Seventy Years of Getting Transistorized

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Vacuum tubes appeared at the break of the 20th century, giving birth to electronics [1]. By the 1930s, they had become established as a mature technology, spreading into areas such as radio communications, long-distance radiotelegraphy, radio broadcasting, telephone communication and switching, sound recording and playing, television, radar, and air navigation [2]. During World War II, vacuum tubes were used in the first electronic computers, which were built in the United Kingdom and the United States [3]. Although vacuum tubes had been a successful technology, they were also bulky, fragile, and expensive; had a short life; and consumed a lot of power to heat the thermo emitters. These drawbacks promoted the search for completely new devices. Alternative solutions had long been considered but without significant developments.

On 23 December 1947, two researchers at Bell Labs, John Bardeen (1908–1991) and Walter H. Brattain (1902–1987), the former a theoretical physicist and the latter a fine experimenter, built a small device that was dubbed the *transistor*, a term coined by John Pierce (from the words *transfer* and *resistor*) and selected from among many others proposed. The device consisted of a semiconductor (the germanium base) fitted with two gold-tip electric contacts (the emitter and the collector) and was capable of amplifying an electrical signal [4].

A month later, on 23 January 1948, William B. Shockley (1910–1989) made the first junction transistor using doped germanium. His device resembled the previous work of Julius Edgar Lilienfeld (1882–1963) and Russell Shoemaker Ohl (1898–1987) [5]. Lilienfeld was a German physicist who had migrated to the United States in 1921, where he had patented a field-effect-transistor-like device in 1925. However, he had been unable to make a working prototype because of a lack of sufficiently pure crystals. Nevertheless, his patents raised a number of concerns for Bell Labs' lawyers in 1948. A similar device, most like an insulated gate field-effect transistor, was patented by Oskar Heil (1908–1994), another German, in 1935, who moved to the United States after World War II. Ohl, an American researcher at Bell Labs, had invented the doping technique and produced the first p–n junction in 1939. The patent application for the transistor was submitted in June 1948. Although Shockley led the team of Bardeen and Brattain at the Solid-State Physics Group, they developed their two devices independently because of the strong antagonism between them, which was not evident in the Bell Labs' celebration pictures (Figure 1). The three men shared the 1956 Nobel Prize in Physics for the invention. At the award ceremony, King Gustaf VI Adolf of Sweden blamed Bardeen for not bringing his whole family with

FIGURE 1 – The famous official picture released by Bell Labs of (from left) John Bardeen, William Shockley, and Walter Brattain to celebrate the invention of the transistor in 1948 conceals the grudge that had grown between Bardeen and Brattain and their group leader. (Photo courtesy of Wikimedia Commons.)

him. In response, Bardeen promised he would bring all of them the next time. Bardeen was a dependable man and kept this promise when he went to Stockholm to receive his second Nobel Prize in Physics in 1972. That time, he was awarded the Nobel Prize with Leon Cooper and John Schrieffer for the BCS (from their initials) theory of superconductivity. He remains the only person to have been awarded the Nobel Prize for Physics twice and one of only four people who have been awarded two Nobel Prizes, the others being Maria Sklodowska-Curie, Linus Pauling, and Frederick Sanger.

Shockley played a major, although controversial, role in the development of solid-state electronics and microelectronics after moving to California in 1953 [6]. He also claimed the paternity of the thyristor in 1950, namely the first power solid-state device, which was built at Bell Labs four years later [7].

Bardeen and Brattain preceded Herbert Mataré (1912–2011) and Heinrich Welker (1912–1981) by a few months. These two German physicists, who worked in a Westinghouse-controlled French company, independently invented a solid-state device dubbed the *transistron* and patented it on 14 August 1948. It was actually a point-contact transistor on a germanium crystal [8]. During World War II, Mataré had been engaged in German radar research, and, at that time, he had made the very first observations

FIGURE 2 – The Seiko Astron, the first commercial quartz wristwatch. The miniaturization of a quartz clock was made possible by transitors. (Photo courtesy of A Blog to Watch, http://www.ablogtowatch.com.)

THE FIRST TRANSISTOR WRISTWATCHES WERE PRESENTED BY THE FRENCH COMPANY LIP WATCH AND THE ELGIN NATIONAL WATCH COMPANY, ILLINOIS, ON 19 MARCH 1952.

of transconductance in solid-state devices, which became a fundamental concept in electronics.

Bell Labs remained at the cutting edge of the new research. Obtaining germanium with the purity and without defects as needed for manufacturing the device in a reproducible way resulted in a very difficult challenge. This was solved at Bell Labs in 1948 by Gordon K. Teal (1907–2003) and John B. Little within an almost underground research program that resulted in the adaptation of a method to produce monocrystals serendipitously invented by Polish chemist Jan Czochralski (1885–1953) in 1916 [9]. In 1950, Teal, Shockley, and Morgan Sparks (1916–2008) developed the double-doped technique, which led to a viable bipolar negative-positive-negative junction germanium transistor [10]. A much better process for producing doped monocrystals was conceived by Morris Tanenbaum (b. 1928) at Bell Labs in 1955.

The world's first transistor manufacturing facility was started by Western Electric, the production branch of American Telephone & Telegraph, in Allentown, Pennsylvania on 1 October 1951. It made point-contact germanium transistors. The industrial production of transistors gained momentum in the following two years. Mataré founded the Intermetall Company in Düsseldorf, Germany, in 1952. Texas Instruments (TI), which had been founded in Dallas in 1951, decided to enter the new semiconductor market and acquired a license from Western Electric to produce germanium transistors in 1952. Raytheon of Waltham, Massachusetts, marketed low-cost germanium junction transistors in 1953 (US$7.60, which dropped to US$0.99 in 1956). In the same year, Philco, based in Philadelphia, developed the first high-frequency surface-barrier transistor, which proved to be suitable for high-speed computers.

At Bell Labs, Teal and Ernest Buehler extended the germanium technique to the production of doped silicon monocrystals in 1952, and Tanenbaum produced the first silicon transistor in January 1954. In the same year, Teal, then director of research at TI, produced a silicon transistor capable of operating in a wider temperature range, which was immediately marketed. Transistor technology gained momentum by the mid-1950s, particularly in the United States, thanks to funding from the U.S. Department of Defense, which was interested in its potential military applications. As Nathan Rosenberg wrote in 1982: "The [semiconductor] industry represents perhaps the most outstanding 'success story,' in terms of government policy to stimulate technical progressiveness and growth of output and employment, in the postwar period in the United States" [11]. At the same time, this was one of the early great technological successes of quantum mechanics, a theory that had been considered highly abstract and far from application at its appearance at the beginning of the 20th century.

The first transistor wristwatches were presented by the French company Lip Watch and the Elgin National Watch Company, Illinois, on 19 March 1952. Five years later, American Hamilton Watch was the first company to market an electronic wristwatch. Quartz wristwatches, which include transistors, were first produced by Center Electronique Horloger in Neuchâtel, Switzerland, in July 1967, and they were marketed by Seiko in December 1969 (Figure 2) [12]. The addition of a light-emitting diode display resulted in the first electronic watches without mobile parts (except sundials), which were first produced by Hamilton Watch in 1970.

The first commercial transistorized appliance was a hearing aid that was launched by Sonotone Corporation of Elmsford, New York, in December 1952. It used two subminiature tubes (very small vacuum tubes that had been developed since 1940) and a transistor, which allowed for a much lower power consumption than the previous models based only on subminiature tubes. This arrangement

FIGURE 3 – The Sonotone Model 1010 Hybrid Hearing Aid, which consisted of two vacuum tubes and one transistor. This hearing aid was the first commercial product in the world to use a transistor. It was introduced in the United States on 29 December 1952. (Photo courtesy of France1978, Flickr.)

FIGURE 4 – The very first portable transistor radio, exhibited by Intermetall at the Dusseldorf Radio Exhibition in 1953. (Photo courtesy of AIP Emilio Segrè Visual Archives, Gift of Herbert Matare.)

resulted in a much longer battery life and, consequently, lower operational costs (Figure 3). The first fully transistorized and miniaturized hearing aids were produced in 1953, but they were initially hampered by an operating life of only a few weeks due to transistor damping.

Transistors made it possible to build small implantable pacemakers. In 1957, Earl Bakken (b. 1924) of Minneapolis made the first wearable external pacemaker, provided with electrodes passing through the skin to reach the myocardium. It was installed on a patient the following year. In 1958, the engineer Rune Elmqvist (1906–1996) of Siemens-Elema, a Swedish company controlled by Siemens and Halske, made the first implantable model, which was placed in contact with the myocardium. It was implanted by Swedish surgeon Ake Senning (1915–2000), and it only worked for three hours, but it demonstrated the feasibility of the procedure and paved the way for a new field of therapeutic devices. Previous pacemakers used vacuum tubes and were therefore cumbersome. The first one, made in 1950, was a transcutaneous grid-powered device that had to be placed near the patient.

In 1953, Intermetall presented the first efficient transistor (four units) radio at the Düsseldorf Radio Fair. It was a unique handmade model that was not intended for commercialization (Figure 4) [13]. A year later, TI, after some previous inefficient prototypes, came out with a portable radio that was based on six transistors; however, it was too expensive to be marketed. In fact, the spread in the characteristics of the six transistors required expensive manual selection and calibration work. The first commercial transistorized radio was presented by Industrial Development Engineering Associate (IDEA), a small Indianapolis company, in November 1954 and marketed the following year. The Regency TR-1 used only four TI transistors and featured an innovative circuit topology conceived by Richard C. Koch (1922–2010) that was insensitive to the dispersion of transistor characteristics [14]. It also performed superheterodyne tuning, was powered by a 22.5-V battery, and weighed 340 g. This radio was provided with a very attractive design (Figure 5) and was priced at about US$50 (corresponding to US$455 in modern currency). The TR-1 sold 150,000 units in the United States, a considerable success given its poor sound quality. Very early pocket-sized radio receivers had appeared from 1945 and were based on subminiature tubes (the Belmont Boulevard receiver adopted five Raytheon tubes and a superheterodyne circuit). Besides being much more compact, these devices consumed less power than conventional vacuum tubes. However, early transistor radios provided a further step ahead. Tiny electronic circuits left room for a speaker, instead of an earphone, and consumed much less power. Consequently, transistor radios could be powered by small batteries with good autonomy (20–30 h at a time). The success of the Regency TR-1 was reputedly influenced by sociopolitical factors. In the Cold War years, the American population was appalled by the fear of a Soviet ballistic nuclear missile attack, and radios that could always be

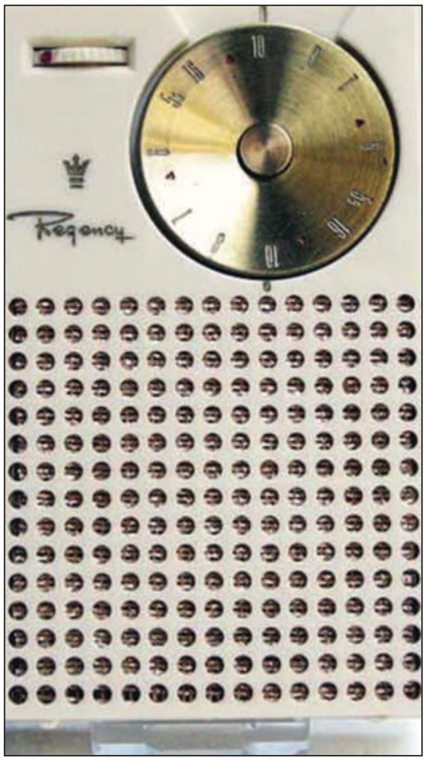

FIGURE 5 – The IDEA Regency TR-1 of 1954 was the first commercial transistor radio receiver. An innovative circuit topology designed by Richard C. Koch allowed the use of only four transistors and made the radio insensitive to the dispersion of their characteristics. (Photo courtesy of Robert Davidson.)

kept in a pocket were perceived as a tool that was capable of alerting people at any time, allowing them to reach atomic shelters quickly [15].

The first European commercial transistor portable radio was produced by British Pye in 1956. Ten years earlier, Masaru Ibuka (1908–1997) and Akio Morita (1921–1999) had founded a small company named Tokyo Tsushin Kogyo in Japan. In 1950, during a trip to the United States, Ikuba had acquired a manufacturing license and instructions to produce junction transistors from Bell Labs for US$50,000 (US$457,000 today). In 1955, they presented and marketed the TR-55, the first portable Japanese transistorized (five units) radio, at that time the smallest in the world. It was initially distributed in small quantities for the domestic market. In 1958, the company changed its name to Sony Corporation and produced the TR-63 model, which gained tremendous success on the world market and pushed the company to become one of the largest consumer electronics companies worldwide. In 1961, Sony sold the TV8-301, the first transistorized, compact, lightweight, and semiportable television set.

EVERY YEAR, MANY BILLIONS OF TRANSISTORS ARE MANUFACTURED AS DISCRETE DEVICES, AND MANY MORE ARE USED IN INTEGRATED CIRCUITS AS PART OF COMPLETE ELECTRONIC CIRCUITS.

Transistors were also quickly adopted in cutting-edge technology. Tom Kilburn (1921–2001) built the first transistorized computer at the Victoria University of Manchester in November 1953 [16]. This was a 48-b demonstrative device based on 92 point-contact germanium transistors and 550 vacuum tubes. Transistor digital computer, the first transistorized American computer (featuring 800 transistors but also thermoelectric valves and an amazing 1-MHz clock) was built by Bell Labs in 1954. It was designed for U.S. Air Force airborne uses and it consumed fewer than 100 W, much less than any model based on vacuum tubes. Transistor Electronic Digital Automatic Computer, the first fully transistorized computer, was introduced in 1955. It was built at the Atomic Research Establishment in Harwell, United Kingdom. It used 324 point-contact transistors built by British company Standard Telephones and Cables and 76 junction transistors. Its clock operated at 58 kHz, and its 64-kB memory was provided by a magnetic drum. TX-0 was built using 3,600 Philco transistors at the Massachusetts Institute of Technology, Cambridge, in 1955, and it started operations in 1956. The Japanese ETL Mark III was put into operation in July 1956, and the Canadian Defense Research Telecommunications Establishment Computer appeared in 1957. Mailüfterl was designed by Heinz Zemanek (1920–2014) at Technische Universität Wien (then the College of Technology) in 1954, when it was possibly the first project of a fully transistorized computer [17]. Built in an underground work making use of 3,000 transistors donated by Philips, it was completed in 1958, becoming the first computer of that kind in continental Europe. It operated at the pretty high clock frequency of 132 kHz (Figure 6). The first commercial transistorized computer was the Metrovick 950, which was built by British Metropolitan-Vickers in 1956. Two years later, five companies launched their commercial models: Siemens and Halske with 2002 (heir of K. Zuse's models), Olivetti with Elea 9003, International Business Machines with 7070, Digital Equipment with PDP-1, and Sperry Rand.

FIGURE 6 – The control panel of the Mailüfterl, completed by Heinz Zemanek in 1958. The design, started four years earlier, was an early transistorized computer. (Photo courtesy of Wikimedia Commons.)

The era of solid-state electronics had begun. As in the case of other technological breakthroughs, the repercussions of the invention of the transistor expanded much further than its inventors could have imagined. In the United States, more than elsewhere, federal support together with the commercial success of the first transistor appliances provided the financial resources that were required to develop the very expensive processes for the production of the high-purity semiconductors. As market expanded, transistors could be mass produced in highly automated processes at an extremely low cost.

The possibility of operating both as a two-state electronic switch, similar to a relay but much faster, and for signal modulation with very low losses and size, unlike vacuum tubes, allowed transistors to be used in an incredible number of functions, in both information and power applications. In just a few decades, they became the key components of almost all modern electronics, revolutionizing signal processing, information technologies, and power electronics. The transistor has become as ubiquitous as few other products. Every year, many billions of transistors are manufactured as discrete devices, and many more are used in integrated circuits (ICs) as part of complete electronic circuits. A processor transistor can now incorporate some millions of transistors. With these credentials, the transistor has conquered areas that traditionally pertained to other technologies. It is often easier and cheaper to use a microcontroller (a type of IC) and implement into it a program for executing a control function than to perform the same operation with a mechanical controller. Few devices have had such a profound influence on industrial production and social life.

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