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Norriss Hetherington

## SHOCKLEY, WILLIAM BRADFORD

(b. London, United Kingdom, 13 February 1910; d. Stanford, California, 12 August 1989), *solid-state physics, invention of the transistor, operations research, eugenics*.

Shockley was one of the most innovative scientists of the twentieth century and a principal figure in establishing the discipline of solid-state physics. Together with

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John Bardeen and Walter Brattain, he invented the transistor, sharing the 1956 Nobel Prize in Physics with them for this achievement. In particular, he conceived the junction transistor, a solid-state amplifier and switch that was commercialized during the 1950s and eventually led to the microelectronics revolution. In founding the Shockley Semiconductor Laboratory in California, he catalyzed the emergence of Silicon Valley as the epicenter of the global semiconductor industry. As a Stanford University professor during the last two decades of his life, he espoused controversial views on race and intelligence that brought him substantial public attention and notoriety.

**Early Years.** Shockley was born in London on 13 February 1910, the only son of William Hillman Shockley, a Massachusetts Institute of Technology (MIT)–educated mining engineer and consultant, and Cora May Shockley (née Bradford), who had graduated from Stanford with degrees in art and mathematics. Both Americans, they returned to the United States in 1913 and lived in Palo Alto, California, while the elder Shockley taught mining engineering part time at Stanford. Young William was schooled at home until he was eight, after which he attended private grammar schools. A major influence during this period was Perley Ross, a professor of physics at Stanford and a neighbor, who stimulated his interest in science. In 1923 the family moved to Hollywood, where he attended Hollywood High School for the next four years, graduating in 1927. During his high school years, he began to demonstrate great proficiency in mathematics and science, especially physics.

After a year at the University of California, Southern Branch (now known as UCLA), Shockley transferred in 1928 to the new California Institute of Technology (Caltech) in nearby Pasadena. Under Nobel laureate Robert Millikan, Caltech was then becoming established as one of the premier American institutions of science and technology. There Shockley was exposed to the revolutionary ideas of quantum mechanics by such professors as William Houston, Linus Pauling, and Richard Tolman. In 1932 he drove east to begin graduate study in physics at MIT, doing theoretical research on solid-state physics under John Slater, one of the acknowledged founders of the new discipline. In his PhD dissertation, submitted in early 1936, Shockley calculated the energy-band structure of sodium chloride—the quantum-mechanical energy levels at which electrons can (or cannot) flow through a crystal lattice of this compound. It was among the first attempts to do such calculations for a compound rather than a chemical element.

As a graduate student at MIT, Shockley had met and married Jean Alberta Bailey of Los Angeles while home for the summer of 1933. The couple had their first child,

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Alison, the following year. In the summer of 1936, the family relocated from Cambridge, Massachusetts, to New York City. Shockley began his first professional job there as a physicist at Bell Telephone Laboratories, then located in Manhattan. He had been hired by Bell Labs research director Mervin Kelly, who impressed him with the Bell System's need for some kind of solid-state switch to replace the slow, unreliable electromechanical switches then in wide use. The key to Kelly's ultimate vision of electronic switching systems, this device became one of Shockley's major research goals for the next quarter century. He proposed at least two ideas for such a device during the next five years, both based on the compound semiconductor material copper oxide, but neither of them worked as he had hoped.

As it did for almost all U.S. physicists, the onset of World War II interrupted Shockley's research. At first he worked on radar systems at Bell Labs and Western Electric, the manufacturing arm of parent company AT&T. But in the spring of 1942 he was recruited by Philip Morse (under whom he had studied quantum mechanics at MIT) to become the research director of the U.S. Navy's new Anti-Submarine Warfare Operations Research Group. Headquartered initially at Columbia University, this team of scientists and mathematicians applied probability, statistics, and scientific methods to the analysis and improvement of military operations—in particular the naval campaign against German U-boats in the Atlantic Ocean. Operations research and airborne radar systems effectively eliminated this threat by 1943. Following that, Shockley began working in Washington as a special consultant in the office of the secretary of war. Using operations-research methods, he planned and implemented a training program for B-29 crews employing an advanced short-wavelength, high-altitude radar bombing system manufactured by Western Electric. The program proved so effective in the air war against Japan that in October 1946 Shockley was awarded the National Medal of Merit, the nation's highest civilian honor for wartime activities.

**The Invention of the Transistor.** In early 1945 Shockley returned part time to Bell Labs, which had moved to Murray Hill, New Jersey, and began organizing a solid-state physics research group. Experimental physicists Walter Brattain and Gerald Pearson joined it at the outset; that fall theorist John Bardeen was lured away from the University of Minnesota, where he had planned to return after war ended. Shockley also revived his prewar research on solid-state devices.

In April 1945 he conceived a solid-state switch based on the semiconductor materials silicon and germanium; the technology of these elements had advanced tremendously during wartime radar research. In what is now

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called a field-effect transistor, Shockley suggested that a strong electric field applied by a metal plate just above the semiconductor surface would penetrate into the bulk material and dramatically increase the population there of charge carriers—in this case free electrons. A voltage across the semiconductor chip would thus lead to a proportional increase in the current through it. Therefore an electrical signal on the plate could be used to modulate the current flowing through this semiconductor device, which should then act as an amplifier or switch.

But attempts by Brattain and others to make such a device failed miserably in the spring of 1945, and Shockley turned to other research, including the theory of crystalline defects. When Bardeen joined the group that fall, Shockley assigned him the task of trying to understand why, based on the existing semiconductor theory, almost no effect had been observed. In March 1946 Bardeen proposed his surface-state theory: that a layer of electrons drawn to the semiconductor surface by the electric field was blocking penetration of the field into the bulk material, so that no increase in charge carriers could occur.

Based on this hypothesis, Bardeen and Brattain then pursued a long series of experiments that eventually led to their successful invention of the point-contact transistor in December 1947. By a combination of experimental ingenuity, theoretical insight, and plain old serendipity, they stumbled across a technique to overcome the barrier layer by using two closely spaced metal points that contacted the surface of a germanium sliver. As Shockley and Bell Labs executives watched on 23 December 1947, the rickety device amplified 1 KHz AC signals by a factor of forty.

In a memoir written twenty-five years later, Shockley dubbed this breakthrough “a magnificent Christmas present for Bell Labs,” which had staunchly supported his group's program of basic research on solid-state physics. But, he continued, “My elation with the group's success was tempered by not being one of the inventors. I experienced frustration that my personal efforts, started more than eight years before, had not resulted in a significant inventive contribution of my own” (Shockley, 1976, p. 612). Shockley also recognized that this fragile, “proof-of-principle” device would be almost impossible to manufacture with stable, reproducible characteristics. Thus only a month later, on 23 January 1948, he conceived his own particular variety of transistor, called the junction transistor. It was a three-layer sandwich of *n*-type and *p*-type germanium or silicon; *n*-type semiconductors have a slight excess—and *p*-type a slight deficit—of electrons. Electrical action at the interfaces, known as *p-n* junctions, between two dissimilar layers perform the same physical function as the point contacts in Bardeen and Brattain's device. In Shockley's junction transistor, a small electrical



**William Bradford Shockley.** *Shockley in his laboratory with transistor.* AP IMAGES.

signal on the inner, or “base,” layer—the meat in the sandwich—would modulate the current flowing from end to end through the device.

But the successful operation of the junction transistor depended upon a new, hypothetical process that Shockley called “minority carrier injection,” which was not initially obvious. Quantum mechanical entities called “holes”—which correspond to the electron deficits in a crystal lattice and respond like positively charged entities to an electric field—had to be able to survive at least briefly in the presence of an excess of electrons. Or vice versa. Normally an electron and a hole will “recombine” to produce light when they meet, but Shockley guessed that they

might last long enough in close proximity for his junction transistor to work. After a February 1948 experiment at Bell Labs showed that minority carrier injection did indeed occur, he boldly announced his invention to Bardeen, Brattain, and other surprised colleagues.

Shockley published his detailed theory of this device as “The Theory of  $p$ - $n$  Junctions in Semiconductors and  $p$ - $n$  Junction Transistors” in the January 1949 issue of the *Bell System Technical Journal*. When it appeared, no successful demonstration of such a device had yet occurred. But that April Morgan Sparks, a physical chemist in Shockley’s group, fabricated a crude junction transistor from germanium that amplified signals by up to sixteen

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times. Shockley was then busy writing up this research for a book, *Electrons and Holes in Semiconductors*. Published by Van Nostrand in 1950, it quickly became the bible of the emerging semiconductor industry.

The successful development of a commercial junction transistor took another two years, prodded by military requirements for proximity fuses in the Korean War. A crucial enabling technology was the growth of large single crystals of germanium by Bell Labs chemist Gordon Teal; electrons and holes can drift faster and therefore farther in crystalline semiconductor materials under the influence of an electric field. In the spring of 1951, Sparks and Teal succeeded in fabricating germanium junction transistors with narrow base layers less than 50 micrometers thick that amplified electrical signals above 1 megahertz. Consuming only microwatts of power, these transistors exceeded the performance of point-contact transistors in every respect. News of this breakthrough was announced by Bell Labs on 4 July 1951; that same month it was published in a *Physical Review* article by Shockley, Sparks, and Teal.

Shockley continued to invent, patent, and publish at a feverish rate for the next few years. One of his most noteworthy inventions was the junction field-effect transistor, which combined features of these two approaches to transistor design. Another important conception was the four-layer *nnpn* diode, or "avalanche" diode, a bistable device with potential applications in electronic switching systems. In a 1954 reorganization, he became the head of a new transistor physics group at Bell Labs responsible for spearheading research on these kinds of advanced devices.

During the decade after World War II, Shockley also maintained the close connections with the military that he had developed during wartime. Beginning in 1947, he served on the policy committee of the Joint Research and Development Board of the armed services, specializing in electronics. With Vannevar Bush, who had led the U.S. Office of Scientific Research and Development during the war, he helped establish the Weapons Systems Evaluation Group at the Defense Department in 1948. This operations-research-style group brought civilian researchers into the Pentagon from industry and academia; they worked closely with military analysts, advising the armed services on highly sophisticated Cold War weaponry such as the hydrogen bomb, intercontinental ballistic missiles, and anti-ballistic-missile systems. Shockley finally stepped in as deputy director of this group for a year, in 1954 to 1955.

He also began to get increasingly widespread recognition in the scientific community for his achievements. In April 1951 he became a member of the National Academy of Sciences, one of the youngest scientists ever to attain this honor. In 1953 the American Physical Society

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awarded Shockley its first Oliver E. Buckley Prize for advancements in solid-state and condensed-matter physics. And in 1954 he received the National Academy's prestigious Comstock Prize, awarded every five years for major advances in electricity and magnetism.

But these achievements and honors came at the cost of mounting disaffection from his family. Although close to his daughter Alison, Shockley grew distant from his two sons William and Richard, born in 1942 and 1947, because of the amount of time he spent away from home. This deterioration culminated in a 1955 divorce from his wife Jean, at the time recovering from uterine cancer. That November he remarried, to Emmy Lanning, a psychiatric nurse he had met in Washington while working at the Pentagon.

**Shockley Semiconductor Laboratory.** Shockley also was increasingly dissatisfied with his employment at Bell Labs. Under his leadership, the transistor physics group had spearheaded development of high-frequency junction transistors based on the diffusion of chemical impurities to form extremely narrow base layers in crystalline silicon. These transistors are able to amplify and switch electrical signals at frequencies above 100 MHz, typical in FM radio and television transmission. But he felt his advancement at the labs was blocked, and he wanted to make his fortune in the emerging semiconductor industry.

Thus in the summer of 1955, with Mervin Kelly's blessings, he began to seek outside financial support to found his own semiconductor Research & Development company. That September he met with fellow Caltech alumnus Arnold Beckman, a successful chemist and businessman who had founded Beckman Industries; they agreed to set up Shockley Semiconductor Laboratory in California as a division of Beckman Industries. Their agreement stated that "the development of automatic means for the production of diffused-base transistors" was to be one of its principal projects.

Shockley began recruiting scientists and engineers for the new firm, which in February 1956 formally began operations near Palo Alto in Mountain View. Among his early recruits were Robert Noyce, who had earned his PhD in physics from MIT and was working on transistors at Philco, and Gordon Moore, a Caltech-educated physical chemist. With about a dozen other scientists and engineers, they toasted their leader that November, after it was announced that he would share the 1956 Nobel Prize in Physics with Bardeen and Brattain for the invention of the transistor.

But all was not well at the fledgling semiconductor firm, the first of its kind in northern California. Shockley repeatedly took his talented recruits off work related to the main goal of developing diffused-base transistors from

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silicon and reassigned them to research on the junction field-effect transistor, the four-layer diode, and other more challenging projects that were far from commercialization. Add to that his extremely difficult management style, and the seeds of a revolt began to take root among his technical staff.

In September 1957 eight of his best scientists and engineers including Noyce and Moore resigned to form the Fairchild Semiconductor Corporation with funding from the Fairchild Camera and Instrument Company of Syosset, New York. Within a year this renegade firm had manufactured silicon diffused-base transistors for sale to IBM Corporation and was operating profitably. In March 1961 Fairchild began to market its Micrologic series of integrated circuits built around silicon transistors, the first microelectronic circuits to be commercialized. During the early 1960s, these and successive microcircuits found quick application in the Minuteman ballistic missile system and the Apollo Moon-landing project. Later that decade, Noyce and Moore left Fairchild to found the Intel Corporation.

The Shockley Semiconductor Laboratory struggled on under Shockley's leadership. He hired another group of scientists and engineers, which concentrated most of its efforts on the four-layer diode, called the Shockley diode, which he viewed as the key to Kelly's vision of electronic telephone switching systems. But it proved far too difficult to manufacture in quantity with reliable, reproducible characteristics. The company was reorganized into the Shockley Transistor Corporation in 1958 and sold to the Clevite Corporation in 1960, never having realized a profit.

During these Mountain View and Palo Alto years, Shockley kept on making valuable contributions to the literature on semiconductor physics. With Noyce and another scientist, he wrote an important 1957 article on electron-hole recombination in *p-n* junctions, and in 1961 coauthored a theoretical paper on the efficiency of photovoltaic cells. But his creative scientific and technological career essentially ended in 1961 after a disastrous head-on automobile collision that almost killed him and left him and Emmy hospitalized for months. Afterward his scientific productivity slowed to a crawl.

**The Stanford Years.** In 1963 Stanford University invited Shockley to join its faculty as the new Alexander M. Poniatoff Professor of Engineering and Applied Science. At first it was a part-time position, as he still had ongoing responsibilities directing the company. He taught seminars and advised graduate students in semiconductor physics and electronics. Then he branched out into the study of human creativity, especially as applied to science and mathematics, lecturing a freshman course on what is

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now known as conceptual blockbusting. He began publishing on the subject, advocating his own "try simplest cases first" approach to problem solving. In 1965, after Clevite sold the company to International Telephone and Telegraph, Shockley returned to Bell Labs part time as a special consultant on scientific training, while continuing to teach at Stanford. He retired from Stanford in 1972 and from Bell Labs in 1975.

About this time Shockley also began to espouse controversial ideas on race and intelligence, initially in connection with two Nobel symposia at the Gustavus Adolphus College in Minnesota in 1963 and 1965. He argued that people of lesser intelligence (as determined by IQ tests) appeared to have more children and that intelligence was a genetically inheritable trait. Thus a kind of reverse evolution or "dysgenics," as he termed it, is unwittingly at play in advanced societies because almost everyone survives today thanks to modern medicine. The fact that he was a Nobel laureate and a Stanford professor meant that these observations attracted major media attention, helping to stoke raging fires of controversy in the mid-1960s. Interviews in *U.S. News and World Report* (1965) and *Playboy* (1980) brought Shockley widespread notoriety and charges of racism after he noted that African Americans generally scored well below average on IQ tests. He began advocating a version of eugenics, based on his operations-research approach to improving human quality, as he viewed it. He never abandoned this topic, pursuing nearly every opportunity to expound his views on it for the rest of his life. Because of his obsession with the subject, his friends and colleagues increasingly avoided contact with him as he aged.

In 1987 Shockley learned that he had prostate cancer but did not choose to undergo surgery. Within a year it had metastasized to his bones and he began receiving x-ray treatments, to little avail. He died at home on the morning of 12 August 1989, age 79.

At the time of his death, Shockley had over one hundred publications in scientific and technical journals, as well as more than ninety patents awarded him, including the crucial U.S. Patent 2,569,347 (issued 25 September 1951) on the junction transistor. In addition to being a member of the National Academy of Sciences, he was a Fellow of the American Academy of Arts and Sciences, the American Physical Society, and the Institute of Electrical and Electronics Engineers. His colleagues recall his intellectual brilliance, especially how quickly he could dig down to the core issues of a scientific or technological problem, reducing it to fundamentals that could be readily tested by experimental or theoretical means. The physics he pursued was usually closely related to practical devices that could have significant impacts on our lives.

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He was also adept at explaining physics to nonspecialists, in both his writings and lectures.

In addition to all his scientific and technological achievements, Shockley was an accomplished rock climber and mountaineer, credited with several first ascents. In the 1960s he began pursuing the sport of sailing, especially after his 1961 accident, and soon became skilled at it, winning local competitions. He was also an excellent amateur magician, often using parlor tricks to enhance his scientific presentations.

Shockley's greatest legacies are the transistor, arguably the most important invention of the twentieth century, and the rise of Silicon Valley as the epicenter of the global semiconductor industry. Far more than any other person, he relentlessly pursued the goal of a solid-state amplifier and switch from a hazy conception to its eventual realization as the commercial product that has become ubiquitous in daily life. Shockley also brought the technologies of silicon and diffusion from Bell Labs to the San Francisco Bay area, while gathering together the team of talented scientists and engineers who extended these technologies at Fairchild Semiconductor and took the next step of commercializing integrated circuits. To knowledgeable observers, he deserves to be recognized as the "father of Silicon Valley." Few, if any, people have had a greater impact on what it means to be modern.

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Michael Riordan

**SHOEMAKER, EUGENE MERLE** (*b.* Los Angeles, California, 28 April, 1928; *d.* near Alice Springs, Australia, 18 July 1997), *space science, astrogeology, studies of the populations of comets and asteroids, specifically those that could strike the Earth*.

Shoemaker began a new science—the history of the solar system and the often violent interactions among the planets—called astrogeology. His early studies of lunar craters suggested that these features were the result of impacts, and that the crater record could provide an indication of the level of risk by impact to the Earth. These studies led to his training of astronauts for the Apollo program in the 1960s. Shoemaker's interests then turned from the effects of impact to the objects themselves, the comets and asteroids that do the impacting. This phase of his career reached its climax in July 1994, when the comet he helped to discover, Shoemaker-Levy 9, collided with Jupiter in a cosmic and forceful demonstration of his ideas.