in device quality and in outlook, before the "translinear view" [8] would replace the older "beta-view" $I_C = \beta I_B$ still taught in many textbooks. It surely had not yet made its appearance when Becker and Shive struggled to explain how their new amplifier worked. Yet the underlying idea of generating carriers by biasing a junction with a voltage and measuring the resulting current had already been tentatively explored [9], and this, one would have thought, should have made it clear that the BJT is very much like the vacuum tube, in being decidedly a transconductance device. So, Pierce's justification for the newly coined name is fortuitous, in retrospect, but we are grateful to him for thinking of it. As for "amplifier," a few other uses for this now virus-sized device have indeed since been found.

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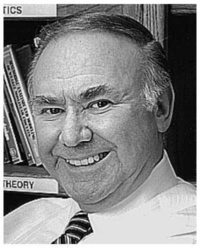

Barrie Gilbert (Fellow, IEEE) was born in Bournemouth, U.K., in 1937.

His first encounter with the bipolar transistor dates to 1954. Using alloy-junction devices in avalanche mode, he pioneered gigahertz sampling oscilloscopes and other high-speed techniques at Mullard Ltd. He joined Tektronix in 1964 and designed advanced oscilloscopes and their first integrated circuits. Several fundamental analog design techniques, including translinear circuits, carrier-domain devices, and the concept of superintegration, a forerunner of I2L, were developed during that period. From 1970 to 1972, he was a Group Leader at Plessey Research Labs, developing OCR systems, optical holographic and semiconductor memories, and communications IC's. He joined Analog Devices, Inc. (ADI), in 1972, was appointed ADI Fellow in 1979, and currently manages the Northwest Labs in Beaverton, OR. He has some 50 issued patents, authored about 40 papers, and is co-author of several books.

Dr. Gilbert has received the ISSCC Best Paper Award five times, the IEEE Outstanding Achievement Award in 1970, the SSCC Outstanding Development Award in 1986, the Oregon Researcher of the Year Award in 1990, and the Solid State Circuits Award in 1992 for "Contributions to Nonlinear Signal Processing." He was also awarded an Honorary Doctorate of Engineering from Oregon State University.