**History of the Transistor**

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A transistor is a semiconductor device with at least three terminals for connection to an electric circuit. The vacuum-tube triode, also called a (thermionic) valve, was the transistor's precursor, introduced in 1907.

**Invention of the transistor**

The first patent for the field-effect transistor principle was filed in Canada by Austrian-Hungarian physicist Julius Edgar Lilienfeld on October 22, 1925, but Lilienfeld published no research articles about his devices, and his work was ignored by industry. In 1934 German physicist Dr. Oskar Heil patented another field-effect transistor. There is no direct evidence that these devices were built, but later work in the 1990s show that one of Lilienfeld's designs worked as described and gave substantial gain. Legal papers from the Bell Labs patent show that William Shockley and a co-worker at Bell Labs, Gerald Pearson, had built operational versions from Lilienfeld's patents, yet they never referenced this work in any of their later research papers or historical articles.

John Bardeen, William Shockley and Walter Brattain at Bell Labs, 1948.

The work emerged from their war-time efforts to produce extremely pure germanium "crystal" mixer diodes, used in radar units as a frequency mixer element in microwave radar receivers. A parallel project on germanium diodes at Purdue University succeeded in producing the good-quality germanium semiconducting crystals that were used at Bell Labs. Early tube-based technology did not switch fast enough for this role, leading the Bell team to use solid state diodes instead. With this knowledge in hand they turned to the design of a triode, but found this was not at all easy. John Bardeen eventually developed a new branch of quantum mechanics known as surface physics to account for the "odd" behavior they saw, and Bardeen and Walter Brattain eventually succeeded in building a working device.

After the war, Shockley decided to attempt the building of a triode-like semiconductor device. He secured funding and lab space, and went to work on the problem with Bardeen and Brattain.

The key to the development of the transistor was the further understanding of the process of the electron mobility in a semiconductor. It was realized that if there was some way to control the flow of the electrons from the emitter to the collector of this newly discovered diode (discovered 1874; patented 1906), one could build an amplifier. For instance, if you placed contacts on either side of a single type of crystal the current would not flow through it. However if a third contact could then "inject" electrons or holes into the material, the current would flow.

Actually doing this appeared to be very difficult. If the crystal were of any reasonable size, the number of electrons (or holes) required to be injected would have to be very large -– making it less useful than an amplifier because it would require a large injection current to start with. That said, the whole idea of the crystal diode was that the crystal itself could provide the electrons over a very small distance, the depletion region. The key appeared to be to place the input and output contacts very close together on the surface of the crystal on either side of this region.

Brattain started working on building such a device, and tantalizing hints of amplification continued to appear as the team worked on the problem. Sometimes the system would work but then stop working unexpectedly. In one instance a non-working system started working when placed in water. The electrons in any one piece of the crystal would migrate about due to nearby charges. Electrons in the emitters, or the "holes" in the collectors, would cluster at the surface of the crystal where they could find their opposite charge "floating around" in the air (or water). Yet they could be pushed away from the surface with the application of a small amount of charge from any other location on the crystal. Instead of needing a large supply of injected electrons, a very small number in the right place on the crystal would accomplish the same thing.

Their understanding solved the problem of needing a very small control area to some degree. Instead of needing two separate semiconductors connected by a common, but tiny, region, a single larger surface would serve. The emitter and collector leads would both be placed very close together on the top, with the control lead placed on the base of the crystal. When current was applied to the "base" lead, the electrons or holes would be pushed out, across the block of semiconductor, and collect on the far surface. As long as the emitter and collector were very close together, this should allow enough electrons or holes between them to allow conduction to start.

An early witness of the phenomenon was Ralph Bray, a young graduate student. He joined the germanium effort at Purdue University in November 1943 and was given the tricky task of measuring the spreading resistance at the metal-semiconductor contact. Bray found a great many anomalies, such as internal high-resistivity barriers in some samples of germanium. The most curious phenomenon was the exceptionally low resistance observed when voltage pulses were applied. This effect remained a mystery because nobody realized, until 1948, that Bray had observed minority carrier injection - the effect that was identified by William Shockley at Bell Labs and made the transistor a reality.

Bray wrote: "That was the one aspect that we missed, but even had we understood the idea of minority carrier injection...we would have said, 'Oh, this explains our effects.' We might not necessarily have gone ahead and said, 'Let's start making transistors,' open up a factory and sell them... At that time the important device was the high back voltage rectifier".

**The first transistor**

A stylized replica of the first transistor

The Bell team made many attempts to build such a system with various tools, but generally failed. Setups where the contacts were close enough were invariably as fragile as the original cat's whisker detectors had been, and would work briefly, if at all. Eventually they had a practical breakthrough. A piece of gold foil was glued to the edge of a plastic wedge, and then the foil was sliced with a razor at the tip of the triangle. The result was two very closely spaced contacts of gold. When the plastic was pushed down onto the surface of a crystal and voltage applied to the other side (on the base of the crystal), current started to flow from one contact to the other as the base voltage pushed the electrons away from the base towards the other side near the contacts. The point-contact transistor had been invented.

On 15 December 1947, "When the points were, very close together got voltage amp about 2 but not power amp. This voltage amplification was independent of frequency 10 to 10,000 cycles".

On 16 December 1947, "Using this double point contact, contact was made to a germanium surface that had been anodized to 90 volts, electrolyte washed off in H2O and then had some gold spots evaporated on it. The gold contacts were pressed down on the bare surface. Both gold contacts to the surface rectified nicely... The separation between points was about 4x10-3 cm. One point was used as a grid and the other point as a plate. The bias (D.C.) on the grid had to be positive to get amplification... power gain 1.3 voltage gain 15 on a plate bias of about 15 volts".

Brattain and H. R. Moore made a demonstration to several of their colleagues and managers at Bell Labs on the afternoon of 23 December 1947, often given as the birth date of the transistor. The "PNP point-contact germanium transistor" operated as a speech amplifier with a power gain of 18 in that trial. In 1956 John Bardeen, Walter Houser Brattain, and William Bradford Shockley were honored with the Nobel Prize in Physics "for their researches on semiconductors and their discovery of the transistor effect".

Twelve people are mentioned as directly involved in the invention of the transistor in the Bell Laboratory.

At the same time some European scientists were led by the idea of solid-state amplifiers. In August 1948 German physicists Herbert F. Mataré (1912–2011) and Heinrich Welker (1912–1981), working at Compagnie des Freins et Signaux Westinghouse in Aulnay-sous-Bois, France applied for a patent on an amplifier based on the minority carrier injection process which they called the "transistron". Since Bell Labs did not make a public announcement of the transistor until June 1948, the transistron was considered to be independently developed. Mataré had first observed transconductance effects during the manufacture of germanium diodes for German radar equipment during WWII. Transistrons were commercially manufactured for the French telephone company and military, and in 1953 a solid-state radio receiver with four transistrons was demonstrated at the Düsseldorf Radio Fair.

**Origin of the term**

Bell Telephone Laboratories needed a generic name for the new invention: "Semiconductor Triode", "Solid Triode", "Surface States Triode", "Crystal Triode" and "Iotatron" were all considered, but "transistor," coined by John R. Pierce, was the clear winner of an internal ballot (owing in part to the affinity that Bell engineers had developed for the suffix "-istor"). The rationale for the name is described in the following extract from the company's Technical Memorandum calling for votes:

Transistor. This is an abbreviated combination of the words "transconductance" or "transfer", and "varistor". The device logically belongs in the varistor family, and has the transconductance or transfer impedance of a device having gain, so that this combination is descriptive.

— Bell Telephone Laboratories — Technical Memorandum (May 28, 1948)

Pierce recalled the naming somewhat differently:

The way I provided the name, was to think of what the device did. And at that time, it was supposed to be the dual of the vacuum tube. The vacuum tube had transconductance, so the transistor would have 'transresistance.' And the name should fit in with the names of other devices, such as varistor and thermistor. And. . . I suggested the name 'transistor.'

— John R. Pierce, interviewed for PBS show "Transistorized!"

The Nobel Foundation states that the term is a combination of the words "transfer" and "resistor" – Nobelprize.org – The Transistor.

**Production and commercialization**

By 1953, the transistor was being used in some products, such as hearing aids and telephone exchanges, but there were still significant issues preventing its broader application, such as sensitivity to moisture and the fragility of the wires attached to germanium crystals. Donald G. Fink, Philco's director of research, summarized the status of the transistor's commercial potential with an analogy: "Is it a pimpled adolescent, now awkward, but promising future vigor? Or has it arrived at maturity, full of languor, surrounded by disappointments?"

**Transistor radios**

Main article: Transistor Radio

The Regency TR-1 which used Texas Instruments' NPN transistors was the world's first commercially-produced transistor radio.

Bell immediately put the point-contact transistor into limited production at Western Electric in Allentown, Pennsylvania. Prototypes of all-transistor AM radio receivers were demonstrated, but were really only laboratory curiosities. However, in 1950 Shockley developed a radically different type of solid-state amplifier which became known as the Bipolar Junction "transistor". Although it works on a completely different principle to the point-contact "transistor", this is the device which is most commonly referred to as simply a "transistor" today. Morgan Sparks made the bipolar junction transistor into a practical device. These were also licensed to a number of other electronics companies, including Texas Instruments, who produced a limited run of transistor radios as a sales tool. Early transistors were chemically unstable and only suitable for low-power, low-frequency applications, but as transistor design developed, these problems were slowly overcome.

There are numerous claimants to the title of the first company to produce practical transistor radios. Texas Instruments had demonstrated all-transistor AM radios as early as 1952, but their performance was well below that of equivalent battery tube models. A workable all-transistor radio was demonstrated in August 1953 at the Düsseldorf Radio Fair by the German firm Intermetall. It was built with four of Intermetall's hand-made transistors, based upon the 1948 invention of Herbert Mataré and Heinrich Welker. However, as with the early Texas units (and others) only prototypes were ever built; it was never put into commercial production.

The production of the first commercially successful transistor radio is often incorrectly attributed to Sony (originally Tokyo Tsushin Kogyo). However the Regency TR-1, made by the Regency Division of I.D.E.A. (Industrial Development Engineering Associates) of Indianapolis, Indiana, was the first practical transistor radio made in any significant numbers. The TR-1 was announced on October 18, 1954 and put on sale in November 1954 for $49.95 (the equivalent of about $361 in year-2005 dollars) and sold about 150,000 units.

The TR-1 used four Texas NPN transistors and had to be powered by a 22.5 Volt battery, since the only way to get adequate radio frequency performance out of early transistors was to run them close to their collector-to-emitter breakdown voltage. This made the TR-1 very expensive to run, and it was far more popular for its novelty or status value that its actual performance, rather in the fashion of the first MP3 players.

Still, aside from its indifferent performance, the TR-1 was a very advanced product for its time, using printed circuit boards, and what were then considered micro-miniature components.

Masaru Ibuka, co-founder of the Japanese firm Sony, was visiting the USA when Bell Labs announced the availability of manufacturing licenses, including detailed instructions on how to manufacture junction transistors. Ibuka obtained special permission from the Japanese Ministry of Finance to pay the $50,000 license fee, and in 1955 the company introduced their own five-transistor "coatpocket" radio, the TR-55, under the new brand name Sony. This product was soon followed by more ambitious designs, but it is generally regarded as marking the commencement of Sony's growth into a manufacturing superpower.

The TR-55 was quite similar to the Regency TR-1 in many ways, being powered by the same sort of 22.5 volt battery, and was not much more practical. Very few were distributed outside of Japan. It was not until 1957 that Sony produced their ground-breaking "TR-63" shirt pocket radio, a much more advanced design that ran on a standard 9 volt battery and could compete favorably with vacuum tube portables. The TR-63 was also the first transistor radio to utilize all miniature components. (The term "pocket" was a matter of some interpretation, as Sony allegedly had special shirts made with over-sized pockets for their salesmen)

**Chrysler Mopar 914HR - First transistor car radio**

1955 Chrysler - Philco all transistor car radio - "Breaking News" radio broadcast announcement.

Chrysler and Philco announced that they had developed and produced the World’s First All-Transistor car radio and it was announced in the April 28th 1955 edition of the Wall Street Journal. Chrysler made the all-transistor car radio, Mopar model 914HR, available as an "option" in Fall 1955 for its new line of 1956 Chrysler and Imperial cars, which hit the showroom floor on October 21, 1955. The all-transistor car radio was a $150 option.

All-Transistor car radio - Chrysler Mopar model 914HR

**Computers**

The world’s first transistor computer was built at the University of Manchester in November 1953. The computer was built by Dick Grimsdale, then a research student in the Department of Electrical Engineering and later a Professor of Electronic Engineering at Sussex University.

The machine used point-contact transistors, made in small quantities by STC and Mullard. These consisted of a single crystal of germanium with two fine wires, resembling the crystal and cat’s whisker of the 1920s. These transistors had the useful property that a single transistor could possess two stable states. The memory was a magnetic drum, a cylindrical version of today’s hard disk drives. The arithmetic and control registers were on the drum, in the form of delay lines with reading heads displaced a short distance from the writing heads around the circumference. The development of the machine was severely hampered by the unreliability of the transistors, which consumed 150 watts.

The CDC 1604 was the first practical commercial computer based on transistors.

**Improvements in transistor design**

Shockley was upset about the device being credited to Brattain and Bardeen, whom he felt had built it "behind his back" to take the glory. Matters became worse when Bell Labs lawyers found that some of Shockley's own writings on the transistor were close enough to those of an earlier 1925 patent by Julius Edgar Lilienfeld that they thought it best that his name be left off the patent application.

Shockley was incensed, and decided to demonstrate who was the real brains of the operation. Only a few months later he invented an entirely new type of transistor with a layer or "sandwich" structure. This new form was considerably more robust than the fragile point-contact system, and would go on to be used for the vast majority of all transistors into the 1960s. It would evolve into the bipolar junction transistor.

Further developments included the grown-junction transistor (1951), the surface-barrier transistor (1953), the diffusion transistor, the tetrode transistor, and the pentode transistor. The diffused silicon 'mesa transistor' was developed at Bell in 1955 and made commercially available by Fairchild Semiconductor in 1958. The spacistor was a type of transistor developed in the 1950s as an improvement over the point-contact transistor and the later alloy junction transistor.

Philco surface-barrier transistor developed and produced in 1953

First high frequency transistor developed by Philco in 1953

In 1953, Philco had developed the world's first high frequency surface-barrier transistor, which was also the first transistor that was suitable for high speed computers. The world's first all-transistor car radio was manufactured by Philco in 1955, used the surface-barrier transistors in its radio's circuitry design.

With the fragility problems solved, a remaining problem was purity. Making germanium of the required purity was proving to be a serious problem, and limited the number of transistors that actually worked from a given batch of material. Germanium's sensitivity to temperature also limited its usefulness. Scientists theorized that silicon would be easier to fabricate, but few bothered to investigate this possibility. Morris Tanenbaum et al. at Bell Laboratories (Jl. of Applied Physics, 26, 686-692, 1955) were the first to develop a working silicon transistor on January 26, 1954. A few months later, Gordon Teal, working independently at the nascent Texas Instruments (not published), developed a similar device. Both of these devices were made by controlling the doping of silicon single crystals while they were grown from molten silicon. A far superior method was developed by Morris Tanenbaum and Calvin S. Fuller at Bell Laboratories (Bell System Technical J., 35, 1-34, 1955) in early 1955 by the gaseous diffusion of donor and acceptor impurities into single crystal silicon chips. That technology was later used by Jack Kilby and Robert Noyce in their invention of integrated circuitry, thereby initiating the "Silicon Age". Germanium disappeared from most transistors by the late 1960s.

Within a few years, transistor-based products, most notably radios, were appearing on the market. A major improvement in manufacturing yield came when a chemist advised the companies fabricating semiconductors to use distilled water rather than tap water: calcium ions were the cause of the poor yields. "Zone melting", a technique using a moving band of molten material through the crystal, further increased the purity of the available crystals.

The first gallium-arsenide Schottky-gate field-effect transistor (MESFET) was made by Carver Mead and reported in 1966.

**Patents**

* US 1745175 Julius Edgar Lilienfeld: "Method and apparatus for controlling electric current" first filed in Canada on 22.10.1925, describing a device similar to a MESFET
* US 1900018 Julius Edgar Lilienfeld: "Device for controlling electric current" filed on 28.03.1928, a thin film MOSFET
* GB 439457 Oskar Heil: "Improvements in or relating to electrical amplifiers and other control arrangements and devices" first filed in Germany on 02.03.1934
* US 2524035 J. Bardeen et al.: "Three-electrode circuit element utilizing semiconductive materials" oldest priority 26.02.1948
* US 2569347 W. Shockley: "Circuit element utilizing semiconductive material" oldest priority 26.06.1948

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