

# William Shockley

(1910–1989)



William Shockley invented the transistor, initiating a revolution in electronics. (© The Nobel Foundation)

## Inventor of the Transistor

A jogger wearing a Walkman is a common site. He can enjoy his music despite the jostling, and if he drops the Walkman, it will usually still work. In the early 1900s, the radio employed bulky, fragile *vacuum tubes*, as did early computers. Today people can carry personal computers in the palm of their hand; it is amazing to think that 50 years ago, a computer capable of performing similar tasks would have occupied an entire building. These incredible advances

are possible due to the invention of the *transistor* by a team of scientists led by the American physicist William Shockley in the 1950s. Transistors can amplify electrical signals and act as electronic switches to turn a current on or off. Because they contain no moving parts, they are more durable than vacuum tubes and work faster than a mechanical switch.

## Specialization in Solid-State Physics

William Bradford Shockley was born on February 13, 1910, while his American parents were living in London, England. His father, William Hillman Shockley, was a mining engineer, and his mother, May Bradford Shockley, was a mineral surveyor. The family returned to the United States when William was three years old. They lived in Palo Alto, California, and his mother home-schooled him until he was eight years old. A neighbor who was a professor of physics at Stanford University helped encourage William's early interest in physics. As a teenager, William attended the Palo Alto Military Academy and the Los Angeles Coaching School, where he studied physics. He graduated from Hollywood High School in 1927. He attended the University of California in Los Angeles for one year and then transferred to the California Institute of Technology, earning a bachelor's degree in physics in 1932.

In 1933, Shockley married Jean Alberta Bailey, with whom he had two sons and one daughter. They lived in Cambridge, where Shockley obtained a teaching fellowship and performed research in solid-state physics at the Massachusetts Institute of Technology. Solid-state physics seeks to explain the internal atomic structure and the electronic properties of materials such as metals and plastics. He received a Ph.D. in physics in 1936 with a dissertation titled "Calculation of Wave Functions for Electrons in Sodium Chloride Crystals." This background in solid-state physics prepared Shockley for his first job.

## The Old Technology

Bell Telephone Laboratories, in Murray Hill, New Jersey, offered Shockley a position exploring improvements in communications

mechanisms. At the time, vacuum tubes were used to amplify signals in many electronic devices. Vacuum tubes consisted of a glass outer shell from which all the air had been removed and at least two electrodes inside the bulb that were connected to outside electrical circuits. The positively charged electrode (*anode*) was called the collector, and the negatively charged electrode (*cathode*) was called the emitter. When the vacuum tube was connected to a current from an outside source such as a battery, electrons left the emitter. A wire mesh grid between the collector and emitter controlled the strength of the signal entering the tube by electrically repelling some electrons, preventing their passage. Vacuum tubes were used as rectifiers to change an *alternating current* to a *direct current*, to amplify an electronic signal, or to act as an *oscillator*. Oscillators change a direct current into an alternating current of a particular frequency.

The vacuum tube revolutionized communications technology after British scientist John A. Fleming modified the one originally designed by American inventor Thomas A. Edison to intercept wireless radio signals. Improvements in vacuum tube manufacture soon led to the tubes' widespread use in many electronic devices. Though considered one of the most important inventions of the 20th century, they were fragile, expensive to produce, inefficient, and did not last long.

When Shockley started working at Bell, his job was to design an improved vacuum tube for amplifying electric signals. Radios depended on vacuum tubes to *rectify* and amplify antenna signals from radio waves. Shockley knew that the earliest radios utilized one *semiconductor*, galena, as a rectifier before vacuum tubes were developed. (Semiconductors are discussed later in this chapter.) He thought something solid might perform better and have wider applications than a vacuum tube, so he applied his expertise to begin developing a rectifying semiconductor. Unfortunately, the pure materials he required were not yet available, and the Second World War delayed his research.

During World War II, Shockley developed radar equipment for the military. He also served as research director of the U.S. Navy's Anti-Submarine Warfare Operations Research Group at Columbia University and as an expert consultant to the secretary of war. In 1945, he returned to industrial research as the director of Bell's

solid-state physics research program, and he began collaborating with theoretical physicist John Bardeen and experimental physicist Walter H. Brattain. Shockley's goal was to replace the vacuum tube with a solid-state amplifier. The team spent one year unsuccessfully attempting to build Shockley's apparatus. When Bardeen suggested that electrons might get trapped on the surface rather than penetrate into the crystal, they went back to the drawing board to learn more about semiconductors.

## Semiconductors

Shockley still believed that a semiconductor could be used as an efficient electrical switch and to control the flow of an electrical current. Semiconductors are substances whose electrical conductivity is intermediate between good conductors, such as copper, and

insulators, such as plastic, that block currents. An electrical current is simply a flow of electrons through a conductive material. Semiconductors are ideal for electronic uses because they allow for control over the amount and direction of flow. Germanium was once popular, but silicon is the most widely used semiconductor today. A single atom of silicon contains four electrons in the outermost, or *valence*, shell. These electrons can each participate in a covalent chemical bond with valence electrons from neighboring silicon atoms—one above, one below, and one on each side. When they do so, they form a crystal lattice. The overlapping energy shells combine to form energy bands (analogous to the energy shells of a single atom), with the highest band containing electrons being called the valence band. The band one level higher is called the conduction band. During conduction of an electric current through the semiconductor, an electron moves to an unoccupied energy

### The Team

While Shockley was the originator of the concept of the transistor, a trio of scientists at Bell Laboratories brought the goal to fruition. Shockley shared the 1956 Nobel Prize in physics with John Bardeen and Walter Brattain for "their researches on semiconductors and their discovery of the transistor effect."

John Bardeen was born on May 23, 1908, in Madison, Wisconsin. He obtained a degree in electrical engineering from the University of Wisconsin in 1928. He continued his studies as a graduate research assistant working on mathematical problems in applied geophysics and on radiation from antennas. After two years, he moved to Pittsburgh, Pennsylvania, to work at the Gulf Research Laboratories, where he investigated magnetism and gravitational surveys for three years. In 1933, he

resumed his graduate studies on the theory of the work function of metals at Princeton University and earned a doctorate degree in mathematical physics in 1936. He next served as a fellow at Harvard University, then as assistant professor of physics at the University of Minnesota, and as a civilian physicist at the Naval Ordnance Laboratory in Washington, D.C., before he landed at Bell Laboratories in 1945. Bardeen was awarded a second Nobel Prize in physics in 1972, an honor he shared with Leon Neil Cooper and John Robert Schrieffer for their jointly developed theory of superconductivity, usually called the BCS-theory. Bardeen died on January 30, 1991.

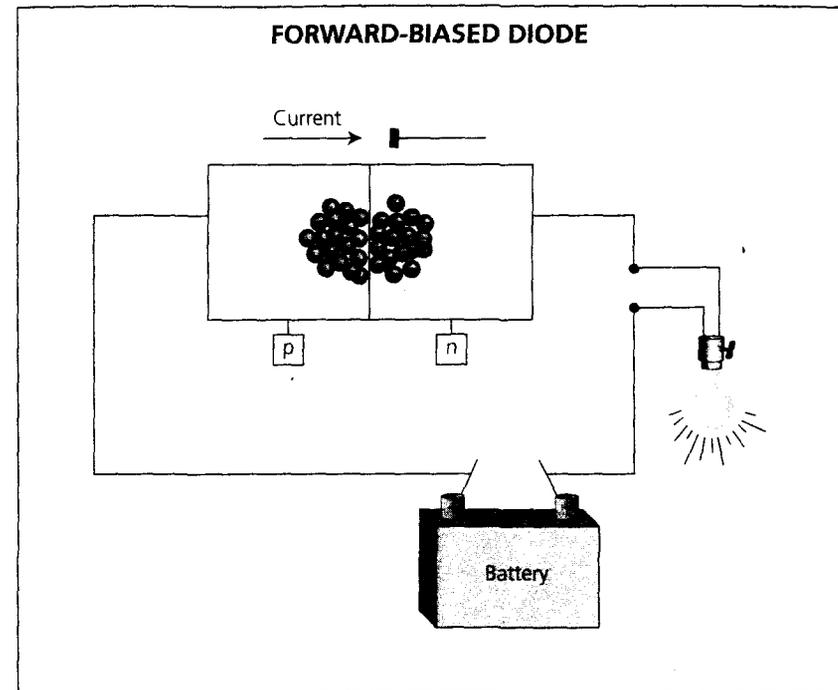
Walter H. Brattain was born on February 10, 1902, in Amoy, China, but grew up on the family ranch in the state of Washington. He earned a bachelor of science degree in 1924 from Whitman College, a master of arts degree in 1926 from the University of Oregon, and a Ph.D. in physics from the University of Minnesota in 1929. After obtaining his doctorate, he accepted a position at Bell Laboratories, where his major research focus was the surface properties of solids. He died on October 13, 1987.

level, leaving behind a hole that can be filled by another electron moving into that empty position.

*Doping* is a process whereby impurities are added to the otherwise pure semiconductor in order to modify its conduction properties. For example, boron may be added to silicon. Boron has one less valence electron than silicon, thus the doped semiconductor contains an overall shortage of electrons. This type of semiconductor is called a P-semiconductor, because the lack of electrons effectively acts like an extra positive charge, though it should be noted that the semiconductor retains a net charge of zero. In P-type semiconductors, holes carry the current through the solid. In the process of N-doping, the added impurity has one more electron in its valence shell compared to silicon, making it easier for electrons to make the jump up to the conduction band. The element phosphorus, which has five valence electrons, is an example of an N-type dopant. In N-type semiconductors, negatively charged electrons carry the current. The amount of dopant is very tiny—roughly one atom per 10,000,000 atoms of the semiconductor.

## The First Transistor

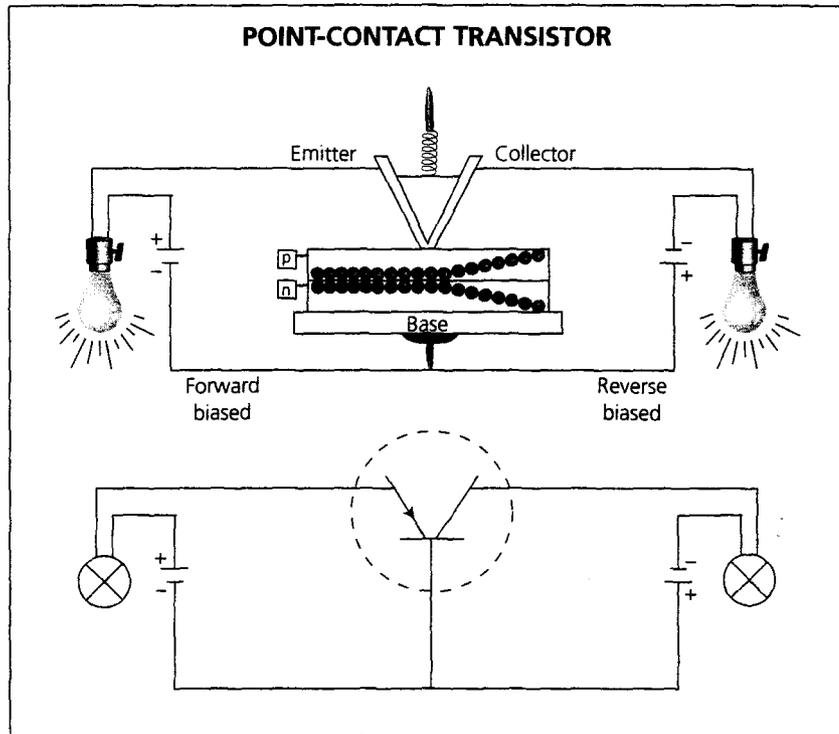
Bardeen and Brattain announced their success in building the first transistor (named by combining the terms *transfer* and *resistor*) at a press conference during the summer of 1948. In order to understand how it functioned, consider the following. When a P-type and an N-type semiconductor are placed next to one another to create a P-N junction, there is an excess of electrons on the N side of the junction and a deficiency on the P side. This formation is called a *diode*, and the current can flow in only one direction. When the diode is connected to a battery such that the positive pole is connected to the P side and the negative pole is connected to the N side, the electrons and the holes in the semiconductors are drawn toward the P-N junction. The nearness allows the electrons to jump into the holes, and current flows through the diode. If the battery is connected in the reverse order, then no current will flow. Diodes are used as detectors in television and radio receivers and to convert alternating currents to direct currents.



In a forward-biased diode, the electrons and holes gather near the P-N junction, where their proximity to one another allows the electrons to jump into the holes.

Bardeen and Brattain had built a point contact transistor that consisted of a block of N-type germanium, two gold contacts on one face of the crystal, and a tungsten base on the opposite side. This transistor was actually a triode, since there were three electrical terminals compared to two in a diode. One gold point contact was connected to a battery creating a forward-biased circuit; the other was reverse-biased. The gold contact where the current entered the semiconductor (on the forward-biased side) was called the emitter, and the other gold contact (on the reverse-biased side) was called the collector. The contact at the metal base acted as the base-electrode. Having two gold contacts allowed some control over the circuit. When voltage was applied, holes in the germanium near the emitter gold contact flowed to the collector, amplifying the signal at the collector in the process.

Within a few months, Shockley suggested improvements that led to the junction transistor that was first built in 1951. He proposed

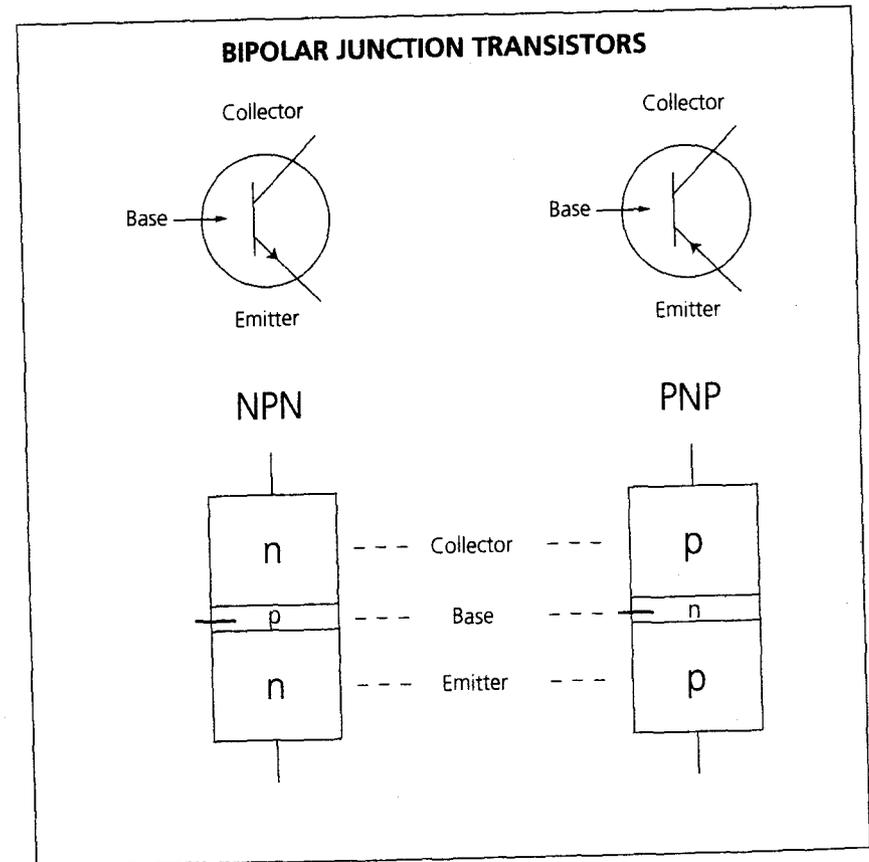


No current flows in a reverse-biased circuit alone, but when paired with a forward-biased circuit in a triode, activation occurs.

sandwiching a thin P-region between two N-regions to create an NPN junction and giving all the regions separate contacts. When a positive voltage was applied to the collector, the current flowed into the transistor through the collector, through the base, and out the emitter. Applying a small current to the base restricted the flow through the transistor, while amplification could be achieved by applying a large current to the base, supplying extra charge carriers. By the early 1950s, the junction transistor already was being used in hearing aids, radios, and microphones. The junction transistor eventually evolved into the more modern field-effect transistors (FETs) that also have three electric terminals but operate in a slightly different manner. Shockley, Bardeen, and Brattain shared the Nobel Prize in physics in 1956 for their research on semiconductors and their discovery of the transistor effect.

## Controversy

In 1954, Shockley resigned from Bell Laboratories and served as deputy director and research director for the Weapon System Evaluation Group of the Defense Department for one year. After moving his family to Palo Alto, California, he founded the Shockley Semiconductor Laboratory, later named the Shockley Transistor Corporation. The company was sold a few times and closed in 1969. He began consulting for Bell Labs again in 1965. Shockley's first marriage had ended in divorce in 1955, and he married Emily I. Lanning.

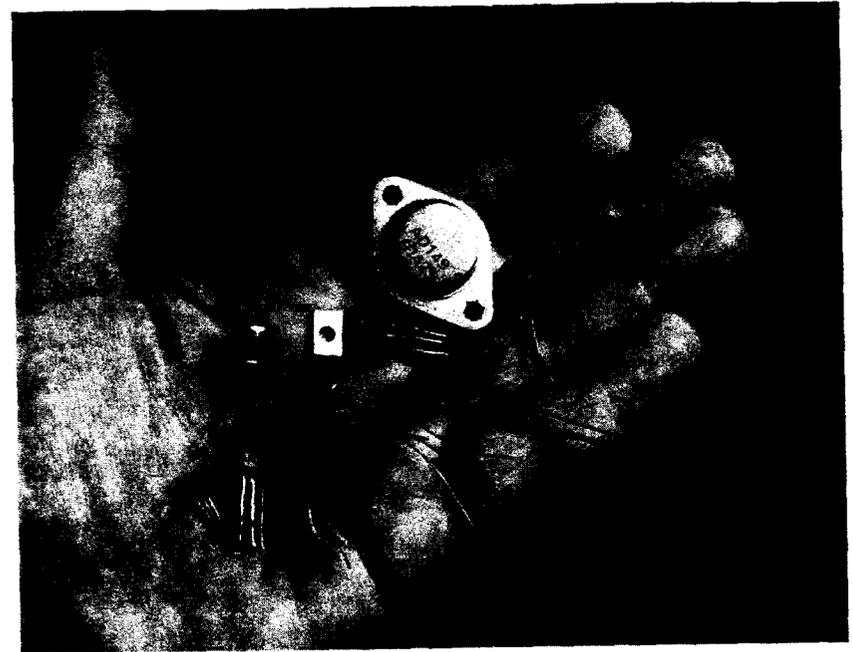


A bipolar junction transistor contains an opposed pair of P-N diodes in a single crystal.

Stanford University appointed Shockley the first Alexander M. Poniatoff Professor of Engineering and Applied Sciences in 1962. He taught electrical engineering at Stanford until he became a professor emeritus of electrical engineering in 1972, but his time there was marked by his controversial pronouncements concerning the relationship between race and intelligence. Though he never received formal training in a related field, he formulated the outrageous opinion that African Americans were not as naturally intelligent as Caucasians. He went further to suggest that more "white" genes would give an African American a greater mental capacity. Atrociously, he recommended that people with IQs lower than 100 be paid to undergo surgical *sterilization* in order to improve the human race. Though psychologists and educators rejected his conclusions, the offensive implications incited much controversy. Students protested in his classes, and his scientific reputation was called into question.

## Initiation of the Computer Revolution

William Shockley died from prostate cancer on August 12, 1989, in Palo Alto, California. Though actions during his later years marred his reputation, Shockley's expertise in electrical engineering and his ability to solve problems stimulated the computer revolution. He obtained more than 90 patents for his valuable inventions, and many academic organizations honored his achievements. He received the Morris Leibmann Memorial Prize from the Institute of Radio Engineers in 1952, the Oliver E. Buckley Solid-State Physics Prize from the American Physical Society in 1953, the National Academy of Sciences Comstock Prize in 1954, the American Society of Mechanical Engineers Holley Medal in 1962, the Institute of Electrical and Electronic Engineers Gold Medal in 1972, and their Medal of Honor in 1980. He received the U.S. Medal of Merit in 1946 for his work with the war department, was appointed to the President's Scientific Advisory Committee in 1962, and was named to the National Inventors Hall of Fame in 1974. Shockley also was awarded honorary doctorate degrees from the University of Pennsylvania, Rutgers University, and Gustavus Adolphus College in Minnesota.



Transistors, such as these examples from the 1960s to 1990s, have allowed the miniaturization of electronic components. (Tony Craddock/Photo Researchers, Inc.)

Shockley's transistor was a revolutionary invention; however, it was bulky and difficult to produce en masse. Contemporary field-effect transistors (FETs) are used more generally. The type most commonly found in personal computers, metal oxide semiconductor field effect transistors (MOSFETs), contain different layers of doped silicon. Transistors range in size from  $3.9 \times 10^{-5}$  inch (0.001 mm) to slightly less than one inch (2.54 cm) in width. Millions can be placed on tiny silicon chips called integrated circuits, microprocessors, or computer chips. Electronic circuits running through these computer chips carry out the work of computers, such as performing calculations and forming images on the monitor. Shockley passed away before the Internet became popularized, but he would no doubt have been pleased to see such a remarkable application of the technology he helped create. His invention of the transistor was responsible for the miniaturization of circuits and the affordability and reliability of the electronic devices we enjoy today.

**CHRONOLOGY**

- 1910** William Shockley is born on February 13 in London, England
- 1932** Receives a bachelor of science degree in physics from the California Institute of Technology
- 1936** Obtains a doctorate degree in physics from the Massachusetts Institute of Technology and starts working at Bell Telephone Laboratories
- 1942-45** Participates in war effort by researching radar and anti-submarine warfare and consulting to the secretary of war
- 1945** Returns to Bell Laboratories and researches the use of semiconductors to replace vacuum tubes
- 1947** Bardeen and Brattain build the first successful point contact transistor
- 1951** Shockley's junction transistor is built
- 1955** Leaves Bell Laboratories and starts own company, Shockley Semiconductor Laboratory, later named Shockley Transistor Corporation
- 1956** Shockley shares the Nobel Prize in physics with Bardeen and Brattain for their research on semiconductors and for developing the transistor
- 1962** Becomes the first Alexander M. Poniatoff Professor of Engineering and Applied Sciences at Stanford University
- 1972** Retires from Stanford University
- 1989** On August 12, Shockley dies from prostate cancer at age 79, in Palo Alto, California

**FURTHER READING**

*Biographical Memoirs of Fellows of the Royal Society*. Vol. 68. London: The Royal Society, 1996. Authoritative, full memoir written by a distinguished colleague; includes a complete bibliography.

- Encyclopedia of World Biography, Second Edition*. Vol. 14. Detroit: Gale Research, 1998. Brief biographies of notable figures and summaries of their accomplishments. Written for high school students.
- Garraty, John A., and Mark C. Carnes, eds. *American National Biography*. Vol. 19. New York: Oxford University Press, 1999. Brief accounts of the lives and work of famous Americans in encyclopedia format.
- Nobelprize.org. "The Nobel Prize in Physics 1956." Available online. URL: <http://www.nobelprize.org/physics/laureates/1956>. Last modified on June 16, 2000. Contains links for Shockley's biography, his Nobel lecture, and other related resources.
- Saari, Peggy, and Stephen Allison, eds. *The Lives and Works of 150 Scientists*. Vol. 3. Detroit: U\*X\*L, 1996. Alphabetically arranged introductions to the contributions of scientists from a variety of fields. Appropriate for middle school students.